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DIGITALISATION AND PRODUCTIVITY: IN SEARCH OF THE HOLY GRAIL - FIRM-LEVEL EMPIRICAL EVIDENCE FROM EUROPEAN COUNTRIES

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ABSTRACT/RÉSUMÉ

Digitalisation and productivity: In search of the holy grail Firm-level empirical evidence from European countries

This paper assesses how the adoption of a range of digital technologies affects firm productivity. It combines cross-country firm-level data on productivity and industry-level data on digital technology adoption in an empirical framework that accounts for firm heterogeneity. The results provide robust evidence that digital adoption in an industry is associated to productivity gains at the firm level. Effects are relatively stronger in manufacturing and routine-intensive activities. They also tend to be stronger for more productive firms and weaker in presence of skill shortages, which may relate to the complementarities between digital technologies and other forms of capital (e.g. skills, organisation, or intangibles). As a result, digital technologies may have contributed to the growing dispersion in productivity performance across firms. Hence, policies to support digital adoption should go hand in hand with creating the conditions to enable the catch-up of lagging firms, notably by easing access to skills

JEL classification codes: D24, J24, O33

Keywords: digitalisation, ICT, productivity, skills, high-speed internet, cloud computing

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Numérisation et productivité : à la quête du Graal Résultats empiriques sur données d'entreprises des pays européens

Ce document évalue l'incidence de l'adoption d'une gamme de technologies numériques sur la productivité des entreprises. Il combine des données sur la productivité des entreprises dans plusieurs pays et des données sur l'adoption des technologies numériques au niveau sectoriel dans un cadre empirique tenant compte de l'hétérogénéité des entreprises. Les résultats attestent de manière solide que l'adoption numérique dans une industrie est associée à des gains de productivité au niveau de l'entreprise. Les effets sont relativement plus forts dans les activités manufacturières et intensives en tâches routinières. Ils ont également tendance à être plus forts pour les entreprises plus productives et plus faibles en cas de pénurie de main-d'œuvre qualifiée, ce qui peut être lié aux complémentarités entre les technologies numériques et d'autres formes de capital (compétences, organisation ou actifs incorporels, par exemple). En conséquence, les technologies numériques peuvent avoir contribué à la dispersion croissante des performances de productivité entre les entreprises. Par conséquent, les politiques visant à soutenir l'adoption du numérique devraient aller de pair avec la création des conditions permettant le rattrapage des entreprises en retard, notamment en facilitant l'accès aux compétences.

Codes de classification JEL : D24, J24, O33

Mots-clés : numérisation, TIC, productivité, compétences, Internet haut débit, cloud computing

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DIGITALISATION AND PRODUCTIVITY: IN SEARCH OF THE HOLY GRAIL FIRM-LEVEL EMPIRICAL EVIDENCE FROM EUROPEAN COUNTRIES

By Peter Gal, Giuseppe Nicoletti, Théodore Renault, Stéphane Sorbe and Christina Timiliotis[1]

1. Introduction and main findings

1. Why is innovation everywhere except in productivity statistics? This famous 1987 question by Robert Solow was recently revived and adapted to the digital era by Brynjolfsson et al. (2017[1]). There are good reasons to believe that investment in digital technologies should have strong positive effects on productivity (Syverson, 2011[2]; Brynjolfsson and McAfee, 2014[3]). Yet, the empirical evidence at the industry and firm levels has been more nuanced (Acemoglu et al., 2014[4]; Bartelsman, Van Leeuwen and Polder, 2017[5]; DeStefano, Kneller and Timmis, 2018[6]; Cette, Lopez and Mairesse, 2017[7]), and aggregate productivity has generally been slowing down over the past decade, partly reflecting increasing dispersion in productivity performance across firms (Berlingieri et al., 2017[8]; Decker et al., 2018[9]). Notably, Andrews et al. (2016[10]) and Berlingieri et al. (2018[11]) have shown that aggregate patterns mask a widening productivity gap between a handful of frontier firms and a mass of laggard firms, especially in highly digitalised industries (Figure 1).

2. At the same time, cross-country data on firm-level adoption of digital technologies suggest that dispersion of adoption across firms is also wide and differs significantly across countries (Hagsten et al., 2013[12]; DeStefano, De Backer and Moussiegt, 2017[13]), as shown in Figure 2. For instance, adoption of cloud computing is more than twice more common in large firms than in small firms in the average OECD country (OECD, 2017[14]). Andrews et al. (2018[15]) have related this dispersion to adoption obstacles that depend crucially on capabilities and incentives, whose strength differs across firms, industries and countries.

3. This paper uses cross-country firm-level data to assess the productivity effects of industry-level digital adoption. We find strong evidence that operating in a digitalised environment benefits productivity, though not to the same extent across firms and industries, and explore some of the reasons why these benefits may have been disappointing at the aggregate level. We argue that the heterogeneity of adoption rates and adoption effects across firms and industries may contribute to explain why aggregate gains from digitalisation have been disappointing and too weak to offset other factors contributing to the productivity slowdown.

4. Econometrically, identifying causal effects of digital adoption on firm productivity poses multiple challenges. A first issue is reverse causality – does productivity increase due

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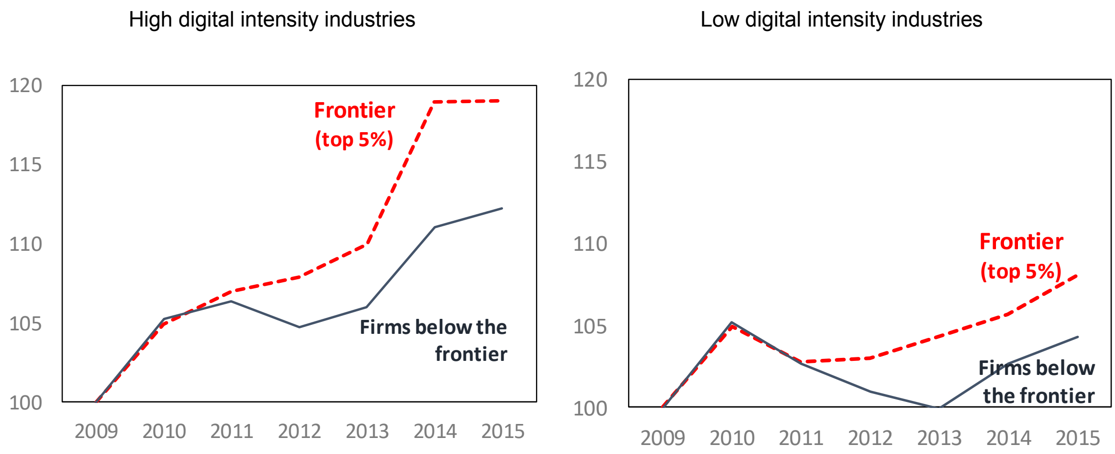
to adoption or is adoption just easier for high-productivity growth firms? Related to this, firm performance and adoption are likely to be driven by a number of common factors (e.g. skills or competitive pressures). Spillovers also pose identification issues: is productivity increasing due to within-firm adoption or due to the benefits of operating in a highly digitalised industry? Studies have shown that spillover effects across firms can be important (Syverson, 2011[2]) and pure firm-level analysis obviously tends to miss them. Industry-level studies cover such spillovers, but they are by nature unable to account for the heterogeneous firm-level patterns that characterise adoption and its productivity effects.

Figure 1. Dispersion in multi-factor productivity (MFP) has widened across firms, especially in digital intensive industries

MFP at the productivity frontier and for the average non-frontier firm (2009=100)



Note: The "frontier" is measured by the average of log multi-factor productivity, based on the Wooldridge (2009) methodology, for the top 5% of companies with the highest productivity levels in each 2-digit industry and year, across 24 countries. The "firms below the frontier" lines capture the averages of the log-productivity distribution in each industry and year (excluding the top 5%). The values obtained for the detailed 2-digit industries are averaged to industry groups that are classified either as having "high" or "low" digital intensities according to the methodology in Calvino et al. (2018[16]). The series are normalised to 100 in the starting year (2009=100).

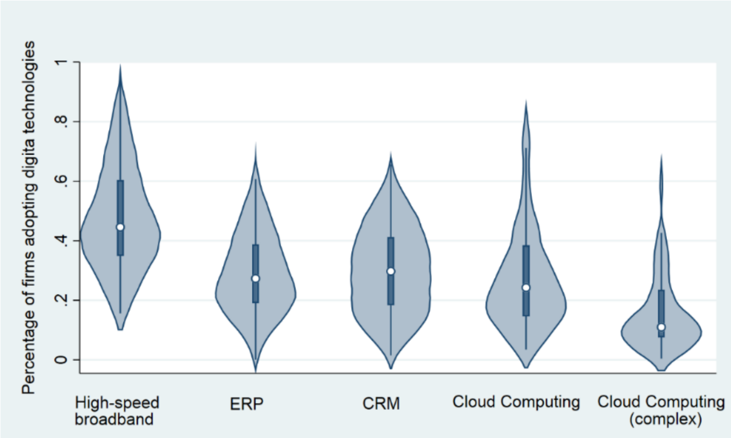
Source: Calculations using Orbis data of Bureau van Dijk, following the methodology in Andrews et al. (2016[10]).

5. In this paper, we address some of these issues by combining industry-level cross-country data on adoption of a range of digital technologies with firm-level cross-country data on multifactor productivity in an empirical framework allowing for productivity heterogeneity across firms. Relying on adoption rates at industry rather than firm level is a way to mitigate endogeneity issues and to account for spillover effects from early adopters to other firms in the industry. This is because industry-level adoption rates will reflect both the adoption propensity (i) of the firm whose productivity is being assessed (direct effect), and (ii) of other firms in the same industry (spillover effect). As a result, industry-level adoption is less likely than firm-level adoption to be endogenous to firm-level productivity performance, though clearly other sources of endogeneity persist and need to be controlled for in estimates. Moreover, focusing on firm-level productivity performance helps identifying which categories of firms benefit most from adoption, for example depending on their size or productivity, and allows controlling for the effects of catching up to the

technological frontier. Finally, looking at specific digital technologies instead of an aggregate ICT index accounts for the different effects they can have on productivity.

Figure 2. The dispersion of digital technologies across countries remains wide

Kernel densities based on the percentage of enterprises with >10 employees adopting digital technologies by country, 2017



Note: This figure offers a visualisation of the distribution of digital adoption rates in 2017 across countries using a rotated kernel density plot (outer shape) and a boxplot (inner figure) indicating the median (white dot), the 25th and the 75th percentile of the distribution (top and bottom of the bar). The graph is based on country-year observations of the overall share of firms adopting a certain technology, where *high-speed broadband* refers to access to high-speed broadband (>30Mbits); *ERP* stands for the adoption of Enterprise resource planning systems, a software-based tool that can integrate the management of internal and external flows, from material and human resources to finance, accounting and customer relations; *CRM* stands for Customer Relationship Management software; *Cloud Computing* refers to ICT services used over the internet as a set of computing resources; and *Cloud Computing (complex)* is a subset of relatively more complex uses of Cloud Computing (e.g. accounting applications, CRM software, or computing power). See Annex D of Andrews et al. (2018[15]) for a detailed description of each technology.
Source: Eurostat, Digital Economy and Society Statistics, comprehensive database.

6. We rely on two main sources of data, the Eurostat Digital Economy and Society database for digital adoption and the Orbis database for firm-level productivity and other characteristics. We cover five major digital technologies (high-speed broadband internet, simple and complex cloud computing services, Enterprise Resource Planning and Customer Relationship Management softwares) in 19 EU countries and Turkey and 22 industries over 2010-15, which corresponds to the period sufficiently well covered by the Eurostat adoption rates and is also an important period for the adoption of these technologies (OECD, 2017[14]). Both datasets are restricted to firms with at least 10 employees.

7. These technologies have been selected for their potential to improve firm productivity. For example, cloud computing gives firms flexibility to scale up or down their operations without incurring the cost of building and maintaining IT infrastructure, while also offering the possibility to access documents and software from anywhere in real time. Enterprise resource planning (ERP) software integrates and automates various functions, such as planning, purchasing, inventory, sales, marketing, finance and human resources into a single system, which can improve the speed and reliability of information exchanges within firms as well as with suppliers and customers. For more details, see Andrews, Nicoletti and Timiliotis (2018[15])

8. Our main result is that industry-level digital adoption is associated with significant productivity returns at the firm level. While the data do not permit to disentangle whether these are mainly driven by within-firm adoption or spillovers from other digitalised firms, our attempts to control for within-firm investment (in tangible or intangible assets) tentatively suggest that both channels may play a role. Our results are little affected by the inclusion of potential common drivers of adoption and productivity (such as skills and the regulatory environment), suggesting that they are not driven by the omission of these factors. Results are also robust to using adoption rates lagged by one year, or alternatively adoption rates at the beginning of the sample period, suggesting that they are not primarily driven by reverse causality.

9. Interestingly, we find that productivity gains are strongest for high productivity firms, suggesting that digital adoption in an industry has contributed to the increasing productivity dispersion across firms of this industry. This is in line with recent evidence showing that the catch-up of laggard firms is weaker in industries that rely more on ICT specialists (Berlingieri et al., 2018[11]). In contrast, productivity gains do not systematically depend on firm size. Different technologies have different effects in this respect. For example, Enterprise Resource Planning is more beneficial for larger firms and cloud computing for smaller ones, which is consistent with the idea that cloud computing is attractive for small firms as a means to avoid investing in a large IT infrastructure, in line with a recent finding by Bloom and Pierri (2018[17]) for the United States. Further, we find that the productivity benefits of adoption are significantly thwarted by skill and occupational shortages, pointing to synergies between digitalisation and other kinds of intangibles. Finally, we find that digitalisation is on average more beneficial in manufacturing than service firms, and more broadly in industries involving a high share of routine tasks, which is consistent with previous findings (Akerman, Gaarder and Mogstad, 2013[18]; Dhyne et al., 2018[19]).

10. While further research is needed to identify the firm-level sources of the estimated productivity benefits, our evidence is consistent with three drivers. First, the fact that highly productive firms benefit most from digital technologies and that skill shortages reduce these benefits points to the existence of important complementarities between these technologies and other intangible investments that raise productivity, such as managerial competence or workers' skills. This echoes earlier results by Andrews, Nicoletti and Timiliotis (2018[15]), who found a strong association between the propensity to adopt digital technologies and access to such intangibles at the industry level. Second, interactions with digitalised firms (within an industry or more broadly in global value chains) can generate positive spillovers, for example thanks to back and front office digital integration with suppliers and customers. Third, a strong incidence of routine tasks may generate scope for taking advantage of digital technologies by streamlining production processes.

