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Explanation of symbols

.	= data not available
*	= provisional figure
x	= publication prohibited (confidential figure)
–	= nil or less than half of unit concerned
–	= (between two figures) inclusive
0 (0,0)	= less than half of unit concerned
blank	= not applicable
2007–2008	= 2007 to 2008 inclusive
2007/2008	= average of 2007 up to and including 2008
2007/'08	= crop year, financial year, school year etc. beginning in 2007 and ending in 2008
2005/'06–2007/'08	= crop year, financial year, etc. 2005/'06 to 2007/'08 inclusive

Due to rounding, some totals may not correspond with the sum of the separate figures.

Productivity effects of innovation modes

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Abstract

Many empirical studies have confirmed the positive impact of innovation on productivity at the firm level. The focus tends to be either on R&D driven technological innovation on the one hand, or on organisational changes complemented by ICT on the other. To investigate the effect of different types of innovations on productivity, we propose a model with two innovation input equations (R&D and ICT) that feed into a knowledge production function consisting of a system of three innovation output equations (product innovation, process innovation and organisational innovation), which ultimately feeds into a productivity equation. We find that ICT is an important driver of innovation in both manufacturing and services. Doing more R&D has a positive effect on product innovation in manufacturing. Organisational innovation has the strongest productivity effects. We only find positive effects of product and process innovation when combined with an organisational innovation.

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1. Introduction

Innovation is considered to be a key driver of productivity growth. The introduction of new goods and services, as well as novelties in methods of production and non-technological aspects as management and marketing, allow firms to improve efficiency. There is much empirical research on the contribution of various instances of innovation on productivity and, moreover, on what in turn are the drivers of innovation. Despite sharing a clear common ground, it seems that there are roughly two separate strands of literature to be distinguished: one strand dealing with R&D driven technological innovation, and another strand that seeks to explain productivity differences from organisational changes propagated by the use of information technology. In this paper we aim to provide a more encompassing empirical description of the innovation process in firms, by combining elements from both strands of literature.

In the pioneering work by Griliches (1979), the production function is augmented with R&D to account for the fact that knowledge, and the generation thereof, contributes to the output of a firm. Crépon, Duguet, and Mairesse (CDM, 1998) extended this insight to a distinction between innovation input (e.g. R&D) and innovation output (i.e. knowledge). The idea is that innovation input (research effort, and sources of knowledge) leads to the generation of knowledge, which may manifest itself in an improved product or better production methods, and is put to use in the production process. Since the seminal contribution by CDM, many studies have confirmed the positive impact of innovation on productivity at the firm level. Examples of such studies include Lööf and Heshmati (2002) and Van Leeuwen and Klomp (2006). As in CDM, the focus in these studies is on product innovation, the main reason being that this type of innovation is the only one for which a quantitative output measure is readily available (e.g. the share of innovative products in sales from innovation surveys, or patent data). However, as mentioned above and recognized in current innovation surveys, there are various types of innovation, such as process innovation, organisational innovation and other types of non-technological innovation.

Changes in organisation and, in particular, its combination with investment in IT, is the topic of empirical work by Brynjolfsson and Hitt (2000) and Brynjolfsson et al. (2006). In their work, IT enables organisational investments (business processes and work practices), which in turn lead to cost reductions and improved output and, hence, productivity gains. Investment in information and communication technology (ICT)[1] can therefore be considered as a separate input into the innovation process, which can lead to new services (e.g. internet banking), new ways of doing business (e.g. B2B), new ways of producing goods and services (e.g. integrated management)

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[1] In this paper we will look at ICT rather than IT, as communication technology is also likely to be of importance for improving both innovative capabilities and productivity. Bloom et al. (2009) show that information technology and communication technology are associated with different types of organisational change.

or new ways of marketing (e.g. electronic cataloguing).[2] Besides the emphasis on the complementarity between ICT and changes in the organisation of the firm, there is evidence that the use of ICT also has a positive effect on product innovation and productivity (Van Leeuwen, 2008).

In this paper, we bring together the insights from both the work on R&D and technological innovation, as well as from that on organisational innovation and ICT. We extend the CDM framework to include both technological as non-technological innovation output, and ICT as an additional innovation input besides R&D. This is one of the first studies to include three types of innovation as well as modelling ICT as an enabler of innovation. The plan is as follows. In section 2, we briefly review some related literature on the effects of various types of innovation on productivity and the role of ICT. In section 3 we outline our model and estimation strategy. In section 4 we describe the data and the main variables, whereas in section 5 we present the estimation results. Section 6 concludes and gives directions for further research.

2. Related literature

The CDM model has been estimated on firm data originating from innovation surveys in OECD and non-OECD countries. The models differ by the types of innovation that are considered, the modelling of their interactions, the use of quantitative or qualitative innovation indicators, and the econometric methods used to account for simultaneity and selectivity. In this brief survey, we shall focus on two generalizations of the original CDM model, the introduction of process innovations besides product innovations, and the introduction of ICT indicators. The former are readily available in the innovation surveys, the latter requires merging the innovation survey data with data from ICT surveys. Moreover, we discuss some related literature on the importance of ICT and the role of organisational innovation.

