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REGULAR ARTICLE

Productivity, technological innovations and broadband connectivity: firm-level evidence for ten European countries

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Abstract
This study investigates the link between productivity and innovations (technological as well as non-technological), taking into account the information and communication technology (ICT) intensity of firms, measured as the proportion of broadband internet connected employees. The analysis is based on official firm-level data on innovation activities and ICT usage in firms for the years 2002–2010, linked to the business registers and the production statistics in ten European countries. The datasets encompass 117,000 firm-year observations. Estimation results reveal that firm productivity is significantly related to product innovations, but to a lesser extent than broadband connected employees. The strength of the association varies across countries and between manufacturing and service firms. As a contrast, process, marketing and organizational innovations are not significantly related to productivity in the majority of countries. Overall, broadband usage appears to be a better predictor of productivity than product innovations.

Keywords Firm-level data · Broadband usage · Technological innovations · Productivity · Firm behavior

JEL Classification C81 · D22 · O33

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1 Introduction

Technological innovations, such as information and communication technology (ICT), have long since been identified as important drivers of productivity in firms. Studies (mainly of manufacturers) based on data from the European Community Innovation Survey (CIS) show significant correlations between firm productivity and technological innovations, while the association with process innovations is more ambiguous (Crépon et al. 1998; Griffith et al. 2006; Mansury and Love 2008; see Hall 2011 and Mohnen and Hall 2013 for recent surveys).

Another strand of the literature demonstrates the significant link between investments in ICT (measured as ICT capital or ICT usage) and firm productivity (Greenan and Mairesse 2000; Black and Lynch 2001; Bresnahan et al. 2002; Brynjolfsson and Hitt 2003; Arvanitis 2005; Hempell 2005; Badescu and Garcés-Ayerbe 2009; for a survey see Cardona et al. 2013). In contrast, Acemoglu et al. (2014) find poor productivity effects in US ICT intensive manufacturing industries for the period 1980–2009, by measuring ICT usage as the ratio of industry computer expenditures to total capital expenditures. Firm-level analyses of the association between productivity and specific ICT usages such as broadband internet (or e-commerce applications) are less common (for exceptions see Bertschek et al. 2013; Colombo et al. 2013; Hagsten 2016; Hagsten and Sabadash 2017).

In this study, the relationship between innovations (technological and non-technological) and productivity is investigated, taking into account the ICT intensity of firms, measured as broadband internet connected employees. The analysis is based on multi-linked and internationally comparable firm-level data for ten European countries during the period 2002–2010 and the innovation variables follow the definitions of the Oslo manual distinguishing between technological, organizational and marketing innovations (OECD/Eurostat 2005). Due to data specifics, Ordinary Least Squares (OLS) are used to estimate the parameters of the augmented Cobb–Douglas production function.

Few studies have investigated the productivity effects of innovation activities jointly with ICT investments or usage (see for exceptions, Polder et al. 2010; Hall et al. 2013; Bartelsman et al. 2017). Recently, Bartelsman et al. (2017) find that ICT human capital and product innovations are significant drivers of productivity using micro-aggregated panel data for 13 European countries (sub-industry or firm-size level). There is also evidence that ICT investments facilitate technological innovations (Hempell and Zwick 2008). Similarly, Bertschek et al. (2013) demonstrate that internet broadband in firms is significantly positively related to innovation activities. Given the indication of a correlation between ICT usage and innovation activities, these factors are important to account for simultaneously.

Changes in the statistical laws have made it legally possible to link data across sources, but there are still many limitations. Previous studies have linked the Eurostat ICT usage in enterprise survey with production statistics (Hagsten 2016), Dutch CIS with production data (Klomp and van Leeuwen 2001), Estonian CIS data with the Business register (Masso and Vahter 2012), Italian CIS with balance sheets information (e.g. Barbieri et al. 2018), Swedish CIS with production and other firm-level data (Baum et al. 2017) and United Kingdom CIS with the annual business inquiry (Criscuolo et al. 2003).

Linked firm-level datasets offer several advantages and possible new research insights compared to single surveys (see Wagner 2012 for Germany), because they include more information about firm characteristics and firm behavior. However, analyses of datasets linked at the level of the firm may also be inconclusive, due to large heterogeneity even in narrowly defined industries (Bartelsman and Doms 2000; Syverson 2011). Another disadvantage of linked firm-level data often originates from measures to ease the response burden of firms (Hagsten and Sabadash 2017). This means that different surveys do not necessarily overlap and that there is a high degree of panel attrition over time (Raymond et al. 2015) restricting the choice of estimation methods that can be used.

The main contribution of this study is the simultaneous estimation of the relationship between productivity and four types of innovations and ICT intensity of firms, based on comparable data for manufacturing and service firms in a large group of European countries. Another strength of the study is the uniquely multi-linked datasets, covering several surveys as well as an uninterrupted period of time. Research based on linked firm-level data is not uncommon, although it is usually confined to a single country. The inclusion of more than two surveys is rare, as is the use of longer periods of time or more than one wave (3-year average) of innovation data.

The estimations reveal that, while there is a significant and positive link between firm productivity and product innovations, both in manufacturing and services, this link is weakened when ICT intensity, measured as the proportion of broadband internet connected employees, is included.

The study is organized as follows: the next section introduces the conceptual background and the empirical model. Then the data underlying the analysis is presented, followed by a discussion of the results and some concluding remarks.

2 Conceptual background and empirical model

Literature describes several alternative empirical approaches to investigate productivity effects of ICT or technological innovations. One method is to calculate total factor productivity (TFP) indirectly and then regress the TFP indicator on the innovation or ICT variables (see for instance, Black and Lynch 2001; Rochina-Barrachina et al. 2010; Aiello and Ricotta 2016). Another approach uses an augmented Cobb–Douglas production function to estimate the relationships (Tambe and Hitt 2012). Parisi et al. (2006) compare both approaches and find few differences in the results. If innovation activities are treated as endogenous, simultaneous equation frameworks are often employed (Crépon et al. 1998). Studies solely based on the Community Innovation Survey commonly use labor productivity as the dependent variable, since this information is available in the survey itself (Crépon et al. 1998; Crespi and Zuniga 2012).

Product innovations are expected to have a positive impact on labor productivity given other inputs (Griffith et al. 2006). A novel product generates new demand and thereby increases output in the case of a single product, but with multiple products, the overall effect is unclear (Van Reenen 1997). Process innovations often occur in form of introduction of new machines (Edquist et al. 2001). Such innovations can increase productivity and efficiency of firms. Huergo and Jaumandreu (2004) find that process innovations lead to extra productivity growth based on firm-level data for Spanish manufacturers.

