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Digital adoption and productivity: understanding micro drivers of the aggregate effect

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Digital adoption and productivity: understanding micro drivers of the aggregate effect [1]

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Abstract

Digital technologies have the scope to engender positive effects on productivity at firm and aggregate level. However, empirical evidence and theoretical contributions are ambiguous as mixed findings and diverse explanations have been put forward. We use a rich and representative sample of Portuguese firms over the period 2014-2019 to empirically assess the relationship between digital technologies adoption and productivity. Based on estimations over the entire distribution of firm's productivity, we find that heterogeneous digital technologies affect differently the dynamics of productivity and the convergence to the frontier. This leads to mixed findings with scope to diverse impact in the aggregate productivity. Moreover, positive and significant effects on productivity require an upgrading on the degree of sophistication and complementarity among digital technologies and benefit from the ability of firms to interact and learn with digitalised peers in the same industry.

Keywords: Digital technologies, Productivity, Spillover effects

JEL Classification: L20, H81, L25

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1. Introduction

Significant scholarly attention has recently been devoted to understanding the evolution of aggregate productivity, particularly in developed countries, as it has been showing a declining trend, despite significant technological changes, capital investment and various public programs supporting firms. In a context of slow global productivity growth, several studies have led to renewed discussions about Robert Solow's 1987 productivity paradox. These studies suggest that the effects of recent technological changes, and similarly of various programs to support firms, tend not to be visible in terms of aggregate productivity. Some contributions, for example, Pinheiro Alves (2017) for the case of the Portuguese economy, were carried out to document and explain the phenomenon. Additionally, since the beginning of the 2000s, there has been a decrease in business dynamics in several countries (Criscuolo et al., 2014), which indicates constraints in terms of resources reallocation and, consequently, in obtaining productivity gains.

Although the innovation effort by the most innovative firms did not register significant decreases, Andrews et al. (2015) suggest that a possible explanation for the absence of visible effects in terms of aggregate productivity could be a decrease in the rate at which innovations spread and replicate across the economy. Andrews et al. (2015) named it as a break in the technological diffusion machine. The ability of other firms to learn from more innovative frontier firms may have decreased, which is consistent with previous evidence in terms of penetration rate of new technologies (e.g., Comin and Mestieri, 2013) or even the possibility of innovators to appropriate all the dynamics and benefits arising from innovation (Gabaix and Landier, 2008). However, other authors argue that the growing digitization of economic activities may reactivate the technological diffusion machine, as it makes business trialling faster and cheaper and the possibility of replicating innovations faster and more accurate (Brynjolfsson and McAfee, 2012). If so, positive effects in terms of firm level and aggregate productivity can be expected as digital technologies adoption spreads out across firms and industries.

In fact, some authors argue that there are good reasons to believe that digital technologies should have the power to engender strong positive effects on productivity (Syverson, 2011; Brynjolfsson and McAfee, 2014). Innovation is how the productivity growth happens and many innovations emerge from recombining existing solutions and elements in order to make them more valuable. Digital technologies assist this kind of innovation by making it easier to combine ideas. When firms began to make widespread efforts to integrate digital technologies into their business, for example by improving business processes, automating certain routine tasks, and reducing costs of interacting with suppliers and customers, productivity gains are likely to emerge (Bartel et al., 2007; Akerman et al., 2015).

Yet, the empirical evidence at the industry and firm levels has yield mixed findings with scope to diverse explanations and many directions of further research (see, for instance, Acemoglu et al., 2014; Bartelsman et al., 2017; DeStefano et al., 2018). Andrews et al. (2016) and Berlingieri et al. (2020) have shown that aggregate patterns mask a widening productivity gap between a handful of frontier firms and a mass of laggard firms (firms that operate at the bottom of productivity distribution), especially in highly digitalized industries. Moreover, digital technologies tend to engender productivity gains only in combination with other factors such as organisational and management skills (e.g., Bloom et al., 2012), R&D and intangible investments (e.g., Corrado et al., 2017) and regulatory environment that enables the efficient resources reallocation (e.g., Bartelsman, 2013). In addition, digital technologies are a heterogeneous set of technologies that may affect firms´ productivity in different ways. Therefore, previous evidence points out that the links between digital adoption and productivity are complex (for a survey, see, e.g., Gal et al., 2019) and deserve further empirical research.

The objective of this paper is three-fold. Firstly, we take a broader perspective and assess how the adoption of a range of digital technologies could affect productivity at firm level for a representative sample of Portuguese firms over the period 2014-2019. The digital technologies under scrutiny are a set o heterogenous technologies and have been selected for their potential to improve firm productivity and for being in different maturity stages. Second, we explore some of the reasons why the benefits at firm level could be disappointing at the aggregate level. In particular, we explore whether there are differences in the productivity benefits from digital technologies adoption among firms belonging to different industries and with different levels of productivity and whether digital adoption is able to foster productivity convergence between frontier and laggard firms. Third, another important issue in understanding the link between digital adoption and productivity is related to benefits that could be derived from interactions with digitalised peers in the same industry. This implies to rely into detailed firm level and to define an empirical framework that helps in disentangling whether productivity benefits are driven by within-firm adoption or from spillovers due to interactions with other digitalised firms in the same industry.

As far as we are aware, there is no similar study applied to Portuguese firms. Assessing the impact of digitalisation on firm-level productivity and the way it translates into productivity growth at aggregate level is crucial and could provide important implications for public policy related to the support of digital adoption and the creation of conditions that enable a catch-up process of laggard firms. Moreover, to date, there is only some initial evidence that the latest generation of new technologies, namely big data and highly automated production modes, have positive effects on productivity. Furthermore, by analysing technologies in different maturity stages, we provide evidence to the extent productivity is following a J-curve shape (Brynjolfsson et al., 2021). Therefore, our study provides a contribution to this new strand of literature, analysing those effects associated with the adoption of such transformative technologies in a developed country but, in the context of the European Union (EU), a small, open, and peripheral economy.

The paper is organised as follows. Section 2 presents an overview on the links between digital technologies and productivity. Section 3 describes the data, empirical variables, and provides a description of digital technologies adoption by Portuguese firms. Section 4 describes the empirical strategy. Subsequently, econometric results are presented and discussed in Section 5. Section 6 concludes and discusses policy implications.

2. Digital technologies and firm's productivity

It has been widely recognised by scholars that innovation is a crucial driver of productivity increase. At the firm-level, innovation may lead to productivity increases through exploitation of scale economies, efficiency change, technological change and also through the use of unused capacity utilisation. The vast extant literature on the topic has shown that innovation may affect productivity in different ways depending on its type – product, process or organizsational, and novelty – incremental and/or radical (Mohnen and Hall, 2013).

Process innovations in the form of new technologies – such as digital technologies, are seen as powerful productivity drivers. Digital technologies, also called intelligent or smart technologies (Brynjolfsson and McAfee, 2012), are seen as envisaging the Fourth Industrial Revolution. They are particularly important because they are an example of general purpose technologies (GPTs), that is, technologies that are introduced very infrequently but they can have a significant impact on firms and on the productivity of an economy (Bresnahan and Trajtenberg, 1995; Jovanovic and Rousseau, 2005). This is because they have both the capacity to change the ways in which firms conduct business and a pervasive nature, i.e., they can be applied in many ways and areas with far-reaching economic and social consequences (Bresnahan and Trajtenberg, 1995).

Despite the potential positive impact of digital technologies on firms´ productivity, their adoption is not instantaneous. It is an empirical regularity that the diffusion of new technologies is a process that takes time, typically described by a sigmoid curve (Stoneman, 2001). The technology diffusion literature shows that a firm decision to adopt process technologies is determined by a set of factors relating the technology (e.g. novelty, complexity) and firm-specific characteristics (e.g. resources and knowledge endowments), as well as the external context in which the firm operates (e.g. competition, number of current adopters, different demand conditions, level and cumulativeness of knowledge (Malerba and Orsenigo, 1996). Thereby, it is an empirical regularity that as technology diffusion takes place one observes differences in the adoption rates across firms, which in turn leads to firm productivity heterogeneity (Hall et al., 2009).

In the case of digital technologies adoption is expected to take time due a number of aspects. The radicalness of technologies usually implies a destruction of routines as the new technology may not be compatible with the firms existing production lines or with old technologies embedded in old capital (Hobijn and Jovanovic, 2001). Also, the adoption of these technologies requires complementary assets such as management practices, skill-specific labour or the internal organization adjustments necessary to deploy digital technologies successfully (Bresnahan et al., 2002; Bloom et al., 2012). So, the general view is that digital technologies require an initial learning period, during which the firm becomes more productive through the efficient use of these technologies. This implies that productivity growth tends to decline in the early stages of the diffusion of the new technology, which has been described as a productivity J-curve (Brynjolfsson et al., 2021).