Given that productivity gains are related to production efficiency and factor saving, it can be argued that an analysis of the productivity effects of innovation that focuses exclusively on product innovation is too restrictive. However, due to the lack of continuous output measures it is not straightforward to extend the model to other types of innovation. For product innovations most of the time it is the share of total sales that are due to innovative products that is used to measure the intensity of innovation, or alternatively the number of patents. For other types of innovation (process, organisation), it is usually only observed whether a firm has performed the innovation or not.

Griffith et al. (2006, henceforth GHMP) use the binary indicators for product and process innovation in the augmented production function as measures for innovation

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[2] Murphy (2002) provides an overview of examples of organisational changes, documenting its relation with ICT and evidence for its effect on firm performance.

output in a study for four countries: France, Germany, Spain, and the UK. They estimate the corresponding knowledge production function, linking innovation inputs to innovation outputs, by two separate probits, calculate the propensities for both types of innovation, and replace them *in lieu* of the product and process dummies in the augmented production function. This controls for the possible endogeneity of innovation output. Robin and Mairesse (2008, henceforth RM) for France adjust the GHMP model slightly by estimating the knowledge production function as a bivariate probit, which allows to calculate the propensity of performing both a product and a process innovation together in addition to the probabilities of performing them separately. This term can be used to assess the possible complementarity between the two types of innovation. For manufacturing, GHMP only find a positive significant effect for process innovation in France; in the other countries it is insignificant. Product innovation, on the other hand, has a positive significant effect in all countries but Germany. For France, RM find positive effects for product and process innovation separately, and also for their combined occurrence. Their findings hold for both the manufacturing and the services sector.

Roper et al. (2008) use binary indicators for product and process innovation, as well as a mix of a continuous measure for product innovation and a binary decision variable for process innovation. Based on the Irish Innovation Panel (IIP), they find no significant effect of both types on productivity when using the binary specification. They find a significant negative effect for product innovation when using the continuous measure of innovation success.[3] This is interpreted as a possible disruption effect. The authors do not control for potential endogeneity, because they argue that 'the recursive nature of the innovation value chain suggests that innovation output measures are necessarily predetermined' (*op. cit.* p. 964). Mairesse, Mohnen and Kremp (2009) compare the effects on TFP of various (quantitative and qualitative) product and process innovation indicators, introducing them individually and controlling for their endogeneity by estimating the respective models by Asymptotic Least Squares. Contrary to Roper et al. (2008), they find a higher impact for process than for product innovation, and no significant impact of either one only when innovation output is not corrected for its endogeneity, irrespective of whether innovation is measured by qualitative or quantitative indicators.

The German innovation survey is the only exception we are aware of that includes a quantitative measure of process innovation, namely the percentage of cost reduction due to innovation. Using these data, Peters (2008) estimates the knowledge production function as two separate type-II tobit models (according to the terminology of Amemiya, 1984), and uses the predictions for product and process innovation output in the augmented production function. She finds a positive effect for product innovation, but only weak evidence for a positive impact of process innovation. Other studies using specifications with product and process innovation are Criscuolo and Haskel (2003) for the UK and Parisi et al. (2006) for Italy. Criscuolo and Haskel (2003)

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[3] Since their productivity measure is value added per employee, and capital intensity is controlled for, their result may be viewed as a total factor productivity (TFP) effect.

find a (weak) positive effect of production innovation only when it is new to market; process innovation has a negative effect when it is novel, otherwise it has no effect.[4] Parisi et al. (2006) find a positive effect for process innovation and not for product innovation. From this overview, it appears that there is at least some degree of heterogeneity in the findings about the importance and direction of both product and process innovation.

With respect to the role of ICT, our work is closely related to that of the Eurostat ICT impacts project (see Eurostat, 2008). Because data on ICT investment are not available in the survey on ICT use, this international micro-data study proposes to use other metrics such as the share of PC enabled personnel, the adoption of broadband and e-commerce variables as indicators for firm-level ICT-intensity. The study reveals that – on average – ICT usage is positively related to firm performance. The strength of these results varies over countries, however, and it also appears that the benefits of different types of ICT usage are industry specific. Broadband use seems to be associated with a capital deepening effect (that is, the use of broadband is indicative of a larger stock of ICT capital), whereas electronic sales shows a true efficiency effect. Van Leeuwen (2008, Chapter 12 of the Eurostat report) incorporates the broadband and e-commerce variables into the standard CDM model (with innovation output represented by innovative sales per employee). It is shown that e-sales and broadband use affect productivity significantly through their effect on innovation output. Broadband use only has a direct effect on productivity if R&D is not considered in the model as an input to innovation. As regards ICT, the model used in this paper can be seen as a modification and extension of the model in Van Leeuwen (2008).

Another line of literature motivates the importance of ICT for organisational innovation in particular. An overview of this literature is given by Brynjolfsson and Hitt (2000). Case studies reveal that the introduction of information technology is combined with a transformation of the firm, investment in intangible assets, and of the relation with suppliers and customers. Electronic procurement, for instance, increases the control of inventories and decreases the costs of coordinating with suppliers, and ICT offers the possibility for flexible production: just-in-time inventory management, integration of sales with production planning, et cetera. A lack of proper control for intangible assets seems to be the answer to the well-known remark by Solow that ICT is everywhere but in the productivity statistics. In addition, a lack of investment in intangible assets is seen as a possible candidate for explaining the differences in productivity growth that are observed between Europe and the US. The available econometric evidence at firm level shows that a combination of investment in ICT and changes in organisations and work practices facilitated by these technologies contributes to firms' productivity growth. More evidence on this relation is provided by Crespi et al. (2007). Using CIS data for the UK, they find a positive effect on firm performance of the interaction between IT and organisational

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[4] The CIS3 questionnaire for the UK had a question on the novelty of process innovations. The standard CIS questionnaire makes this novelty distinction only for product innovations.

innovation, but not for the individual variables. They also find a significant effect of competition on organisational innovation.