11. Our results raise both opportunities and challenges for policies aimed at enhancing aggregate productivity via wider technology adoption. The generally positive effects of digital adoption and the importance of complementarities suggest that broad-based policies that support the diffusion of digital technology, such as the roll out of high-speed broadband and the upgrade of the skill pool, can bring important aggregate productivity benefits (Sorbe et al., 2019[20]). However, an important characteristic of digitalisation is that high-productivity firms have tended to benefit more from it than less productive ones. This probably reflects a combination of (i) a higher propensity to adopt digital technologies, (ii) greater productivity benefits from adoption thanks to higher endowment in skills and organisational capital, and (iii) more positive spillovers from interacting with digitalised peers (the empirical analysis in this paper cannot disentangle these three factors). In turn,

the higher productivity gains enjoyed by more productive firms may have compounded productivity dispersion across firms, a phenomenon that has been shown to underlie some of the productivity slowdown (Andrews, Criscuolo and Gal, 2016[10]; Decker et al., 2018[9]). Moreover, to the extent that some of the benefits of digitalisation depend on the ability of adopting firms to automate routine tasks (including by shedding labour), policies may also have to deal with the potential labour market implications of widespread adoption of digital technologies.

12. The paper is organised as follows. In the next section, we relate our work to previous research and highlight the issues involved in estimating the productivity effects of digitalisation. The following section describes the empirical methodology and the data. We then present the results for the average firm and explore the heterogeneity of the digital-productivity link across industries and firms. We conclude discussing open research issues and policy implications.

2. Digitalisation and productivity: a complex link

13. A number of firm- and industry-level studies provide evidence of positive links between investment in digital technologies and productivity performance – see for example reviews in Dedrick et al. (2003[21]), Draca et al. (2009[22]), Syverson (2011[2]), Munch et al. (2018[23]), Annex C.[2] Digital technologies enable firms to innovate, for example by improving business processes, and to automate certain routine tasks; they also reduce the costs of interacting with suppliers and customers (Bartel, Ichniowski and Shaw, 2007[24]; Brynjolfsson et al., 2008[25]; Akerman, Gaarder and Mogstad, 2013[18]). However, three recent studies contrast with this literature. Acemoglu et al. (2014[4]) find no effect of IT intensity on manufacturing productivity except in the computer-producing industry, using US firm-level data over 1977-2007. Bartelsman et al. (2017[5]) find no significant effect of broadband access on within-firm productivity, but still a positive effect at the aggregate level, which may indicate positive effects from reallocation (i.e. more productive firms growing in size relatively to less productive firms), firm entry and exit, or spillovers across firms. Similarly, DeStefano et al. (2018[6]) find that broadband ADSL positively affected firm size but not firm productivity, based on UK data for the early 2000s. In a context of slow global productivity growth, these papers have led to renewed discussions about Robert Solow's 1987 productivity paradox.

14. This overall puzzling picture reflects the fact that links between adoption of digital technology and productivity are complex and their empirical identification challenging. The key reason is that digital technologies typically support productivity in combination with other factors. Indeed, past studies have shown strong complementarities of digital technologies with organisational capital and management skills (Brynjolfsson and Hitt, 2000[26]; Basu et al., 2003[27]; Bloom, Sadun and Van Reenen, 2012[28]; Aral, Brynjolfsson and Wu, 2012[29]), R&D and intangible investments (Corrado, Haskel and Jona-Lasinio, 2017[30]; Mohnen, Polder and Van Leeuwen, 2018[31]),[3] human capital and ICT-related skills (Bugamelli and Pagano, 2004[32]) and a regulatory environment that enables the efficient reallocation of resources (Gust and Marquez, 2004[33]; Conway et al., 2006[34]; Bartelsman, 2013[35]). There are also complementarities between different digital

[2] See Annex C for an overview of the main studies and their results.

[3] In contrast, Hall et al. (2012[83]) find no evidence of complementarity between ICT and R&D investment on firm-level Italian data over 1995-2006.

technologies, for example between high-speed broadband and cloud computing (DeStefano, Kneller and Timmis, 2019[36]) or supply-chain management and customer-relationship software (Wieder et al., 2006[37]; Aral, Brynjolfsson and Wu, 2006[38]; Engelstätter, 2009[39]; Bartelsman, Van Leeuwen and Polder, 2017[5]). Another complication is that productivity gains tend to materialise with a certain lag, as digital adoption can disrupt production processes in the short term and require organisational adjustments to fulfil their potential (Van Ark and Inklaar, 2006[40]; Brynjolfsson, Rock and Syverson, 2017[1]). This in turn can result in productivity mismeasurement that may lead to a productivity J-curve if complementary intangible investments are imperfectly measured (Brynjolfsson, Rock and Syverson, 2018[41]).

15. Beyond these factors, a number of more technical reasons complicate the econometric identification of the productivity effects of digital technologies. A key one is endogeneity, which can result from both reverse causality and common factors influencing productivity and adoption. Reverse causality arises from the fact that digital adoption may be easier for high-productivity firms, because their high productivity can give them the financial means to invest in new digital technologies. In addition, certain potential drivers of digital adoption (e.g. managerial skills, organisational capital, favourable business and regulatory environment) can also support productivity directly, i.e. beyond their impact through digital adoption. If not properly addressed, this endogeneity can bias estimates upwards.

16. Another issue is the level of aggregation used in the analysis. Both the firm and the industry levels have advantages and downsides. Firm-level analyses are typically more subject to the endogeneity issues discussed above, although certain studies have developed original instrumentation techniques to overcome them (De Stefano, Kneller and Timmis, 2014[42]). In addition, firm-level studies can miss the positive spillovers generated by adoption by other firms, which past research has shown to be significant (Syverson, 2011[2]). In contrast, industry-level studies take into account both within-firm and spillover effects (typically without being able to disentangle them), but they do not take into account the firm-level heterogeneity in productivity drivers and performance. This can lead to less accurate specifications and hinder the identification of heterogeneous effects of adoption across firms.

17. Finally, the way to measure digital adoption also opens a number of questions. A number of papers rely on broad measures of digital intensity (e.g. spending on ICT, number of computers per worker), while others focus on adoption of specific technologies, such as Enterprise Resource Planning software (Hunton, Lippincott and Reck, 2003[43]). Certain studies cover several specific technologies, but they tend to focus only on single countries (Aral, Brynjolfsson and Wu, 2006[38]; Engelstätter, 2009[39]). Overall, broad measures of digital intensity offer more general results, but may rely on less precise identification and cannot assess heterogeneous effects of technologies across firms (e.g. small firms may benefit relatively more from certain technologies, such as cloud computing) or complementarities between technologies.

18. This paper aims to address some of these issues to provide robust cross-country evidence on the links between digital adoption and productivity. The combination of industry-level data on adoption and firm-level data on productivity is a way to mitigate endogeneity concerns, as discussed below, while it allows to cover both within-firm and spillover effects of adoption. In addition, it permits accounting for firm heterogeneity and assessing how different industries and types of firm (e.g. in terms of size or productivity) benefit from digital technologies – an area that has been relatively little explored, especially

in a cross-country perspective. The joint focus on several specific digital technologies, which is relatively new for a cross-country analysis, allows for a more refined identification. Finally, complementarities between technologies are explored by testing the effect of the first principal component of the adoption variables considered.

19. Nevertheless, the approach in this paper has a number of limitations, as further discussed below. While it covers both within-firm effects of adoption and within-industry spillovers, it leaves aside reallocation effects as well cross-industry spillovers, and in this respect probably underestimates productivity gains from adoption. In addition, it cannot directly disentangle within-firm and spillover effects, although it explores indirect ways to do so. Another limitation is that the measure of digital adoption used in this paper is binary at the firm level (surveyed firms report using the technology or not) hence it does not take into account the changing firm-level intensity in the use of technologies.

3. Empirical approach and data

3.1. Model specification

20. The empirical specification takes the neo-Schumpeterian growth approach to technology diffusion and innovation by Aghion and Howitt (1997[44]) and Acemoglu et al. (2006[45]), which has been implemented in a number of empirical studies at the firm (Griffith, Redding and Simpson, 2006[46]; Arnold, Nicoletti and Scarpetta, 2011[47]; Andrews and Criscuolo, 2013[48]; Andrews, Criscuolo and Gal, 2016[10]; Adalet McGowan, Andrews and Millot, 2017[49]) and industry levels (Nicoletti and Scarpetta, 2003[50]; Bourlès et al., 2013[51]). Multi-factor productivity (MFP) is assumed to follow an error correction model of the form:[4]

$$\Delta MFP_{f,s,c,t} = \alpha_1 \Delta MFP_{Frontier\ s,t} + \alpha_2 Gap_{f,s,c,t-1} + \beta\ Dig\_adopt_{s,c,\bar{t}} + \gamma X_{f,sc,t} + \delta_{c,t} + \delta_i + \varepsilon_{c,t} \quad \textbf{(1)}$$

21. $\Delta MFP_{f,sc,t}$ is the change in the logarithm of multi-factor productivity (MFP) of firm f, which operates in sector s and country c, in year t, estimated with the Wooldridge (2009) method. MFP growth of firm f is assumed to depend on MFP growth of the productivity frontier ($\Delta MFP_{Frontier\ s,t}$), which is defined as the average MFP among the 5% most productive firms in sector *s* and year t across the countries in the sample,[5] and on the lagged distance to the frontier ($Gap_{f,sc,t-1} = MFP_{Frontie\ r\ s,t-1} - MFP_{f,s,t-1}$). Frontier firms are excluded from the sample to avoid endogeneity issues. Based on economic theory and previous estimations of this model, one should expect α_1 to be positive but below 1, indicating that innovation at the frontier benefits other firms but only partially so, and α_2 to be positive, indicating that firms below the frontier benefit from a catch-up effect. However, the speed of frontier growth, the variance of non-modelled productivity shocks and the nature of firm entry and exit (productivity enhancing or not) can either lead to productivity convergence or divergence across firms. In practice,

[4] See Bourlès et al. (2013[51]) for a derivation of a similar specification from a co-integrating relationship in levels relating MFP to frontier MFP.

[5] In line with past studies, we use the global industry frontier as opposed to the national frontier. In theory, both can be relevant to productivity catch-up, but the global frontier is likely to be measured more consistently and with less noise in our dataset.

divergence has generally been prevailing over recent years at the OECD level (Figure 1), although not necessarily within each country.

22. The main coefficient of interest is β, which captures the effect of industry-level digital adoption on firm-level productivity growth. $Dig\_adopt_{s,c,\bar{t}}$ represents the share of firms in sector s and country c that report using a specific digital technology (e.g. high-speed broadband internet connection, cloud computing) averaged over the period 2010-15. The effect of different digital technologies is assessed in separate identical regressions (i.e. one regression per technology). In addition, their combined effect is assessed using a composite indicator of adoption, which is constructed as the principal component of five variables representing the adoption of different digital technologies (high-speed broadband, simple and complex cloud computing, ERP and CRM software), in the spirit of Andrews et al. (2018[15]).

23. As digital adoption is typically observed only for one or two years in the period of interest, the regression relies on the average of the digital adoption variable over the available years ($Dig\_adopt_{sc,\bar{t}}$), meaning that adoption does not vary over time. While this may hinder identification, it also mitigates potential endogeneity issues (e.g. if adoption and productivity in a specific year were driven by a common factor) and can help capturing lagged benefits of adoption. Since the digital adoption variable only varies at the country-industry level (and not across firms in an industry or over time) standard errors are clustered at the country-industry level to address potential correlation of residuals.

24. Longer time series are available in the data only for the adoption of ERP software. This allows the estimation of alternative specifications less subject to potential endogeneity issues. Two options are considered: using (i) adoption rates lagged by one year, or (ii) adoption rates in the first year of the sample period (2010).

25. The baseline specification also includes a vector of control variables ($X_{fsc,t}$), including firm size (measured as the log of employment) and age, as well as industry and country-year fixed effects.[6] In alternative specifications, additional controls are included to account for potential common determinants of productivity and digital adoption at the industry level, such as skill shortage and regulatory environment indicators. In an attempt to disentangle the within-firm effect of digital adoption from spillovers resulting from digital adoption by other firms in the industry, we also control in a separate specification for firm-level investment (tangible or intangible) as a proxy for firm-level digital adoption. With this additional control capturing within-firm effects, the estimated β coefficient should only reflect spillover effects. However, these proxies are clearly imperfect (but the only ones available in our dataset) and corresponding results should be considered as illustrative.

26. Overall, this empirical framework offers the benefit of taking account of firm heterogeneities and firm-specific drivers of productivity, making it richer and more robust than an industry-level framework. In addition, the use of industry-level adoption as a determinant of firm-level adoption addresses certain endogeneity concerns since industry-level adoption is less likely than firm-level adoption to be influenced by firm-level productivity.

27. Still, one should keep in mind a number of caveats. First, it is possible that some endogeneity still persists despite the benefits of the general approach combining industry

6 Results are also robust to including industry-year fixed effects.

and firm-level data and the additional control variables introduced (and, in the case of ERP, the use of lagged and initial digital adoption rates). This would be the case if unobserved factors were affecting simultaneously adoption levels in an industry and productivity growth rates of the firms in this industry in a way that is not captured by industry and country-year fixed effects and by the additional control variables. Second, it is possible that the productivity catch-up of lagging firms is achieved via the adoption of digital technologies that more advanced firms have already adopted, in which case this effect may be captured (at least partially) by the productivity gap variable rather than the digital adoption. Results are robust to dropping the catch-up term in the regression, suggesting that this is not an issue.[7] Another potential concern is that dropping the firms at the productivity frontier (i.e. the top 5% in each industry) may lead to underestimating the effect of relatively new technologies that they may be the first ones to adopt (e.g. complex cloud computing services). Finally, as shown by past research, reaping the benefits of digital adoption generally requires broader organisational changes, which are likely to be per se productivity-enhancing. Given that the estimates encompass a combination of the effect of adoption and such concomitant reorganisations, they reflect the productivity gains from digitalisation in a broad sense (i.e. including the effect of these reorganisations).

28. In addition to the specifications described above, a number of refinements of the baseline specification are introduced to assess which industries and firms benefit most from digitalisation and what are the potential complementarities with other factors:

- To assess which industries benefit more from digital adoption, we interact the digital adoption variable with (i) a categorical variable separating manufacturing and service industries, (ii) a variable capturing the average routine intensity of tasks in each industry, with the idea that industries with higher routine intensity may benefit more from digitalisation through the automation of routine tasks;
- To assess which firms benefit more from the diffusion of digital technologies, the digital adoption variable is successively interacted with two categorical variables splitting the sample into (i) four size classes (from smallest to largest firms) and (ii) four productivity classes (from least to most productive). As a different way to test if productivity effects of digitalisation vary according to productivity levels, the digital adoption variable is also interacted with lagged distance to the frontier.
- To better understand complementarities of digital technologies with skills, we explore if skill shortages in ICT-related areas affect the adoption-productivity link by interacting industry and country level measures of skill shortages with the digital adoption variable;

3.2. Combining firm and industry-level data

29. We combine various industry-level sources on digital adoption, routine intensity and occupational or skill shortages with firm-level information on productivity. Digital adoption data are drawn from the Eurostat "community survey on ICT usage and e-commerce in enterprises" and have country and industry dimensions and, for a subsample of technologies, also a time dimension. The survey provides a compilation of data on the use of various types of information and communication technologies in enterprises with

[7] That results are robust to omitting the productivity gap variable is also an indication that they are not subject to a potential bias that may result from including a transformation of the lagged level of the dependent variable as an explanatory variable.

more than 10 employees. To the best of our knowledge, this dataset is the only source of comparable cross-country data on digital adoption rates at the industry level.