Recent studies on digital technologies adoption and their impact on firm productivity have been recognising that digital technologies are not homogenous and should be treated differently (Syverson, 2017; DeStefano et al., 2018; Ballestar et al., 2020). Digital technologies relate to various technologies where the most preeminent are enterprise resource planning (ERP), customer relationship management (CRM), and enterprise content management (ECM), cloud computing, big data and automation, each with different capabilities (Frank et al., 2019). ERP and CRM technologies are mature software systems and data technologies, which lack more sophisticated features encompassed by big data analytics and automation. Likewise, recent developments in industrial robotics allowing its connection between artificial intelligence and the second-digital-wave technologies (i.e., machine-learning, internet of things, cloud computing, big data, or 3D printing) have brought robotics into a new level of technological sophistication, generating renewed academic interest in their effects on productivity and employment.

Empirical evidence on digital technologies adoption and impact on productivity has almost exclusively focused on their first wave (i.e., ICT relating to internet use and ERP and CRM technologies), but do not discriminate among different technologies (e.g., Corrado et al., 2017; Chun et al., 2015; Pieri et al., 2018; Stiroh, 2002). Overall, this research shows a positive impact of ICT on firm productivity through improvements in efficiency at the firm level. These contributions also find that the impact of ICT investments on productivity growth is higher in sectors that produce or intensively use ICT capital goods and when complemented with other internal capabilities.

More recent studies have investigated the impact of set of latest generation of new technologies on productivity, namely robots (Ballestar et al., 2020; Jungmittag, 2021) and artificial intelligence, big data, flexible automation (Venturini, 2021). They essentially corroborate the evidence found in previous generations of technologies, in that, they find a positive link between these technologies and productivity. In addition, their evidence corroborates the hypothesis of the productivity J – curve, as initially these technologies increase productivity dispersion and only after the initial phase some convergence is observed.

In addition to the within-firm effect of digital technologies-driven productivity dispersion among firms, some contributions (Chun et al., 2015; Corrado et al., 2017; Pieri et al., 2018) have found that between-firms effects are equally important to explain aggregate productivity. Specifically, Chun et al. (2015) show there are significant cross-industry variations in firm-level resource reallocation from less productive firms to more productive ones. Thereby, industries in which the reallocation mechanism is more efficient will be able to attain higher productivity levels. More recently, Corrado et al. (2017) and Pieri et al. (2018) add to these findings and find that digital technologies alongside R&D have been particularly effective in generating inter-industry spillovers that contribute to productivity growth. The spillovers effect of digital technologies appears to be stronger in high-tech sectors. Audretsch and Belitski (2020) have found corroborating evidence of the importance of knowledge spillovers associated with new technologies to explain firm productivity, highlighting the importance of the phenomenon.

3. Data and empirical variables

In this paper we rely on two main panel datasets provided by the Portuguese National Institute of Statistic (INE): *Inquérito à utilização de tecnologias de informação e comunicação nas empresas* (IUTIC) for digital adoption and *Sistema de Contas Integradas das Empresas* (SCIE for firm-level productivity and other firm-specific characteristics. IUTIC is part of the Community Survey on ICT Usage and E-Commerce and is an annually survey conducted since 2004. In Portugal, this survey is a census for large firms (with more than 250 employees or turnover larger than 25 million euros) and a stratified random sample based on size and industry affiliation for other firms. The survey is compulsory by law for selected firms, which makes it a reliable, rich and valuable dataset. The survey encompasses several questions related to e-commerce and developments in digital technologies' usage in enterprises that allow us to assess the adoption of digital technologies in transforming the business world.

Looking at digital technologies, the survey asks several questions that goes from a simple internet usage to a more sophisticated and intensive usage of digital technologies, such as cloud computing, robots, big data collected from digital social media, sensors or other digital devices, or digital technologies to share information among firm's departments and customers. We interpret the answer to these questions as indicating that a firm adopts digital technology that could affect productivity. In particular, to our purpose, we focus on three digital technologies: ERP (Enterprise Resource Planning) and CRM (Customer Relationship Management) technologies - which are firm-wide and inter-firm system applications-, Big Data, and use of robots. These questions are intermittently available since 2014. Therefore, the time span of our main analysis is the period 2014-2019, even though with the gaps for different variables. Table 1 describe the intensity of usage of the analysed digital technologies, along with the diferences among specific types of firms. We consider firm's size, technological and digital intensity at industry level as the criteria to identify types of firms. The criterion to identify firms belonging to high-tech industry was based on (Galindo-Rueda and Verger, 2016). In turn, we consider industries as digital-intensive if they were classified by Calvino et al. (2018) as medium-high or high digital intensive for the period 2013-2015.

Table 1: Distribution of digital technologies across firms

	(1) N	(2) mean	(3) sd	(4) min	(5) max
PANEL A: All firms					
Adoption of ERP and CRM technologies	24,417	0.513	0.500	0	1
Adoption of Big data analysis and usage	18,134	0.141	0.348	0	1
Adoption of robotic technologies	12,519	0.092	0.289	0	1
PANEL B: Large firms					
Adoption of ERP and CRM technologies	866	0.932	0.252	0	1
Adoption of Big data analysis and usage	772	0.323	0.468	0	1
Adoption of robotic technologies	759	0.298	0.458	0	1
PANEL C: SME firms					
Adoption of ERP and CRM technologies	11,966	0.705	0.456	0	1
Adoption of Big data analysis and usage	9,064	0.186	0.389	0	1
Adoption of robotic technologies	5,725	0.139	0.346	0	1
PANEL D: Firms in high-tech industries					
Adoption of ERP and CRM technologies	1,870	0.620	0.485	0	1
Adoption of Big data analysis and usage	954	0.237	0.425	0	1
Adoption of robotic technologies	502	0.062	0.241	0	1
PANEL E: Firms in high-digital intensity					
Adoption of ERP and CRM technologies	4,846	0.577	0.494	0	1
Adoption of Big data analysis and usage	2,495	0.155	0.362	0	1
Adoption of robotic technologies	1,241	0.062	0.241	0	1

All firms report the adoption of cloud computing, which suggest that they are aware of the need and the benefits extracted from digital technologies. Therefore, cloud computing could not be seen as having predictive power in explaining differentials in firms' productivity gains or performance and, hence it is not included in this study. More interestingly, Portuguese firms seem to follow a heterogenous behaviour in terms of adoption of digital technologies. ERP and CRM technologies are adopted for more than 50% of firms, regardless of the type of firms one could consider. It is a digital technology largely spread across firms, which also indicate some maturity in its usage.

Conversely, the adoption of robotic technologies is a more recente phenomena, with a small percentage of adopters. Less than 10% of firms report having adopted such digital technology. Comparing with other European countries the difference is even more striking. In 2015, the adoption rate of robots was 22% in Spain (Ballestar et al., 2020) and 64% in Germany (Jungmittag, 2021). And, interestingly, firms belonging to hightech or high-digital intensity industries seem not be those more prone to adopt robotic technologies, suggesting that the drivers for adoption of these technologies is somewhat unrelated to digital and technological intensity at industry level. To some extent, this low diffusion of robots in Portuguese firms reflects the countrys industry specialization in sectors that are less prone to adopt robots, like wood and paper, textiles or even chemicals. Nonetheless, another possible reason is because the investment required to robotic technologies is quite capital demanding that only some firms are able to do so. In particular, large firms, irrespectively the industry where they belong, are those more prone to adopt robotic technologies. Moreover, large firms appear to be the big adopters of digital technologies, suggesting that firm's size could be an important driver of digital technology adoption.

Looking at Big Data analysis and usage, apart from firm's size, technological intensity at industry-level appears to foster the adoption of this digital technology. Firms belonging to high-tech industries seem to attach more value to the digital transformation associated to the analysis and use of big data, as a way to empower them with differentiable capabilities to reach markets, adjust products and process to customers needs, and to obtain performance gains. Comparatively, the analysis and use of big data seem to be the distinctive feature of high-tech firms with respect to digital technological adoption and transformation.

We then match IUTIC firm-level data with data from SCIE, which is an annual census for Portuguese firms, encompassing a rich set of firm-level information such as gross output, added value, capital stock, employment and workforce characteristics, export, and the industry in which firms operate according to the NACE classification (Classification of Economic Activities in the European Union). The SCIE database also provide information on the number of employees developing research activities and firms' sales in domestic and external markets, allowing us to compute firm's export intensity and R&D intensity. This set of information is the basis for computing variables affecting productivity performance such as firm size, technological opportunities, and export orientation (Bartelsman and Doms, 2000), apart from our variables of interest related to digital technologies adoption.