3. Model

The modelling approach follows GHMP and RM, who use an augmented CDM model to incorporate product as well as process innovation. We extend their model to include an equation for ICT as an enabler of innovation and organizational innovation as an indicator of innovation output. Quantitative as well as qualitative data are used to model innovation inputs, whereas only qualitative information is used for innovation outputs. We measure productivity as labour productivity controlling for the capital/labour ratio, the remaining terms explaining total factor productivity.

3.1 Innovation inputs: R&D and ICT

We distinguish two types of innovation inputs: R&D expenditures and ICT investment. We measure R&D investments by the total of intramural and extramural R&D expenditures. This variable is subject to selectivity, however. The question is only asked to firms with a completed/ongoing/abandoned, product and/or process, innovation, whereas other firms can also perform R&D. In addition, the variable may be censored because R&D performers may not always report R&D (e.g. when it is performed by workers in an informal way). Furthermore, only continuous R&D performers that stated to have positive R&D expenditures are used in the estimation.

In analogy to R&D, we use the investment in ICT as a measure for ICT input. There are many periods in which firms do not report investment in ICT, so in fact ICT investment is also a censored variable. Again, firms that do not report investment may in fact still have positive ICT input, e.g. through own-account development which is not recorded as investment.

For both indicators, we therefore have a certain number of zero values and missing observations. To model this pattern of zero/missing and positive observations, we use a tobit type II model, see Amemiya (1984). For R&D we have a dichotomous variable d_R that takes value 1 when R&D is observed and 0 otherwise. We associate to d_R a latent variable d_R^* such that

(1) $d_R = 1$ when $d_R^* = \alpha_1' w_{1t} + \eta_{1t} > 0$ and

$d_R = 0$ otherwise.

Likewise for ICT we have a dichotomous variable d_{ICT} to which we associate a latent variable d_{ICT}^* such that

(2) $d_{ICT} = 1$ when $d_{ICT}^* = \alpha_2' w_{2t} + \eta_{2t} > 0$ and

$d_{ICT} = 0$ otherwise.

The amount of R&D, measured by (the log of) R&D expenditures per employee, and denoted by r_t is related to another latent variable r_t^* such that

(3) $r_t = r_t^* = \beta_1' x_{1t} + \varepsilon_{1t}$ when $d_R = 1$ and zero otherwise.

Likewise, the amount of ICT, measured by (the log of) ICT investment per employee, and denoted by ICT_t is related to a latent variable ICT_t^* such that

(4) $ICT_t = ICT_t^* = \beta_2' x_{2t} + \varepsilon_{2t}$ when $d_{ICT} = 1$ and zero otherwise.

We drop the firm subscript to avoid notational clutter. For year t, w_{jt} and x_{jt} ($j = \{1,2\}$) are vectors of exogenous explanatory variables some of which may be common to both vectors. Each pair of random disturbances η_{1t} and ε_{1t}, and η_{2t} and ε_{2t}, is jointly iid normally distributed.

The specification for the R&D selection equation is similar to that of RM. For reasons of symmetry we use the same explanatory variables in the selection equation for ICT. Besides dummy variables for industry and size, we used the following common variables in the two selection equations: a dummy variable for being part of an enterprise group, and a dummy variable referring to the dependence on foreign markets. To model the amount of R&D and ICT, we again use the same specification as applied for R&D by RM, except for the appropriability conditions for which, unlike RM, we have no observations in the Dutch innovation surveys.

Equations (1) and (3) and (2) and (4) are estimated by maximum likelihood. From these estimations, we calculate the unconditional predictions for the latent R&D and ICT investments, which feed into the innovation output equations. As in GHMP, the predictions are also calculated for the firms with zero investments.[5] Thus, by assumption, all firms have a certain amount of (unobserved) research effort and/or ICT investment.

3.2 Innovation output: product, process and organisation

Innovation input leads to innovation output, also known as 'knowledge production'. In this study, we consider three types of innovation, namely product, process and organisational innovations. The three innovation equations are given by

(5a) $pdt_t^* = \beta_3' x_{3t} + \varepsilon_{3t}$

(5b) $pcs_t^* = \beta_4' x_{4t} + \varepsilon_{4t}$

(5c) $org_t^* = \beta_5' x_{5t} + \varepsilon_{5t}$

where x_3 to x_5 include the (unconditional) predictions of the innovation input variables from the primary equations (3) and (4). As with innovation input, the levels of generated knowledge are latent. In this case, we only observe whether a firm had a

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[5] When predicting R&D and ICT we assume that there is no cooperation and no source of funding for non-innovators, i.e. we set these variables at zero for these firms.

certain type of innovation or not.[6] If *pdt, pcs* and *org* are the corresponding dummy variables to these events, we have

$$
\begin{aligned}
\Pr[pdt_t = 1] \quad &= \Pr[pdt_t^* > 0] \\
&= \Pr[\beta_3'x_{3t} + \varepsilon_{3t} > 0] \\
&= \Pr[\varepsilon_{3t} < \beta_3'x_{3t}], \\
\Pr[pcs_t = 1] \quad &= \Pr[\varepsilon_{4t} < \beta_4'x_{4t}], \\
\Pr[org_t = 1] \quad &= \Pr[\varepsilon_{5t} < \beta_5'x_{5t}].
\end{aligned}
$$