30. Our analysis focuses on a subset of five indicators selected from a list of several hundred variables available in the Eurostat dataset. The selected indicators are the availability of high-speed broadband internet access, use of simple or complex cloud computing (CC, CC_HI), and the use of front or back office applications – customer relationship management (CRM), and enterprise resource planning (ERP). Technologies were selected based on their potential to improve within-firm productivity as well as having spillovers on other firms (e.g. ERP and CRM) and potential complementarities between themselves (e.g. broadband access with other technologies). An additional selection criterion was to maximise cross-country, cross-industry coverage.[8]

31. Since adoption rates of different technologies are positively correlated (Table A.4) and there could be complementarities from adopting them jointly, we also combine them into a single index using their first principal component (i.e. the linear combination of adoption rates that accounts for the largest fraction of their total variance). The first principal component explains a high fraction (more than 60%) of the overall variation in the digital adoption indicators (Table A.5, Panel A), and the weights assigned to them are relatively close to each other (Table A.5, Panel B), implying that all technologies are important contributors to the first principal component. More broadly, this index may capture a general tendency of digital technology adoption in a given country-industry cell, in which case it is possible that it captures to some extent the adoption of other digital technologies not covered in this paper.

32. Productivity and other firm-level variables come from Orbis, a widely used harmonized cross-country longitudinal firm-level database, building on the data construction steps described in Gal (2013[52]), Andrews et al. (2016[10]), and Gopinath et al. (2017[53]).[9] The underlying data are sourced from annual balance sheet and income statements, collected by Bureau van Dijk (BvD) – an electronic publishing firm – using a variety of underlying sources ranging from credit rating agencies (Cerved in Italy) to national banks (National Bank of Belgium). It is the largest available cross-country firm-level database for economic and financial research, which contains not only publicly listed but also privately owned companies. However, important processing and cleaning work needs to be undertaken to transform the financial information to a database suited for economic analysis.

33. This involves the three broad following steps: (i) ensuring comparability of nominal variables across countries and over time (industry-level PPP conversion and deflation based on Inklaar and Timmer (2014[54]) and the OECD STAN database, respectively); (ii) deriving new variables that are used in the analysis (real capital stock, productivity); and (iii) keeping only company accounts with valid and relevant information for our present purposes (filtering and cleaning).[10] We obtain productivity as a residual from estimating

[8] For more details see a companion paper examining the drivers of digital adoption by Andrews et al. (2018[15]) where the same set of indicators are used.

[9] The version used throughout this paper was made available to the OECD by BvD in March 2017.

[10] We prefer unconsolidated accounts in case a firm reports both unconsolidated and consolidated accounts so as to ensure that the covered economic activity refers to the local, domestic markets and does not reflect global activities in case of multinational firms. Further, we drop firms that report extreme growth rates in productivity and employment, i.e. which are in the top or bottom 1% of the growth distribution within each country and

value-added based production functions, separately for each detailed industry, using the control function approach based on intermediate inputs to mitigate the endogeneity of input choices (Wooldridge, 2009[55]).[11] We restrict the sample to firms that have an average of at least 10 employees (over our sample period) to match the reference group of the industry level digital adoption variable.

34. Concerning control variables at the industry level, we utilise a recently developed indicator for the routine content intensity of tasks in each industry (Marcolin, Miroudot and Squicciarini, 2016[56]). This indicator provides a measure of the routine content of occupations, based on data from the OECD Survey of Adult Skills (PIAAC). It measures the degree of independence and freedom in planning and organising the tasks to be performed on the job as a proxy for non-routine content. The occupation-level index is translated into an industry-level index by constructing the weighted average of the occupation-based index by industry, with the occupational weights by industry obtained from the European Labour Force Survey (1995-2015).

35. Occupational and skill shortages rely on the OECD Skills for Jobs database, which uses labour market signals at the occupation level – in particular, relative wages, hours worked, employment and unemployment as well as qualification mismatches – to derive indicators of skill shortages in an industry (OECD, 2018[57]). The indicators cover a rich set of skills, of which we use the following ones: *i)* resource management skills, which capture the ability to allocate resources efficiently; *ii)* management of personnel resources, which identifies how well managers motivate, develop and direct people as they work, and identify the best people for each job; *iii)* computer and electronics skills, which refers to the knowledge of circuit boards, processors, chips, electronic equipment, computer hardware and software, including application and programming; and *iv)* technical skills, which are associated with workers' capacity to design, set-up, operate and correct malfunctions, involving application of machines or technological systems.

36. Our combined dataset contains about 1.5 million firm-year observations in the baseline specification, spanning across 20 OECD countries (all from the European Union plus Turkey) and 22 industries over 2010-2015 (Table 1).[12] A simple descriptive chart (Figure 3) suggests that firms tend to have higher productivity when they operate in industries where digital adoption rates are higher, but also that they exhibit higher dispersion in productivity, which is consistent with the evidence presented in Figure 1 that uses a broader classification of digital intensity following Calvino et al. (2018[16]).

industry. This step also serves to mitigate the risk of retaining company accounts that are affected by abrupt and large changes resulting from mergers, acquisitions or split-ups.

[11] A number of limitations that commonly affect productivity measurement should be noted. First, differences in the quality and utilisation of capital and labour inputs cannot be accounted for as the capital stock is measured in book values and labour input by the number of employees. Secondly, measuring outputs and inputs in internationally comparable price levels remains an important challenge. Finally, similar to most firm-level datasets, Orbis contains variables on outputs and inputs in nominal values and no additional separate information on firm-specific prices and quantities. For further details, see Andrews et al. (2016[10]).

[12] The set of countries are as follows: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, the Netherlands, Poland, Portugal, Slovenia, Spain, Sweden, Turkey and the United Kingdom. The industries covered range from manufacturing to administrative and other support services, excluding the financial sector (i.e. 2-digit codes between 10 and 82, excluding 64-66).

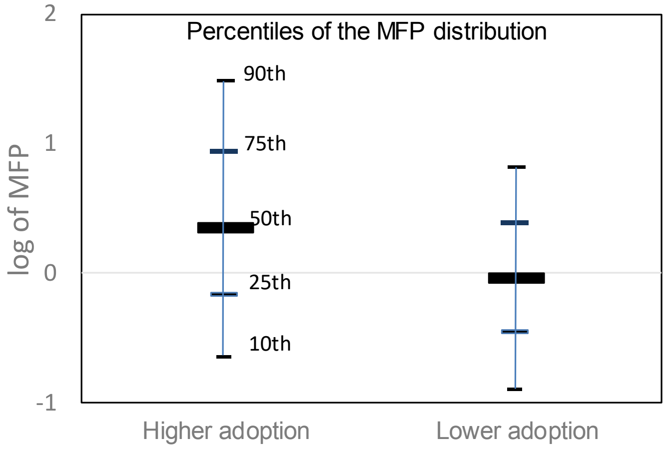
Table 1. Descriptive statistics

	Mean	Median	Bottom decile	Top decile	Standard deviation	Observations
Digital variables						
High-speed broadband	0.3585627	0.30074	0.155292	0.649704	0.1820864	401
Enterprise Resource Planning	0.328646	0.3049324	0.1073742	0.584564	0.179027	417
Customer Relationship Management	0.3268234	0.288089	0.143113	0.5753257	0.1701879	409
Cloud Computing	0.2442139	0.1983755	0.074526	0.4820525	0.1619827	391
Cloud Computing (complex)	0.138116	0.1053469	0.033503	0.2861333	0.1142393	380
1st principal component	0.8534867	0.351125	-1.63686	4.340654	2.380591	349
Firm-level variables						
MFP growth	0.0099924	0.0095434	-0.2552748	0.27631	0.2641691	1,803,155
Frontier growth	0.0190791	0.0187607	-0.0319347	0.0745354	0.0447191	2,449,946
Gap to frontier (lagged)	1.710548	1.619003	0.8597827	2.614367	0.7716009	1,737,330
Age	21.96713	18	4	43	17.80941	3,318,977
Employees (log)	3.534132	3.218876	2.484907	4.976734	1.075448	3,367,107
Capex (log)	11.27541	11.2249	8.437047	14.19981	2.331976	809,083
Intangibles (log)	11.27592	11.36433	7.316711	15.19365	3.262974	2,627,018
Other (industry-level)						
Routine intensity	-0.1009339	0.0240777	-0.7299849	0.3154604	0.3690799	22
Knowledge intensity	0.4225333	0.38	0.26	0.62	0.1671307	22
Skill shortages	-0.0531344	-0.036923	-0.2325579	0.1307846	0.1557511	1577
Resource management skills	0.0048168	0.0065826	-0.0280658	0.0395762	0.0288059	1577
Management of personnel resources	0.0055604	0.0067688	-0.034883	0.0479654	0.0341106	1577
Computer and electronics	0.0168042	0.0103106	-0.0317479	0.0811364	0.0442032	1577
Technical skills	-0.0017983	-0.0008761	-0.0185557	0.0157017	0.016532	1577
Regulatory impact	0.1194431	0.0719498	0.0273529	0.3371291	0.1132468	339

Note: MFP is measured in logarithms, based on the Wooldridge (2009) methodology, and dMFP denotes its first difference. The first principal component (i.e. the one associated with the largest eigenvalue) is obtained from the five digital adoption indicators. For a detailed description of each indicator, please refer to Table A.1.
Source: OECD calculations

Figure 3. Productivity is higher and more dispersed when digital technology adoption is higher

MFP distribution in industries with high vs. low digital adoption rates



Note: "Higher adoption" and "lower adoption" denotes industries that are above and below, respectively, of the median industry in terms of the first principal component (i.e. the one associated with the largest eigenvalue) of the five digital adoption indicators. The percentiles are calculated within each industry and then averaged to the two industry groups, and are shown in relative terms to the median across firms with lower adoption.
Source: Orbis database of Bureau van Dijk; Eurostat, Digital Economy and Society Statistics, comprehensive database.

4. Results

4.1. Digital adoption and productivity in the average firm

37. Table 2 shows the results of estimating the baseline MFP model by ordinary least squares (OLS). All coefficients have the expected sign and significance. Roughly 20 percent of increases in frontier growth are passed to the average firm and 10 percent of the gap with frontier is filled each year via catch-up (column 1), which are standard magnitudes at firm level and consistent with an overall pattern of productivity dispersion (Andrews, Criscuolo and Gal, 2016[10]). The main result is that an industry environment characterised by high digital adoption rates is associated with higher MFP growth in the average firm. With the exception of complex cloud computing, all digital technologies are positively and significantly associated with MFP growth. This is also the case for the first principal component of the five digital technologies (last column), which captures the simultaneous co-variation and potential complementarities of several technologies (see Annex A).[13]

[13] An alternative approach would consist of including the adoption rates of different technologies separately in the same regression, but their individual coefficients could be difficult to interpret as the non-negligible correlation between the adoption of different technologies could give rise to multicollinearity.

Table 2. Baseline results

Dependent variable: MFP growth

	Basic	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.218***	0.222***	0.212***	0.218***	0.215***	0.230***	0.236***
	(0.0353)	(0.0383)	(0.0374)	(0.0378)	(0.0377)	(0.0381)	(0.0394)
Gap to frontier (lagged)	0.105***	0.104***	0.104***	0.105***	0.104***	0.107***	0.107***
	(0.0106)	(0.0118)	(0.0114)	(0.0117)	(0.0114)	(0.0118)	(0.0126)
Age	-0.0002***	-0.0003***	-0.0003***	-0.0002***	-0.0003***	-0.0003***	-0.0003***
	(5.19e-05)	(5.89e-05)	(5.53e-05)	(5.78e-05)	(5.67e-05)	(5.75e-05)	(6.24e-05)
Employees (log)	0.0224***	0.0216***	0.0216***	0.0220***	0.0217***	0.0233***	0.0233***
	(0.00252)	(0.00275)	(0.00266)	(0.00272)	(0.00268)	(0.00277)	(0.00295)
Digital Technology		0.143***	0.101**	0.187***	0.0864**	0.0419	0.0161***
		(0.0343)	(0.0402)	(0.0347)	(0.0437)	(0.0555)	(0.00391)
Observations	1,681,981	1,453,519	1,503,462	1,485,781	1,505,867	1,435,145	1,348,670
R-squared	0.063	0.062	0.062	0.063	0.062	0.064	0.064

Note: This table reports the estimates of the baseline equation where firm-level multifactor productivity (MFP) growth is regressed on average MFP growth of the 5 percent firms with highest MFP in each sector-year cell, the firm's lagged gap to this productivity frontier, age and size (measured by the number of employees), and the average country-sector level adoption rates of individual digital technologies. The last column shows results for the 1st principal component of the five technologies. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.

Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

38. These results are robust to using (i) digital adoption rates lagged by one year, or (ii) adoption rates at the beginning of the sample period (Table B.2). While this could only be tested for ERP software (the only technology in our sample with sufficient time coverage in the data), it nevertheless suggests that results are not primarily driven by reverse causality.[14]

39. If one interprets the results as causal, they imply that a 10 percentage point increase in adoption of high-speed broadband (or cloud computing) would translate into an instantaneous increase in MFP growth by 1.4 percentage points (or 0.9 percentage point). After 5 years, this would imply a 5.8 per cent (or 3.5 per cent) higher MFP level for the average firm.[15] Effects found for other technologies are of the same order of magnitude, but as shown below exhibit different patterns across industries and firms, underlining the importance of distinguishing their respective association with productivity rather than bundling all technologies in a single ICT aggregate. Overall, results suggest that at least on

[14] Results are also robust to restricting the estimation period of the baseline regression to the years 2014-15, a period for which all digital technology variables are available (see Annex Table B.1).

[15] The effect after 5 years results from cumulated annual increases in MFP growth combined with weaker catch-up due to progressively higher MFP levels.

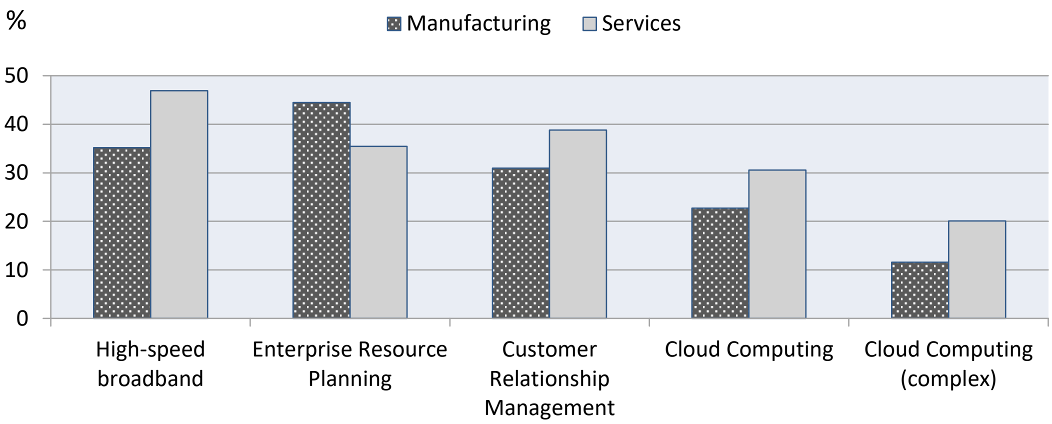
average there is no apparent productivity paradox at the firm level: the digitalisation of an industry is indeed linked to better productivity performance of its firms.