As both datasets include the same unique firm identifiers, we are able to trace firms over time and conduct the empirical assessment. We match 26,018 unique firms for which we have intermittently information on digital technologies adoption. This intermittency is due to variations on the IUTIC survey design and sampling scheme. Therefore, our final sample consists of 39,411 firm-year observations, where 5,909 firms are observed in at least two years. Table A.1 in Appendix A describe the measurement and source of the empirical variables used in the analysis, whereas Table 2 reports some descriptive statistics for dependent and control variables, averaged over all firm-year observations and over several different partitions of the data. For each partition, the last column shows the statistical difference (given by a t-test) of the means of these variables for the types of firms identified.

Table 2: Descriptive statistics of dependent and control variables

	All firms		SMEs		High-Tech		High-Digital	
	Mean	Sd.	Mean	Diff.	Mean	Diff.	Mean	Diff.
Dependent variables								
Labour Productivity	10.14	1.058	10.35	0.409***	10.40	0.278***	10.14	0.004
Turnover	14.15	2.502	15.87	3.254***	13.91	-0.264***	13.934	-0.266***
Distance to productivity frontier	0.921	0.079	0.935	0.029***	0.915	-0.006***	0.914	-0.008***
Control variables								
Intensity of ICT	0.025	0.108	0.010	0.030***	0.095	0.076***	0.062	0.047***
Firm’s size	14.09	2.534	15.688	3.042***	14.00	-0.105**	13.82	-0.342***
Exporting intensity	0.090	0.232	0.148	0.112***	0.065	-0.026***	0.056	-0.041***
Financial constraints	1.073	13.47	0.676	-0.760***	1.165	0.100	0.925	-0.184
Intensity of R&D	0.006	0.050	0.008	0.005***	0.024	0.019***	0.008	0.003***

Notes: ***. **, * indicate that the difference in means is statistically significant at the 1%, 5%, 10%, respectively.

Overall, Portuguese firms report a very low intensity on R&D and a low share of workers involved only in ICT activities, suggesting that their performance and efficiency could be strongly compromised. In particular, on average, the low share of workers involved only in ICT activities could be interpreted as indicating that the process of digital technologies adoption deepness is still at the beginning, with, potentially, a low degree of sophistication and combinations of use. Portuguese firms seemingly are more prone to adopt digital technologies that could be supported by external consulting or assistance, rather than more sophisticated digital technologies that require a permanent assistance and in-house improvements in their use. Nonetheless, firms belonging to hightech or digital intensive industries have, on average, higher shares of workers involved only in ICT activities, suggesting that a deeper and longer involvement on digital technologies adoption and greater ICT-based capabilities. Instead, SMEs appear to be much less intensive in ICT workers, which could be interpreted as being at the initial phase of digital technologies adoption process.

On the other hand, Portuguese firms reveal strong financial constraints as the reported liabilities are, on average, greater than total assets. This could be a relevant constraint for the adoption process and the way firms are able to extract performance gains from digital technologies. Interestingly, the nature of industries - high-tech or digital intensive - seems not impose, comparatively, additional financial constraints. The little involvement in international markets, and hence their reduced exposure to more competitive markets, could be seen as an indictor of a fragility to improve performance. Only 30.4% of the firms are exporters and, for them, the average of exporting intensity does not exceed 30%, indicating that there is a large scope to expand activity in international markets and, potentially, performance. More importantly, firms belonging to high-tech or digital intensive industries have a smaller exposure to international - more competitive - markets, suggesting some difficulty to overcome barrier in operating in these markets with statistically significant and negative impact on turnover and on the ability to shorten the gap to frontier firms.

These heterogeneity in terms of firm's resources and competence could be seen as having predictive power for the heterogenous performance, measured by labour productivity and turnover, and as moderate factors for the relationship between performance and digital technologies adoption.

4. Empirical strategy

To examine the relationship between firms' productivity and digital technologies adoption across the whole conditional distribution and to allow for the possibility of the existence of asymmetric dynamics, we apply quantile regression models as they are able to describe that relationship at different points in the conditional distribution of firm's productivity. It is a powerful tool for comparing, more thoroughly than the mean, various relevant points of a distribution across different patterns of variables of interest and other covariates. And, hence, it may show whether the variables of interest related to digital technologies exerts a significant influence on one tail of the distribution but not on the other. In particular, it allows us to asses whether a productivity gap between laggard and frontier firms is being widened or shortened.

By modelling the conditional quantiles, $q \in (0,1)$ of the form $Q_q(Y|\boldsymbol{x}, z) = x_q^{'}\alpha_q + z_q^{'}\beta_q$ where Y is the alternative measures of firm's productivity, x is a vetor of variables related to digital technologies adoption and z is a vector of control variables that account for differences in several observable attributes of the firm. Although its computation requires linear programming methods, the quantile regression estimator is asymptotically normally distributed, more robust to outliers than the OLS regression, and its semi-parametric nature avoids assumptions about the parametric distribution of the error process (Koenker, 2005).

Estimation was performed using the SQREG procedure in STATA and a bootstrap resampling approach, based on 100 replications, were performed to estimate the entire variance-covariance matrix of the estimators. The relevance of the bootstrapping procedure hinges on its robustness property; in particular when the errors from the quantile equation are not homogeneously distributed. Another important point is that the full sample is used for every quantile regression and not only the observations belonging to marginal quantiles (i.e. the raw quantiles of the Y function). This implies that all covariates are valid predictors in all quantiles.

Other important feature of our empirical strategy concerns the time-lagged variables in the model specification. Here, the short length of our unbalanced panel data, due to the frequent changes on the IUTIC survey questions related to digital technologies adoption over the years, prevent us to directly specify a time-lag for the covariates. This would imply a drastic loss of sampled firms and observations. Nonetheless, the IUTIC survey variables reflect firm's status at the beginning of each year, whereas the productivity and control variables were measured at the end of each year. Thus, in practice, our data already consider a certain time lag between our main independent variables and the alternative measures of productivity. Therefore, our specification, in certain sense, considers that the effect of digital technologies adoption could take time to affect firm's productivity.

On the other hand, to control to potential spurious correlations between productivity and adoption of digital technologies due to, for instance, demand shocks that affect both the choice of adoption and firm productivity or technological progress that leads firms to invest in digital technologies and, simultaneously, in other productivity-enhancing activities, our specification allow for industry-specific effects in order to control for these potentially confounding trends at industry-level.

5. Impact of digital technologies adoption and productivity

Here, the empirical results related to the relationship between digital technologies adoption are presented. In the first stage, empirical results based on all firms in our sample are presented and discussed. Our focus is on three digital technologies - ERP and CRM, Big Data, and Robots - and firm's labour productivity. Moreover, each empirical model considers a direct impact of a single adoption of a digital technology, an effect related to the degree of sophistication and combinations of use of different digital technologies - proxied by the share of workers involved only in ICT activities ar firm level -, and an interaction term of both as a way to measuring the impact of the complementarity of digital strategic resources.

In the second stage, the robustness of the results is addressed and discussed. For that, the alternative models are re-estimated using several different partitions of the data, which allows us to uncover potentially heterogeneous relationships between digital technologies adoption and productivity and, hence, to understanding the aggregate effect. These partitions are based on firm's size, high-tech industries based on Galindo-Rueda and Verger (2016) and digital-intensive industries based on Calvino et al. (2018).

5.1 All firms

Although firms may adopt some digital technologies for purposes that do not target productivity growth directly (e.g. investments that aim simply to substitute an existing technology by a new up-to-date solution without engendering noticeable changes on products and production), they do expect qualitative impacts, such as better sharing and use of in-house information that would generate performance improvements indirectly. In this sense, any investment in digital technologies ultimately is expected to engender performance gains. Table 3 shows the estimated impact of different digital technologies over the distribution of labour productivity at firm-level.

