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The impact of ICT adoption on productivity: evidence from Portuguese firm-level data

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Abstract
This paper studies the impact of ICT adoption on labour productivity and TFP of Portuguese firms in the period 2004–2020. We merge annual survey data on the adoption of six ICT dimensions—PC, internet, ICT staff, website, online purchases and online sales—and firm-level variables that make it possible to compute productivity measures and control for different heterogeneity dimensions. The paper proxies the ICT adoption of each firm using a principal component approach and takes a leave-one-out instrumental variable to assess causality. Results show a positive and sizeable impact of ICT adoption on TFP and labour productivity. When ICT dimensions are considered separately, online sales and the existence of a website stand out as the most important dimensions for productivity gains. The existence of ICT staff in the firm, which is complementary to other technologies, also has an important impact.

Keywords ICT · Digitalization · Productivity · Portugal · Firm-level data · Instrumental variables

JEL Classification O3 · O4 · J24

1 Introduction

Technological progress has always been one of the strongest forces shaping the world economy, driving productivity and economic growth in the long run. Economic growth literature has been studying the link between the adoption of new technologies by firms and productivity gains since the seminal contribution by

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Solow (1956). Recent decades witnessed intense technological progress. The ICT revolution gained traction in the 80s and made it possible for firms to compute and communicate at a much lower cost, also impacting on their access to information both in the internal market and across borders. The ICT revolution is interpreted as the emergence a general purpose technology that paved the way to the modern digital world, which involves the utilization of robots, 3D printing, big data, cloud computing and AI in the production process.

The quantification of impacts from ICT adoption took time to emerge in the literature. In a 1987 famous quote Nobel Laureate Robert Solow said “we could see computers everywhere but in the productivity statistics”, initiating the so-called “Solow paradox”. Since then, there has been significant progress in the analysis of ICT and productivity. Initial contributions focused on incorporating these technologies in growth models and growth accounting exercises. An important contribution is that of Draca et al. (2009), which not only includes a survey of the micro and macro literature on the topic, but also finds an important role for ICT on productivity, basing both on growth accounting and econometric evidence. Two more recent surveys are Cardona et al. (2013), which argues that more theoretical and empirical research is needed, notably for European countries, and Biagi (2013), which also includes a discussion about the link between ICT adoption and the EU–US productivity gap.

The empirical strand of the literature splits into growth accounting exercises, case-studies, sectoral analysis (often with multiple countries), and firm-level studies based on panel data. Some papers advance explanations for the impact of ICT on productivity, including the notion of complementary organizational capital, while others focus on the quantification of its impacts. One important contribution is Gal et al. (2019), which combines cross-country firm-level data on productivity and industry-level data on digital technologies to assess how their adoption is associated with firms’ performance, while accounting for heterogeneity. Although not trying to establish a causal relationship, the results state that ICT adoption in an industry is associated with productivity gains at the firm level. These effects are stronger in manufacturing and routine-intensive activities, and for more productive firms. In this context, authors argue that digital technologies may have contributed to the growing dispersion in productivity performance across firms, which couples with the broader discussion on the causes for the productivity slowdown (Syverson 2017).

Measuring the impact of ICT on productivity is quite important. Indeed, there are many firms whose access to ICT is not complete, thus further productivity gains may be expected. In addition, public policies have selected digitalization as an investment priority and ICT adoption is prerequisite for that goal. This trend is visible in the European Union (EU), where digitalization was put forward as a priority by the European Commission, it stands as one pillar of the Next Generation EU funds and it is an important part of the Recovery and Resilience Facility put in place in the aftermath of the COVID-19 pandemics.

It is acknowledged that the literature on the causal impacts of ICT adoption on the performance of firms is still limited (Draca et al. 2009). There is scarce suitable firm-level data, as this type of study requires information on the adoption of specific technologies, as well as knowledge about several other firms’ characteristics.

Contrarily to related topics, such as the impact of introducing computers in schools, tailored natural experiments are non-existent. Therefore, existing papers use other panel data methods to go beyond correlations and to establish causal relationships between ICT and firms' performance, defined in terms of productivity, sales, profits or engagement in foreign markets. One of such papers is Abramovsky and Griffith (2006), which considers the impact ICT on firms' decisions about the location of activity, and whether to produce in-house or outsource services offshore. The paper takes an instrumental variables approach and explores within industry firm-level variation, using UK census data at the establishment level. Another recent contribution is that of Cette et al. (2020), which assesses the impact of ICT and digitalization on productivity and labour share for a sample of French manufacturing firms.

Our paper follows closely the contribution by Cette et al. (2020). We also take an instrumental variables approach and construct the leave-one-out mean at the sector level. As in Cette et al. (2020), we use survey data on ICT adoption by firms. Our survey data is annual and covers several digitalization dimensions between 2004 and 2020. However, the sample of firms and the set of digitalization dimensions covered changes along the time. There is a notable increase in the number of firms surveyed after 2010 and the most advanced digitalization techniques are considered only in the latest vintages. As for outcome variables, we consider labour productivity and total factor productivity (TFP).

We conclude that there is a positive and robust relationship between the adoption of ICT technologies and firms' performance in terms of labour productivity and TFP. When we analyse ICT dimensions separately, the creation of a website and online sales stand out as the most relevant dimensions for productivity gains.