4.2. Sectoral differences and routine tasks

40. Economy-wide coefficient estimates may nonetheless mask differences in the co-variation of productivity and adoption in different parts of the economy. Indeed, the take-up of digital technologies varies significantly across industries (Figure 4 and Table A.3) and is generally higher in services than in manufacturing.[16] However, the association of digital adoption with higher firm-level productivity is much stronger in manufacturing than services for most technologies, with the notable exception of high-speed broadband (Table 3).

Figure 4. The diffusion of digital technologies across sectors

Selected technologies, 2016 (or latest available)



Note: This figure shows the average adoption rate of selected digital technologies in the manufacturing sector (NACE Rev.2 10-33) and the services sector (NACE Rev.2 45-82) of the 20 countries included in this analysis.
Source: OECD calculations based on Eurostat, Digital Economy and Society Statistics, comprehensive database.

41. One relevant factor for the effect of digital adoption is the intensity in routine tasks, which digital technologies can presumably replace or streamline (Akerman, Gaarder and Mogstad, 2013[18]). We therefore augment our baseline specification with the interaction between digital technology adoption and the indicator of sectoral routine task intensity proposed by Marcolin et al. (2016[56]).[17] Results (Table 4), consistent with Chevalier and Luciani (2018[58]), show that digital adoption is more closely associated with productivity gains in sectors highly intensive in routine tasks than elsewhere, perhaps reflecting a wider scope for substitution between technology and labour in these sectors. If one assumes that

[16] This is consistent with findings in previous research, such as Dhyne et al. (2018[19]).

[17] We use the indicator for the US, under the assumption that it reflects structural sectoral features in a relatively frictionless economy, which would be common in all countries. This also avoids possible endogeneity issues between adoption rates and routine intensity. Results are also robust to replacing the Marcolin et al.'s indicator of sectoral routine intensity with the indicator of sectoral knowledge intensity used in Andrews et al. (2018[15]) (Annex Table B.3).

these effects are causal, Figure 5 shows for instance that the productivity benefits of raising adoption in a high routine-intensive sector are significantly higher than in other industries.

Table 3. Differentiating between manufacturing and services

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.184***	0.170***	0.178***	0.179***	0.182***	0.189***
	(0.0413)	(0.0400)	(0.0410)	(0.0409)	(0.0421)	(0.0443)
Gap to frontier (lagged)	0.127***	0.125***	0.126***	0.126***	0.128***	0.129***
	(0.00540)	(0.00508)	(0.00512)	(0.00522)	(0.00523)	(0.00561)
Age	-0.000204***	-0.000215***	-0.000203***	-0.000219***	-0.000282***	-0.000270***
	(5.38e-05)	(5.04e-05)	(5.31e-05)	(5.17e-05)	(4.97e-05)	(5.30e-05)
Employees (log)	0.0256***	0.0254***	0.0257***	0.0258***	0.0271***	0.0273***
	(0.00201)	(0.00194)	(0.00195)	(0.00199)	(0.00207)	(0.00217)
Digital technology (Manufacturing)	0.119**	0.113***	0.211***	0.189***	0.359***	0.0264***
	(0.0535)	(0.0419)	(0.0481)	(0.0524)	(0.115)	(0.00517)
Digital technology (Services)	0.173***	0.0526	0.158***	0.0589	0.0644	0.0140***
	(0.0329)	(0.0578)	(0.0384)	(0.0509)	(0.0574)	(0.00395)
Observations	1,223,625	1,273,088	1,256,137	1,275,982	1,221,521	1,135,046
R-squared	0.073	0.073	0.073	0.073	0.074	0.074

Note: Colum 1-6 of this table show the results of the equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, the firm's gap to this frontier, age and size (measured by the number of employees), and the interaction between digital technology adoption rates and a dummy for the sector. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. The last column shows results for the 1st principal component of the five technologies. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table 4. Differentiating according to sector routine intensity

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.236***	0.235***	0.239***	0.234***	0.267***	0.264***
	(0.0483)	(0.0480)	(0.0478)	(0.0481)	(0.0472)	(0.0474)
Gap to frontier (lagged)	0.101***	0.101***	0.102***	0.101***	0.105***	0.107***
	(0.0152)	(0.0150)	(0.0154)	(0.0153)	(0.0161)	(0.0166)
Age	-0.000286***	-0.000286***	-0.000284***	-0.000278***	-0.000319***	-0.000323***
	(6.28e-05)	(6.28e-05)	(6.33e-05)	(6.29e-05)	(7.21e-05)	(7.47e-05)
Employees (log)	0.0195***	0.0194***	0.0200***	0.0194***	0.0206***	0.0213***
	(0.00317)	(0.00314)	(0.00323)	(0.00318)	(0.00332)	(0.00345)
Digital technology	0.168***	0.0551	0.177***	0.123**	0.185*	0.0229***
	(0.0580)	(0.0517)	(0.0470)	(0.0593)	(0.101)	(0.00564)
Digital technology X routine intensity	0.0177	0.136**	0.133*	0.162**	0.286**	0.0222***
	(0.0658)	(0.0617)	(0.0777)	(0.0653)	(0.128)	(0.00569)
Observations	1,137,711	1,142,895	1,138,659	1,138,021	1,070,569	1,052,191
R-squared	0.063	0.062	0.063	0.063	0.065	0.065

Note: This table reports estimates of the baseline equation augmented with an interaction between digital technologies and the country-sector-level intensity of routine tasks (see Marcolin et al., 2016, for a description of the indicator). All regressions include sector and country-year fixed effects and are clustered at the country-sector level. The last column shows results for the 1st principal component of the five technologies. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15 and routine intensity refers to the average over the period 2010-15. ***, ** and * represent $p<0.01$, $p<0.05$ and $p<0.1$ respectively.

Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Figure 5. Sectors intensive in routine tasks benefit more from digitalisation

Productivity gain for the average firm
associated with a 10 percentage point increase in industry-level adoption

Note: Estimates are derived from the baseline equation augmented with an interaction between digital technologies and the country-sector-level intensity of routine tasks (Marcolin et al., 2016) (Table 4). High routine intensity represents the 75th percentile of the distribution in this classification.

4.3. Channels and robustness to omitted variable bias

42. While our estimates are suggestive of a positive link between digital adoption and productivity performance, they suffer from a number of limitations already mentioned in previous sections. Here, we attempt to identify the channels underlying the links (within-firm adoption vs. spillovers from other firms) and the potential role of omitted variables.

43. To try disentangling the effects of the spillovers vs. within firm, we run regressions including total firm-level capital expenditure or expenditure on intangible assets, which are available in the Orbis database (Annex Table B.4, Panels A and B). Coefficient estimates barely change for most of the digital technologies, save for cloud computing whose coefficient either declines (when including intangible investment) or loses significance (when including total capital expenditure). It would seem, therefore, that for most technologies the effects captured reflect either mainly sector-wide spillovers or benefits from within-firm adoption that cannot be controlled for using the available set of information from company accounts.

44. A potential source of concern is that sector-level adoption rates may capture the effects of other sectoral drivers of productivity that are correlated with adoption. For instance, Andrews et al. (2018[15]) find that digital adoption rates are influenced by a number of sector-level structural and policy factors affecting firm-level capabilities and incentives to adopt. A number of these factors, such as the regulatory environment and the availability of skills may also directly affect firm-level productivity growth (Arnold, Nicoletti and Scarpetta, 2011[47]; Andrews, Criscuolo and Gal, 2016[10]).

45. Omitting these factors could artificially inflate the estimated effects of sector-level digital adoption rates. To control for this possibility, we extend the model with two additional control variables: (i) the OECD indicator of the impact of upstream anticompetitive regulations in each sector (Conway and Nicoletti, 2006[59]; Égert and Wanner, 2016[60]), and (ii) a new indicator of sectoral occupational shortages recently published in the OECD Skills for Jobs Database (2018[57]). Reassuringly, while both

regulatory burdens and lack of skills have the expected negative association with productivity performance,[18] the finding that higher digital adoption rates are associated with higher MFP growth remains largely unaffected when we account for the direct influence of these variables (Annex Table B.4, Panel C).

4.4. The role of skills

46. The likely complementarity between digital technologies and other intangible investments suggests that skill shortages in a sector could impede digital adoption from yielding its full productivity benefits. We test this conjecture by further extending the baseline model to include the interaction between digital adoption and skill shortages. One concern with this approach could be that industries in which adoption is high (or low) may cause (or suffer from) skill shortages, and this endogeneity could bias estimates in unpredictable ways. However, there appears to be no systematic correlation between adoption and shortages in the data (Annex Table A.6). Since the OECD Skills for Jobs database includes a large number of occupations and skills, we concentrate first on general shortages and subsequently focus more specifically on skills that are likely to be most complementary to digital adoption (managerial, computer and electronics, and technical).[19]

47. Consistent with the idea that digital technologies are complementary to organisational and human capital, we find that general occupational shortages in an industry curb the linkage between adoption rates and productivity performance (Table 5) for specific technologies (such as high-speed broadband, CRM and cloud computing) and for all technologies combined (1st principal component).[20] Digging deeper (Annex Table B.5), shortages in managerial, electronic and technical skills all inhibit the ability of firms to reap the productivity benefits of higher sector-level adoption rates. The damaging effects of skill shortages on the productivity gains from adoption are substantive (Figure 6, Panel A). For instance, moving from relatively low to high shortages would reduce the estimated firm-level productivity growth gains from an increase in high-speed broadband internet diffusion by more than a quarter; a similar reduction in productivity gains due to shortages is estimated for CRM. Focusing on specific skills, the strongest downward effects of shortages on productivity gains from wider sector-level adoption rates (of all technologies combined) are found for electronic and technical skills (Figure 6, Panel B).

[18] The lack of significance of the regulatory impact indicator is most likely related to the relatively short time period spanned, as most of the variation in this indicator is within country-industry in the sample of relatively homogeneous EU countries mostly covered by our analysis.

[19] “Occupational shortages” pools shortages in all occupational categories covered by the OECD dataset; managerial shortages covers “Resource management skills” (ability to allocate resources efficiently) and “Management of personnel resources” (how well managers motivate, develop and direct people and identify best people for each job); “Computer and electronics” refers to the knowledge of circuit boards, processors, chips, electronic equipment, computer hardware and software, including application and programming; “Technical skills” are associated with workers’ capacity to design, set up, operate and correct malfunctions, involving application of machines or technological systems. See OECD (2018[57]) for details.

[20] Since skill shortages are constructed by relying among other factors on differences in wage dynamics across occupations, they could also capture to some extent differences in industry productivity, which in turn are related to average firm productivity. However, this is mitigated by the fact that wages enter only with a small weight (20%) into the skill shortage indicator (see Section 3.2 and OECD (2018[57])).

Table 5. Assessing the effects of skill shortages

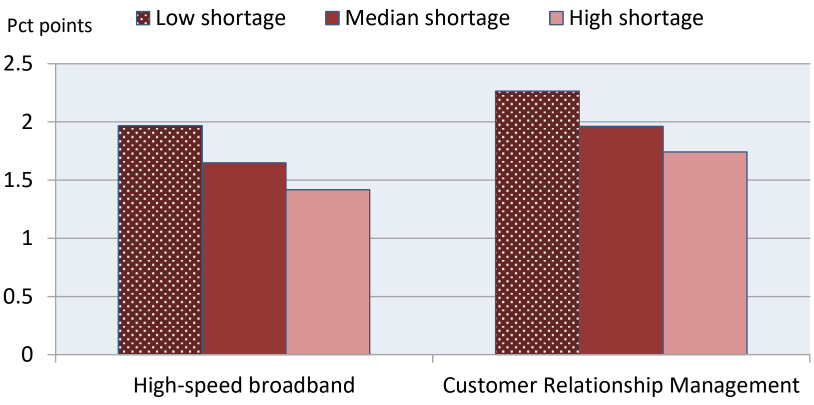
Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.154***	0.128***	0.141***	0.133***	0.133***	0.145***
	(0.0372)	(0.0378)	(0.0373)	(0.0374)	(0.0374)	(0.0375)
Gap to frontier (lagged)	0.105***	0.104***	0.106***	0.104***	0.105***	0.106***
	(0.0133)	(0.0126)	(0.0130)	(0.0126)	(0.0126)	(0.0136)
Age	-0.0003***	-0.0003***	-0.0003***	-0.0003***	-0.0004***	-0.0004***
	(6.30e-05)	(6.13e-05)	(6.25e-05)	(6.12e-05)	(6.15e-05)	(6.67e-05)
Employees (log)	0.0228***	0.0224***	0.0230***	0.0225***	0.0228***	0.0231***
	(0.00303)	(0.00290)	(0.00298)	(0.00290)	(0.00291)	(0.00311)
Occupational shortage	-0.0363***	-0.0264*	-0.0316***	-0.0232	-0.0232	-0.0309**
	(0.0128)	(0.0140)	(0.0110)	(0.0142)	(0.0141)	(0.0124)
Digital technology	0.170***	0.0465	0.201***	0.0957**	0.0247	0.0163***
	(0.0420)	(0.0468)	(0.0408)	(0.0478)	(0.0664)	(0.00411)
Occupational shortage X digital technology	-0.287***	-0.121	-0.274***	-0.0411	-0.170**	-0.0186***
	(0.0851)	(0.105)	(0.0935)	(0.0649)	(0.0802)	(0.00534)
Observations	1,106,487	1,142,249	1,128,495	1,149,976	1,151,662	1,080,849
R-squared	0.062	0.061	0.062	0.062	0.062	0.062

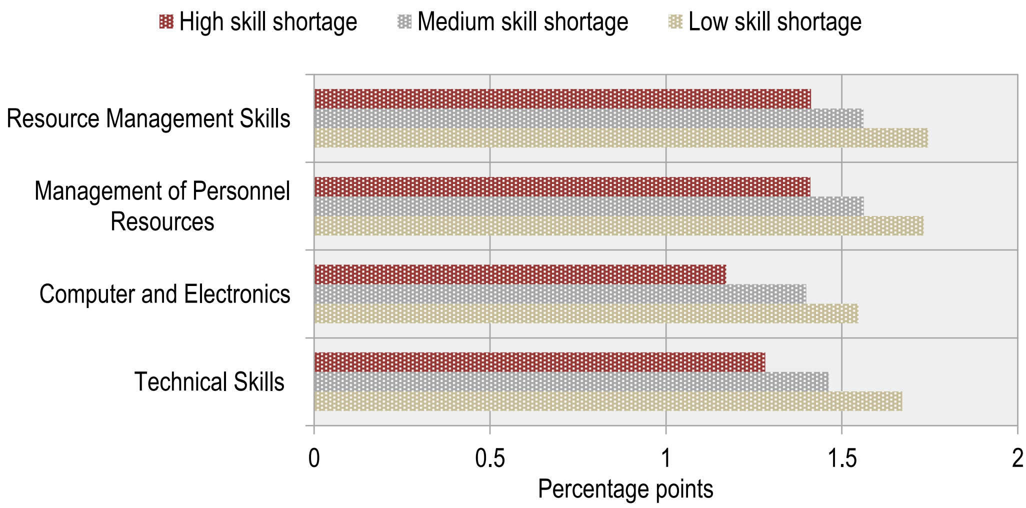
Note: This table reports the estimates of the baseline equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, the firm's gap to this frontier, age and size (measured by the number of employees), average country-sector level adoption rates of individual digital technologies, an index capturing sector-level general occupational shortages, and their interaction with the digital adoption variable. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. The last column shows results for the 1st principal component of the five technologies. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2011-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Figure 6. Skill shortages curb the returns from digitalisation

Panel A: Increase in MFP growth associated with a ten percentage point increase in the diffusion of digital technologies in the presence of general occupational shortages



Panel B: Increase in MFP growth associated with a ten percentage point increase in the diffusion of high-speed broadband, for specific skill shortages



Note: These figures show the ceteris paribus impact of a ten percentage point increase in the diffusion of high-speed broadband or customer relationship management in a labour market environment characterised by a low (25th percentile of the distribution), medium (median of the distribution) or high (75th percentile of the distribution) shortage in occupations (Panel A) or specific skills (Panel B). Calculations are based on estimates from Table 5 (Panel A) and Annex Table B5 (Panel B). Resource management skills capture the ability to allocate resources efficiently; management of personnel resources identifies how well managers motivate, develop and direct people as they work, and identify the best people for each job; computer and electronics refers to the knowledge of circuit boards, processors, chips, electronic equipment, computer hardware and software, including application and programming; and technical skills are associated with worker's capacity to design, set-up, operate and correct malfunctions, involving application of machines or technological systems. See OECD (2018[57]), for more information.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, OECD (2018[57]).