Organizational innovations consist of many diverse activities including adoption of new business practices, new work practices, knowledge management systems and changes in external relations (outsourcing and contracting-out activities) (Edquist et al. 2001; OECD/Eurostat 2005). Changes in work practices and new human resource management systems can lead to increases in productivity by reducing costs or improving the quality of existing products (Bresnahan et al. 2002; Ichniowski et al. 1997). Bloom and Van Reenen (2011) find that certain types of human resource management practices, such as changes in work organization raise productivity at the firm-level.

In addition to technological and organizational innovations, there are also innovations in the marketing of goods and services. According to the Oslo manual, marketing innovations consist of significant changes in product design or packaging, new techniques for product promotion, new methods for product placement or new methods of pricing (OECD/Eurostat 2005). The productivity effects of marketing innovations is an unexplored field. Marketing innovations can have a positive influence on output given inputs. However, the magnitude of this effect is likely to be small since the functional characteristics of the products are not necessarily affected by new marketing methods. The business literature finds that marketing capability is important for firm performance (Krasnikov and Jayachandran 2008, based on a meta-analysis).

Besides innovations, the ICT intensity may have a positive influence on productivity. For instance, broadband internet usage among employees facilitates higher speed in business transactions and streamlines the production activities (Haller and Lyons 2015). In this context, ICT intensity is measured as the proportion of broadband internet connected employees in firms. This variable is superior to many other commonly used broadband measures because it is continuous and reflects both a minimum quality of the technology and a human capital element in the diffusion within and across firms over time.

Previous studies often use dummy variables to measure broadband internet access at the firm-level, implying that changes in intensity cannot be investigated, even if several studies distinguish between high and low speed (Grimes et al. 2012; Bertschek et al. 2013; Colombo et al. 2013; Howell and Grimes 2010; Haller and Lyons 2015). The results of these studies are ambiguous, although with an indication that analyses based on data for the early 2000s exhibit fewer significant results than those employing more recent data. Hagsten (2016), for instance, uses the proportion of broadband connected employees as the main productivity determinant and finds significant relationships for manufacturing and service firms in a majority of 14 European countries investigated, based on harmonized and linked firm-level data. However, this dataset only links one sample survey to the production statistics: the ICT in enterprise. An alternative approach to approximate the ICT intensity of firms is to use the share of workers with an occupation or degree in information science or related fields such as mathematics, engineering and other natural science fields (Bartelsman et al. 2017; Hagsten and Sabadash 2017).

The relationship between innovations and productivity, including the measure of ICT intensity of firms, is investigated by use of a Cobb–Douglas production function including output (Y), capital (K) and labor (L):

$$Y = f(A, K, L) = AK^{\alpha}L^{\beta}. \tag{1}$$

Coefficients (α) and (β) are the output elasticities of each input with a given technology (A). Transformed into log-linear form the production function reads:

$$\ln Y_{it} = \ln A + \alpha \ln K_{it} + \beta \ln L_{it} + \varepsilon_{it}. \tag{2}$$

where i denotes firm, t year, ln() the natural logarithm and ε_{it} is the stochastic error term. The technology level is usually not directly observable and thus in the following assumed to depend on innovation activities ***(IN)***, ICT intensity (*BROADpct*), other specific firm characteristics ($\boldsymbol{Z}$, $\boldsymbol{D}^c$) as well as time and industry fixed effects ($\boldsymbol{D}^f$) :

$$\ln A = \mathrm{f}(\boldsymbol{IN},\ BROADpct, \mathbf{Z},\ \boldsymbol{D}^c, \boldsymbol{D}^f). \tag{3}$$

Thus, the augmented standard Cobb–Douglas production function is specified as:

$$\ln VA_{it} = c + \tilde{\alpha} \ln K_{it} + \tilde{\beta} \ln L_{it} + IN_{it}\gamma_1 + \gamma_2 BROADpct_{it} + Z_{it}\gamma_3 + D^c\gamma_4 + D^f\gamma_5 + \tilde{\varepsilon}_{it}, \tag{4}$$

where c is the intercept and firm output is represented by value added (VA) in constant prices, capital (K) by the capital stock in constant prices and labor (L) by the number of employees. Technological and non-technological innovations are measured as a set of dummy variables encompassed in the vector (***IN***): (a) product innovations (*INPD*), (b) process innovations (*INPS*), (c) organizational innovations (*ORGIN*) and (d) marketing innovations (*MRKIN*). Variable (*BROADpct),* the proportion of employees with broadband internet access, indicates the ICT intensity of firms.

In addition to the main innovation and technology variables of interest, several factors accounting for firm heterogeneity are included (Bartelsman and Doms 2000; Syverson 2011). Age and its squared term is represented by vector ($\boldsymbol{Z}$). The inclusion of firm age can be motivated by learning-by-doing effects that occur when firms become older and manage to optimize their production processes, and by doing this they are also more likely to stay in business than younger firms (Jovanovic 1982). Old age might as well have a reverse effect, if the firms become less productive over time (Barron et al. 1994). This indicates a possible inverted u-shaped relationship between productivity and firm age, represented by its square term. Besides age, the relationship with productivity is also controlled by other firm characteristics $\boldsymbol{D^c}$, including dummy variables for size-class and international experience (exporter and foreign affiliation). Williamson (1967) was one of the first to derive a link between firm size and efficiency and thus also productivity, where large companies on average are more efficient than small ones. This is due to factors such as market power and economies of scale.

The hypothesis of learning by export states that companies acquire knowledge through export, which leads to an increase in productivity (Clerides et al. 1998; Bernard and Jensen 1999). However, the empirical evidence on the impact of internationalization on firm productivity is ambiguous, and a reverse causality may exist, where above average productive firms are more likely to export (Wagner 2007).

Another stylized fact is that multinational enterprises (domestic or foreign-owned) on average are more productive due to superiority in terms of knowledge, use of advanced technologies and managerial skills (Blomström and Kokko 1998). Based on firm level data for the UK, Griffith et al. (2004) show that foreign-owned firms have higher value added per employee than domestic ones. The theoretical model by Melitz (2003) predicts that the most productive firms are multinational, followed by exporting firms, while the least productive ones are domestic. Vector $\boldsymbol{D}^f$ encompasses time and industry fixed effects.

The production function will be estimated by OLS on data pooled across industries and over time. Separate estimations are provided by country, distinguishing between manufacturing and service firms. The choice of estimation method is data driven. More information on data sources and characteristics is found in Sect. 3.