The paper is organized as follows. Section 2 describes the data and is divided in three subsections. The first subsection describes the databases that were merged for the analysis. The second subsection contains basic descriptive statistics and the third presents the principal components procedure used to proxy the adoption of ICT technologies at the firm level. Section 3 presents the empirical strategy. Section 4 presents our results and it is also divided in three blocks. Firstly, it presents the results of instrumental variable regressions using labour productivity and TFP as outcome variables and the first principal component that proxies ICT adoption as regressor. Secondly, due to its different nature, we analyse the impact of separating the ICT staff from other technologies. Finally, we run regressions for each separate ICT dimension and take specifications that put together those where there is more data variation. Section 5 presents some concluding remarks.

2 Data

2.1 Database

Our paper combines two rich Portuguese firm-level databases. The first set of data corresponds to answers given by firms to a survey designated "*Inquérito à Utilizaçao das Tecnologias de Informação e Comunicação nas Empresas*" (IUTICE), conducted by the Portuguese national institute of statistics (Statistics Portugal). This statistical operation is carried out annually within the framework of EU legislation (EC regulation No. 808/2004), which establishes a set of harmonization guidelines, thus ensuring the availability of comparable statistical results on ICT adoption across member states. The survey is available since 2004 and we use information up until 2020. The set of firms surveyed partially changes along yearly vintages and its total number has increased, notably since 2010. The set of questions posed to firms has also changed along the different vintages of the survey. These questions range from availability of a PC at the firm, internet connection, website, electronic payments, electronic invoicing, existence of ICT staff at the firm and ICT training. In its latest editions, the survey contains questions regarding dimensions of digitalization, such as the existence of robots, 3D printing or the utilization of big data, cloud computing and AI. The database is an unbalanced panel and the number of firms surveyed in some sectors and along the size and age dimensions is sometimes small. We thus removed the sectors of Agriculture, Extractive, Education, Health & Social and Arts & Sport. Nevertheless, there is sufficient variation in the data to obtain significant and robust results, while controlling for firm's characteristics.

Although changes in ICT dimensions surveyed are numerous, there is a subset of questions that remained broadly unaltered in our period of analysis. In order to maximize the number of observations we focus on six ICT dimensions, namely existence at the firm of: PC, website, internet, ICT staff, online purchases and online sales. Contrarily to Cette et al. (2020), which asks firms directly about the length of ICT adoption and observes its performance in one moment of time, we identify the existence of ICT in each year, in parallel with productivity measures. Therefore, our original data consists of dummy variables that assume the value one if the firm refers that the specific technology is in use, and zero for all alternative answers. Since we do not have a balanced panel database, we are unable to identify the length of ICT adoption in the firm. The option of restricting the sample to firms that adopt technologies only after being initially surveyed and that stay in the sample afterwards, thus creating a balanced panel, severely reduces the number of observations. Although, it is likely that the impact of ICT technologies accumulates with time, the bulk of the impact should accrue to its existence in the firm in a given year. Overall, we have an unbalanced panel containing 33,098 different firms and a total of 68,075 observations.

The second database used is the "*Sistema de contas integradas das empresas*", also compiled by Statistics Portugal. This very rich database builds on mandatory legal reporting by Portuguese firms to Statistics Portugal, tax administration, Banco de Portugal and Ministry of Justice. In this dataset we have a large number of balance sheet and income statement variables, which allow us to control for firm heterogeneity and to compute labour productivity (GVA per worker) and TFP. Nominal variables were deflated using sectoral information contained in the Portuguese national accounts.

It is widely acknowledged that TFP plays a critical role in economic growth and to explain per capita income differences across countries. The seminal contribution by Solow (1956) defined TFP as the portion of the output not explained by the amount of labor and capital (e.g. total fixed assets) used in production. In our paper, firm-level TFP is obtained using the method developed by Levinsohn and Petrin

(2003). An important issue in the estimation of the TFP is the correlation between unobservable productivity shocks and input levels, which leads to biased estimates. In order to account for these unobservable shocks, the Levinsohn and Petrin (2003) method uses a proxy variable in the estimation process. Wooldridge (2009) and Ackerberg et al. (2006) have later improved this method and the estimation, but the fundamentals remained unchanged. We implemented the procedure with the STATA command "prodest", which estimates the production functions using a control function approach. By default, the command requires the log gross output variable—in our case, the log of the GVA, at market prices—a set of free variables—typically the log of labor—a set of state variables—the log capital—and lastly, a set of proxy variables—which, in our case is the cost of goods sold. These options are similar to those of reference papers, such as Gal et al. (2019). Capital stock corresponds to total fixed assets of the firm, as reported in the balance sheet. The coefficients of our Levinsohn and Petrin (2003) estimation are plausible and are presented in Table 14 in appendix.

2.2 Descriptive statistics

In this subsection we briefly discuss the level of ICT adoption in Portugal in comparison with other EU countries and present some basic descriptive statistics for our database. As previously mentioned, our database is derived from different vintages of the IUTICE, whose samples and questions have changed along time. Therefore, our descriptive statistics are not comparable to official data, which incorporate imputation and other adjustments.

In order to frame Portugal in a broader context, Fig. 1 presents the digital intensity index (DII) for EU countries in 2022, ranking the share of firms with high and very high digitalization. The DII measures the use of different technologies by firms and is based on 12 variables, with each of them scoring 1 point and distinguishing along four levels of digital intensity for each enterprise: very low (0–3 points), low (4–6 points), high (7–9 points), very high (10–12 points). The top three countries are Denmark, Finland and Sweden and the bottom three are Bulgaria, Greece and Romania. Portugal stands in the upper half of the distribution of the DII and above the EU27 average, with shares of firms with high and very high digitalization of 30.8% and 4.7%, respectively. As mentioned, we focus on a subset of six ICT technologies, because the IUTICE survey only recently started to collect information bout the adoption of more advanced digital technologies.