We assume that ε_{3t}, ε_{4t}, and ε_{5t} follow a multivariate normal distribution. Then the three-equation system is estimated by simulated maximum likelihood using the GHK simulator (see Train, 2003). Besides reflecting the assumption that also firms that do not report investment have a certain amount of research effort or ICT investment, the advantage of using predictions for innovation input is that we are able to use the whole sample. This means that the number of observations is increased and selectivity bias is circumvented. In addition, at least if all explanatory variables in the R&D and ICT equations are exogenous, endogeneity of the innovation inputs is controlled for. Following GHMP and RM, we construct propensities for each possible combination of innovation type, and include these as proxies for knowledge in the augmented production function. Standard errors of the estimates are computed by bootstrapping. Following Van Leeuwen (2008), we also include broadband intensity and e-commerce variable in the knowledge equation, to capture the application and degree of sophistication of ICT.

3.3 Production function

Finally, we estimate an augmented production function to determine the semi-elasticities of productivity with respect to dichotomous innovation output measures. The equation is

$$
(6) \qquad VA_t/L_t = [\textstyle\sum_{ijk} \beta_{ijk} \, I(pdt = i, pcs = j, org = k)]
$$

$$
+ \beta_6'x_{6t} + \varepsilon_{6t}, \qquad\qquad (i,j,k \in \{0,1\})
$$

where VA_t/L_t is the (log of the) productivity of a firm (measured as value added per full-time employee (fte)), I(·) is a binary indicator, and x_6 includes additional explanatory variables including capital intensity and firm size. We use I(0,0,0) as a reference category. Thus, there are seven dummies reflecting the different combinations of innovation types: (0,0,1), (0,1,0), (0,1,1), …, (1,1,1). Since these innovation

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[6] For product innovation, we actually observe the percentage of total sales due to innovative products. To treat the three types of innovation in the same manner, however, we also restrict product innovation to a binary variable.

output measures are endogenous, they are replaced by predictions from the trivariate probit in section 3.2.[7] Standard errors are computed by bootstrapping.

4. Data

The data used in this exercise are sourced from different surveys at Statistics Netherlands, which are linked at the firm level. The sample includes firms in the manufacturing sector (SIC 15 to 37) as well as the services sector (SIC 50 to 93).[8] The innovation variables are sourced from the Community Innovation Survey (CIS). We pool the 2002, 2004, and 2006 editions (also referred to as respectively CIS 3.5, CIS 4 and CIS 4.5). Information on ICT use comes from the Business ICT (E-commerce) survey. Investment in ICT is taken from the Investment Statistics (IS). Finally, production data (production value, factor costs) are taken from the Production Statistics (PS). We use price information at the lowest available level from the Supply and Use tables (AGT); this results in deflators at a mixed 4-digit and 3-digit levels of the standard industrial classification (SBI). [9]

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[7] The predictions correspond to the propensities for the respective combinations. Since these add up to one, it is still necessary to use one combination as a reference category to avoid perfect collinearity.

[8] We exclude SIC 73, the commercial R&D sector.

[9] The assumption that firms within the same industry are subject to the same price development is not trivial though. Besides the usual critique that firms are heterogeneous even at very low levels of aggregation, it is in this context not unlikely that on the output-side innovators show a different pricing behaviour from non-innovators. For example, new products may initially be more expensive due to high production costs (e.g. LCD TV's). In addition, firms may benefit from a certain monopoly position when product innovations have not yet been imitated, whereas a large part of the production costs may also go into marketing the new product.

Our definitions of the different innovation types follow those in the innovation survey. Thus, product innovation is defined as a new or (significantly) improved good or service. Process innovation is defined as a significantly improved method of production or logistics, or supporting activities such as maintenance and operations for purchasing, accounting, or computing. Finally, organisational innovations include the introduction of new business practices, knowledge management systems, methods of workplace organisation (i.e. system of decision making), and organisation of external relations (including outsourcing and subcontracting). In all cases, the innovation needs to be new to at least the firm, and may be developed by the firm itself or by another enterprise (or in collaboration).

Table 1a. Summary statistics, 2002-2006

	CIS		CIS ∩ IS		CIS ∩ ICT		CIS ∩ ICT ∩ IS	
	mean	N	mean	N	mean	N	mean	N
Belonging to a group (%)	0.55	31241	0.58	24844	0.61	9479	0.66	6435
Main market: international (%)	0.34	31241	0.36	24844	0.34	9479	0.39	6435
Cooperation for innovation (%)	0.14	31241	0.15	24844	0.19	9479	0.21	6435
Local funding for innovation (%)	0.02	31241	0.02	24844	0.02	9479	0.02	6435
National funding for innovation (%)	0.08	31241	0.09	24844	0.11	9479	0.13	6435
EU funding for innovation (%)	0.02	31241	0.02	24844	0.02	9479	0.03	6435
Having access to broadband (%)	0.44	9177	0.43	7897	0.44	9177	0.44	6197
Doing e-purchases (%)	0.05	8760	0.05	7527	0.05	8760	0.05	5887
Doing e-sales (%)	0.05	9051	0.05	8140	0.05	9051	0.05	6435
R&D expenditures per fte (1000s €)	4.35	10091	3.80	8386	4.88	3666	4.33	2722
ICT investment per fte (1000s €)	0.71	24814	0.71	24814	0.67	8166	0.64	6129
Employment (CIS, fte)	164.27	30905	169.56	24725	249.05	9271	270.25	6421
Employment (PS, fte)	151.10	18822	158.29	17275	224.38	6435	224.38	6435
Value added per fte (1000s €)	69.31	18822	69.02	17275	71.69	6435	71.69	6435

CIS: Community Innovation Survey, ICT: E-commerce Survey, IS: Investment Statistics, PS: Production Statistics.