Table 3: Impact of digital technologies on labour productivity

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	0.009	0.007	-0.037***	-0.093***	-0.183***
	(0.023)	(0.012)	(0.012)	(0.016)	(0.023)
Intensity of ICT	0.230*	0.428***	0.558***	0.750***	0.573***
	(0.130)	(0.107)	(0.080)	(0.103)	(0.063)
Intensity of ICT x Adoption of ERP and CRM technologies	0.410***	0.319**	0.556***	0.972***	1.746***
	(0.150)	(0.139)	(0.131)	(0.212)	(0.376)
Control variables					
Firm’s size	0.149***	0.168***	0.205***	0.267***	0.344***
	(0.005)	(0.003)	(0.003)	(0.004)	(0.005)
Exporting intensity	-0.043	-0.054**	-0.079***	-0.156***	-0.201***
	(0.031)	(0.022)	(0.021)	(0.031)	(0.052)
Financial constraints	0.330***	-0.158***	-0.066***	-0.017**	0.003
	(0.030)	(0.021)	(0.011)	(0.007)	(0.008)
Intensity of R&D	0.357	0.432**	0.527***	0.240**	0.027
	(0.236)	(0.218)	(0.086)	(0.117)	(0.159)
Manufacturing firms	0.114***	-0.046***	-0.176***	-0.318***	-0.484***
	(0.019)	(0.011)	(0.010)	(0.015)	(0.020)
Wholesale and retail trade firms	0.144***	0.054***	0.005	0.008	-0.149***
	(0.020)	(0.013)	(0.015)	(0.022)	(0.023)
Constant	7.394***	7.456***	7.315***	6.903***	6.427***
	(0.075)	(0.044)	(0.038)	(0.054)	(0.063)
Pseudo R2	0.15	0.18	0.20	0.23	0.27
N	23,070	23,070	23,070	23,070	23,070
Panel B: Big Data Technologies					
Adoption of Big data analysis and usage	0.019	-0.007	-0.047***	-0.119***	-0.192***
	(0.030)	(0.019)	(0.017)	(0.024)	(0.035)
Intensity of ICT	0.291*	0.506***	0.795***	0.873***	0.911***
	(0.169)	(0.113)	(0.089)	(0.064)	(0.156)
Intensity of ICT x Adoption of Big Data	-0.021	0.121	0.064	1.568	3.405***
	(0.728)	(0.251)	(0.306)	(1.167)	(0.633)
Pseudo R2	0.15	0.18	0.21	0.23	0.27
N	11,842	11,842	11,842	11,842	11,842
Panel C: Robotic Technologies					
Adoption of robotic technologies	0.073	0.016	-0.055*	-0.209***	-0.338***
	(0.046)	(0.033)	(0.032)	(0.048)	(0.056)
Intensity of ICT	0.390	0.549***	0.784***	0.876***	1.232***
	(0.266)	(0.172)	(0.078)	(0.141)	(0.433)
Intensity of ICT x Adoption of robots	0.222	0.640	0.829	0.971	1.623
	(1.461)	(1.101)	(0.958)	(1.215)	(1.602)
Pseudo R2	0.14	0.17	0.21	0.23	0.26
N	6,037	6,037	6,037	6,037	6,037

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables showed on Panel A.

Overall, productivity improvements seem to depend critically on how the digital technology adopted is combined with in-house ICT capabilities, disclosing the role of the degree of sophistication and complementarities among digital technologies and other resources in extracting productivity gains. This result is a well-documented feature in the literature (Brynjolfsson et al., 2021; Chun et al., 2015; DeStefano et al., 2018; Pieri et al., 2018). Regardless of the firm position at the distribution of labour productivity, an increase in ICT capabilities - proxied by the share of employees involved only in ICT activities - and an upgrading in ICT use sophistication (Miyazaki et al., 2012), would yield productivity gains. This positive and statistical effect seems to increase with firm's productivity level, being frontier firms the bigger extractors of productivity benefits. Moreover, the adoption of digital technologies without in-house ICT capabilities, which can be interpreted as an initial (or, take-off) phase of digital technology adoption, seems to engender a negative impact on productivity for firms at the higher quantiles of the productivity distribution (i.e, greater performers and frontier firms). This would imply that initial investments on digital technologies, not complemented with ICT capabilities, could require an learning and adapting process, changes on management practices and decision-processes that appear to impact negatively on production efficiency. Ignoring these complementarities may introduce bias into the estimated effect of digital technologies on productivity. This finding is in line with the productivity J-curve argument developed by Brynjolfsson et al. (2021), in which the need for intangible investments, such as investments in creating new business processes or training workers, in early stages of new general purpose technologies adoption - as it is the case of digital technologies - would cause an initial productivity slowdown.

Further, looking at specific digital technologies, enterprise resource planning (ERP) software and customer relationship management (CRM) technologies, aimed to simplify and centralize business processes and to gain better insights into their customers to make more informed decisions, complemented with in-house ICT capabilities, seems to engender productivity gains for all firms across the productivity distribution. Nonetheless, frontier firms are those that are able to extract greater benefits from that digital technology, suggesting that digitalisation based on ERP and CRM technologies are more likely to exacerbate existing divides, rather than closing productivity gaps. Moreover, these productivity gaps seem to be further exacerbated by the better-informed decision-making processes based on novel data practices related to big data technology. In fact, only frontier firms exploring big data are able to extract productivity gains, indicating that the benefits of big data are still more scare and potentially require the previous deployment of other productivity-enhancing capabilities. Nonetheless, and similarly to Niebel et al. (2019), our findings provide evidence on the economic value of big data. But not all firms that adopt such digital technology exhibit productivity gains. The complementarity of other resources and capabilities could be an explanation for the estimated differential impact.

A more challenging finding is that related to robotic technologies adoption. The empirical results suggest that Portuguese firms investing in robotic technologies are still not able to extract productivity gains, even when combined with different degrees of ICT intensity and sophistication. Nonetheless, the positive, although statistically insignificant, estimates for adopters with in-house ICT capabilities can be interpreted as an indication that there may be scope to extract productivity gains from robotic technologies. These results also suggest that a digitalisation strategy based on robotic technologies may require a longer time span to engender productivity gains. These digital technologies tend to be longer duration investments that could prolong the effects of the J-curve.

On the side of other variables affecting productivity gains, some interesting findings emerge. Apart from the stylised facts that firm's size and R&D have predictive power in explaining productivity differentials, financial constraints emerge as a important factor in shaping productivity gains. In particular, only frontier firms seem to escape to this tie, as productivity gains of them are not affected by financial constraints. To other firms, greater financial constraints seem to lead to an increasing productivity gap. Moreover, looking at laggard firms, those operating into the manufacturing or wholesale and retail trade sectors seems to perform better than other firms, suggesting that they are more likely to climb the productivity distribution.

Another important perspective is to assess whether digital technologies have an important role in closing the productivity gap to frontier firms. Table 4 shows the estimated impacts of different digital technologies over the distribution of the distance to frontier firms, i.e. the greatest performers at industry-year level based on labour productivity.

Table 4: Impact of digital technologies on distance to frontier firms based on labour productivity

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	0.006**	-0.001	-0.003***	-0.007***	-0.009***
	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)
Intensity of ICT	0.006	0.003	0.002	0.004	0.015**
	(0.008)	(0.009)	(0.005)	(0.010)	(0.007)
Intensity of ICT x Adoption of ERP and CRM tecnologies	0.012	0.011	0.015	0.037***	0.062***
	(0.014)	(0.014)	(0.012)	(0.013)	(0.015)
Control variables					
Firm's size	0.006***	0.008***	0.009***	0.011***	0.013***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Exporting intensity	0.007	0.003	0.005***	0.005**	0.012***
	(0.004)	(0.002)	(0.002)	(0.002)	(0.004)
Financial constraints	0.020***	-0.009***	-0.005***	-0.002***	-0.001
	(0.003)	(0.002)	(0.001)	(0.001)	(0.000)
Intensity of R&D	-0.007	0.029**	0.026***	0.004	-0.003
	(0.027)	(0.015)	(0.009)	(0.009)	(0.012)
Manufacturing firms	0.046***	0.024***	0.004***	-0.006***	-0.017***
	(0.003)	(0.002)	(0.001)	(0.001)	(0.002)
Wholesale and retail trade firms	0.037***	0.021***	0.008***	0.002	0.007***
	(0.003)	(0.002)	(0.001)	(0.001)	(0.002)
Constant	0.750***	0.773***	0.801***	0.818***	0.822***
	(0.008)	(0.004)	(0.003)	(0.004)	(0.005)
Pseudo R2	0.07	0.07	0.07	0.09	0.10
N	23,070	23,070	23,070	23,070	23,070
Panel B: Big Data Technologies					
Adoption of Big data analysis and usage	-0.002	0.001	-0.004**	-0.005***	-0.009***
	(0.004)	(0.002)	(0.002)	(0.002)	(0.003)
Intensity of ICT	0.016	0.021*	0.013**	0.026***	0.049***
	(0.014)	(0.013)	(0.006)	(0.009)	(0.014)

Intensity of ICT x Adoption of Big Data	0.011	-0.004	0.018	0.008	0.002
	(0.076)	(0.034)	(0.024)	(0.016)	(0.076)
Pseudo R2	0.08	0.08	0.07	0.08	0.11
N	11,842	11,842	11,842	11,842	11,842
Panel C: Robotic Technologies					
Adoption of robotic technologies	0.011**	0.002	-0.004	-0.009***	-0.022***
	(0.005)	(0.003)	(0.003)	(0.003)	(0.005)
Intensity of ICT	0.015	0.019	0.013	0.010	0.025
	(0.024)	(0.019)	(0.008)	(0.009)	(0.015)
Intensity of ICT x Adoption of robots	-0.003	-0.035	-0.057	0.010	-0.020
	(0.092)	(0.053)	(0.097)	(0.103)	(0.112)
Pseudo R2	0.07	0.07	0.07	0.08	0.11
N	6,037	6,037	6,037	6,037	6,037

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables showed on Panel A.