Table 1 presents the share of firms in our database with each specific ICT technology (PC, internet, website, ICT staff, online purchases and online sales) in each of the 12 sectors considered in 2010 and 2018. Even if our database is not designed to mimic official statistics, as it would be expected, there is a very large share of firms with PC and internet access in the overall sample, which has increased from 2010 to 2018, reaching close to 100 percent in the latter year. This means that the variation across firm's ICT adoption originating from this technology is lower than in other dimensions. The same is true for internet access, but to a lower extent. The existence of website and, especially, ICT staff are less pervasive in firms, with

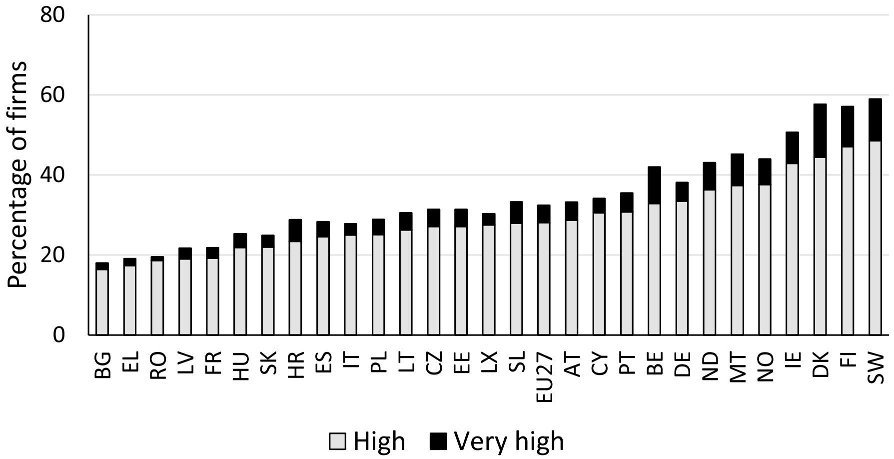

Fig. 1 Digital intensity index, 2022. *Source*: Eurostat. Note: The digital intensity index (DII) is a composite indicator, derived from the EU survey on ICT usage and e-commerce in firms. The indicator is calculated with 12 variables, with each of the variables having a score of 1 point. The DII distinguishes 4 levels of digital intensity for each enterprise: 0–3 points: very low; 4–6 points: low; 7–9 points: high; 10–12 points: very high. The index refers to firms with 10 persons employed or more, considering all activities except the financial sector

overall shares around 60 and 30 percent in the two years considered.[1] The shares of firms with online purchases and online sales are lower, which is helpful in terms of adding variation to the sample. At the sectoral level, the existence of website, ICT staff, online purchases and online sales is relatively more pervasive in the Information and communication and Other services.

The top panel of Table 2 presents the share of firms in our database that have adopted each ICT technology according to their size class (micro, small, medium and large), in 2010 and 2018. The result that stands out is the fact that the pervasiveness of all ICT dimensions increases monotonically with the size of the firms. In 2018 the share of ICT staff in large firms is about ten times larger than in micro firms and more than three times larger than that of small firms. As for online purchases and online sales this divide is also very large, but we should bear in mind that the small number of firms in some classes of our database limits the accuracy of comparisons. The bottom panel of Table 2 replicates the previous analysis but taking into consideration firms' age classes (1–5 years, 6–10, 11–20 and more than 20 years). Although size and age are correlated, results do not show a gap between young and old firms as wide as the one between micro and large firms. For example, in 2010, 15 percent of firms between 1 and 5 years of age in our database reported to have ICT staff, while the share for firms above 20 years was slightly below 50

[1] Contrary to official statistics, in our database these shares decreased from 2010 to 2018, but we attribute the result to the low coverage of the IUTICE survey in some sectors.

Table 1 Share of firms with each ICT dimension in the database, by sector

SECTOR	Nb. firms		PC		Internet		Website		ICT staff		Online purchases		Online sales	
	2010	2018	2010	2018	2010	2018	2010	2018	2010	2018	2010	2018	2010	2018
Manufacturing	1025	1693	95	97	93	96	70	63	43	30	20	17	12	4
Electricity and gas	29	47	79	85	69	83	55	55	28	30	14	21		13
Water	49	101	100	100	98	100	80	86	43	35	14	19	4	4
Construction	285	279	86	91	83	90	55	47	29	19	13	9	4	0
Wholesale	1035	1269	92	98	88	97	64	64	35	30	22	18	13	10
Transport	188	285	86	87	85	85	69	54	43	27	22	16	8	9
Accommodation	318	850	69	86	60	74	44	37	18	9	10	6	7	5
Information	276	436	98	98	97	98	87	83	61	57	40	38	18	11
Real estate	455	301	76	91	73	88	44	47	11	6	4	3	1	1
Consult	274	238	98	99	97	99	51	61	28	30	14	18	4	5
Administrative act	322	384	97	99	96	98	80	74	34	26	18	15	12	4
Other services	39	76	97	97	95	97	69	72	54	63	49	50	23	14
Total	4295	5959	90	95	87	92	64	60	34	27	18	16	10	6