Table 1b. Distribution of combinations of innovation types, 2002-2006

Product	Process	Organisation	N[a]	N[b]	R&D[c]	ICT[c]	Value added[c]
no	no	no	0.59	0.49	2.069[d]	0.473	75.869
no	no	yes	0.14	0.14	2.997[d]	0.647	81.070
no	yes	no	0.02	0.02	2.766	0.653	76.827
no	yes	yes	0.02	0.02	0.562	0.454	62.939
yes	no	no	0.07	0.08	4.341	0.848	69.244
yes	no	yes	0.06	0.07	4.048	0.705	71.324
yes	yes	no	0.04	0.06	5.981	0.905	66.795
yes	yes	yes	0.07	0.11	7.022	1.313	72.671

[a] Percentage of CIS sample; number of observations is 31,236.
[b] Production function sample (CIS ∩ ICT ∩ PS, number of observations is 5285).
[c] In 1000s of euro per (full-time) employee.
[d] Note: R&D expenditures are only observed for the firms with ongoing/abandoned product or process innovation projects in these groups (211 firms with no innovations, 134 with only an organisational innovation).

Table 1a gives the summary statistics for the variables used in the model, for the different samples used in different equations. The R&D equation only uses CIS data; the ICT equation uses IS and CIS; the knowledge production function uses CIS and ICT data; finally, the TFP equation uses PS, CIS and ICT (the latter two only via the predicted propensities). The overall impression from table 1a is that the means of the variables are pretty much in line in the various samples. Based on the employment variables, however, it looks like crossing the CIS with the E-commerce survey leads to a bias towards larger firms. This is not surprising since the sampling frame of the latter survey is relatively small, and smaller firms are less likely to be sampled in all surveys, so that in crossing data sets these firms have a higher probability to drop out. The tendency towards larger firms seems to go hand in hand with a slight decrease of the ICT intensity, but there is no pattern in the intensity of R&D or value added per employee.

Table 1b shows the distribution of possible combinations of innovation types. Almost 60% of the firms do not innovate at all in the sense that they do not have any of the innovation types aforementioned (this category does include somewhat over 200 firms with an ongoing or abandoned innovation project, however). Most of the innovators perform a single innovation type, of which in turn most perform an organisational innovation. Strikingly, the group that performs all three types appears relatively large compared to the innovators that have two types. In addition, we see that the group performing all three types becomes relatively more important in the estimation sample of the productivity equation.

R&D expenditures and ICT investment are higher for combinations involving product innovation, and are roughly increasing in the number of types. Both R&D and ICT investment are the highest for the group that perform all three types of innovation. The means of these variables are largely determined by a few very large observations, however. Finally, in terms of value added per employee, firms with only an

organisational innovation have the highest productivity. From these figures, however, a clear relation between productivity and a specific type of innovation or the number of innovations cannot be deduced.

5. Results

In this section, the estimation results of the augmented CDM model are presented. Since one may expect that the importance of innovation modes can differ between industries, we estimated the model separately for manufacturing and services.[10]

5.1 Innovation input

Table 2a presents the estimation results for the R&D – (1) and (3) – and ICT – (2) and (4) – equations. All variables are significant without many differences in the results by sector, the only exception being some of the dummies for financial support. EU funding is insignificant in the ICT equations, and national funding only marginally significant. Local funding does not seem to play a role for both the R&D and ICT decisions. The finding that financial support is more important for R&D than for ICT can be understood by the fact that ICT is an instance of a 'general purpose technology' that can be easily bought, and is less plagued by uncertainty and less than R&D subject to a market failure for financing because of asymmetric information.

The positive sign of the indicator for being part of a group could reflect that those firms may benefit from better internal access to finance or knowledge, or other synergies that facilitate the possibility to perform R&D or to invest in ICT. However, in manufacturing being part of a group has a negative effect on selection in the case of ICT. This can be an indication that manufacturing firms that are part of a group centralize ICT services into a single business unit, or that these services are being outsourced. In this case, being part of a group reduces the possibility of positive ICT investment for a single business unit in manufacturing. We also find that firms are likely to spend more on R&D and ICT when cooperating on innovation activities. Finally, the positive sign of the indicator for foreign activities reflects that competing in a foreign market requires firms to be innovative and makes the availability of communication possibilities more vital.[11]

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[10] Industry differences may also be present within manufacturing and services. As far as this concerns industry specific averages, those are controlled for by industry dummies. The effects of the variables of interest cannot be allowed to be different for subindustries, however, due to diminishing numbers of observations at lower levels of aggregation.