Based on literature, positive relationships are expected to be found between product innovations and productivity. In the short run, it is even possible that a stronger link will be found for ICT intensity, since how firms use an innovation might be of larger importance for productivity than the creation of one. The more seldom researched marketing and organizational innovations are expected to show a smaller magnitude of the association, if at all significant. Organizational changes tend to take some time to become effective, implying that a direct link may not be possible to find, or that even a negative association appears. The broadband variable could also harbor effects of unmeasured organizational assets not captured by the innovation variables, as suggested by Bartelsman (2013).

3 Data sources and stylised facts

Data for this analysis originate from the ESSLait project and encompass approximately 117,000 firm-year observations for ten European countries over the period 2002–2010 (Table 1).[1] These datasets hold linked and harmonized official information on manufacturing and service firms (see Fig. 1 in the Appendix for a description of the data linking procedure) sourced from business registers, production statistics (Structural business statistics, SBS) and the EU harmonized surveys on innovation activities and ICT usage in enterprises.[2] In some countries, the underlying production statistics originate from total surveys while in others they are based on large samples. In addition, the export statistics (either goods or both goods and service exports) and the foreign affiliate statistics (FATS) is matched to the dataset. Access to confidential linked firm-level data is legally restricted in most countries and

[1] See https://ec.europa.eu/eurostat/cros/content/esslait-0_en.

[2] See http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database.

Table 1 Data availability, number of firm-year observations Source: ESSLait Databases and own calculations

Country	Manufacturing firms		Service firms	
	Time period	Number	Time period	Number
Austria (AT)	2002–2010	3665	2002–2010	1905
Denmark (DK)	2005–2010	2315	2005–2010	3303
Finland (FI)	2002–2010	4690	2002–2010	2753
France (FR)	2006–2010	6728	2006–2010	5779
Italy (IT)	2002–2008	9377	2002–2008	7278
The Netherlands (NL)	2002–2010	7272	2002–2010	5996
Norway (NO)	2002–2010	5173	2002–2010	4650
Poland (PL)	2002–2010	21498	2003–2010	9411
Sweden (SE)	2006–2010	2750	2006–2010	2300
The United Kingdom (UK)	2002–2010	3369	2002–2010	6686

Manufacturing covers NACE rev 1.1 industries 15–37 and services encompasses industries 50–74

forbidden in others. In this specific case, access has been granted through a common protocol that is run separately on each harmonized and linked country dataset held at the national statistical offices (Bartelsman et al. 2018). The full project database covers 14 European countries, but Ireland, Luxembourg and Slovenia are excluded from this analysis because of absent information on capital or too few observations in the linked datasets. Germany is missing due to legal issues with data linking.

Production statistics contain information on outputs (gross production and value added) and inputs (number of employees, materials and capital). In this study value added, defined as gross output minus intermediate purchases of services and goods, is the output variable favored. Capital is measured either as the capital stock calculated by the perpetual inventory method, the depreciation cost or the book value. Number of employees, age and NACE rev 1.1 two-digit industry classification originate from the business register. Data on exporters stem from the VAT register or trade statistics and information about international affiliation (being part of a domestic or foreign enterprise, MNE) is derived from either the production or foreign affiliate statistics. Nominal prices (value added, capital) have been deflated by EUKLEMS or WIOD two-digit price indexes.[3]

The CIS is the main origin of information on innovation activities in firms. This survey is a representative random sample of firms that is stratified by industry, size, and region. The survey includes manufacturing, mining, energy, water supply, and a selection of service industries (wholesale trade, transport, banking and insurance, computer and related activities, architectural and engineering businesses as well as technical testing and analysis). However, retail trade and hotels and restaurants are only covered on a voluntary basis while construction is excluded.

The four innovation variables employed in this study are all binary and inform on what activities the firms engage in during a three-year period: (a) product

[3] See http://www.euklems.net and http://www.wiod.org.

innovations (introduction of new or significantly improved goods or services), (b) process innovations (implementation of a new or significantly improved production process, distribution method, or support activity for your goods or services), (c) organizational innovations (for instance business practices, knowledge management, workplace organization or external relations) and (d) marketing innovations (a new marketing concept or strategy).

The harmonized survey on ICT usage in enterprises includes a wide range of information on how ICT is employed in firms (internet use, ICT applications such as enterprise resource planning systems and e-commerce activities). This survey is stratified by industry and firm size, which guarantees both representativeness and comparability. In addition, the survey has a broader industry coverage than the innovation questionnaire, including retail trade, hotels and restaurants as well as personal services.

Fazio et al. (2006) conclude that a linking of the ICT usage survey to the production statistics may affect the descriptive statistics due to limited overlapping samples, but the influence on marginal analysis is negligible. In this case, where multiple datasets are linked, a certain bias towards larger firms should be expected, because the sampling schemes used by most statistical offices imply that those firms are the only ones regularly selected. Neither the CIS nor the ICT usage survey target firms with less than 10 employees (although countries can do this on a voluntary basis), which is a shortcoming since in certain industries the innovative activities are high in the smallest firms.

The proportion of broadband internet connected employees is used to reflect the ICT intensity of firms. This composite variable includes information on firm broadband connectivity beyond a minimum speed both within and across firms as well as the proportion of employees with internet access. Thus, the variable is more informative than the commonly employed sole measure of broadband adoption in firms (Bertschek et al. 2013; Haller and Lyons 2015, for instance), since it also relates to human capital and the intensity of usage over time.

Descriptive statistics reveal that there is a clear difference in innovation activities and ICT intensity between manufacturing and service firms (Table 2). Generally, manufacturing firms engage more often in innovation activities than their service counterparts. Almost two out of five manufacturing firms are involved in product innovations and slightly fewer in process innovations. Similar activities appear in one-fourth of the service firms. Marketing innovations and organizational change are less discriminating across industries and occur in between approximately one-fourth and one-third of the firms. Although the extent of the innovation and ICT activities may vary somewhat across countries, the patterns between manufacturing and service firms are relatively robust. In contrast to the innovation activities, the service firms have a stronger representation of broadband connectivity than the manufacturers, almost every second employee.