Table 2 Share of firms with each ICT dimension in the database, by size and age

	Nb. firms		PC		Internet		Website		ICT staff		Online purchases		Online sales	
	2010	2018	2010	2018	2010	2018	2010	2018	2010	2018	2010	2018	2010	2018
SIZE														
Micro	1532	2679	74	90	67	85	31	36	9	7	5	5	2	1
Small	771	1281	97	98	95	97	63	61	23	15	12	8	6	4
Medium	1172	1087	99	100	99	100	84	89	51	51	27	28	13	10
Large	820	912	100	100	100	100	95	96	69	76	37	49	21	18
AGE														
1–5 years	427	2	88	50	81	50	48	50	15		7		4	
6–10 years	807	846	86	95	80	92	52	47	23	15	13	9	6	4
11–20 years	1345	2026	90	95	87	92	61	57	31	23	17	14	9	4
> 20 years	1716	3085	93	95	92	93	75	66	47	34	25	20	13	8

percent. This more muted pattern is also observed when we compare the share of firms with online purchases and online sales by age class.

The previous discussion points to the need to take account of these heterogeneity dimensions when measuring the impact of ICT adoption by firms' on their labour productivity and TFP. Therefore, in our econometric specifications below, we always include fixed effects for sector, size and age. For different reasons, year fixed effects are also warranted.

2.3 The principal components analysis

The existence of multiple ICT dimensions and the fact that firms may adopt them at different moments and in diverse combinations makes it necessary to have a proxy variable that summarizes firm's ICT adoption in each year and in a way that is comparable with other firms. The principal component analysis (PCA) is a well established method for reducing the dimensionality when phenomena are described by multiple variables, thereby increasing interpretability, while minimizing information loss. The method solves an eigenvalue/eigenvector problem to create new uncorrelated variables (the principal components) that successively maximize variance. The PCA is defined as an adaptive data analysis technique because variables are defined by the dataset at hand and not a priori. We implemented the procedure with the STATA command "pca". Since our data consists of dummy variables that take the value one when the firm says that the specific technology is in use, we also tested an algorithm suited for categorical data. More specifically, we used the Multiple Correspondence Analysis (MCA) package in R, which is the counterpart of PCA for categorical data. Reassuringly, results obtained with the MCA package match those obtained with the PCA. In Sect. 4.2 below we also compute the PCA without the ICT staff variable in order to isolate this dimension from the combination of all other technologies.

As mentioned above, there are six ICT dimensions to be included in our PCA exercise: PC, internet, website, ICT staff, online purchases, and online sales. Table 3 presents the six eigenvalues and the proportion of each principal component in explaining variability in the data. The first principal component (pc1) is clearly the most important one, explaining 40 per cent of overall variability in the data, while the second (pc2) explains 23 per cent. Therefore, it is reasonable to take pc1 as our

Table 3 Principal components—eigenvalues

COMPONENT	Eigenvalue	Proportion	Cumulative
pc1	2.40	0.40	0.40
pc2	1.39	0.23	0.63
pc3	0.82	0.14	0.77
pc4	0.73	0.12	0.89
pc4	0.57	0.10	0.98
pc5	0.09	0.02	1.00

Table 4 Principal components—share on each ICT dimension

VARIABLES	pc1	pc2	pc3	pc4	pc5	pc6	Unexplained
PC	0.50	−0.49	0.04	0.07	0.12	0.70	0
Internet	0.53	−0.45	0.02	0.09	0.06	−0.71	0
Website	0.41	0.34	−0.26	0.29	−0.75	0.06	0
ICT staff	0.32	0.43	−0.62	0.00	0.58	0.00	0
Online purchases	0.37	0.25	0.26	−0.85	−0.11	0.00	0
Online sales	0.25	0.45	0.70	0.42	0.27	0.00	0

Table 5 Correlation coefficients between principal components and ICT dimensions

VARIABLES	pc1	pc2	PC	Internet	Website	ICT staff	Online purchases	Online sales
pc1	1.00							
pc2	0.00	1.00						
PC	0.78	−0.58	1.00					
Internet	0.82	−0.53	0.90	1.00				
Website	0.63	0.41	0.22	0.29	1.00			
ICT staff	0.50	0.50	0.12	0.15	0.40	1.00		
Online purchases	0.57	0.29	0.23	0.25	0.29	0.26	1.00	
Online sales	0.39	0.53	0.06	0.09	0.29	0.20	0.25	1.00

All correlations are significant at 1%

proxy for the adoption of ICT at the firm level. The standard deviation of the pc1 is 1.499.

Table 4 presents how much of each ICT dimension is explained by each of the six principal components. The pc1 is not the main contributor to explain variability in all ICT dimensions (not in ICT staff and online sales), but it is dominant overall. Values in Table 5 are the correlations between each ICT dimension and the two main principal components: pc1 and pc2. Most of these correlations are positive and high, and they are all statistically significant at 1 percent. Non surprisingly, the largest correlation is between PC and internet (0.9), but the pair ICT staff–website is also highly correlated (0.4).