Again, different digital technologies affect differently the dynamics of productivity at firm level, in particular the convergence to frontier. Specifically, there is some converge in laggard firms through input deepening in ERP and CRM technologies and in robotics. Laggard firms seem to benefit from the adoption of robotic technologies and ERM and CRM technologies in the initial (or, take-off) phase of the adoption process. Such adoption seems to have scope to mitigate the productivity gap to frontier firms, suggesting that they are able to re-start the engine of productivity growth. Nonetheless, this positive effect in the initial (or, take-off) phase is vanished as firms move up in the productivity distribution, indicating that persistent efforts to close the productivity gap require also investments in complementary resources such as in-house ICT capabilities and more advanced ICT assets. In fact, firms at the end of the distribution - closer to and in the frontier -, are being able to attain even larger productivity gains than laggards through ERP and CRM technologies only when they complement it with internal ICT capabilities. Thus, these results suggest that convergence is weak. The absence of convergence in big data technologies could be due to the early stage diffusion.

5.2 Robustness checks

Here, we explore the robustness of our findings and disclose the possibility of heterogenous effects across different firms and industries. For that, several partitions of the data were made and the models re-estimated on different subsamples. In particular, we assess whether inter-firm and inter-industry heterogenous effects emerge, regarding (i) firm's size, (ii) technological intensity at industry level, and (iii) digital intensity at industry level. Further, the impact of digital technologies on productivity is re-assessed in order to evaluate whether productivity gains could be derived from interactions with other digitalised firms in the same industry.

5.2.1 Inter-firm and inter-industry heterogeneity

The impact of digital technologies can be heterogeneous across different firm sizes and industries technology intensity. On one hand, it has been largely discussed that the use of a single type of ICT asset may not be a strategic resource because competitors also have access to it (Walsh et al., 2010). So, combining various types of ICT and creating complementarity can be decisive for a firm (Chae et al., 2014). Likewise, the notion underlying the productivity J-curve (Brynjolfsson et al., 2021)- in early stages of new general purpose technologies firms experience a learning-by-doing process, implies that firms with more capabilities will benefit more from the adoption of digital technologies. On the other hand, recent evidence (Cataldo et al., 2020) has found firm's size moderates the impact of ICT on productivity: the smaller the company, the more significant the benefits of ICT assets.

We next explore the possibility of heterogeneous effects across different firm sizes. Table 5 shows the impact of digital technologies on productivity of SMEs and Table 6 present the estimates for the impact of digital technologies adoption to closing the distance to frontier firms among SMEs.

For SMEs, increases in firm productivity result mainly from the adoption of ERP and CRM technologies. These are the less technologically complex technologies and most widely spread. Nonetheless, the productivity impact of these technologies only happens when in interaction with the firms´ complementary ICT assets investment, as shown by the interaction term. In line with previous contributions (Ballestar et al., 2020; Cataldo et al., 2020; Chun et al., 2015; Corrado et al., 2017; Pieri et al., 2018), we conclude that it is not the use of ERP and CRM which impacts on firms´ productivity, but rather the degree of sophistication and combinations of use ICT-based capabilities (proxied by Intensity of ICT).

Table 5: Impact of digital technologies on labour productivity - SMEs firms

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	-0.008	-0.006	-0.029	-	-0.038
	(0.030)	(0.016)	(0.018)	(0.017)	(0.025)
Intensity of ICT	1.190***	0.901	1.601***	1.698***	1.704***
	(0.313)	(0.625)	(0.610)	(0.628)	(0.605)
Intensity of ICT x Adoption of ERP and CRM tecnologies	2.416**	3.834***	4.339***	4.807***	4.486***
	(1.023)	(0.892)	(0.698)	(0.875)	(0.810)
Pseudo R2	0.16	0.21	0.24	0.28	0.34
N	11,614	11,614	11,614	11,614	11,614
Panel B: Big Data Technologies					
Adoption of Big data analysis and usage	-0.015	-0.039	-0.033*	-0.092***	-0.163***
	(0.034)	(0.024)	(0.019)	(0.026)	(0.045)
Intensity of ICT	4.516***	5.550***	7.022***	8.908***	9.212***
	(0.720)	(0.359)	(0.552)	(0.864)	(1.231)
Intensity of ICT x Adoption of Big Data	-4.113***	-5.084***	-5.226***	-5.274***	-4.343***
	(1.080)	(1.050)	(1.529)	(1.620)	(1.631)
Pseudo R2	0.15	0.20	0.23	0.27	0.32
N	6,482	6,482	6,482	6,482	6,482
Panel C: Robotic Technologies					
Adoption of robotic technologies	0.083*	0.035	-0.009	-0.104**	-0.185**
	(0.050)	(0.043)	(0.032)	(0.048)	(0.073)
Intensity of ICT	3.000***	4.072***	4.735***	6.456***	6.253**
	(1.017)	(1.135)	(1.308)	(1.536)	(2.533)
Intensity of ICT x Adoption of robots	1.003	-0.691	-1.951	-1.241	1.312
	(3.046)	(1.612)	(2.437)	(4.037)	(4.774)
Pseudo R2	0.14	0.19	0.22	0.26	0.31
N	3,197	3,197	3,197	3,197	3,197

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables *Firm's size*, *Export intensity*, *Financial constraints*, *Intensity of R&D* and sectoral dummies.

Table 6: Impact of digital technologies on distance to frontier firms based on labour productivity - SMEs firms

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	-0.002	-0.004**	-0.004**	-0.007***	-0.010***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Intensity of ICT	-0.069	-0.064	-0.019	0.002	0.009
	(0.080)	(0.085)	(0.045)	(0.058)	(0.044)
Intensity of ICT x Adoption of ERP and CRM technologies	0.086	0.148*	0.133***	0.203***	0.369***
	(0.097)	(0.089)	(0.051)	(0.073)	(0.065)
Pseudo R2	0.09	0.07	0.07	0.09	0.12
N	11,614	11,614	11,614	11,614	11,614
Panel B: Big Data Technologies					
Adoption of Big data analysis and usage	-0.012***	0.000	-0.001	-0.002	-0.005
	(0.004)	(0.003)	(0.002)	(0.002)	(0.003)
Intensity of ICT	0.137**	0.158**	0.264***	0.387***	0.645***
	(0.069)	(0.065)	(0.074)	(0.079)	(0.119)
Intensity of ICT x Adoption of Biga Data	-0.112	-0.182**	-0.316***	-0.345***	-0.550***
	(0.075)	((0.072)	(0.102)	(0.131)	(0.165)
Pseudo R2	0.10	0.08	0.07	0.08	0.12
N	6,482	6,482	6,482	6,482	6,482
Panel C: Robotic Technologies					
Adoption of robotic technologies	0.005	-0.001	-0.004	-0.005	-0.009*
	(0.006)	(0.004)	(0.004)	(0.004)	(0.005)
Intensity of ICT	0.021	0.079	0.134*	0.246**	0.517***
	(0.058)	(0.073)	(0.081)	(0.104)	(0.200)

Intensity of ICT x Adoption of robots	0.088	-0.033	-0.171	-0.085	-0.480*
	(0.218)	(0.204)	(0.244)	(0.199)	(0.279)
Pseudo R2	0.10	0.07	0.06	0.08	0.13
N	3,197	3,197	3,197	3,197	3,197

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables *Firm's size*, *Export intensity*, *Financial constraints*, *Intensity of R&D* and sectoral dummies.

More importantly, perhaps, is the increasing impact of ERP and CRM technologies along firms´ productivity distribution – up to the 75 quantile, with a slight decrease among frontier firms. This result strongly indicates that the benefits from the adoption of digital technologies increase with firm efficiency. Firms that already are more efficient in their production process, reap more benefits, which is in line with the argument that these technologies require internal capabilities (Bresnahan et al., 2002; Bloom et al., 2012). Regarding the other technologies, only robotics is having a positive impact on firm productivity. So far, this effect is limited to laggard firms and is independent from other complementary investments in ICT.