Both the CIS and the ICT usage surveys commonly follow a rotating design to reduce the response burden of firms, a measure that regularly leads to small overlaps between datasets and a high degree of attrition over time. This restricts the choice of econometric approaches, for instance the use of fixed effects as well as first- or

Table 2 Main estimation variables, averages across countries and over time Source: ESSLait Databases and own calculations

Variable	Unit	Manufacturing	Services
Value added per employee, constant prices	Euro, median	50,523	56,736
Product innovations (INPD)	Proportion of firms, %	38.5	25.4
Process innovations (INPS)	Proportion of firms, %	34.9	24.4
Marketing innovations (MRKIN)	Proportion of firms, %	25.5	22.9
Organizational innovations (ORGIN)	Proportion of firms, %	36.1	33.2
Broadband connected employees (BROADpct)	Proportion of employees, %	33.7	49.0

Value added per employee is reported as the median of the country averages

long-differences estimators, as they vastly reduce the number of observations. However, Mairesse and Mohnen (2010) conclude that the main results of CIS based analyses are quite robust to the use of such methods. This situation occurs because the CIS is performed every second year and the innovation indicators refer to a three-year period, leading to a limited time variation in the main explanatory variables.

4 Estimation results

The estimations reveal that there is a significant and positive association between product innovations and productivity for manufacturing firms in seven out of ten countries (Table 3). In contrast, process and other non-technological innovations are generally not significant. Similar results can be observed for service firms (Table 4). In three out of ten cases, there is a significant negative relationship between organizational innovations and productivity in manufacturing firms. Possibly, this relates to time delays in the implementation of new practices, where improvements do not necessarily transform into direct positive associations with productivity. Due to data specifics, however, the relevance of lagged innovation variables cannot be tested.

Overall, manufacturing firms introducing new products exhibit a productivity level between 3 and 9 percent higher than non-innovators. The corresponding magnitude for service firms ranges between 5 and 21 percent, implying that service firms are assumedly more flexible than manufacturing ones, for instance in scaling operations and adapting new practices, to be able to benefit directly from new goods or services. Output elasticities of capital and labor show the expected signs and magnitudes in all cases, that is, positive, and with a larger share for labor, ranging between 0.56 and 0.95, depending on country and sector of the firms.

When the ICT intensity variable is added to the production function, the strength of the association between product innovations and productivity decreases considerably for both manufacturing and service firms. Now only three out of ten countries exhibit significant relationships, at the 5% level (Table 5). Service firms are affected analogously (Table 6). Process innovations are significant and positive for three countries in manufacturing and two in services.

Table 3 Association between innovation activities and productivity in manufacturing firms Source: ESSLait Databases and own calculations

	AT		DK		FI		FR		IT	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
lnK	0.268***	27.97	0.068***	8.25	0.099***	19.29	0.190***	29.75	0.161***	31.39
lnL	0.749***	31.75	0.946***	35.62	0.875***	51.62	0.799***	58.72	0.805***	45.97
INPD	0.041**	2.09	0.039**	1.98	0.038**	2.28	0.056***	3.93	0.030**	2.14
INPS	− 0.003	− 0.17	0.014	0.73	− 0.006	− 0.41	− 0.015	− 1.12	0.030**	2.23
MRKIN	0.022	1.36	0.015	0.78	0.029*	1.72	0.040***	3.02	0.002	0.12
ORGIN	0.006	0.33	− 0.041**	− 2.12	− 0.059***	3.76	0.012	0.91	0.012	0.99
Size, 1–9 employees	− 0.188	− 1.18	0.189	1.06	− 0.084	− 0.86	0.400	1.50	− 0.351**	− 2.41
10–19 employees	− 0.193**	− 2.09	− 0.098	− 0.84	− 0.268***	− 3.47	− 0.295*	− 1.65	− 0.446***	− 6.15
20–49 employees	− 0.144*	− 1.89	− 0.066	− 0.72	− 0.249***	− 3.91	− 0.204***	− 3.63	− 0.363***	− 5.99
50–99 employees	− 0.123**	− 2.11	− 0.029	− 0.40	− 0.193***	− 3.84	− 0.168***	− 3.80	− 0.247***	− 5.16
100–249 employees	− 0.098**	− 2.29	− 0.049	− 0.92	− 0.182***	− 4.75	− 0.211***	− 5.67	− 0.165***	− 4.50
250–499 employees	− 0.070**	− 2.51	− 0.064*	− 1.65	− 0.107***	− 3.36	− 0.178***	− 5.97	− 0.097***	− 3.61
AGE			− 0.002	− 1.19	0.002*	1.78	− 0.002**	− 2.56	0.004***	4.48
AGE squared			0.00001	0.54	− 0.00002**	− 2.54	0.00002***	2.76	− 0.00002	− 1.45
Non-exporter	− 0.119***	− 4.46	− 0.071**	2.35	− 0.081***	− 4.09	− 0.039**	− 2.22		
Non-MNE			0.037*	1.84						
Constant	3.41***	23.49	− 0.66**	− 2.01	4.05***	32.08	3.45***	35.49	3.41***	28.86
Turning point age			367		157		199		486	
Observations	3665		2317		4690		6728		9377	
R^2	0.93		0.91		0.90		0.93		0.90	

Table 3 (continued)

	NL		NO		PL		SE		UK	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
lnK	0.223***	36.41	0.112***	20.49	0.114***	39.45	0.100***	13.97	0.278***	20.78
lnL	0.727***	47.58	0.907***	38.74	0.939***	58.18	0.981***	48.90	0.751***	26.53
INPD	0.034**	2.58	0.008	0.47	0.005	0.37	0.029	1.49	0.092***	3.41
INPS	0.024*	1.84	− 0.008	0.48	0.130***	9.30	− 0.014	− 0.78	− 0.045	− 1.60
MRKIN	0.026*	1.80	0.003	0.15	− 0.001	− 0.04	0.010	0.54	− 0.057**	− 2.26
ORGIN	− 0.039***	− 3.07	− 0.019	1.19	0.071***	5.37	0.044**	2.36		
Size, 1–9 employees	− 0.682***	3.69	− 0.115	0.93	0.175*	1.92	0.315***	3.25	− 0.070	− 0.37
10–19 employees	− 0.772***	7.17	− 0.157	1.54	0.160**	2.34	0.246***	2.98	0.193	0.88
20–49 employees	− 0.527***	8.11	− 0.146*	1.77	0.106*	1.89	0.128*	1.84	0.041	0.48
50–99 employees	− 0.334***	6.31	− 0.123*	1.89	− 0.085*	− 1.94	0.042	0.72	− 0.011	− 0.17
100–249 employees	− 0.294***	6.86	− 0.078	1.56	− 0.072**	− 2.25	0.024	0.55	− 0.020	− 0.51
250–499 employees	− 0.230***	6.96	0.014	0.35	− 0.028	− 1.27	− 0.006	− 0.17	0.012***	2.64
AGE	0.005***	3.12	0.006***	3.14	0.009***	6.14	0.007**	2.49	− 0.00037***	− 3.25
AGE squared	− 0.00009**	2.22	− 0.00016***	3.59	− 0.0003***	− 12.21	− 0.0001*	− 1.88	− 0.063**	− 2.19
Non-exporter	0.011	0.66	− 0.084***	4.05	− 0.211***	− 16.52	− 0.120***	− 4.34	− 0.164***	− 5.46
Non-MNE					− 0.367***	− 6.94	− 0.134***	− 5.56		
Constant	4.04***	38.93	5.66***	34.46	3.60***	29.22	5.34***	39.50	2.65***	13.79
Turning point age	124		81		57		116		62	
Observations	7272		5173		21498		2750		3410	
R^2	0.87		0.88		0.82		0.95		0.76	