3 Empirical strategy

We start the analysis by comparing TFP and the labour productivity levels for two layers of the first principal component (pc1) distribution, corresponding to high and low ICT adopters. More specifically, panel (a) of Fig. 2 plots the distribution of TFP levels for firms above and below the median of the pc1. This representation conveys the message that firms above the median in terms of ICT adoption perform clearly better than those below the median. Panel (b) replicates the analysis for the labour

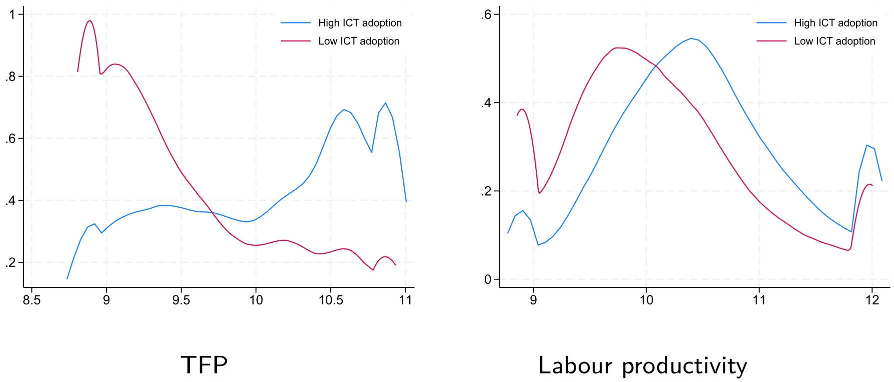

Fig. 2 ICT adoption and productivity. *Note* The panels plot the distribution of TFP and labour productivity (ln) for firms above and below the median of the first principal component (pc1), taken as a proxy for high–low ICT adoption at the firm level

productivity variable. In this case a better performance from firms above the median of ICT adoption is also visible, though not as strong as in the case of the TFP. These patterns are similar if we consider annual distributions, as illustrated in Fig. 3 in appendix, with kernels for 2010 and 2018. This early evidence does not take into account confounding factors between ICT and productivity, neither firms' characteristics, but it puts us on track to test this relationship in a more robust way.

The identification strategy used to establish the relationship between ICT adoption and firm's productivity levels is based on an instrumental variable approach. We follow Cette et al. (2020), which uses a leave-one-out instrumental variable for the exact same purpose we do. In our exercise, the leave-one-out mean in the sector is simply the average of the value of the indicator for all firms in the specific sector except the firm being considered, that is:

$$ICT_{it} = \frac{\sum_{\substack{nt \neq it \\ \forall nt \in j}} ICT_{nt}}{N_{jt} - 1} \tag{1}$$

where ICT_{it} is the variable that identifies the level of ICT adoption by firm i in year t, and N_{jt} is the total number of firms in sector j, to which i also belongs, in period t.

Equation 1 defines the instrumental variable to be used in the second step of the procedure, where the regression to estimate is:

$$Prod_{it} = \alpha + \beta ICT_{it} + \delta_d + \delta_a + \delta_s + \delta_t + \epsilon_{it}, \tag{2}$$

where the dependent variable $Prod_{it}$ corresponds either to the logarithm of labour productivity or TFP of firm i in a given year t. The variable for ICT adoption by the firm is given by ICT_{it} and the corresponding β is our parameter of interest. δ_d, δ_a, δ_s and δ_t correspond to size class, age class, sector and year fixed effects. ϵ_{ijt} is the error term, and we take clustered standard errors at the firm level.

Econometric theory defines that an instrumental variable must be both relevant and exogenous. Relevance is associated with the ability to explain the variation in the variable that stands as the regressor of interest. The relevance (strength) of the instrument can be captured by the value of the F-statistic in the first stage regression (Stock and Yogo 2002). The Staiger and Stock (1997) rule of thumb for the cut off in this statistic is 10, which we also take as a benchmark. The exogeneity of the instrument is much harder to assess. It implies that the instrument correlates with the dependent variable only through the endogenous one. The validity of the leave-one out instrumental variables requires the assumption of the exogeneity of at least one of its components: exogenous shocks or exogenous exposure. We argue that the latter is likely to be our case, notably in a context where sector fixed effects are included in the specification. Since the sector fixed effects capture all sectoral specificities, we are confident that Eq. 2 can be consistently estimated. In fact, although it is quite possible that unspecified events taking place at the sector level are common to the firm (e.g. those due to spillover or network effects), the inclusion of sector fixed effects takes account of this problem. Therefore, the only way for the leave-one out instrument to affect productivity is through the individual adoption of ICT, thus turning the instrument valid.

4 Results

In this section we present the results of our empirical exercise. We begin with productivity impacts associated to the firm-level proxy for ICT adoption that corresponds to the predicted value of the first principal component (pc1), as explained in Sect. 2.3. Next, we assess the specific nature of having ICT staff in the firm by separating its effect from that of other ICT dimensions. Finally, we present regressions with the impacts for each ICT dimension separately, and take together the dimensions where there is more cross-firm variation.

4.1 Impact of ICT on labour productivity and TFP

Table 6 presents the results of our second stage IV regression (Eq. 2). Given the identification strategy previously described, the coefficient for the variable of interest ICT (pc1) measures the impact on a unitary increase in the first principal component on the performance of firms, taking as outcome variable the logarithms of labour productivity and TFP, respectively. Although the methodology to infer causality is the same as in Cette et al. (2020), our data has a different nature and we thus include additional fixed effects. Beyond, sector fixed effects (12 sectors), all regressions include year (between 2004 and 2020), age class and size class fixed effects. As considered in Table 2, the variable age classifies firms along four categories (1–5 years; 6–10 years; 11–20 years and more than 20 years) and the size variable classifies firms along four dimensions (micro, small, medium and large firms), in accordance with the definition used by the European Commission, which combines turnover and number of employees.