Table 6 shows the impact of digital technologies adoption in closing the productivity gap. Our findings indicate that the impact of digital technologies on productivity convergence to frontier among SMEs is limited to ERP and CRM technologies. However, results also show that convergence in productivity is increasing with firm´s own productivity and that laggard firms are not being able to move into the frontier. Hence, these results indicate that there is taking place an aggregate movement towards the frontier but still with significant between-firm differences. More recent digital technologies seem to not be able to engender a convergence effect on productivity among SMEs, with a significant impact on the aggregate productivity as they represent a high proportion of firms across all sectors in the Portuguese economy.

Another reason why there are heterogeneous returns to digital technologies across firms is because they operate in very diverse industries. It has been documented that firms operating in high-tech sectors are able to reap larger benefits from more technologically advanced technologies such as ICT (Corrado et al., 2017; Stiroh, 2002) as they already operate in a context of technologically advanced technologies and hence are more technologically experienced than firms operating in low tech-sectors. Likewise, a similar effect could be observed in digital intensive industries, where firms are more experienced in using and combining to various types of ICT (Chae et al., 2014). Recent evidence (Pieri et al., 2018) has found a positive impact of ICT high-tech sectors and insignificant in low-tech industries.

Thus, we further explore differences across industries technological and digital intensity. Table 7 shows how digital adoption impacts on productivity of firms operating in high-tech sectors. Although limited, we still observe that input deepening in Big data technologies is contributing to increase firms productivity. Yet this effect is limited to firms with higher efficiency levels (situated in the 75 percentile of the productivity distribution). Also, in robotics can be observed a positive impact on productivity, but in the case of these technologies it only happens in interaction with other ICT investments, thereby corroborating the argument that these technologies need to be implemented with complementary assets.

Table 7: Impact of digital technologies on labour productivity - High-tech firms

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	0.048	-0.020	-0.172***	-0.224***	-0.292***
	(0.089)	(0.052)	(0.059)	(0.074)	(0.107)
Intensity of ICT	0.622**	0.520***	0.440**	0.692***	0.362*
	(0.260)	(0.165)	(0.184)	(0.189)	(0.196)
Intensity of ICT x Adoption of ERP and CRM tecnologies	-0.367	-0.296	0.136	0.193	0.565
	(0.337)	(0.212)	(0.284)	(0.385)	(0.436)
Pseudo R2	0.20	0.22	0.22	0.24	0.27
N	1,462	1,462	1,462	1,462	1,462
Panel B: Big Data Technologies					
Adoption of Big data analysis and usage	0.132	0.105	0.090	0.259***	0.157
	(0.120)	(0.074)	(0.069)	(0.100)	(0.131)
Intensity of ICT	-0.060	0.504***	0.635***	0.793***	0.780***
	(0.582)	(0.167)	(0.115)	(0.182)	(0.175)
Intensity of ICT x Adoption of Big Data	-2.276	-3.017**	-0.959	-0.512	-0.830
	(1.400)	(1.311)	(0.962)	(1.251)	(1.499)
Pseudo R2	0.20	0.23	0.23	0.24	0.23
N	748	748	748	748	748
Panel C: Robotic Technologies					
Adoption of robotic technologies	-0.217	-0.354**	-0.382	-0.173	-0511**
	(0.328)	(0.169)	(0.218)	(0.317)	(0.249)
Intensity of ICT	0.209	0.447	0.525***	0.433**	0.339
	(0.680)	(0.326)	(0.126)	(0.210)	(0.229)
Intensity of ICT x Adoption of robots	5.001	2.995	7.622*	6.953	6.378
	(9.347)	(4.424)	(4.314)	(5.156)	(4.963)
Pseudo R2	0.18	0.23	0.24	0.24	0.26
N	398	398	398	398	398

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables *Firm's size*, *Export intensity*, *Financial constraints*, *Intensity of R&D* and sectoral dummies.

In Table 8 we investigate the impact of digital adoption in reducing productivity dispersion among firms in high-tech sectors. Again, we only observe statistically significant impacts among big data and robotics technologies. Big data investments are contributing to reduce the productivity gap but only among firms situated in the lower band of the productivity distribution - the 25 percentile. As for robotics, there is wider and significant impact, as firms with higher efficiency levels are clearly moving towards the frontier as they investment in robotics in complement with other ICT assets. Despite this positive outcome, it still is very restricted to a small part of the distribution of firms, which implies that at the aggregate level we do not observe a significant shift towards the frontier.

Table 8: Impact of digital technologies on distance to frontier firms based on labour productivity - High-tech firms

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	0.007	-0.003	-0.010**	-0.015**	-0.020***
	(0.009)	(0.006)	(0.005)	(0.007)	(0.008)
Intensity of ICT	0.063**	0.048***	0.051***	0.068***	0.050***
	(0.028)	(0.016)	(0.016)	(0.019)	(0.013)
Intensity of ICT x Adoption of ERP and CRM tecnologies	-0.015	-0.016	-0.001	0.002	0.030
	(0.035)	(0.023)	(0.027)	(0.030)	(0.028)
Pseudo R2	0.16	0.16	0.17	0.15	0.18
N	1,462	1,462	1,462	1,462	1,462
Panel B: Big Data Technologies					
Adoption of Big data analysis and usage	0.015	0.013**	0.008	0.013	0.010
	(0.019)	(0.006)	(0.005)	(0.009)	(0.009)
Intensity of ICT	0.043	0.068***	0.056***	0.078***	0.070***
	(0.043)	(0.017)	(0.011)	(0.020)	(0.013)
Intensity of ICT x Adoption of Big Data	-0.220*	-0.224*	-0.083	-0.037	-0.069
	(0.124)	(0.118)	(0.093)	(0.090)	(0.065)
Pseudo R2	0.16	0.17	0.17	0.15	0.17
N	748	748	748	748	748
Panel C: Robotic Technologies					
Adoption of robotic technologies	-0.019	-0.029*	-0.026	-0.033	-0.052*
	(0.031)	(0.015)	(0.017)	(0.022)	(0.030)
Intensity of ICT	0.050	0.035	0.048***	0.028*	0.017
	(0.040)	(0.031)	(0.015)	(0.016)	(0.017)
Intensity of ICT x Adoption of robots	0.749	0.302	0.593	1.056*	0.976*
	(2.262)	(0.703)	(0.548)	(0.570)	(0.584)
Pseudo R2	0.14	0.17	0.17	0.17	0.21
N	398	398	398	398	398

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables *Firm's size*, *Export intensity*, *Financial constraints*, *Intensity of R&D* and sectoral dummies.

Looking at firms operating in digital intensive industries, Tables 9 and 10 show the estimates of the impact o digital technologies adoption for those firms. Results in Table 9 show that only ERM and CRM technologies play a role in explaining firms differences in productivity. Specifically, investments in these technologies when complemented with other assets are leading to increases in productivity of almost all firms, but the benefits are also increasing with firms existing efficiency. The fact that we do not observe any impact of big data and robotics in firms operating in these industries can be explained by the fact that the users of big data and robotics are mostly located in different industries, certainly the case of robotics.

Table 9: Impact of digital technologies on labour productivity - Digital intensive firms

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	-0.084	-0.105***	-0.114***	-0.156***	-0.250***
	(0.053)	(0.036)	(0.024)	(0.034)	(0.057)
Intensity of ICT	0.236	0.423**	0.510***	0.694***	0.465**
	(0.223)	(0.165)	(0.122)	(0.168)	(0.205)
Intensity of ICT x Adoption of ERP and CRM tecnologies	0.497*	0.205	0.407*	0.402	1.222***
	(0.263)	(0.223)	(0.232)	(0.273)	(0.394)
Pseudo R2	0.08	0.09	0.14	0.18	0.21
N	4,371	4,371	4,371	4,371	4,371
Panel B: Big Data Technologies					
Adoption of Big data analysis and usage	0.016	0.029	0.007	-0.046	-0.168*
	(0.090)	(0.075)	(0.044)	(0.050)	(0.095)
Intensity of ICT	0.378	0.566***	0.684***	0.747***	0.780***
	(0.446)	(0.182)	(0.098)	(0.136)	(0.142)
Intensity of ICT x Adoption of Biga Data	-1.841	-0.656	-0.443	-0.239	-0.475
	(1.224)	(1.038)	(0.480)	(0.474)	(1.370)
Pseudo R2	0.07	0.09	0.15	0.18	0.19
N	2,225	2,225	2,225	2,225	2,225
Panel C: Robotic Technologies					
Adoption of robotic technologies	0.101	0.065	-0.027	0.019	-0.151
	(0.200)	(0.118)	(0.099)	(0.132)	(0.165)
Intensity of ICT	0.373	0.625**	0.576***	0.516***	0.298*
	(0.504)	(0.317)	(0.112)	(0.129)	(0.174)
Intensity of ICT x Adoption of robots	0.154	-0.930	-1.262	-0.400	-0.234
	(3.487)	(3.549)	(4.619)	(5.901)	(3.603)
Pseudo R2	0.07	0.09	0.17	0.20	0.20
N	1,118	1,118	1,118	1,118	1,118

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables *Firm's size*, *Export intensity*, *Financial constraints*, *Intensity of R&D* and sectoral dummies.