OLS estimations on data pooled across industries and over time, 2002–2010

Log value added (VA) in constant prices is the dependent variable. (L) means number of employees, (K) denotes capital stock and innovation activities in the field of products, processes, marketing or organization are illustrated by (INPD), (INPS), (MRKIN) and (ORGIN), respectively. Reference category for the size-classes is 500 or more employees. Included but not reported are fixed industry (2-digit NACE rev. 1.1) and time effects. The turning point of age is calculated as the coefficient of age divided by the coefficient of its squared term multiplied by minus 1. Empty cell means that data are not available. Significance at the 1, 5 and 10% levels are denoted by ***, ** and *

Table 4 Association between innovation activities and productivity in service firms Source: ESSLait Databases and own calculations

	AT		DK		FI		FR		IT	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
lnK	0.279***	22.61	0.055***	13.35	0.074***	15.07	0.189***	42.37	0.191***	39.77
lnL	0.762***	20.93	0.939***	47.05	0.918***	38.19	0.750***	68.40	0.789***	38.82
INPD	0.123***	3.71	0.053***	3.12	0.092***	3.86	0.187***	10.91	0.148***	6.55
INPS	− 0.024	0.71	0.016	1.01	− 0.051**	− 2.22	− 0.006	− 0.37	0.019	0.92
MRKIN	0.026	0.81	− 0.002	− 0.14	0.045*	1.72	0.001	0.08	− 0.027	1.30
ORGIN	0.041	1.35	− 0.006	− 0.42	− 0.019	0.88	− 0.002	− 0.15	0.025	1.38
Size, 1–9 employees	0.021	0.09	− 0.033	0.20	− 0.028	− 0.20	− 0.295**	2.51	− 0.373**	− 2.22
10–19 employees	0.086	0.55	− 0.045	0.50	0.056	0.51	− 0.249***	4.61	− 0.189**	− 2.06
20–49 employees	0.113	0.85	− 0.079	1.08	− 0.006	− 0.06	− 0.236***	5.46	− 0.135*	− 1.73
50–99 employees	0.174*	1.65	− 0.028	0.50	0.047	0.63	− 0.183***	4.90	0.006	0.09
100–249 employees	0.087	1.05	− 0.031	0.71	0.112*	1.94	− 0.156***	4.74	− 0.067	− 1.33
250–499 employees	− 0.052	− 0.85	− 0.045	1.38	0.086*	1.83	− 0.133***	6.35	− 0.016	− 0.40
AGE			0.003***	2.87	0.001	0.63	− 0.003***	3.30	0.005***	3.85
AGE squared			− 0.00004***	3.30	− 0.00001	− 0.56	0.000***	2.59	− 0.00004***	− 2.73
Non-exporter	− 0.090***	− 2.86	− 0.032**	2.10	− 0.028	− 1.17	− 0.117***	8.29		
Non-MNE			0.008	0.55						
Constant	2.99***	8.65	− 0.01	− 0.05	3.23***	6.35	4.22***	49.04	3.53***	21.68
Turning point age			139		247		281		224	
Observations	1905		3265		2753		5779		7278	
R^2	0.90		0.93		0.90		0.92		0.86	

Table 4 (continued)

	NL		NO		PL		SE		UK	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
lnK	0.263***	48.67	0.110***	23.76	0.118***	23.19	0.094***	15.23	0.251***	36.48
lnL	0.559***	44.98	0.924***	40.64	0.851***	33.74	0.917***	30.68	0.639***	45.29
INPD	0.066***	3.74	0.027	1.26	− 0.061**	− 2.21	0.043	1.62	0.072***	3.02
INPS	− 0.009	− 0.51	− 0.065***	− 2.89	0.148***	5.59	− 0.020	− 0.73	0.078***	2.93
MRKIN	− 0.014	0.78	0.046**	2.18	− 0.092***	3.82	− 0.012	− 0.47	0.004	0.18
ORGIN	0.052***	3.33	0.015	0.76	0.073***	3.08	0.033	1.28		
Size, 1–9 employees	− 0.662***	− 6.93	0.078	0.64	− 0.241*	− 1.71	0.139	0.88	0.170	0.24
10–19 employees	− 0.764***	− 12.39	0.113	1.11	− 0.253**	− 2.24	0.109	0.81	− 0.193	− 1.12
20–49 employees	− 0.622***	− 13.01	0.086	1.04	− 0.201**	− 2.10	0.135	1.17	− 0.230*	− 1.93
50–99 employees	− 0.446***	− 11.74	0.078	1.19	− 0.193**	− 2.47	0.116	1.21	− 0.113**	− 2.04
100–249 employees	− 0.276***	− 9.19	0.058	1.14	− 0.247***	− 3.96	0.047	0.65	− 0.134***	− 2.75
250–499 employees	− 0.129***	− 4.69	− 0.055	− 1.33	− 0.147***	− 3.09	0.062	1.13	− 0.062**	− 2.13
AGE	− 0.0004	− 0.21	0.008***	3.82	0.005**	2.16	0.009**	2.32	0.023***	5.27
AGE squared	0.00000	0.08	− 0.00019***	3.95	0.000***	3.24	− 0.0002**	− 2.29	− 0.001***	− 4.57
Non-exporter	− 0.076***	− 4.89	− 0.133***	6.99	− 0.218***	− 11.77	− 0.064**	− 2.31	− 0.274***	− 10.72
Non-MNE					− 0.036	− 0.30	− 0.179***	− 6.53	− 0.287***	− 14.34
Constant	4.91***	49.33	5.42***	31.03	3.31***	8.71	5.96***	26.27	3.92***	30.25
Turning point age	n.a		91		61		83		61	
Observations	5996		4654		9411		2300		6717	
R^2	0.86		0.87		0.80		0.93		0.76	

OLS estimations on data pooled across industries and over time, 2002–2010

Significance at the 1, 5 and 10% levels are denoted by ***, ** and *. See Table 3

Marketing innovations are hardly significant anywhere while organizational innovations are still mainly negatively related to productivity in manufacturing firms. In contrast to the innovation variables, there is a highly significant association between broadband connected employees and productivity across industries and countries (except in Denmark), given an otherwise identical specification. The average coefficient of broadband connected employees is identical for both manufacturing and service firms: 0.36, although the span is larger for the former. This coefficient indicates that a surge in the share of broadband internet connected employees by one percentage point is associated with an increase in productivity by approximately 0.36 percent.