Table 6 Impact of ICT adoption on labour productivity and TFP (ln)—IV HDFE regression

Variables	(1) Labour prod	(2) Labour prod	(3) TFP	(4) TFP
ICT (pc1)	0.211***	0.219***	0.131***	0.133***
	(0.027)	(0.027)	(0.015)	(0.015)
Age		0.037***		0.041***
		(0.007)		(0.004)
Size		0.105***		0.360***
		(0.018)		(0.010)
Observations	68,071	68,071	68,071	68,071
F	61.87	499.1	78.34	6489
Size FE	Yes	No	Yes	No
Age FE	Yes	No	Yes	No
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively. pc1 is a proxy of the ICT adoption by the firm, taken as the first principal component from the six dimensions considered (PC, internet, ICT staff, website, online purchases and online sales)

Specifications in columns 1 and 2 of Table 6 refer to the logarithm of labour productivity and are strongly significant. Results suggest that the overall adoption of ICT by the firm has a sizable and significant positive impact on labour productivity. All else constant and taking into account the fixed effects implemented, one standard deviation increase in pc1 leads to an increase of 33 percent in labour productivity. Nevertheless, one standard deviation increase in pc1 is an object difficult to interpret as it combines the six ICT dimensions in a non-linear way. Considering age and size as explanatory variables instead of fixed effects (column 2) basically does not change the coefficient for pc1 and it also confirms the well established result that older and larger firms are more productive.

Specifications in columns 3 and 4 replicate the previous analysis but using the logarithm of TFP as the firm performance variable. Conclusions stay qualitatively unaltered, but the coefficients for the impact of ICT adoption on TFP are smaller in magnitude. One standard deviation increase in pc1 generates a 20 percent increase in the TFP of the firm. Considering age and size as explanatory variables instead of fixed effects (column 4) does not significantly change results. Although the survey that collects our ICT data is designed to represent the universe of Portuguese non-financial corporations, in order to asses a potential sample selection bias we estimate these specifications the with a subsample without micro firms and with a sub sample that disregards large firms. The results obtained with these two sub-samples are robust and are presented in Tables 11 and 12 in appendix.

4.2 Impact of ICT staff

Having ICT staff in the firm is an important feature of ICT adoption (OECD 2004), which in the previous sections we integrated with other ICT dimensions. However, ICT staff is associated to employment, while other ICT dimensions considered correspond to specific tangible or intangible assets. Another way of stating the different nature of ICT staff is to say that it should be considered as complementary to other ICT dimensions. In this vein we performed two exercises. The main exercise separates the ICT staff variable in an IV regression that includes the first principal component computed just with the remaining five ICT dimensions (PC, internet, website, online purchases and online sales). The instrument for the ICT staff variable is computed as a leave-one-out mean at the sector level, similarly to Eq. 1. Table 7 presents the results of this exercise for labour productivity and TFP and shows that the ICT staff coefficients are positive and highly significant, while the pc1 coefficients are smaller than the ones in Table 6.

An additional exercise involves assessing the impact of ICT staff on labour productivity and TFP with the former variable explicitly interacting with the pc1. In this regression we do not take an IV approach and results are presented in appendix. Table 13 shows that the coefficients of the ICT staff—pc1 interaction are positive and highly significant, meaning that the existence of ICT staff at the firm amplifies the positive correlation between the adoption of other ICT dimensions and firms' labour productivity and TFP.

Table 7 Impact of ICT staff on labour productivity and TFP (ln)—IV HDFE regression

Variables	(1) Labour prod	(2) TFP
ICT (pc1)	0.168***	0.106***
	(0.024)	(0.013)
ICT staff	0.572***	0.385***
	(0.117)	(0.067)
Observations	68,071	68,071
F	27.52	37.74
Size FE	Yes	Yes
Age FE	Yes	Yes
Sector FE	Yes	Yes
Year FE	Yes	Yes

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively. The pc1 in the first stage regression is a proxy of the ICT adoption by the firm, taken as the first principal component from five dimensions: PC, internet, website, online purchases and online sales, i.e., without ICT staff, which is included separately

4.3 Impact by ICT dimension

In order to compare the relative impact of each ICT dimension on firms' productivity performance we run high dimensional IV fixed effect regressions, replicating the the leave-one-out instrumental variable described in Eq. 1, but based on each individual ICT dimension and not on the pc1. In addition, we implement two specifications where several individual ICT dimensions are considered in the same regression. It should be noted that coefficients can be compared in terms of magnitude but their levels are difficult to interpret. The second step regression involves two continuous variables, but in the first step regression the dependent variable is a dummy and the instrumental one is continuous. In the cases where more than one ICT dimension is included in the IV regression the interpretation is even harder as there are different instruments (the IVs of the ICT dimensions considered) explaining each dummy variable in the first step regression.

Coefficients that capture the impact of each ICT component on firms' labour productivity are presented in Table 8. All estimated coefficients have the expected positive sign, i.e., the use of each of the six technologies improves labour productivity. The ranking of impacts in columns (1) to (6) indicates that internet, online purchases

Table 8 Impact of individual ICT dimensions on labour productivity

Variables	Labour productivity							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PC	0.467***							
	(0.082)							
Internet		0.164**						
		(0.072)						
ICT staff			0.647***					0.220*
			(0.117)					(0.126)
Website				1.275***			1.188***	1.188***
				(0.133)			(0.144)	(0.146)
Online purchases					0.365***		0.255***	0.269***
					(0.078)		(0.095)	(0.096)
Online sales						1.068***	0.459**	0.379**
						(0.172)	(0.189)	(0.189)
Observations	68,071	68,071	68,071	68,071	68,071	68,071	68,071	68,071
F	32.11	5.227	30.70	91.28	21.75	38.76	30.54	22.64
Size FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Age FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively and PC have the lowest coefficients, while website and online sales have the highest impacts. ICT staff takes the third positions in terms of impact size. As for regressions in columns (7) and (8), the website and online sales dimensions remain in first and second positions, respectively, and, as expected, the estimated coefficients are smaller but all remain positive and statistically significant.