[11] Vice versa, innovative firms may be more likely to enter into foreign markets, receive funding, et cetera, so that one should be careful with drawing conclusions about causality. This also raises the issue of whether the indicators could be endogenous to R&D and/or ICT.

5.2 Innovation output

Results for the knowledge production function are reported in table 2b. The indicators for knowledge are just the binary variables indicating whether a firm had a particular type of innovation in a certain year. The three-equation system is estimated as a trivariate probit, accounting for the mutual dependence of the error terms.[12] Predictions for R&D and ICT investment from the pertinent equations are used as explanatory variables here, to account for possible endogeneity. In addition, since the predictions are the unconditional expectations from equation (2) and (4), these are also used for firms having missing or zero values for these variables, reflecting that those firms may well have innovation input. The use of predicted variables makes the usual standard errors invalid. Therefore, we also report bootstrapped standard errors and use them to judge about the significance of the estimated coefficients. We find that for the predicted variables in the knowledge production equation the bootstrapped standard errors are substantially larger than the usual standard errors. For the other control variables this is not the case.

In line with most of the CDM literature, we find that R&D contributes positively to product innovation in manufacturing. By contrast, it is unimportant for product innovation in services, and for process and organisational innovation in both sectors. Thus, R&D appears to be mainly devoted to developing new and improving existing products, but we find no evidence that these efforts spill over to other innovation types.

On the other hand, ICT investment is important for all types of innovation in services, while it plays a limited role in manufacturing, being only marginally significant for organisational innovation. However, the broadband intensity of a firm seems to make more difference in this sector. Broadband access allows firms to quickly share and obtain information from other agents in the firm's network; following Eurostat (2008) it is seen as an indicator of how advanced the ICT infrastructure of a firm is. In our results it positively affects product as well as organisational innovation in manufacturing, and all types of innovation in services.

As in Eurostat (2008), the e-commerce variables are seen as indicators of how a firm actually uses its ICT infrastructure for selling goods and services in the case of e-sales, and for purchasing inputs in the case of e-purchases. Both electronic sales and purchases seem to matter for process innovation in both sectors. This suggests that making use of electronic channels to sell or buy products, also stimulates innovation in the way products are made. Only in the services sector does it also stimulate the other types of innovation. The positive effect of e-sales on product innovation found in Van Leeuwen (2008) can therefore be understood from the dominance of the ser-

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We do not pursue this possibility here however, so by assumption, the variables are considered to be exogenous.

[12] The estimation routine is adopted from the Stata program by Antoine Terracol.

vices sector. The fact that access to broadband is significant in most cases, even in the presence of the e-commerce variables, indicates that the importance of broadband goes beyond its use in e-commerce.

These results confirm recent findings that ICT is an important enabler of capturing and processing knowledge in the innovation throughput stage. In addition, the industry differences demonstrate that ICT in general, and relatively new ICT applications (such as broadband connectivity and e-commerce) in particular, are more important in services than in manufacturing. Although broadband connectivity enhances innovation in both industries, e-commerce applications seem to be especially important in service innovation.

5.3 Production

Finally, the estimates for the production function are reported in table 3c. We use value added per employee, controlling for capital intensity using data from the PS, so that estimated effects can be interpreted as TFP effects. Two sets of results are presented. Firstly, in the left-hand panel for both sectors, the results are given for the model as discussed above where the knowledge production function consists of a trivariate probit. Secondly, to be able to focus on the contribution of organisational innovation to the equation, we also present the results of a model with only product and process innovation in the spirit of RM.

Starting with the results for the model with three types of innovation, we see that the combinations of innovations that contribute significantly to a higher productivity all involve organisational innovation. It is striking that combinations with product and process innovation do not have a positive effect on productivity when performed in isolation or jointly, but do have a positive effect when combined with an organisational innovation. This finding is consistent with the idea of possible complementarities between the different kinds of innovation, in particular that technological innovations should be backed with an organisational innovation to improve firm performance. When running a test of supermodularity we find indeed signs of complementarity between process and organisational innovation in both sectors, and of product and process innovation in manufacturing.[13]

From these results, it appears that is mainly organisational innovation that increases productivity. In the light of the literature on the effects of product and process innovation (see section 2), we find that the latter types of innovation increase productivity significantly (statistically speaking) only when accompanied by an organisational innovation. The omission of non-technological innovation in existing studies is

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[13] In the presence of three strategies, the presence of supermodularity between product and process innovations implies two inequality restrictions: $TP(0,1,0) < TP(1,1,0) − TP(1,0,0)$ and $TP(0,1,1) − TP(0,0,1) < TP(1,1,1) − TP(1,0,1)$, where $TP(0,1,0)$ for instance is the coefficient of the indicator for the absence of product innovation, the presence of process innovation and the absence of organisational innovation. Similar pairs of restrictions hold for the complementarity between other innovation pairs. See Milgrom and Roberts (1990).

therefore a possible explanation for the varying results with respect to the effect of different types of innovation on productivity. To reinforce this point, we re-estimated the model excluding organisational innovation, specifying the knowledge production equation as a bivariate probit.[14] The results for both sectors are also reported in table 2c. This specification confirms that product and process innovations are complements in manufacturing but not in services. However, when comparing the results of the specifications with two and three innovation modes we see that in manufacturing the combination of product and process innovation is only significant when it is combined with an organisational innovation. Similarly in services, the significance of the introduction of a process innovation is due to the strong significance of its introduction jointly with an organisational innovation. Moreover, in services, the insignificance of performing both a product and a process innovation arises because when they are not combined with organisational innovation, the effect turns out to be negative (see the sign of TP(1,1,0)).[15]

All in all, our results say that product and process innovations do not have a positive effect without organisational innovation. The significance of each of the combinations does not vary much between the sectors. The magnitude of the estimated effects does differ, however, with stronger effects found in services.