4.5. Which firms benefit most from adoption?

48. To study the link between digitalisation and productivity growth across the firm productivity distribution, we test two approaches (Table 6). First, we introduce dummy variables that divide the sample according to productivity quartiles in each industry, from lowest to highest initial productivity levels (columns 1 to 6).[21] Second, we interact digital adoption rates with the gap to the productivity frontier variable (column 7). The results of both approaches are consistent and strongly suggest that the positive association between sector-level diffusion of digital technologies and productivity growth is strongest for high productivity firms (or firms close to the frontier).[22]

49. For instance, if one assumes that the results are causal, the estimated productivity gains from raising adoption rates by 10 percentage points are more than doubled for high productivity relative to low productivity firms in the case of high-speed broadband and CRM (Figure 7). Interestingly, cloud computing is the only technology for which low-productivity firms tend to benefit more, consistent with the idea that it may be less demanding than other technologies (e.g. ERP and CRM) in terms of complementary investments in organisational capital.

[21] Given that these dummies could duplicate the information conveyed by the gap to frontier variable, we also ran the same regression omitting the gap. The results remained unchanged (see Annex Table B.7).

[22] For brevity, we only report results for the 1st principal component in the case of interaction with distance to the frontier. More detailed results can be found in Annex Table B.6. Results by productivity quartile for ERP are also robust to using lagged or initial adoption rates, suggesting that they are not primarily driven by reverse causality (Annex Table B.2).

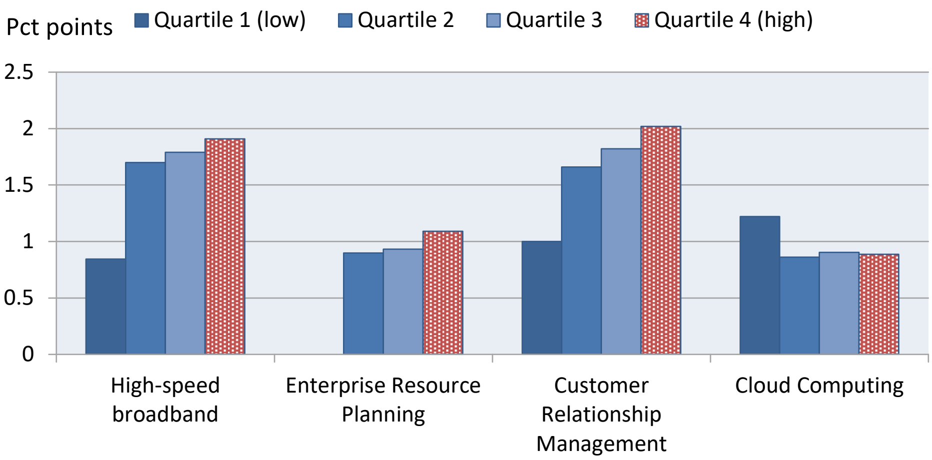
Table 6. The heterogeneous effects of digitalisation across productivity quartiles

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component	1st principal component
Frontier growth	0.206***	0.197***	0.203***	0.201***	0.216***	0.220***	0.235***
	(0.0388)	(0.0377)	(0.0382)	(0.0382)	(0.0387)	(0.0399)	(0.0394)
Gap to frontier (lagged)	0.0741***	0.0760***	0.0762***	0.0758***	0.0807***	0.0780***	0.108***
	(0.0197)	(0.0191)	(0.0195)	(0.0193)	(0.0205)	(0.0208)	(0.0120)
Age	-0.000***	-0.000***	-0.000***	-0.000***	-0.000***	-0.000***	-0.000***
	(4.96e-05)	(4.75e-05)	(4.86e-05)	(4.84e-05)	(4.89e-05)	(5.16e-05)	(5.94e-05)
Employees (log)	0.0198***	0.0197***	0.0202***	0.0198***	0.0212***	0.0216***	0.0235***
	(0.00185)	(0.00178)	(0.00183)	(0.00183)	(0.00193)	(0.00202)	(0.00288)
Quartile 2 (dummy)	-0.0636***	-0.0662***	-0.0577***	-0.0312**	-0.0331**	-0.0392***	
	(0.0124)	(0.0134)	(0.0148)	(0.0140)	(0.0135)	(0.0119)	
Quartile 3 (dummy)	-0.0704***	-0.0710***	-0.0672***	-0.0358*	-0.0363*	-0.0437**	
	(0.0183)	(0.0199)	(0.0215)	(0.0208)	(0.0207)	(0.0194)	
Quartile 4 (dummy)	-0.0852***	-0.0859***	-0.0841***	-0.0457	-0.0459	-0.0554*	
	(0.0263)	(0.0290)	(0.0304)	(0.0298)	(0.0298)	(0.0287)	
Digital technology (Quartile 1)	0.0845***	-0.00483	0.100**	0.122**	0.0668	0.0107**	
	(0.0326)	(0.0452)	(0.0444)	(0.0590)	(0.0741)	(0.00425)	
Digital technology (Quartile 2)	0.170***	0.0898**	0.166***	0.0862*	0.0373	0.0150***	
	(0.0332)	(0.0395)	(0.0330)	(0.0449)	(0.0606)	(0.00382)	
Digital technology (Quartile 3)	0.179***	0.0933**	0.182***	0.0905**	0.0478	0.0156***	
	(0.0358)	(0.0390)	(0.0315)	(0.0410)	(0.0555)	(0.00347)	
Digital technology (Quartile 4)	0.191***	0.109***	0.202***	0.0888**	0.0473	0.0164***	
	(0.0424)	(0.0386)	(0.0347)	(0.0422)	(0.0523)	(0.00365)	
Digital technology							0.0139***
							(0.00394)
Digital technology # gap to frontier (lagged)							-0.00763**
							(0.00323)
Observations	1,403,093	1,451,507	1,434,364	1,453,557	1,383,623	1,299,953	1,348,670
R-squared	0.062	0.062	0.062	0.061	0.062	0.063	0.065

Note: Colum 1-6 of this table show the results of the equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, the firm's gap to this frontier, age and size (measured by the number of employees), a dummy for each productivity quartile (omitting the first quartile for reference), and the interaction between digital technology adoption rates and a dummy for each productivity quartile. Quartile 1 refers to the bottom of the distribution (i.e. low productive firms), quartile 4 to the top. Alternatively, the last column displays results of the baseline equation augmented by an interaction term between digital technologies and the lagged gap to the frontier. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. In all cases, the coefficient estimates of quartile 1 and 4 are statistically different. The 1st principal component refers to the five technologies of column 1-5. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

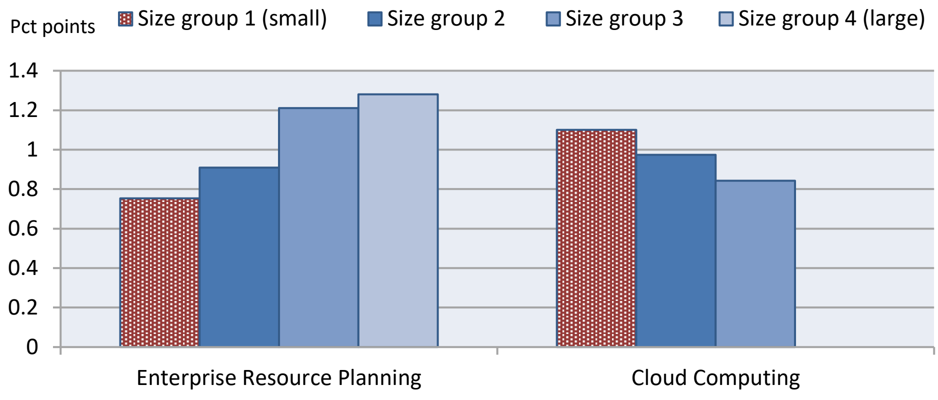
Figure 7. Highly productive firms benefit more from a digitalised environment



Note: This graph shows the ceteris paribus increase in multifactor productivity growth from increasing the diffusion of digital technologies by ten percentage points across different productivity quartiles. Quartile 1 refers to the bottom of the distribution (i.e. low productive firms), quartile 4 to the top of the distribution (i.e. high productive firms). Results for ERP for the least productive firms are not statistically significant. Calculations are based on estimates from Table 6, column 1-4.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

50. Regressions that differentiate firms by size suggest that size matters less than productivity in terms of gains from digital adoption (Figure 8 and Annex Table B.8). Interestingly, the effect of size depends on the technology. As expected, cloud computing has the strongest positive association with productivity performance for the smallest firms, which are for instance able to avoid the fixed costs of investing in data storage and processing facilities, which is a way to acquire "scale without mass" (Bloom and Pierri, 2018[17]). The opposite is found for Enterprise Resource Planning, which is most strongly associated with productivity improvements in the largest firms, due to the well-known economies of scope and scale characterising this technology. Confirming that productivity is the key determinant, crossing the size and productivity criteria shows that, independent of the technology, it is always the highest productivity firms that benefit most (Annex Table B.9).

Figure 8. Benefits from digital technologies also depend on firm size



Note: This graph shows the ceteris paribus increase in multifactor productivity growth from increasing the diffusion of digital technologies by ten percentage points across different size groups. Size group 1 captures firms with 10-20 employees, size group 2 firms with 21-50 employees, size group 3 firms with 51-250 employees, and size group 4 capture very large firms with more than 250 employees. Results for cloud computing for the largest firms are not significant. Calculations are based on estimates from Annex Table B.8.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

51. The finding that sector-level digital adoption is most closely associated with productivity increases in the best performing firms would point to an inherent tendency of digitalisation to increase productivity dispersion as digital technologies spread out. This is consistent with evidence pointing to a rising dispersion in productivity within narrowly-defined sectors (Syverson, 2011[2]) and a rising gap between productivity growth in the best firms and the rest, especially in highly digitalised sectors (Andrews, Criscuolo and Gal, 2016[10]; Berlingieri et al., 2017[8]). It is also in line with recent findings on the speed of catch-up of laggard firms, which is shown to be weaker in industries that rely more on ICT specialists (Berlingieri et al., 2018[11]).

52. A simple back-of-the-envelope calculation suggests that the simultaneous increase in the take-up of all five digital technologies considered in this paper could explain about 0.28-0.35 percentage point per year out of the 0.64 percentage point annual observed divergence in productivity between the top and bottom quartiles over 2010-15, i.e. about half of the total divergence.[23]

53. One potential explanation for the higher gains of high-productivity firms is that adopting digital technologies and exploiting them efficiently requires other endowments, such as managerial ability, know-how or technical skills. It is likely that these endowments are more present in high productivity firms than elsewhere. Consistent with this, additional regressions suggest that skills shortages at the industry level reduce the gains from digitalisation relatively more in less productive firms than in more productive ones,

[23] These results are obtained by using the estimated coefficients on the first principal component from Table 6 (last column) and combining average changes in adoption with the weight of each technology in the first principal component. The average adoption rates in 2010 (2015) are the following: for ERP, 25% (35%), for CRM, 31% (34%). For the other two variables where no data are available in 2010 – cloud computing and high speed broadband – we assumed zero prevalence, with 2015 values being 24% (cloud computing simple), 13% (cloud computing complex) and 35% (high speed broadband). For high-speed broadband, as alternative, we also assumed 20% in the initial year, leading to the two values that define the interval of the final result.

suggesting that it is relatively more difficult for less productive firms to attract workers with relevant skills (Annex Table B.10).

5. Conclusion

54. Our findings support the idea that the adoption of digital technologies is generally associated with substantially higher firm-level productivity. These results hold for a range of different technologies (high-speed broadband access, simple and complex cloud computing, CRM and ERP software). This association is stronger in manufacturing industries and more generally in industries that are intensive in routine tasks, suggesting that digital adoption can streamline production processes and to some extent act as a substitute for routine labour input.

55. The association between the adoption of digital technologies and productivity is also stronger for firms that are already highly productive, hence likely to benefit from complementary organisational and technical skills. This evidence is consistent with a potential for digitalisation to exacerbate dispersion in firm-level performance outcomes (Brynjolfsson and McAfee, 2011[61]). Compared to past innovation waves, gains from digital technologies may have been more difficult to capture for less productive firms, because these gains depend crucially on firm-specific intangible assets and skills (e.g. data, tacit knowledge, organisational capital) and complementary additional investments in these factors, which they are lacking. This is in line with recent evidence at the macroeconomic level that shows a slower diffusion of latest technologies within countries – even though their initial adoption across countries is now faster than in the past (Comin and Mestieri, 2018[62]).

56. This sheds some light on the so-called "modern productivity paradox". Overall gains from digitalisation may appear disappointing compared to past innovation waves or to the potential offered by these technologies since this potential, albeit important, is fully realised only by the most productive firms. A key question is the counterfactual scenario to which one compares current trends. Overall, our results suggest that current productivity growth is clearly stronger (especially among the more productive firms) than in a hypothetical scenario without digitalisation, but weaker than in a scenario where all firms would reap the full benefits from digital technologies.