Overall, the results are consistent with Hagsten (2016) who uses a larger dataset where the ICT usage survey is linked to the structural business statistics for 14 European countries. The more sizable coefficients of the ICT variable found in this analysis may be explained by the fact that the CIS excludes certain parts of the business sector such as less innovative industries (retail trade and partly hotels and restaurants) and that the multi-merged dataset is somewhat biased towards larger firms. In addition, these results might also indicate that the ability to use innovations is more important for productivity than to generate them and that a certain degree of ICT maturity is a prerequisite for more advanced applications.

Presumably, and given the weaker predictive strength of the binary innovation variables, the ICT intensity variable may harbor effects associated with specific unmeasured intangible assets each connected employee makes use of (Bartelsman 2013). Although the relationships cannot be interpreted as causal, the findings indicate that the link between broadband connectivity and productivity is more powerful than that of different types of innovations. As compared with the literature, these new findings down-emphasize the role of technological and organizational innovations for productivity in the short term.

The output elasticities of labor and capital are not affected by the inclusion of ICT intensity, despite the fact that this leads to a slight reduction in the number of observations, due to variations in the overlap between the innovation and ICT usage surveys across countries. Unreported results show that age and age squared are jointly significant in all cases (as calculated by the Wald-test). Larger firms are more productive in a majority of countries and the relationship between productivity and firm age is non-linear, of an inverted u-shaped pattern. However, the turning point is 50 years or older in most cases, which de facto means that productivity increases with firm age. R-squared is close to or above 0.9 on average across the datasets, implying a good fit of the model.

International experience turns out clearly related to productivity. The non-exporter dummy variable is significant and negative for manufacturing firms in six out of nine countries and in seven out of nine for service firms (exporter information on Italy not available). This indicates that exporting firms are more productive than their counterparts selling on the domestic market only, with a productivity differential of approximately ten percent. Not being part of a multinational firms is negative and significant for countries where the variable is available, with estimates stronger than for non-exporting firms, implying that domestically owned firms are less productive.

Table 5 Associations between innovation activities, broadband internet connected employees and productivity in manufacturing firms Source: ESSLait Databases and own calculations

	AT		DK		FI		FR		IT	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
lnK	0.260***	26.01	0.068***	8.24	0.093***	17.65	0.186***	29.21	0.156***	31.02
lnL	0.767***	31.62	0.946***	35.61	0.876***	51.41	0.800***	59.37	0.814***	47.25
BROADpct	0.276***	8.22	− 0.005	− 0.19	0.142***	5.38	0.274***	13.27	0.503***	18.13
INPD	0.040*	1.94	0.039**	1.99	0.033*	1.96	0.045***	3.22	0.005	0.35
INPS	− 0.008	− 0.41	0.014	0.72	− 0.006	− 0.35	− 0.008	− 0.58	0.039***	2.97
MRKIN	0.011	0.63	0.016	0.78	0.024	1.44	0.029**	2.23	− 0.017	− 1.17
ORGIN	0.001	0.07	− 0.041**	2.12	− 0.064***	− 4.02	0.010	0.80	− 0.003	0.22
Size, 1–9 employees	− 0.134	− 0.82	0.189	1.07	− 0.125	1.26	− 0.319*	− 1.69	− 0.341**	− 2.38
10–19 employees	− 0.142	− 1.50	− 0.098	− 0.84	− 0.279***	− 3.60	− 0.221***	− 3.97	− 0.416***	− 5.84
20–49 employees	− 0.110	− 1.41	− 0.066	− 0.72	− 0.258***	− 4.04	− 0.170***	− 3.88	− 0.333***	− 5.57
50–99 employees	− 0.085	− 1.42	− 0.029	− 0.41	− 0.196***	− 3.87	− 0.209***	− 5.68	− 0.226***	− 4.80
100–249 employees	− 0.091**	− 2.07	− 0.049	− 0.92	− 0.186***	− 4.82	− 0.177***	− 6.01	− 0.155***	− 4.30
250–499 employees	− 0.063**	− 2.18	− 0.064*	− 1.66	− 0.111***	− 3.47	− 0.157***	− 8.45	− 0.082***	− 3.10
AGE			− 0.002	− 1.19	0.002**	2.10	− 0.002**	− 2.36	0.004***	4.69
AGE squared			0.00001	0.55	− 0.00002***	− 2.78	0.00002**	− 2.42	− 0.00002*	− 1.92
Non-exporter	− 0.101***	− 3.68	− 0.071**	− 2.36	− 0.076***	− 3.81	− 0.027	− 1.56		
Non-MNE			0.036*	1.82						
Constant	3.23***	21.50	− 0.67**	− 2.02	4.04***	31.83	3.39***	35.16	3.29***	28.25
Turning point age					85		104		192	
Observations	3270		2315		4625		6704		9377	
R^2	0.93		0.92		0.90		0.93		0.91	

Table 5 (continued)