The option of including PC and internet in the regressions with multiple ICT dimensions in parallel, turns these specific parameters either non significant or negative. That is not a surprising outcome because there is much less variation across firms in the adoption of these technologies.

Table 9 replicates the previous analysis for TFP and results regarding the relative importance of each individual ICT dimension are quite consistent. The magnitude of the coefficients for online sales and for the existence of website stand in first and third positions, respectively. Another notable feature is the increase in importance of ICT staff, visible both in columns (3) and (8). Finally, internet and online purchases take the two lowest positions in the ranking both in terms of labour productivity and TFP. A regression without instrumental variables with all ICT dimensions, with fixed effects for size, age sector and year is presented in Table 10 in appendix. Results are broadly consistent with those of the IV regressions of Tables 8 and 9.

Table 9 Impact of individual ICT dimensions on TFP

Variables	Total factor productivity							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PC	0.303***							
	(0.042)							
Internet		0.252***						
		(0.039)						
ICT staff			0.445***					0.272***
			(0.067)					(0.067)
Website				0.396***			0.258***	0.258***
				(0.073)			(0.085)	(0.085)
Online purchases					0.281***		0.252***	0.268***
					(0.042)		(0.050)	(0.049)
Online sales						0.796***	0.700***	0.600***
						(0.101)	(0.105)	(0.105)
Observations	68,071	68,071	68,071	68,071	68,071	68,071	68,071	68,071
F	51.56	42.53	43.76	29.73	45.04	62.67	26.56	21.76
Size FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Age FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively

5 Concluding remarks

The adoption of ICT by firms, alongside with the diffusion of more recent digital technologies, will continue in the coming years. These transformations bring important changes in the way firms operate and positively impacts their productivity levels. Therefore, public policies are actively engaged in promoting this transformation by facilitating access to finance for private digitalization investments, creating public infrastructure and developing digital skills in the population.

In this paper we make use of rich data for Portuguese firms and measure the impact of ICT adoption on TFP and labour productivity. Technologies considered are: PC, internet, website, ICT staff, online purchases and online sales. We adopt an IV approach and take both a proxy of ICT adoption by the firm based on a principal component exercise, and each ICT dimension separately. Moreover, we discuss up to what extent ICT staff and other technologies are complementary, and test several ICT dimensions in the same regression to compare their relative impact on productivity.

Results obtained confirm those from previous research, and point towards sizable and significant productivity gains for firms that adopt ICT technologies. This is true for both measures of performance considered: labour productivity and TFP. When ICT staff is separated from other technologies results remain unaltered in qualitative terms, with the coefficient for the principal component without the former variable becoming smaller and the coefficient for ICT staff being positive and also highly significant. When we consider the different ICT dimensions separately, the ranking of impacts on labour productivity and TFP is quite close. In both cases internet, online purchases and PC have the lowest coefficients, while website and online sales stand amongst the three highest coefficients. Moreover, ICT staff takes the third and second positions in terms of impact on labour productivity and TFP, respectively.

Evidence on the impacts of ICT adoption on firms will certainly build up in the next years. Given the large number of firm level productivity drivers, the key challenge is to setup exercises that capture robust causal relationships. The availability of new databases, ideally comparable across countries, will allow for more robust conclusions. Data for more recent digitalization dimensions, such as robots, 3D printing, big data, cloud computing and AI is still limited in terms of time span, thus leaving the measurement of their impact an open research question.

Other important topics of research in connection with ICT already in progress in the literature are the impact on employment, wages, worker's skills, innovation, participation of firms in external markets, and their related sourcing decisions. Finally, the list of future research avenues includes the relationship between ICT adoption and the incorporation of services in firms' production and export portfolios.