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[14] Using the `biprobit` routine in Stata.

[15] The negative sign of TP(1,1,0) suggests that a combination of product and process innovations that is not complemented by an appropriate change in the organisation is (on average) counterproductive. Alternatively, it can be argued that this combination initially has a disruptive effect but may lead to productivity gains in subsequent periods. Testing for this requires the introduction of dynamics in our model, which is left for further investigation.

Table 2a. Estimation results by industry for the R&D and ICT equations.

		manufacturing				services			
		R&D (*N* = 8536)		ICT (*N* = 7474)		R&D (*N* = 18375)		ICT (*N* = 14299)	
		coeff	se	coeff	se	coeff	se	coeff	se
Intensity	Belonging to a group	0.260***	0.066	0.124***	0.045	0.263***	0.100	0.148***	0.033
	Active on foreign market	0.574***	0.093	0.206***	0.056	0.974***	0.168	0.384***	0.037
	Cooperation[a]	0.432***	0.051	0.228***	0.044	0.247***	0.073	0.479***	0.046
	Local funding[a]	0.049	0.094	-0.038	0.088	0.132	0.158	0.030	0.128
	National funding[a]	0.424***	0.056	0.090*	0.047	0.685***	0.084	0.139*	0.074
	EU funding[a]	0.597***	0.105	0.103	0.104	0.533***	0.170	0.162	0.156
Selection	Belonging to a group	0.136***	0.035	-0.123***	0.033	0.177***	0.029	0.063***	0.023
	Active on foreign market	0.463***	0.034	0.183***	0.032	0.512***	0.030	0.351***	0.025
	N	2578		4660		1676		8831	
	regression error variance (σ)	1.436		1.237		1.981		1.430	
	ρ	0.639***		0.316		0.748***		0.241***	

[a] For innovation.
Dependent variables: Log of R&D expenditures per full-time employee (R&D) and log of ICT investment per full-time employee (ICT). Selection variables: dummy for continuous R&D and positive R&D expenditures (R&D) and positive ICT investment (ICT). Estimation method is ML (type-II tobit). All equations also include size, industry and time dummies not reported. Standard errors are robust. Significance levels: *** = 1%, ** = 5%, * = 10%.

Table 2b. Estimation results by industry for the knowledge production function.

Manufacturing ($N = 2574$)	Product innovation			Process innovation			Organisational innovation		
	coeff	se	se (bootstrap)	coeff	se	se (bootstrap)	coeff	se	se (bootstrap)
R&D[a]	1.044**	0.247	0.435	0.618	0.234	0.400	-0.037	0.223	0.291
ICT[a]	1.039	0.654	1.262	1.415	0.622	1.204	1.540*	0.606	0.872
access to broadband	0.277**	0.096	0.125	-0.033	0.098	0.083	0.388***	0.093	0.073
Doing e-purchases	0.106	0.283	0.357	0.458*	0.267	0.270	0.255	0.272	0.309
Doing e-sales	0.140	0.180	0.200	0.442***	0.171	0.128	-0.053	0.170	0.162
ρ_{12}	0.578***								
ρ_{13}	0.254***								
ρ_{23}	0.314***								

Services ($N = 4913$)	Product innovation			Process innovation			Organisational innovation		
	coeff	se	se (bootstrap)	coeff	se	se (bootstrap)	coeff	se	se (bootstrap)
R&D[a]	-0.831	0.088	0.977	-0.672	0.091	0.831	-0.496	0.085	0.524
ICT[a]	3.295***	0.158	0.897	2.645***	0.167	0.747	1.832***	0.159	0.506
access to broadband	0.441***	0.051	0.070	0.195**	0.059	0.079	0.325*	0.050	0.077
Doing e-purchases	0.395***	0.125	0.080	0.164*	0.144	0.096	0.269*	0.118	0.150
Doing e-sales	0.329**	0.139	0.133	0.161*	0.149	0.097	0.191	0.133	0.158
ρ_{12}	0.510***								
ρ_{13}	0.255***								
ρ_{23}	0.260***								

[a] Predicted investment in 1000 of euros per fte (logs).
Dependent variables: dummies for product, process and organisational innovation. Estimation method: trivariate probit. All equations also include size, industry and year dummies that are not reported. Correlations between the errors of the pertinent equations are denoted by ρ_{ij} ($i,j \in \{1 = \text{product}; 2 = \text{process}; 3 = \text{organisational}\}$). Significance levels: *** = 1%, ** = 5%, * = 10%, based on bootstrapped standard errors.