Table 10: Impact of digital technologies on distance to frontier firms based on labour productivity - Digital intensive firms

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	-0.010*	-0.011***	-0.011***	-0.009***	-0.013***
	(0.005)	(0.004)	(0.004)	(0.003)	(0.004)
Intensity of ICT	0.005	0.033*	0.010	0.031**	0.033**
	(0.017)	(0.018)	(0.011)	(0.015)	(0.015)
Intensity of ICT x Adoption of ERP and CRM technologies	0.033	0.014	0.018	0.011	0.031
	(0.026)	(0.024)	(0.023)	(0.025)	(0.032)
Pseudo R2	0.09	0.09	0.08	0.10	0.13
N	4,371	4,371	4,371	4,371	4,371
Panel B: Big Data Technologies					
Adoption of Big data analysis and usage	-0.004	0.005	-0.007	-0.003	-0.008
	(0.011)	(0.005)	(0.004)	(0.006)	(0.006)
Intensity of ICT	-0.011	0.035**	0.025***	0.033**	0.063***
	(0.032)	(0.016)	(0.009)	(0.013)	(0.014)
Intensity of ICT x Adoption of Biga Data	-0.109	-0.040	-0.010	0.009	-0.030
	(0.105)	(0.089)	(0.051)	(0.054)	(0.065)
Pseudo R2	0.08	0.09	0.09	0.09	0.12
N	2,225	2,225	2,225	2,225	2,225
Panel C: Robotic Technologies					
Adoption of robotic technologies	0.014	0.002	0.011	0.017	-0.001
	(0.011)	(0.008)	(0.010)	(0.012)	(0.011)
Intensity of ICT	0.002	0.017	0.022	0.006	0.014
	(0.034)	(0.026)	(0.016)	(0.012)	(0.017)
Intensity of ICT x Adoption of robots	0.067	0.006	-0.106	-0.130	-0.171
	(0.556)	(0.318)	(0.395)	(0.269)	(0.308)
Pseudo R2	0.09	0.10	0.10	0.11	0.14
N	1,118	1,118	1,118	1,118	1,118

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables *Firm's size*, *Export intensity*, *Financial constraints*, *Intensity of R&D* and sectoral dummies.

5.2.2 Industry spillovers

An important channel through which firms can increase their productivity is by benefiting from industry spillovers, that is, benefits derived from interactions with digitalised peers in the same industry. For that, the models were re-estimated with the addition of an industry spillover variable, which is measured by the intensity of use of each digital technology at the industry in which the firm operates. Table 11 shows the estimated impact to firm's productivity from interactions with digitalised peers for all firms in the sample.

Table 11: Impact of digital technologies on labour productivity - industry spillovers

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	-0.054	-0.030	-0.090***	-0.155***	-0.095**
	(0.041)	(0.022)	(0.024)	(0.032)	(0.040)
Intensity of ICT	0.187	0.299**	0.394***	0.561***	0.458***
	(0.131)	(0.127)	(0.079)	(0.123)	(0.078)
Intensity of ICT x Adoption of ERP and CRM	0.288*	0.245	0.502***	0.973***	1.948***
	(0.158)	(0.152)	(0.152)	(0.254)	(0.423)
ERP and CRM at industry	0.361***	0.384***	0.425***	0.464***	0.526***
	(0.050)	(0.036)	(0.032)	(0.044)	(0.054)
ERP and CRM at industry x Adoption of ERP and CRM	0.013	-0.026	0.015	0.004	-0.293***
	(0.063)	(0.040)	(0.043)	(0.065)	(0.074)
Pseudo R2	0.16	0.18	0.21	0.24	0.27
N	23,070	23,070	23,070	23,070	23,070
Panel B: Big Data Technologies					
Adoption of big data analysis and usage	0.101**	0.003	-0.022	-0.124***	-0.207***
	(0.048)	(0.030)	(0.023)	(0.034)	(0.062)
Intensity of ICT	0.209	0.378***	0.624***	0.736***	0.899***
	(0.184)	(0.103)	(0.095)	(0.106)	(0.167)
Intensity of ICT x Adoption of big data analysis and	0.257	0.433*	0.375*	1.637**	2.913***
	(0.501)	(0.246)	(0.214)	(0.764)	(0.664)
Big Data at industry	0.461***	0.401***	0.443***	0.609***	0.576***
	(0.110)	(0.067)	(0.076)	(0.099)	(0.184)
Big Data at industry x Adoption of big data analysis and	-0.623**	-0.290**	-0.354***	-0.339**	-0.412
	(0.258)	(0.127)	(0.097)	(0.133)	(0.328)
Pseudo R2	0.15	0.18	0.21	0.23	0.27
N	11,842	11,842	11,842	11,842	11,842
Panel C: Robotic Technologies					
Adoption of robotic technologies	-0.028	-0.030	-0.010	-0.165***	-0.302***
	(0.075)	(0.067)	(0.044)	(0.049)	(0.108)
Intensity of ICT	0.345	0.574***	0.775***	0.887***	1.138***
	(0.268)	(0.167)	(0.085)	(0.143)	(0.441)
Intensity of ICT x Adoption of robotic technologies	0.279	0.728	0.896	0.886	2.174
	(1.232)	(1.129)	(0.953)	(1.217)	(1.780)
Robots at industry	0.377***	0.306***	0.419***	0.552***	0.457**
	(0.137)	(0.113)	(0.114)	(0.147)	(0.227)
Robots at industry x Adoption of robotic technologies	0.117	-0.010	-0.340**	-0.368*	-0.369
	(0.200)	(0.160)	(0.135)	(0.188)	(0.300)
Pseudo R2	0.14	0.17	0.21	0.23	0.26
N	6,037	6,037	6,037	6,037	6,037

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables *Firm's size*, *Export intensity*, *Financial constraints*, *Intensity of R&D* and sectoral dummies.

Our findings suggest that there are significant industry spillovers across all digital technologies as well as across the productivity distribution. These benefits are also increasing with firms´ level of production efficiency, thereby corroborating previous findings in that more efficient firms tend to benefit more from digital adoption. Whereas this relationship is linear in the case of ERP and CRM technologies, in the case of big data and robotics there is a slightly larger impact among greater performers (firms in the 75 percentile of the productivity distribution), highlighting the fact that digital technologies are not homogenous entity and thereby their impact on firm productivity is also diverse. Nonetheless, as digital adoption at industry level increases, the lesser are productivity gains extracted from digital technologies adoption at firm level. This interesting finding suggests that adopters are not able to appropriate all productivity benefits related to digital technologies as they spread out to all firms in the industry. It is also worth noting that laggard firms appear to benefit from big data analysis and usage when they are the first adopters in the industry, which could be interpreted as a first-mover advantage for laggard firms. As competitors also have access to digital technologies, the economic value of digital technologies seems to vanish.

A complementary point is to examine whether industry spillovers promote a productivity convergence effect, which would impact positively at aggregate productivity. In Table 12 estimates show in what extent industry spillovers are contributing to productivity convergence.