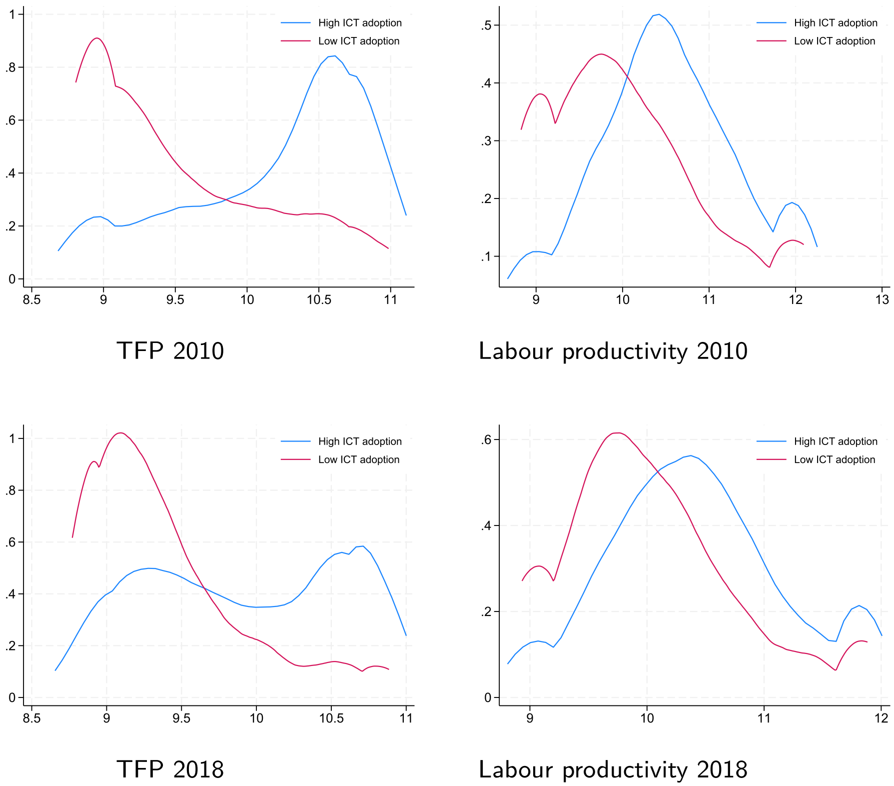

Fig. 3 ICT adoption and productivity in 2010 and 2018. *Note* The panels plot the distribution of TFP and labour productivity (ln) for firms above and below the median of the first principal component (pc1), taken as a proxy for higher–lower ICT adoption at the firm level

Table 10 ICT dimensions taken separately without instrumental variables

Variables	(1) Labour prod	(2) Labour prod	(3) TFP	(4) TFP
PC		−0.016		0.021**
		(0.022)		(0.009)
Internet		0.114***		0.049***
		(0.020)		(0.009)
Website	0.162***	0.147***	0.108***	0.099***
	(0.011)	(0.011)	(0.006)	(0.006)
Online purchases	0.039***	0.034***	0.057***	0.054***
	(0.011)	(0.012)	(0.006)	(0.006)
Online sales	0.027*	0.026*	0.041***	0.041***
	(0.015)	(0.015)	(0.008)	(0.008)
ICT staff	0.130***	0.131***	0.089***	0.089***
	(0.015)	(0.015)	(0.008)	(0.008)
Constant	10.129***	10.057***	9.673***	9.620***
	(0.011)	(0.017)	(0.006)	(0.008)
Observations	68,075	68,075	68,075	68,075
Adj. R^2	0.285	0.286	0.731	0.731
Size FE	Yes	Yes	Yes	Yes
Age FE	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively

Table 11 Impact of ICT on labour productivity and TFP (ln)—No micro firms

Variables	(1) Labour prod	(2) Labour prod	(3) TFP	(4) TFP
ICT (pc1)	0.360***	0.367***	0.151***	0.156***
	(0.105)	(0.106)	(0.057)	(0.057)
Age		−0.015		0.032***
		(0.019)		(0.010)
Size		−0.081		0.298***
		(0.063)		(0.033)
Observations	33,771	33,771	33,771	33,771
F	11.66	43.64	7.108	1325
Size FE	Yes	No	Yes	No
Age FE	Yes	No	Yes	No
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively. pc1 is a proxy of the ICT adoption by the firm, taken as the first principal component from the six dimensions considered (PC, internet, ICT staff, website, online purchases and online sales)

Table 12 Impact of ICT on labour productivity and TFP (ln)—No large firms

Variables	(1) Labour prod	(2) Labour prod	(3) TFP	(4) TFP
ICT (pc1)	0.236***	0.243***	0.093***	0.090***
	(0.041)	(0.041)	(0.021)	(0.020)
Age		0.034***		0.033***
		(0.007)		(0.004)
Size		0.157***		0.455***
		(0.037)		(0.018)
Observations	41,352	41,352	41,352	41,352
F	33.18	750.4	20.33	5410
Size FE	Yes	No	Yes	No
Age FE	Yes	No	Yes	No
IndustryFE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively. pc1 is a proxy of the ICT adoption by the firm, taken as the first principal component from the six dimensions considered (PC, internet, ICT staff, website, online purchases and online sales)

Table 13 Interaction of ICT staff with other ICT dimensions

Variables	(1) Labour prod	(2) TFP
ICT (pc1)	0.068***	0.053***
	(0.004)	(0.002)
ICT staff # pc1	0.020***	0.026***
	(0.007)	(0.003)
Constant	10.285***	9.786***
	(0.007)	(0.003)
Observations	68,075	68,075
F	162.2	357.5
Adj. R^2	0.279	0.727
Size FE	Yes	Yes
Age FE	Yes	Yes
Sector FE	Yes	Yes
Year FE	Yes	Yes

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively. pc1 stands for the first principal component computed with all technologies except the ICT staff (PC, internet, website, online purchases and online sales)

Table 14 Results of the TFP estimation with Levinsohn and Petrin (2003)

Variables	GVA (ln)
Number of workers	0.703***
	(0.00795)
Total fixed assets (ln)	0.214***
	(0.00890)
Observations	68,075
Number of groups	29,382

Standard errors in parentheses. ***, **, and *, indicate the 1%, 5%, and 10% significance levels, respectively. Wald test on constant returns to scale: Chi2 = 97.93 and p = (0.00)

Kernels for 2010 and 2018

All ICT dimensions

See Table 10.

Sub-samples without micro and without large firms

See Tables 11 and 12.

ICT staff interaction

See Table 13.

TFP estimation

See Table 14

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