	NL		NO		PL		SE		UK	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
lnK	0.222***	34.33	0.109***	20.01	0.095***	34.17	0.100***	14.03	0.249***	18.82
lnL	0.731***	45.44	0.899***	38.44	0.970***	62.91	0.977***	48.93	0.755***	27.39
BROADpct	0.290***	11.93	0.292***	11.62	1.129***	45.84	0.174***	6.51	0.614***	13.69
INPD	0.007	0.53	− 0.004	− 0.27	− 0.024*	− 1.80	0.022	1.13	0.060**	2.26
INPS	0.035**	2.52	− 0.006	− 0.36	0.115***	8.66	− 0.011	− 0.57	− 0.030	− 1.09
MRKIN	0.010	0.67	− 0.003	− 0.15	− 0.018	− 1.42	0.011	0.61		
ORGIN	− 0.052***	− 3.91	− 0.028*	− 1.73	0.033***	2.63	0.038**	2.07	− 0.079***	− 3.20
Size, 1–9 employees	− 0.746***	− 6.49	− 0.150	− 1.22	0.204**	2.34	0.292***	3.03		
10–19 employees	− 0.502***	− 7.33	− 0.168	− 1.65	0.197***	3.02	0.227***	2.76	− 0.132	− 0.72
20–49 employees	− 0.312***	− 5.60	− 0.152*	− 1.85	0.153***	2.87	0.120*	1.74	0.053	0.25
50–99 employees	− 0.262***	− 5.80	− 0.120*	− 1.86	− 0.033	− 0.79	0.036	0.62	0.033	0.40
100–249 employees	− 0.213***	− 6.09	− 0.092*	− 1.84	− 0.042	− 1.38	0.017	0.39	− 0.025	− 0.40
250–499 employees	− 0.095***	− 3.20	0.005	0.12	− 0.013	− 0.61	− 0.012	− 0.37	− 0.006	− 0.16
AGE	0.005***	2.96	0.008***	3.73	0.008***	5.66	0.008**	2.54	0.013***	3.10
AGE squared	− 0.0001*	− 1.87	− 0.0002***	− 4.14	− 0.0003***	− 11.66	− 0.0001*	− 1.96	− 0.0004***	− 3.60
Non-exporter	0.009	0.52	− 0.062***	− 2.98	− 0.184***	− 15.02	− 0.109***	− 3.94	− 0.050*	− 1.78
Non-MNE					− 0.350***	− 6.94	− 0.124***	− 5.16	− 0.131***	− 4.46
Constant	3.92***	35.68	5.59***	34.11	3.41***	29.02	5.28***	39.11	2.64***	14.12

Table 5 (continued)

	NL		NO		PL		SE		UK	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
Turning point age	70		42		28		57		33	
Observations	6448		5108		21498		2742		3408	
R^2	0.87		0.88		0.84		0.95		0.77	

OLS estimations on data pooled across industries and over time, 2002–2010

Log value added (VA) in constant prices is the dependent variable. (L) means number of employees, (K) denotes capital stock, (BROADpct) broadband internet-enabled employees and innovation activities in the field of products, processes, marketing or organization are illustrated by (INPD), (INPS), (MRKIN) and (ORGIN), respectively. Reference category for the size-classes is 500 or more employees. Included but not reported are fixed industry (2-digit NACE rev. 1.1) and time effects. The turning point of age is calculated as the coefficient of age divided by the coefficient of its squared term multiplied by minus 1. Empty cell means that data are not available, except turning point for Danish manufacturers, which is not significant. Significance at the 1, 5 and 10% levels are denoted by ***, ** and *

Table 6 Associations between broadband internet-enabled employees, innovation activities and productivity in service firms Source: ESSLait Databases and own calculations

	AT		DK		FI		FR		IT	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
lnK	0.272***	21.41	0.055***	13.29	0.069***	14.17	0.180***	41.61	0.176***	37.45
lnL	0.781***	20.94	0.939***	47.06	0.926***	38.54	0.766***	71.93	0.817***	41.43
BROADpct	0.487***	11.58	− 0.018	− 1.09	0.268***	8.62	0.361***	19.87	0.561***	22.09
INPD	0.068*	1.95	0.053***	3.14	0.063***	2.67	0.148***	8.84	0.102***	4.63
INPS	− 0.032	− 0.93	0.016	1.02	− 0.041*	− 1.79	− 0.008	− 0.46	0.025	1.20
MRKIN	− 0.009	− 0.26	− 0.002	− 0.15	0.043*	1.67	− 0.005	− 0.36	− 0.038*	− 1.88
ORGIN	0.014	0.46	− 0.007	− 0.42	− 0.039*	− 1.80	− 0.006	− 0.36	− 0.013	− 0.73
Size, 1–9 employees	0.131	0.58	− 0.037	− 0.23	− 0.004	− 0.03	− 0.307***	− 2.71	− 0.400**	− 2.47
10–19 employees	0.123	0.77	− 0.045	− 0.51	0.074	0.67	− 0.301***	− 5.73	− 0.182**	− 2.05
20–49 employees	0.140	1.02	− 0.079	− 1.08	− 0.005	− 0.06	− 0.254***	− 6.05	− 0.137*	− 1.80
50–99 employees	0.187*	1.73	− 0.029	− 0.51	0.042	0.58	− 0.192***	− 5.29	− 0.007	− 0.11
100–249 employees	0.081	0.94	− 0.031	− 0.72	0.119**	2.07	− 0.158***	− 4.97	− 0.068	− 1.41
250–499 employees	− 0.050	− 0.80	− 0.045	− 1.39	0.090*	1.92	− 0.130***	− 6.42	− 0.013	− 0.33
AGE			0.003***	2.85	0.001	0.81	− 0.002**	− 2.45	0.005***	4.15
AGE squared			− 0.00004***	− 3.26	− 0.00001	− 0.81	0.00002*	1.96	− 0.00004***	− 2.95
Non-exporter	− 0.066**	− 2.02	− 0.032**	− 2.11	− 0.016	− 0.67	− 0.071***	− 5.10		
Not part of MNE			0.007	0.47						
Constant	2.41***	6.91	0.11*	1.80	2.98***	5.92	3.95***	46.77	3.15***	19.87
Turning point age			70		111		137		112	
Observations	1704		3303		2728		5762		7277	
R^2	0.90		0.93		0.90		0.92		0.87	

Table 6 (continued)