Table 12: Impact of digital technologies on distance to frontier firms based on labour productivity - industry spillovers

	Quantiles				
	10 (Laggard firms)	25	50	75	90 (Frontier firms)
Panel A: ERM and CRM Technologies					
Adoption of ERP and CRM technologies	0.034***	0.008**	-0.002	-0.008***	0.004
	(0.006)	(0.003)	(0.002)	(0.002)	(0.003)
Intensity of ICT	0.006	0.017	0.022***	0.025**	0.029***
	(0.011)	(0.012)	(0.006)	(0.010)	(0.008)
Intensity of ICT x Adoption of ERP and CRM technologies	0.008	0.013	0.020	0.025	0.060***
	(0.018)	(0.014)	(0.013)	(0.016)	(0.018)
ERP and CRM at industry	-0.023***	-0.056***	-0.062***	-0.058***	-0.043***
	(0.007)	(0.005)	(0.003)	(0.004)	(0.004)
ERP and CRM at industry x Adoption of ERP and CRM	-0.041***	-0.004	0.009**	0.015***	-0.012*
	(0.011)	(0.006)	(0.004)	(0.005)	(0.006)
Pseudo R2	0.06	0.08	0.09	0.10	0.12
N	23,070	23,070	23,070	23,070	23,070
Panel B: Big Data Technologies					
Adoption of big data analysis and usage	0.024***	0.004	-0.005	-0.004	-0.007
	(0.005)	(0.004)	(0.003)	(0.003)	(0.004)
Intensity of ICT	0.008	0.019*	0.018***	0.029***	0.042***
	(0.016)	(0.010)	(0.006)	(0.009)	(0.012)
Intensity of ICT x Adoption of big data analysis and	0.017	0.001	0.013	0.011	0.047
	(0.036)	(0.026)	(0.018)	(0.018)	(0.059)
Big Data at industry	-0.051***	-0.058***	-0.068***	-0.044***	-0.032**
	(0.016)	(0.009)	(0.008)	(0.010)	(0.013)
Big Data at industry x Adoption of big data analysis and	-0.091***	-0.000	0.028**	0.016	-0.001
	(0.028)	(0.022)	(0.012)	(0.013)	(0.017)
Pseudo R2	0.07	0.08	0.08	0.09	0.11
N	11,482	11,482	11,482	11,482	11,482
Panel C: Robotic Technologies					
Adoption of robotic technologies	0.002	-0.007	-0.009*	-0.009	-0.013*
	(0.009)	(0.006)	(0.004)	(0.006)	(0.008)
Intensity of ICT	0.000	0.011	0.007	0.012	0.025
	(0.018)	(0.015)	(0.010)	(0.010)	(0.016)
Intensity of ICT x Adoption of robotic technologies	0.033	-0.020	-0.050	0.004	-0.053
	(0.067)	(0.049)	(0.064)	(0.114)	(0.154)
Robots at industry	-0.039	-0.065***	-0.050***	-0.034**	-0.024
	(0.027)	(0.015)	(0.009)	(0.014)	(0.020)
Robots at industry x Adoption of robotic technologies	0.037	0.050**	0.038***	0.020	0.009
	(0.029)	(0.021)	(0.012)	(0.021)	(0.023)
Pseudo R2	0.05	0.06	0.07	0.08	0.11
N	6,037	6,037	6,037	6,037	6,037

Notes: Standard errors are computed by bootstrap based on 100 replications. Significance levels: *, 10%; **, 5%; ***, 1%. All models included the control variables *Firm's size*, *Export intensity*, *Financial constraints*, *Intensity of R&D* and sectoral dummies.

The first interesting result emerging from these estimates is that convergence only occurs through the interaction term between firm´s own adoption and the industrys intensity use of the particular technology. So, as technologies diffuse across markets and industries the spillover effect from these stock effects (Colombo and Mosconi, 1995) will increase firm´s productivity if the firm itself invests in these technologies.

As we observe some convergence effect across all types of digital technologies, their size and breath are different across technologies and firms. Now, there seems to be more convergence among ERP, CRM and robotics than among big data technologies. Also, firms situated in the median of the distribution, are benefiting more from these spillovers, than firms located at the ends of the productivity distribution.

Looking at laggard firms, the first-mover advantage seems to also emerge in terms of convergence to productivity frontier. When they are the first adopters in the industry of ERP and CRM technologies or big data, they appear to follow a pattern of convergence to frontier. This positive effect, however, is eliminated as more firms in the industry adopt this digital technology, suggesting again that an appropriation issue is at work and reinforcing the economic value of industry spillovers.

6. Concluding remarks and policy recommendations

Digital technologies, in particular the latest generation of new technologies, which allow a faster adaptation to the changing productive and business environment and are adopted in different areas of the economy, are considered pathbreaking innovations with important expected effects on productivity and growth. Using a large-scale, representative sample of Portuguese firms, operating in manufacturing and services industries, between 2014 and 2019, we performed a quantile regression analysis relating productivity at firm-level to the adoption of different digital technologies in order to analyse the new sources of productivity and the scope of digital technologies to close the productivity gap between frontier and laggard firms.

Our main contribution is the uncovering of heterogenous productivity effects across different digital technologies and different types of firms and industries, which offer important insights in explaining the productivity aggregate effect of digital technologies. Overall, we found that heterogenous digital technologies affect differently the dynamics of productivity and the convergence to the frontier. The persistent efforts to close the productivity gap require an upgrading on the degree of sophistication and complementarities among digital technologies and other productivity-enhancing resources. The lack of such combination could shrink productivity, which seems to be frequent in the early phase of digital technology adoption and empirically corroborating the view of a J-curve patterns of the relationship between digital technologies and productivity.

More importantly, frontier firms appear to be the greater extractors of productivity gains associated to digital technologies, suggesting that digital technologies could be more likely to exacerbate existing divides, rather than closing the productivity gap and improving aggregate productivity.

Looking at the impact of digital technologies on productivity among SMEs, which represent a high proportion of firms across all sectors in the Portuguese economy, new insights on the productivity convergence to frontier and its impact on aggregate productivity have emerged. Apart from ERP and CRM technologies, more mature technologies, second wave of digital technologies, such as big data and robots, seem yet to be not helpful in closing the productivity gap among SMEs. On the contrary, there is some evidence suggesting an increase in the existing divides, which would impact negatively in the aggregate productivity.

Moreover, the ability of firms to learn from more innovative firms at industry level seems to be at work and rendering productivity gains. Our findings indicate a visible effect on productivity associated to the rate at which digital technologies spread and replicate across industries. However, as that rate of adoption increases, firms seem to be less able to appropriate itself all the dynamics and benefits arising from digital technologies adoption. The diffusion of productivity benefits imply a less convergence rate but an expected positive effect on aggregate productivity.

As our findings were based on large-scale data that are representative for a wide variety of manufacturing and service industries, they are also valuable for policy makers and allow us to derive some policy implications. First, it is important to emphasise the need to coordinate efforts in the joint promotion of digital technologies adoptions and use with an upgrading in ICT use sophistication, organisational changes and human capital improvement. Digital technologies potential would not be realised without business and organisational changes and an increase in other complementary productivity-enhancing resources. Partial public policies to promote digitalisation at firm level without considering other investment in complementar resources and capabilities which affect productivity, may limit the expected positive effects at micro or aggregated level. Therefore, based on our findings, a more efficient choice and combination of policy initiatives and measures is desired.

Second, as digital technologies generate heterogenous productivity effects across firms of different size, public policies to promote digitalisation without considering this issue may not render positive impact at aggregate level, giving rise to the productivity paradox argument. For the Portuguese economy, it is a crucial point given the high proportion of SMEs across all sectors.

Third, apart from the positive impact on productivity associated to the rate of adoption at industry level, for laggard firms a first-move advantage related to digital technologies adoption is a finding that should deserve policy makers attention. In industries with no digital technologies adoption, policy initiatives and measures aiming to activate the technological diffusion machine are more prone to engender positive effects if they pay special attention to laggard firms, rather than to pick up frontier firms.

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Appendix A: Variables

Table A.1: Variables, measurement and source

Variables	Measurement	Source
Dependent variables		
Labour Productivity	log of value added per worker	SCIE
Turnover	log of firm's turnover	SCIE
Distance to productivity frontier	Ratio of firm's labour productivity to 95th percentile of labour productivity distribution at industry-year level	SCIE
Digital technologies		
Adoption of ERM and CRM technologies	Indicator variable if the firm reports using enterprise resource planning (ERP) or customer relationship management (CRM)	IUTIC
Adoption of Big Data analysis and usage	Indicator variable if the firm report analysing and using big data	IUTIC
Adoption of robotic technologies	Indicator variable if the firm report working with robots	IUTIC
ICT intensity	Share of employees involved only in ICT activities	IUTIC
ERP and CRM at industry	Share of firms that have adopted ERP and/or CRM technologies at industry-year level	IUTIC
Big Data at industry	Share of firms that have adopted Big Data technologies at industry-year level	IUTIC
Robots at industry	Share of firms that have adopted robotic technologies at industry-year level	IUTIC
Control variables		
Firm's size	log of total assets	SCIE
Exporting intensity	Share of sales in international markets	SCIE
Financial constraints	Share of liabilities on total assets	SCIE
R&D intensity	Share of employees involved in R&D activities	SCIE
Manufacturing firms	Indicator variable if the firm belongs to NACE 10 to 33 industry	SCIE
Wholesale and retail trade firms	Indicator variable if the firm belongs to NACE 45 to 47 industry	SCIE

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