57. While this finding contributes to explaining disappointing productivity growth, it does not explain by itself the broad-based productivity slowdown observed since the mid-2000s in OECD countries. This suggests either that a first, more significant wave of ICT adoption – leading to productivity gains in manufacturing and certain services such as distribution or finance, especially in the United States (Cette, Fernald and Mojon, 2016[63]; Van Ark, O'Mahony and Timmer, 2008[64]) – has run its course, or that other negative factors may have masked the productivity gains from digitalisation. For example, weakening business dynamism (Decker et al., 2016[65]; Calvino, Criscuolo and Verlhac, 2018[66]) and legacies of the global financial crisis (Adler et al., 2017[67]) have been drags on overall productivity growth.

58. More broadly, the ability of less productive firms to catch up has apparently diminished, resulting in an increasing dispersion in productivity outcomes (Andrews, Criscuolo and Gal, 2016[10]; Berlingieri et al., 2017[8]; Berlingieri et al., 2018[11]). As discussed in this paper, digitalisation is a factor that has contributed to this divergence – a back-of-the-envelope calculation suggests that it could have contributed to about half of the observed divergence between the top and bottom productivity quartiles in each industry over 2010-15. Our findings suggest that shortages in technical and managerial skills in an

industry tend to amplify this divergence, since they affect predominantly less productive firms.

59. Looking ahead, there is a risk that a wide and enduring productivity gap across firms is not only a reflection of weaker diffusion of innovation, business dynamism and potentially competition, but may in itself fuel a further weakening of these factors. For example, the most productive firms may become more difficult to challenge because they benefit from firm-specific intangible assets and can attract the most skilled workers. Andrews et al. (2016[10]) find that industries where productivity dispersion widens more also tend to have weaker aggregate productivity growth. Mounting evidence of rising mark-ups – especially in digitally intensive industries – and sector concentration (Calligaris, Criscuolo and Marcolin, 2018[68]; Bajgar et al., 2019[69]), as well as declining firm entry and exit rates (Calvino, Criscuolo and Menon, 2015[70]; Adalet McGowan, Andrews and Millot, 2017[71]) – again, especially in highly digitalised sectors (Calvino and Criscuolo, 2018[72]) – are consistent with this picture.

60. These findings raise challenges and opportunities for policies aimed at making the best of digital technologies. Policies encouraging digital adoption are warranted given the intrinsic potential of these technologies to support productivity, but should be accompanied by efforts to create the conditions enabling the catch-up of productivity laggards and the efficient reallocation of resources in the economy (Sorbe et al., 2019[20]). This includes smoothing the costs of the digital transition for displaced workers and maximising their reemployment potential.

61. As shown by Andrews et al. (2018[15]), both capabilities (e.g. enhancing managerial and digital-friendly skills) and incentives (e.g. reducing entry and exit barriers) are relevant to stimulate digital adoption. Moreover, certain drivers of digital adoption identified by Andrews et al. (2018[15]) are also likely to support the performance of lagging firms (e.g. widening the skill pool, improving access to financing, reducing entry barriers to certain markets). Enhancing skills is particularly important in this respect, as lagging firms are more affected by skill shortages than more productive firms. In addition, further efforts may be needed to ensure that large incumbents do not create barriers to the entry and growth of competitors and the diffusion of innovation in the economy (Berlingieri et al., 2018[11]).

62. Further research is needed to improve our understanding of the links between digital adoption and productivity. More specifically, two issues that were not covered in this paper due to data limitations would deserve further attention. First, better disentangling the benefits of within-firm digital adoption from the positive spillovers via adoption in other firms (a question this paper could only explore tentatively) would be useful. Second, it would be interesting to broaden the perspective to account for reallocation effects (does digital adoption enable more productive firms to grow faster than less productive ones?) as well as the propensity for entry and exit of firms in a more digitalised environment.

63. More broadly, the benefits of digitalisation could be assessed beyond the scope of firm productivity. Indeed, households and governments also likely benefit from the use of digital technologies, and from a more digitalised environment in general. There are probably important complementarities to be explored between digital adoption in firms, households and governments, as joint increases in adoption can facilitate interactions between them as well as skill upgrades.

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Annex A. Description of the data and variables used

Table A.1. Description of variables and sources

	Description	Coverage	Dimension used in analysis	Source	Link
Digital Technologies					
High-speed Broadband	Maximum contracted download speed of the fastest internet connection is at least 30 Mb/s (e_ispdf_ge30)	2014-2016	Sector, Country	Eurostat - Digital economy and society statistics - households and individuals	http://ec.europa.eu/eurostat/web/digital-economy-and-society/data/comprehensive-database
CC	Buy cloud computing services used over the internet (E_CC)	2014-2016	Sector, Country	Eurostat - Digital economy and society statistics - households and individuals	http://ec.europa.eu/eurostat/web/digital-economy-and-society/data/comprehensive-database
ERP	Enterprises who have ERP software package to share information between different functional areas (E_ERP1)	2010; 2012-15	Sector, Country, (Time)	Eurostat - Digital economy and society statistics - households and individuals	http://ec.europa.eu/eurostat/web/digital-economy-and-society/data/comprehensive-database
CRM	Enterprises using software solutions like Customer Relationship Management (CRM)	2010; 2014-2015	Sector, Country	Eurostat - Digital economy and society statistics - households and individuals	http://ec.europa.eu/eurostat/web/digital-economy-and-society/data/comprehensive-database
CC complex	Buy high CC services (accounting software applications, CRM software, computing power)(E_CC_HI)	2014-2016	Sector, Country	Eurostat - Digital economy and society statistics - households and individuals	http://ec.europa.eu/eurostat/web/digital-economy-and-society/data/comprehensive-database
SCM	Automatic linking of enterprises to their suppliers and/or customers application	2010-15	Sector, Country, Time	Eurostat - Digital economy and society statistics - households and individuals	http://ec.europa.eu/eurostat/web/digital-economy-and-society/data/comprehensive-database
Firm-level variables					
Frontier growth	Average growth of the top 5 percent firms in each sector-year cell	2009-2015	Sector, Time	ORBIS, based on Bureau van Dijk (BvD)	N.A.

Gap to frontier	Firms' lagged distance to the frontier	2009-2015	Firm, Sector, Country, Time	ORBIS, based on Bureau van Dijk (BvD)	N.A.
Age	Firms' age	2009-2015	Firm, Sector, Country, Time	ORBIS, based on Bureau van Dijk (BvD)	N.A.
Employees	Firms' number of employees (log)	2009-2015	Firm, Sector, Country, Time	ORBIS, based on Bureau van Dijk (BvD)	N.A.
Intangibles	Stock of intangible capital (log)	2009-2015	Firm, Sector, Country, Time	ORBIS, based on Bureau van Dijk (BvD)	N.A.
Capex	Capital expenditures (log)	2009-2015	Firm, Sector, Country, Time	ORBIS, based on Bureau van Dijk (BvD)	N.A.
Other					
Routine tasks	Routine content intensity (US)	2010-15	Sector	Marcolin et al. (2016), based on the OECD Programme for the International Assessment of Adult Competencies (PIAAC) and European Labour Force Survey (1995-2015).	
Knowledge Intensity	Share of labour compensation of personnel with tertiary education (US)	1995-2000	Sector	OECD (2013)	http://dx.doi.org/10.1787/9789264193307-en
Occupational shortages	General skill shortage	2011-15	Sector, Country	OECD, 2018	http://dx.doi.org/10.1787/9789264277878-en.
Resource management skills	Ability to allocate resources efficiently	2011-15	Sector, Country	OECD, 2018	http://dx.doi.org/10.1787/9789264277878-en.
Management of personnel resources	Ability of managers to motivate, develop and direct people as they work, and identify the best people for each job	2011-15	Sector, Country	OECD, 2018	http://dx.doi.org/10.1787/9789264277878-en.
Computer and electronics	Knowledge of circuit boards, processors, chips, electronic equipment, computer hardware and software, including application and programming	2011-15	Sector, Country	OECD, 2018	http://dx.doi.org/10.1787/9789264277878-en.
Technical skills	Worker's capacity to design, set-up, operate and correct malfunctions, involving application of machines or technological systems	2011-15	Sector, Country	OECD, 2018	http://dx.doi.org/10.1787/9789264277878-en.

Table A.2. Country coverage

Austria	Belgium	Denmark	Estonia	Finland
France	Germany	Greece	Hungary	Ireland
Italy	Latvia	Netherlands	Poland	Portugal
Slovenia	Spain	Sweden	Turkey	United Kingdom

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Table A.3. Average adoption rates by sector (2010-2016)

NACE Rev 2	Description	ERP	CRM	CC	CC (complex)
10-12	Manufacture of beverages, food and tobacco products	0.271245	0.188223	0.179248	0.099456
13-15	Manufacture of textiles, wearing apparel, leather and related products	0.308204	0.212234	0.181328	0.084579
16-18	Manufacture of wood & products of wood & cork, except furniture; articles of straw & plaiting materials; paper & paper products; printing & reproduction of recorded media	0.291412	0.26719	0.188538	0.090067
19-23	Manufacture of coke, refined petroleum, chemical & basic pharmaceutical products, rubber & plastics, other non-metallic mineral products	0.42955	0.326845	0.227648	0.112065
24-25	Manufacture of basic metals & fabricated metal products excluding machines & equipments	0.333373	0.248728	0.178942	0.080149
26	Manufacture of computer, electronic and optical products	0.556172	0.447013	0.278731	0.147594
27-28	Manufacture of electrical equipment, machinery and equipment n.e.c.	0.455789	0.352506	0.187869	0.086747
29-30	Manufacture of motor vehicles, trailers and semi-trailers, other transport equipment	0.501986	0.276797	0.212032	0.095408
31-33	Manufacture of furniture and other manufacturing; repair and installation of machinery and equipment	0.272652	0.228846	0.191396	0.094772
35_39	Electricity, gas, steam, air conditioning and water supply	0.341647	0.32225	0.259049	0.133773
41_43	Construction	0.156103	0.144789	0.199024	0.112612
45	Trade of motor vehicles and motorcycles	0.301579	0.427382	0.182405	0.115079
46	Wholesale trade, except of motor vehicles and motorcycles	0.402495	0.393588	0.235896	0.130059
47	Retail trade, except of motor vehicles and motorcycles	0.22922	0.238353	0.177975	0.103962
49_53	Transportation and storage	0.198024	0.203841	0.195679	0.103173
55_56	Accommodation and Food and beverage service activities	0.111989	0.16216	0.165641	0.104095
58-60	Publishing activities; motion picture, video & television programme production, sound recording & music publishing; programming & broadcasting	0.330037	0.42285	0.385612	0.247627
61	Telecommunications	0.480137	0.659599	0.389523	0.254364
62-63	Computer programming, consultancy and related activities, information service activities	0.445565	0.605442	0.555143	0.402173
68	Real estate activities	0.225138	0.284749	0.256101	0.153134
69-74	Professional, scientific and technical activities	0.256945	0.333358	0.337497	0.203696
77-82	Administrative and support service activities	0.199038	0.279514	0.250756	0.161046

Note: This table reports average adoption rates across industries for a set of 20 countries over the time period 2010-2016 (depending on data availability).
Source: based on Eurostat, Digital Economy and Society (database), http://ec.europa.eu/eurostat/web/digital-economy-and-society/data/comprehensivedatabase (accessed September 2017).

Table A.4. Correlations across digital technologies

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)
High-speed broadband	1				
Enterprise Resource Planning	0.152***	1			
Customer Relationship Management	0.3252***	0.5318***	1		
Cloud Computing	0.2312***	0.0744***	0.4108***	1	
Cloud Computing (complex)	0.1331***	0.0791***	0.4582***	0.762***	1

Note: ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively. Estimates are purged of country and industry fixed effects.

Table A.5. Principal Component Analysis

Panel A: Eigenvalue

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	3.05223	1.93051	0.6104	0.6104
Comp2	1.12172	0.547131	0.2243	0.8348
Comp3	0.574586	0.375566	0.1149	0.9497
Comp4	0.19902	0.146568	0.0398	0.9895
Comp5	0.0524514	.	0.0105	1

Panel B: Eigenvector

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)
1st principal component	0.4207	0.3088	0.4816	0.4917	0.5039

Note: ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.

Table A.6. The correlation between skill shortages and digital adoption

	Computer skills	Technical skills	Management of Personnel Resources	Resource Management skills
High-speed broadband	0.0645***	0.079***	0.0894***	0.0932***
Enterprise Resource Planning	-0.0807***	-0.0918**	-0.0602***	-0.0557***
Customer Relationship Management	-0.0484***	-0.0399***	-0.04***	-0.036***
Cloud Computing	0.0529***	0.0555***	0.0413***	0.0415***
Cloud Computing (complex)	0.0097***	-0.0096***	-0.023**	-0.0208***

Note: ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively. Estimates are purged of country and industry fixed effects.

Annex B. Additional regression results

Table B.1. Cross-sectional regression (2014-15)

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.0485	0.0543	0.0554	0.0626	0.0711	0.0598
	(0.0435)	(0.0431)	(0.0432)	(0.0442)	(0.0452)	(0.0453)
Gap to frontier (lagged)	0.102***	0.102***	0.103***	0.0995***	0.102***	0.102***
	(0.0126)	(0.0126)	(0.0126)	(0.0120)	(0.0121)	(0.0129)
Age	-0.000350***	-0.000357***	-0.000342***	-0.000315***	-0.000356***	-0.000358***
	(6.30e-05)	(6.22e-05)	(6.27e-05)	(5.79e-05)	(6.14e-05)	(6.53e-05)
Employees (log)	0.0202***	0.0203***	0.0205***	0.0195***	0.0208***	0.0211***
	(0.00287)	(0.00287)	(0.00287)	(0.00272)	(0.00274)	(0.00290)
Digital Technologies	0.175***	0.119***	0.195***	0.158***	0.0668	0.0167***
	(0.0454)	(0.0364)	(0.0327)	(0.0455)	(0.0494)	(0.00347)
Observations	470,813	474,425	476,635	476,480	467,091	443,077
R-squared	0.059	0.059	0.060	0.057	0.058	0.059

Note: This table reports the estimates of the baseline equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, the firm's gap to this frontier, age and size (measured by the number of employees), and the average country-sector level adoption rates of individual digital technologies. The last column shows results for the 1st principal component of the five technologies. Firms at the sector-year frontier are excluded from the regressions. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2014-15 for firms with more than 10 employees. Unweighted averages of each digital technology variable are used over the period 2014-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.

Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table B.2. Robustness to endogeneity concerns

Dependent variable: MFP growth
Digital technology: ERP software

	Lagged adoption rate	Initial (2010) adoption rate	Lagged adoption rate (by prod. quartile)	Initial adoption rate (by prod. quartile)
Frontier growth	0.118**	0.124***	0.109**	0.110***
	(0.0500)	(0.0352)	(0.0495)	(0.0351)
Gap to frontier (lagged)	0.0931***	0.0990***	0.0723***	0.0725***
	(0.00508)	(0.0116)	(0.00871)	(0.0191)
Age	-0.000341***	-0.000335***	-0.000324***	-0.000324***
	(3.29e-05)	(5.88e-05)	(3.04e-05)	(5.13e-05)
Employees (log)	0.0170***	0.0199***	0.0180***	0.0179***
	(0.00119)	(0.00261)	(0.000908)	(0.00171)
ERP	0.0410**	0.0479**		
	(0.0197)	(0.0228)		
Quartile 2 (dummy)			-0.0608***	-0.0585***
			(0.00630)	(0.0126)
Quartile 3 (dummy)			-0.0659***	-0.0627***
			(0.00930)	(0.0192)
Quartile 4 (dummy)			-0.0799***	-0.0744***
			(0.0133)	(0.0281)
ERP (Quartile 1)			-0.0424*	-0.0330
			(0.0248)	(0.0305)
ERP (Quartile 2)			0.0438**	0.0574**
			(0.0214)	(0.0232)
ERP (Quartile 3)			0.0529***	0.0644**
			(0.0205)	(0.0251)
ERP (Quartile 4)			0.0698***	0.0746***
			(0.0200)	(0.0265)
Observations	1,182,855	1,226,046	1,182,855	1,184,608
R-squared	0.055	0.058	0.058	0.057

Note: This table reports estimates of the baseline equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, the firm's gap to this frontier, age and size (measured by the number of employees) and a digital adoption variable. The adoption variable in this table always relates to ERP software (time variation not being available for the other variables in the sample). Results are presented for the the adoption rate lagged by one year (column 1) and the initial adoption rate in the sample (year 2010, column 2). In the last two columns, the digital adoption variable is interacted with a dummy for each productivity quartile, as in Table 6. All regressions include sector and country-year fixed effects and are clustered at the country-sector level (except columns 1 and 3, which are clustered at the country-industry-year level since the digital variable varies at this level in these cases). Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table B.3. Replacing routine intensity with knowledge intensity

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.222***	0.212***	0.218***	0.213***	0.230***	0.235***
	(0.0382)	(0.0374)	(0.0379)	(0.0373)	(0.0381)	(0.0392)
Gap to frontier (lagged)	0.104***	0.104***	0.105***	0.104***	0.107***	0.108***
	(0.0118)	(0.0114)	(0.0117)	(0.0115)	(0.0118)	(0.0127)
Age	-0.000304***	-0.000306***	-0.000295***	-0.000303***	-0.000372***	-0.000373***
	(5.89e-05)	(5.49e-05)	(5.86e-05)	(5.63e-05)	(5.75e-05)	(6.24e-05)
Employees (log)	0.0216***	0.0216***	0.0221***	0.0218***	0.0233***	0.0235***
	(0.00275)	(0.00267)	(0.00274)	(0.00269)	(0.00277)	(0.00297)
Digital technology	0.114*	0.121*	0.282***	0.202***	0.113	0.0309***
	(0.0642)	(0.0719)	(0.0625)	(0.0708)	(0.134)	(0.00633)
Digital technology # knowledge intensity	0.0476	-0.0554	-0.234*	-0.232**	-0.121	-0.0263***
	(0.0920)	(0.144)	(0.129)	(0.109)	(0.199)	(0.00892)
Observations	1,453,519	1,503,462	1,485,781	1,505,867	1,435,145	1,348,670
R-squared	0.062	0.062	0.063	0.062	0.064	0.064

Note: This table reports estimates of the baseline equation augmented with an interaction between digital technologies and knowledge intensity, defined as the share of labour compensation of personnel with tertiary education (see Annex A). All regressions include sector and country-year fixed effects and are clustered at the country-sector level. The last column shows results for the 1st principal component of the five technologies. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15 and routine intensity refers to the average over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table B.4. Baseline estimates controlling for additional variables

Panel A: controlling for intangible capital

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.220***	0.211***	0.218***	0.214***	0.231***	0.238***
	(0.0384)	(0.0373)	(0.0378)	(0.0377)	(0.0383)	(0.0394)
Gap to frontier (lagged)	0.103***	0.103***	0.104***	0.103***	0.107***	0.107***
	(0.0131)	(0.0127)	(0.0129)	(0.0127)	(0.0132)	(0.0140)
Age	-0.000292***	-0.000292***	-0.000279***	-0.000291***	-0.000358***	-0.000358***
	(6.21e-05)	(5.83e-05)	(6.11e-05)	(5.98e-05)	(6.12e-05)	(6.63e-05)
Employees (log)	0.0198***	0.0198***	0.0201***	0.0198***	0.0218***	0.0221***
	(0.00289)	(0.00279)	(0.00285)	(0.00281)	(0.00288)	(0.00307)
Digital technology	0.139***	0.111***	0.172***	0.0795*	0.0404	0.0161***
	(0.0342)	(0.0371)	(0.0349)	(0.0427)	(0.0542)	(0.00382)
Intangible capital stock (log)	0.00159***	0.00155***	0.00154***	0.00165***	0.00148***	0.00136***
	(0.000413)	(0.000402)	(0.000404)	(0.000404)	(0.000437)	(0.000457)
Observations	1,229,670	1,269,595	1,255,462	1,270,278	1,203,570	1,136,071
R-squared	0.062	0.062	0.062	0.062	0.064	0.064

Panel B: controlling for capital expenditures

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.201***	0.195***	0.201***	0.198***	0.216***	0.219***
	(0.0433)	(0.0420)	(0.0424)	(0.0426)	(0.0430)	(0.0441)
Gap to frontier (lagged)	0.102***	0.102***	0.103***	0.102***	0.106***	0.106***
	(0.0138)	(0.0135)	(0.0138)	(0.0135)	(0.0139)	(0.0147)
Age	-0.000399***	-0.000392***	-0.000383***	-0.000395***	-0.000494***	-0.000495***
	(7.94e-05)	(7.55e-05)	(7.83e-05)	(7.71e-05)	(8.20e-05)	(8.79e-05)
Employees (log)	0.0183***	0.0181***	0.0186***	0.0181***	0.0198***	0.0200***
	(0.00269)	(0.00261)	(0.00267)	(0.00264)	(0.00270)	(0.00284)
Capital expenditures (log)	0.00207***	0.00220***	0.00214***	0.00226***	0.00240***	0.00225***
	(0.000651)	(0.000632)	(0.000638)	(0.000641)	(0.000679)	(0.000698)
Digital technology	0.137***	0.110***	0.182***	0.0638	0.0137	0.0149***
	(0.0392)	(0.0401)	(0.0359)	(0.0473)	(0.0651)	(0.00404)
Observations	512,728	528,586	523,247	528,936	497,239	470,143
R-squared	0.065	0.065	0.066	0.065	0.068	0.068

Panel C: controlling for omitted variables bias

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.169***	0.152***	0.161***	0.161***	0.163***	0.171***
	(0.0436)	(0.0432)	(0.0430)	(0.0436)	(0.0437)	(0.0444)
Gap to frontier (lagged)	0.102***	0.102***	0.103***	0.102***	0.103***	0.103***
	(0.0166)	(0.0162)	(0.0166)	(0.0162)	(0.0162)	(0.0171)
Age	-0.000492***	-0.000473***	-0.000479***	-0.000482***	-0.000501***	-0.000502***
	(9.56e-05)	(9.35e-05)	(9.53e-05)	(9.27e-05)	(9.44e-05)	(0.000101)
Employees (log)	0.0213***	0.0210***	0.0216***	0.0211***	0.0217***	0.0216***
	(0.00329)	(0.00325)	(0.00335)	(0.00325)	(0.00322)	(0.00341)
Regulatory impact	0.0114	0.0132	0.0303	0.0471	0.0224	0.0397
	(0.0454)	(0.0485)	(0.0424)	(0.0530)	(0.0503)	(0.0484)
Occupational shortage	-0.0353***	-0.0311**	-0.0266**	-0.0344**	-0.0318**	-0.0333**
	(0.0132)	(0.0136)	(0.0127)	(0.0138)	(0.0143)	(0.0132)
Capex (log)	0.00164**	0.00175**	0.00167**	0.00178**	0.00176**	0.00170**
	(0.000767)	(0.000748)	(0.000756)	(0.000751)	(0.000754)	(0.000785)
Digital Technology	0.164***	0.0695	0.214***	0.0861*	-0.0458	0.0162***
	(0.0533)	(0.0508)	(0.0510)	(0.0487)	(0.0848)	(0.00494)
Observations	343,890	352,794	348,719	355,672	354,379	335,739
R-squared	0.067	0.067	0.068	0.067	0.067	0.067

Note: These tables report estimates of the baseline equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, the firm's gap to this frontier, age and size (measured by the number of employees), augmented with the firm-level stock of intangible capital (Panel A), firm-level capital expenditures (Panel B), or a set of control variable accounting for the potential omitted variables bias (i.e. impact of regulatory barriers to competition, firm-level capital expenditures, and occupational shortages). The indicator of regulatory impact quantifies the potential costs of anti-competitive regulations in non-manufacturing sectors on all industries the United States that use the output of these sectors as intermediate inputs (see Égert and Wanner, 2016). The 1st principal component is based on the five technologies of column 1-5. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database and the OECD Indicators of Product Market Regulations.

Table B.5. Digital technology productivity benefits are diminished by technical and managerial skill shortages

Panel A: Testing for the effect of different skill shortages on the returns from high speed broadband

Dependent variable: MFP growth	Resource Management Skills	Management of Personnel Resources	Computers and Electronics	Technical Skills
Frontier growth	0.159***	0.160***	0.155***	0.152***
	(0.0372)	(0.0373)	(0.0368)	(0.0369)
Gap to frontier (lagged)	0.105***	0.105***	0.105***	0.105***
	(0.0133)	(0.0133)	(0.0132)	(0.0132)
Age	-0.000392***	-0.000392***	-0.000393***	-0.000394***
	(6.31e-05)	(6.31e-05)	(6.32e-05)	(6.30e-05)
Employees (log)	0.0227***	0.0227***	0.0227***	0.0227***
	(0.00303)	(0.00303)	(0.00303)	(0.00301)
High-speed broadband	0.164***	0.164***	0.149***	0.151***
	(0.0435)	(0.0429)	(0.0446)	(0.0443)
Skill shortage	-0.273***	-0.227***	-0.197***	-0.339***
	(0.0724)	(0.0597)	(0.0539)	(0.124)
Skill shortage # High-speed broadband	-1.020**	-0.898**	-0.705**	-2.236***
	(0.435)	(0.371)	(0.318)	(0.645)
Observations	1,106,487	1,106,487	1,106,487	1,106,487
R-squared	0.062	0.062	0.062	0.062

Panel B: The role of knowledge about computers and electronics for productivity returns

Dependent variable: MFP growth	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.155***	0.134***	0.145***	0.142***	0.142***	0.152***
	(0.0368)	(0.0374)	(0.0369)	(0.0376)	(0.0374)	(0.0374)
Gap to frontier (lagged)	0.105***	0.104***	0.106***	0.105***	0.105***	0.106***
	(0.0132)	(0.0126)	(0.0130)	(0.0126)	(0.0126)	(0.0135)
Age	-0.0003***	-0.0003***	-0.0003***	-0.0003***	-0.0004***	-0.0004***
	(6.32e-05)	(6.16e-05)	(6.27e-05)	(6.12e-05)	(6.15e-05)	(6.69e-05)
Employees (log)	0.0227***	0.0224***	0.0230***	0.0226***	0.0229***	0.0231***
	(0.00303)	(0.00289)	(0.00298)	(0.00289)	(0.00290)	(0.00310)
Digital Technology	0.149***	0.0584	0.195***	0.103**	0.0252	0.0166***
	(0.0446)	(0.0438)	(0.0406)	(0.0436)	(0.0668)	(0.00419)
Computers and electronics skill shortage	-0.197***	-0.180***	-0.164***	-0.186***	-0.169***	-0.176***
	(0.0539)	(0.0581)	(0.0508)	(0.0656)	(0.0635)	(0.0611)
Computers and electronics skill shortage #Digital Technology	-0.705**	0.141	-0.689*	0.0250	-0.287	-0.0363**
	(0.318)	(0.360)	(0.352)	(0.202)	(0.244)	(0.0163)
Observations	1,106,487	1,142,249	1,128,495	1,149,976	1,151,662	1,080,849
R-squared	0.062	0.062	0.062	0.062	0.062	0.062

Note: These tables reports the estimates of the baseline equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, the firm's gap to this frontier, age and size (measured by the number of employees), average country-sector level adoption rates of individual digital technologies, an index capturing sector-level skill shortages, and their effect on the productivity returns from digitalisation. *Resource management skills* refer the ability to allocate resources efficiently; *management of personnel resources* identifies how well managers motivate, develop and direct people as they work, and identify the best people for each job; *computer and electronics* refers to the knowledge of circuit boards, processors, chips, electronic equipment, computer hardware and software, including application and programming; and *technical skills* are associated with worker's capacity to design, set-up, operate and correct malfunctions, involving application of machines or technological systems (see OECD (2018[57]), for more information). Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2011-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.

Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table B.6. Interacting lagged gap with digital technologies

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.222***	0.211***	0.215***	0.215***	0.229***	0.235***
	(0.0382)	(0.0375)	(0.0382)	(0.0372)	(0.0381)	(0.0394)
Gap to frontier (lagged)	0.104***	0.103***	0.103***	0.106***	0.107***	0.108***
	(0.0114)	(0.0111)	(0.0113)	(0.00992)	(0.0116)	(0.0120)
Age	-0.000301***	-0.000308***	-0.000289***	-0.000294***	-0.000366***	-0.000355***
	(6.42e-05)	(5.45e-05)	(5.59e-05)	(5.42e-05)	(5.57e-05)	(5.94e-05)
Employees (log)	0.0216***	0.0214***	0.0219***	0.0222***	0.0234***	0.0235***
	(0.00273)	(0.00262)	(0.00268)	(0.00246)	(0.00272)	(0.00288)
Digital technology	0.149***	0.0761*	0.157***	0.0757*	0.0155	0.0139***
	(0.0425)	(0.0416)	(0.0361)	(0.0434)	(0.0593)	(0.00394)
Digital technology # Lagged gap	-0.0192	-0.0827**	-0.0933**	-0.0853	-0.0816	-0.00763**
	(0.0494)	(0.0378)	(0.0393)	(0.0523)	(0.0652)	(0.00323)
Observations	1,453,519	1,503,462	1,485,781	1,505,867	1,435,145	1,348,670
R-squared	0.062	0.063	0.064	0.063	0.064	0.065

Note: This table shows the results of the baseline equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, the firm's gap to this frontier, age and size (measured by the number of employees), augmented by an interaction term between digital technologies and the lagged gap to the frontier. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. The 1st principal component refers to the five technologies of column 1-5. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table B.7. By productivity quartile without gap