Table 2c. Estimation results by industry for the augmented production function.

| innovation types | manufacturing (N = 1992) | | | | | | services (N = 3319) | | | | | |
| | product, process, Organisational | | | product, process | | | product, process, organisational | | | product, process | | |
	coeff	se	se (btstr)	coeff	se	se (btstr)	coeff	se	se (btstr)	coeff	se	se (btstr)
Capital intensity	0.207***	0.017	0.013	0.207***	0.017	0.016	0.250***	0.012	0.011	0.261***	0.013	0.014
Employment	-0.013	0.022	0.018	0.038**	0.017	0.017	-0.233***	0.020	0.014	-0.131***	0.017	0.025
TP(0,0,1)	1.654***	0.421	0.491				4.345***	0.472	0.571			
TP(0,1,0)	-0.905	0.766	1.100				-2.703	1.217	1.943			
TP(0,1,1)	0.984*	0.818	0.537				17.114***	2.304	2.213			
TP(1,0,0)	0.468	0.473	0.300				0.808	0.969	1.275			
TP(1,0,1)	-0.015	0.548	0.455				-0.804	0.548	0.705			
TP(1,1,0)	-0.130	0.357	0.400				-8.327***	1.328	1.262			
TP(1,1,1)	0.891***	0.199	0.193				3.932***	0.420	0.459			
BP(0,1)				0.095	0.421	0.485				7.252***	1.574	2.357
BP(1,0)				-0.079	0.172	0.160				0.917***	0.194	0.312
BP(1,1)				0.202***	0.075	0.068				-0.033	0.163	0.285
	R^2	0.31		R^2	0.30		R^2	0.36		R^2	0.31	

All specifications include industry and time dummies. BP denotes the cluster variables of the Bivariate Probit model. The combinations (0/1,0/1) reflect whether a firm has product and/or process innovation (0 = no, 1 = yes). TP refers to the combinations of the Trivariate Probit model: the combinations (0/1, 0/1, 0/1) reflect whether a firm has a product, process and/or organisational innovation. The dummies for combinations of innovation types are replaced by predicted propensities from respectively the bivariate probit and trivariate probit knowledge production function. Dependent variable is log value added per fte. Capital intensity (depreciation per fte) and employment are in logs. Estimation method is OLS. Significance levels: *** = 1%, ** = 5%, * = 10%, based on bootstrapped standard errors.

Finally, we look at the estimated coefficients for capital and labour. Capital intensity (proxied by depreciation per fte) is positive and significant for both sectors. The coefficient on labour, which measures the deviation from constant returns to scale in this specification,[16] is insignificant for manufacturing but significantly negative for services. This indicates substantial decreasing returns to scale in this sector. This can be explained by a typical feature of services. This industry consists of many small firms operating on suboptimal scales. Kox et al. (2007) show that scale economies in services are very local and that productivity in services across size classes is hump-shaped with increasing economies of scale for small firms and decreasing economies of scale for large firms. Although we control in our model for size related selectivity, it cannot be circumvented that the linking of various data sources leads to the under representation of small firms, especially in services. Thus, having relatively more large firms in the matched samples may explain the negative estimate for the returns to scale parameter in services.

6. Conclusions and further research

In this paper, we investigate the relation between innovation and productivity, combining insights from the literature on R&D driven technological innovation and that on non-technological innovation complemented by ICT. The standard CDM framework is extended to include investment in ICT as an input to innovation next to R&D, and process and organisational innovation next to product innovation. Including ICT investment reflects the idea that it is an enabler of innovation success, and thus a determinant of innovation output. Extending the model with process and organisational innovation reflects that productivity gains are not solely achieved by product innovation. Lacking continuous measures for the output of process and organisational innovation, innovation output is measured by dichotomous variables reflecting whether a firm performed a particular type of innovation or not. Our modelling approach of the innovation output is an extension of Robin and Mairesse (2008) to a trivariate probit including organisational innovation.

We reach some interesting conclusions:

- R&D affects the output of product innovation in the manufacturing sector. We find no evidence for an effect on process and organisational innovation in this sector. In the services sector, there is no evidence for an effect of R&D on any of the innovation types. Using R&D as a measure of innovation, as encountered frequently in the literature, therefore implicitly focuses on product innovation, and is probably most appropriate in manufacturing;

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[16] Starting with the Cobb-Douglas function for value added we have, $VA = A \cdot K^{\alpha} L^{\beta}$, and our specification is a rewritten of this, i.e. $VA/L = A(K/L)^{\alpha} L^{\alpha+\beta-1}$. Thus, CRS ($\alpha + \beta = 1$) would imply the coefficient on labour to be zero in our specification.

- ICT is most important for innovation success in the services sector. ICT investment, the use of broadband, and doing e-commerce, positively affect all three types of innovation in this sector. For manufacturing, ICT seems less important, although broadband use positively affects product and organisational innovation, and e-commerce is positively related to process innovation;

- Organisational innovation is the only innovation type that leads to higher contemporaneous TFP levels. Product and process innovation only lead to higher TFP when performed together with an organisational innovation. This is true for both sectors, though we find stronger effects in services. This finding puts into perspective existing work on productivity effects of innovation not taking into account non-technological innovation.

There are a number of issues that deserve further research. Firstly, since we have available various waves of the CIS, it is possible to investigate dynamics. For example, current R&D expenditures may lead to innovation only after a period of time. Likewise, innovation may not immediately materialize into productivity gains. However, the introduction of feedback and/or autoregressive effects severely complicates the econometrics for this model.

The availability of a panel also allows to introduce firm-specific effects. Among other things, this may make the results more robust to omitted variables and various other sources of bias (provided they are approximately time-invariant). Finally, we also came across the technical problem of calculating the marginal effects for a multivariate probit model. This issue does not seem to have been tackled appropriately in the available literature. We plan on presenting a solution for this in a follow-up to this research.

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