	NL		NO		PL		SE		UK	
	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
lnK	0.257***	45.62	0.114***	25.00	0.113***	22.51	0.090***	14.57	0.228***	34.01
lnL	0.558***	43.58	0.925***	41.68	0.866***	34.89	0.920***	30.93	0.686***	49.96
BROADpct	0.289***	13.87	0.264***	10.35	0.502***	17.55	0.180***	5.48	0.616***	23.11
INPD	0.049***	2.69	0.018	0.83	– 0.074***	– 2.70	0.037	1.41	0.042*	1.82
INPS	– 0.011	– 0.64	– 0.072***	– 3.26	0.130***	4.99	– 0.017	– 0.63	0.070***	2.72
MRKIN	– 0.029	– 1.54	0.035*	1.72	– 0.100***	– 4.21	– 0.015	– 0.58		
ORGIN	0.041**	2.52	0.017	0.89	0.046**	1.99	0.029	1.11	– 0.007	– 0.39
Size, 1–9 employees	– 0.642***	– 6.29	0.097	0.81	– 0.178	– 1.28	0.131	0.84	– 0.041	– 0.06
10–19 employees	– 0.828***	– 12.93	0.127	1.28	– 0.214*	– 1.92	0.098	0.73	– 0.254	– 1.53
20–49 employees	– 0.668***	– 13.49	0.098	1.22	– 0.176*	– 1.87	0.126	1.10	– 0.183	– 1.60
50–99 employees	– 0.468***	– 11.98	0.083	1.29	– 0.183**	– 2.38	0.104	1.09	– 0.065	– 1.22
100–249 employees	– 0.297***	– 9.59	0.059	1.19	– 0.238***	– 3.88	0.041	0.58	– 0.133***	– 2.83
250–499 employees	– 0.151***	– 5.29	– 0.056	– 1.38	– 0.138***	– 2.96	0.055	1.00	– 0.065**	– 2.32
AGE	0.001	0.45	0.008***	3.60	0.004*	1.72	0.009**	2.28	0.025***	5.88
AGE squared	– 0.00002	– 0.35	– 0.0002***	3.60	– 0.0002***	– 2.79	– 0.0002**	– 2.27	– 0.001***	– 5.02
Non-exporter	– 0.073***	– 4.49	– 0.093***	– 4.91	– 0.173***	– 9.40	– 0.049*	– 1.78	– 0.158***	– 6.30
Non-MNE					– 0.057	– 0.49	– 0.162***	– 5.93	– 0.220***	– 11.28
Constant	4.73***	45.72	5.10***	29.41	2.92***	7.78	5.85***	25.81	3.22***	25.03
Turning point age	53		47		28		41		31	
Observations	5454		4603		9411		2292		6717	
R^2	0.86		0.87		0.81		0.93		0.78	

OLS estimations on data pooled across industries and over time, 2002–2010

Significance at the 1, 5 and 10% levels are denoted by ***, ** and *. See Table 5

Several robustness checks are performed. Firstly, the production function is re-estimated using a gross output specification with materials. Unreported results show that the main estimates are not affected by the choice of output measure, as demonstrated by Syverson (2011), for instance (results are available upon request). Secondly, the innovation variables are estimated in combinations, although this does not make them more powerful. Thirdly, given the possibility that influential observations might distort the estimation results, a generic outlier correction procedure has been performed, where possible outliers have been identified by a first stage regression of productivity on input factors and categorical dummy variables. This did not affect the estimates.

5 Concluding remarks

This study investigates the link between productivity and innovations (technological as well as non-technological), taking into account the ICT intensity of firms, measured as the proportion of broadband internet connected employees. The estimations are based on linked and internationally comparable official firm-level data from ten European countries covering the years 2002–2010 and show that there is indeed a direct, positive and significant relationship between innovation activities and productivity in manufacturing as well as in service firms in most countries. However, this is only valid for product innovations, while no obvious pattern appears for process, organizational or marketing innovations. In contrast, the proportion of broadband internet connected employees is clearly related to productivity across industries in all but one country, with a magnitude distinctly larger than that of product innovations. The inclusion of the ICT intensity variable also diminishes the power and significance of the innovation variables. This could follow from the fact that broadband connected employees are capable to make use of additional unmeasured intangible assets. Although the approach does not allow causal effects to be interpreted, the results may indicate that ICT intensity, or the ability to use innovations, is more important for productivity than the innovative process in firms. Alternatively, there might be indirect links between innovation activities and productivity, or the innovations may need some time to establish the association. The direct significant negative effect of organizational innovations across industries in some countries may stress needs for a phase of adjustment before the firms benefit from the changes.

As is commonly the case, data characteristics drive the choice of estimation method, and this study is no exception. The high attrition of the data following response burden issues and the small time-variation of the innovation variables reduce the opportunities to employ dynamic modelling such as fixed effects estimations. Likewise, endogeneity of inputs in the production function are difficult to account for, and possible instrumental variables are scarce. Correcting for the simultaneity of inputs and outputs require either detailed information on the structure of investments (Olley and Pakes 1996) or on material inputs (Levinsohn and Petrin 2003). This information is not available in the ESSLait datasets, but the approaches may as well be less functional for datasets including large amounts of service firms, since they were initially developed for analyses of manufacturing firms. Another aspect of importance is the longevity of the measure of ICT intensity in firms. Presumably, the proportion of broadband connected employees reaches saturation at some not too distant point in time, while other kinds of ICTs continue to be crucial to firms. Alternative approaches could be to interact human capital and ICT, or to focus on measures of automation or robotism.

Because of the possible presence of individual unobserved characteristics that might influence productivity, the relationships in this analysis are not interpreted as causal. One solution to overcome this shortcoming is to employ pseudo-panel methods using micro-aggregated data by industry or firm characteristics such as size (Bartelsman et al. 2018). Another limitation is that micro enterprises are excluded in the underlying innovation and ICT usage surveys. These firms would have been important to include, because in certain industries they typically show a high degree of innovativeness (Baumann and Kritikos 2016).

There are several suggestions for future work. Analysis of linked firm-level data is promising, since it increases the amount of observable firm characteristics that can be controlled for. One idea is to match the research and development (R&D) survey to the structural business statistics. This survey contains information on R&D expenditures in firms whereas the CIS only includes information on innovation input, in cases when these activities are already ongoing or successful. The linked R&D and production statistics would make it possible to estimate a knowledge production function. There is also a need for improved innovation variables, preferably continuous ones. It cannot be excluded that less rough measures than those available would give a clearer picture of how innovations relate to productivity.

Appendix

See Fig. 1.

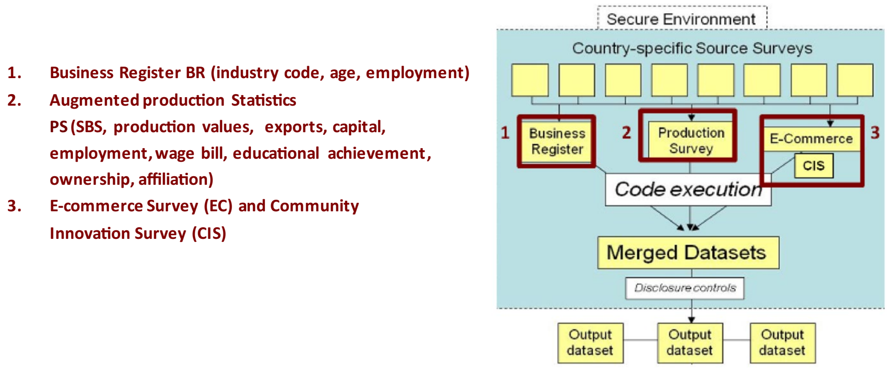

Fig. 1 Compilation of the harmonized and merged datasets Source: ESSLait project

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