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.174***	0.164***	0.170***	0.168***	0.181***	0.186***
	(0.0367)	(0.0358)	(0.0363)	(0.0363)	(0.0372)	(0.0384)
Age	-0.000309***	-0.000326***	-0.000312***	-0.000323***	-0.000398***	-0.000388***
	(4.75e-05)	(4.72e-05)	(4.75e-05)	(4.73e-05)	(4.75e-05)	(5.02e-05)
Employees (log)	0.0178***	0.0176***	0.0180***	0.0177***	0.0188***	0.0192***
	(0.00141)	(0.00136)	(0.00138)	(0.00140)	(0.00147)	(0.00154)
Quartile 2 (dummy)	-0.110***	-0.115***	-0.108***	-0.0767***	-0.0827***	-0.0879***
	(0.00934)	(0.00779)	(0.00887)	(0.00682)	(0.00650)	(0.00492)
Quartile 3 (dummy)	-0.143***	-0.144***	-0.142***	-0.109***	-0.116***	-0.123***
	(0.0113)	(0.0106)	(0.0114)	(0.00819)	(0.00786)	(0.00610)
Quartile 4 (dummy)	-0.207***	-0.210***	-0.208***	-0.170***	-0.178***	-0.186***
	(0.0139)	(0.0143)	(0.0153)	(0.0111)	(0.0105)	(0.00803)
Digital (Quartile 1)	0.0694**	-0.0275	0.0780*	0.146***	0.108	0.00981**
	(0.0300)	(0.0412)	(0.0410)	(0.0531)	(0.0681)	(0.00387)
Digital (Quartile 2)	0.155***	0.0699*	0.154***	0.102**	0.0709	0.0142***
	(0.0305)	(0.0366)	(0.0316)	(0.0427)	(0.0585)	(0.00354)
Digital (Quartile 3)	0.155***	0.0559	0.152***	0.0962**	0.0673	0.0136***
	(0.0323)	(0.0347)	(0.0282)	(0.0396)	(0.0538)	(0.00311)
Digital (Quartile 4)	0.161***	0.0701**	0.165***	0.0914**	0.0593	0.0140***
	(0.0358)	(0.0336)	(0.0297)	(0.0401)	(0.0507)	(0.00314)
Observations	1,419,356	1,468,278	1,450,888	1,470,164	1,398,222	1,313,619
R-squared	0.057	0.056	0.057	0.056	0.056	0.057

Note: This table shows the results of the equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, age and size (measured by the number of employees), a dummy for each productivity quartile (omitting the first quartile for reference), and the interaction between digital technology adoption rates and each productivity quartile. Compared with the baseline equation the gap to the frontier is omitted from this regression. Quartile 1 refers to the bottom of the distribution (i.e. low productive firms), quartile 4 to the top. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. The coefficient estimates of quartile 1 and 4 are always statistically different. The 1st principal component refers to the five technologies of column 1-5. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent $p<0.01$, $p<0.05$ and $p<0.1$ respectively.

Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table B.8. The effects of digital adoption on productivity by size group

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.222***	0.211***	0.218***	0.215***	0.229***	0.236***
	(0.0383)	(0.0373)	(0.0378)	(0.0376)	(0.0381)	(0.0393)
Gap to frontier (lagged)	0.103***	0.103***	0.104***	0.103***	0.106***	0.107***
	(0.0116)	(0.0112)	(0.0115)	(0.0112)	(0.0116)	(0.0124)
Age	-0.000283***	-0.000288***	-0.000269***	-0.000281***	-0.000348***	-0.000346***
	(5.89e-05)	(5.57e-05)	(5.82e-05)	(5.71e-05)	(5.79e-05)	(6.30e-05)
Size class 2 (dummy)	0.0157***	0.0133***	0.0159***	0.0206***	0.0212***	0.0186***
	(0.00343)	(0.00424)	(0.00398)	(0.00349)	(0.00316)	(0.00275)
Size class 3 (dummy)	0.0490***	0.0318***	0.0451***	0.0516***	0.0558***	0.0486***
	(0.00727)	(0.00776)	(0.00800)	(0.00696)	(0.00656)	(0.00576)
Size class 4 (dummy)	0.0756***	0.0517***	0.0735***	0.0844***	0.0836***	0.0716***
	(0.00920)	(0.00831)	(0.00925)	(0.00927)	(0.00816)	(0.00724)
Digital (Size class 1)	0.142***	0.0753*	0.184***	0.110**	0.0906	0.0172***
	(0.0343)	(0.0425)	(0.0365)	(0.0463)	(0.0600)	(0.00409)
Digital (Size class 2)	0.149***	0.0909**	0.191***	0.0974**	0.0658	0.0169***
	(0.0347)	(0.0411)	(0.0347)	(0.0444)	(0.0559)	(0.00392)
Digital (Size class 3)	0.128***	0.121***	0.188***	0.0842*	0.0191	0.0156***
	(0.0359)	(0.0370)	(0.0351)	(0.0447)	(0.0572)	(0.00387)
Digital (Size class 4)	0.113***	0.128***	0.167***	0.0349	-0.0278	0.0126***
	(0.0385)	(0.0375)	(0.0360)	(0.0439)	(0.0565)	(0.00382)
Observations	1,453,519	1,503,462	1,485,781	1,505,867	1,435,145	1,348,670
R-squared	0.062	0.062	0.063	0.062	0.064	0.064

Note: This table shows the results of the equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, age and size (measured by the number of employees), a dummy for each size group (omitting the first group for reference), and the interaction between digital technology adoption rates and each size group. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. Compared with the baseline equation the gap to the frontier is omitted from this regression. Size group 1 captures firms with 10-20 employees, size group 2 firms from 21-50 employees, size group 3 firms with 51-250 employees, and size group 4 capture very large firms with more than 250 employees. In all cases, the coefficient estimates of size group 1 and 4 are statistically different. The 1st principal component refers to the five technologies of column 1-5. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.

Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table B.9. The effects of digital adoption on productivity by productivity quartile and size group

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.220***	0.205***	0.213***	0.210***	0.224***	0.231***
	(0.0391)	(0.0393)	(0.0400)	(0.0402)	(0.0404)	(0.0409)
Gap to frontier (lagged)	0.0985***	0.102***	0.102***	0.102***	0.107***	0.104***
	(0.0253)	(0.0251)	(0.0252)	(0.0248)	(0.0263)	(0.0270)
Age	-0.000503***	-0.000554***	-0.000518***	-0.000541***	-0.000684***	-0.000666***
	(9.24e-05)	(8.72e-05)	(8.91e-05)	(9.02e-05)	(9.46e-05)	(0.000101)
Employees (log)	0.00851***	0.00813***	0.00849***	0.00829***	0.0107***	0.0105***
	(0.00281)	(0.00266)	(0.00279)	(0.00280)	(0.00308)	(0.00312)
Dummy (High productive; Small)	-0.0650*	-0.0724*	-0.0817**	-0.0221	-0.0241	-0.0245
	(0.0352)	(0.0388)	(0.0389)	(0.0367)	(0.0367)	(0.0363)
Dummy (Low productive; Large)	0.113***	0.0720***	0.109***	0.122***	0.119***	0.0852***
	(0.0148)	(0.0174)	(0.0154)	(0.0122)	(0.0116)	(0.00720)
Dummy (High productive; Large)	-0.00980	-0.0287	-0.0156	0.0227	0.0213	0.0139
	(0.0337)	(0.0345)	(0.0366)	(0.0361)	(0.0364)	(0.0358)
Digital technology (Low productive; Small)	0.126***	0.0236	0.0965**	0.0277	0.0165	0.00789
	(0.0339)	(0.0514)	(0.0456)	(0.0758)	(0.0793)	(0.00490)
Digital technology (High productive; Small)	0.279***	0.205***	0.299***	0.0350	0.0898	0.0193***
	(0.0673)	(0.0573)	(0.0522)	(0.0624)	(0.0658)	(0.00468)
Digital technology (Low productive; Large)	0.0352	0.0706	0.0110	-0.134	-0.316**	-0.00413
	(0.0501)	(0.0811)	(0.0719)	(0.0985)	(0.137)	(0.00639)
Digital technology (High productive; Large)	0.216***	0.185***	0.210***	0.00977	-0.00122	0.0137***
	(0.0553)	(0.0455)	(0.0440)	(0.0565)	(0.0598)	(0.00448)
Observations	292,650	307,626	301,775	309,532	297,656	272,312
R-squared	0.083	0.084	0.084	0.082	0.084	0.085

Note: This table shows the results of the equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, age and size (measured by the number of employees), a dummy for each four different size/productivity groups (low productive and small; high productive and small; low productive and large; high productive and large),omitting the first group for reference, and the interaction between digital technology adoption rates and each group. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. The 1st principal component refers to the five technologies of column 1-5. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Table B.10. Skill shortages disproportionately curb the returns from digitalisation in low productive firms

Dependent variable: MFP growth

	High-speed broadband	Enterprise Resource Planning	Customer Relationship Management	Cloud Computing	Cloud Computing (complex)	1st principal component
Frontier growth	0.136***	0.115***	0.125***	0.117***	0.119***	0.125***
	(0.0366)	(0.0372)	(0.0366)	(0.0370)	(0.0371)	(0.0385)
Gap to frontier (lagged)	0.0777***	0.0777***	0.0788***	0.0788***	0.0795***	0.0770***
	(0.0217)	(0.0206)	(0.0212)	(0.0209)	(0.0211)	(0.0216)
Age	-0.000355***	-0.000374***	-0.000366***	-0.000371***	-0.000387***	-0.000386***
	(5.09e-05)	(5.12e-05)	(5.09e-05)	(4.98e-05)	(5.08e-05)	(5.50e-05)
Employees (log)	0.0207***	0.0200***	0.0208***	0.0201***	0.0205***	0.0212***
	(0.00194)	(0.00186)	(0.00190)	(0.00183)	(0.00191)	(0.00203)
Digital (Quartile 1)	0.0969***	-0.0717	0.121**	0.168**	0.140	0.00602
	(0.0364)	(0.0519)	(0.0537)	(0.0695)	(0.108)	(0.00515)
Digital (Quartile 2)	0.208***	0.0470	0.201***	0.0839*	0.0336	0.0144***
	(0.0375)	(0.0448)	(0.0373)	(0.0464)	(0.0696)	(0.00407)
Digital (Quartile 3)	0.208***	0.0433	0.204***	0.0804*	0.0247	0.0157***
	(0.0425)	(0.0441)	(0.0377)	(0.0440)	(0.0660)	(0.00391)
Digital (Quartile 4)	0.239***	0.0648	0.234***	0.0961**	0.0519	0.0180***
	(0.0534)	(0.0431)	(0.0430)	(0.0471)	(0.0724)	(0.00432)
Digital (Quartile 1) X Occupation shortage	-0.269***	-0.153*	-0.213**	-0.307***	-0.581**	-0.00877
	(0.0730)	(0.0870)	(0.0912)	(0.116)	(0.244)	(0.0141)
Digital (Quartile 2) X Occupation shortage	-0.215***	-0.174***	-0.187***	-0.155***	-0.334***	-0.0210**
	(0.0401)	(0.0424)	(0.0356)	(0.0443)	(0.0890)	(0.00815)
Digital (Quartile 3) X Occupation shortage	-0.102**	-0.0461	-0.0451	-0.0327	-0.116	-0.0177***
	(0.0404)	(0.0494)	(0.0481)	(0.0587)	(0.105)	(0.00660)
Digital (Quartile 4) X Occupation shortage	0.0854	0.0933	0.122*	0.142*	0.239	-0.0160
	(0.0535)	(0.0674)	(0.0682)	(0.0794)	(0.146)	(0.0120)
Observations	1,067,412	1,102,176	1,088,798	1,109,472	1,110,981	1,042,252
R-squared	0.063	0.062	0.062	0.061	0.061	0.061

Note: This table shows the results of the equation where firm-level multifactor productivity growth is regressed on growth of the top 5 percent frontier firms in each sector-year cell, age and size (measured by the number of employees), an interaction between each productivity quartile and digital technologies, and the interaction between the latter and occupational shortages. Quartile 1 refers to the bottom of the distribution (i.e. low productive firms), quartile 4 to the top. All regressions include sector and country-year fixed effects and are clustered at the country-sector level. The 1st principal component refers to the five technologies of column 1-5. Firms at the sector-year frontier are excluded from the regressions. Regressions are based on firm-level data from 20 countries and 22 sectors (NACE Rev 2, 10-82) over the period 2010-15 for firms with more than 10 employees. To maximise coverage, unweighted averages of each digital technology variable are used over the period 2010-15. ***, ** and * represent p<0.01, p<0.05 and p<0.1 respectively.
Source: OECD calculations based on ORBIS and Eurostat, Digital Economy and Society Statistics, comprehensive database.

Annex C. Literature review

Focus	Author and year	Title	Measure of ICT	Time	Country coverage	Main source of data	Main finding
US-studies	(Brynjolffson, 1996[73])	Paradox Lost? Firm-level Evidence on the Returns to Information Systems Spending	Computer Capital; Information System Staff	1987-1991;	United States	Firm level data; International Data Group (IDG) annual survey of IT spending; Compustat.	IT capital and labour are significantly related to output, and their marginal products are larger than their non-IT counterparts. (Black, 2001[74])
US-studies	(Brynjolfsson and Hitt, 2000[26])	Computing Productivity: Firm-Level Evidence,	Computer equipment	1987-1994;	United States	Firm-level data; Computer Intelligence InfoCorp (CII), Compustat.	IT capital makes a significant contribution to productivity and output growth in the short run (1 year lag), but the contribution is five times larger in the long run (5-7 years lag).
US-studies	(Black, 2001[74])	How to Compete. The impact of Workplace Practices and Information Technology on Productivity	Share of workers using computers	1987-1993	United States	Plant-level data; Bureau of the Census' Longitudinal Research Database (LRD)	The greater the proportion of non-managerial workers using computers, the higher plant productivity.
US-studies	(Hunton, Lippincott and Reck, 2003[43])	Enterprise resource planning systems: comparing firm performance of adopters and non-adopters	Enterprise Resource Planning (ERP)	1990-1998	United States	Firm-level data; Compustat; Hayes DC,	Return on assets (ROA), return on investment (ROI), and asset turnover (ATO) were significantly better over a 3-year period for adopters, as compared to nonadopters.
US-studies	(Nicolau, 2005[75])	Organizational performance effects of ERP systems usage: The impact of post-implementation changes	Enterprise Resource Planning (ERP)	2004	United States	Firm-level data; Lexis/Nexis database	Subsequent changes in ERP systems often help resolve or surface implementation issues that affect subsequent use of and success from the use of such systems. Specific findings indicate that ERP-adopting firms, which initiate early enhancements in the form of either add-ons or upgrades, may enjoy superior differential financial performance in comparison to other ERP-adopting firms' differential performance.
US-studies	(Aral, Brynjolfsson and Wu, 2006[38])	"Which Came First, IT or Productivity? Virtuous Cycle of Investment and Use in Enterprise Systems"	Enterprise Resource Planning (ERP), Customer Relationship Management Systens (CRM), Supply Chain Management Systems (SCM).	1998-2005;	United States	Firm-level data; HCM vendor data; Compustat	Firms that successfully implement IT, react by investing in more IT. Our work suggests replacing either-or views of causality with a positive feedback loop conceptualization in which successful IT investments initiate a virtuous cycle of investment and gain

US-studies	(Bartel, Ichniowski and Shaw, 2007[24])	How Does Information Technology Affect Productivity? Plant-Level Comparisons ofProduct Innovation, Process Improvement, and Worker Skills	IT equipment various measures, e.g. number of computer numerically controlled machines)	1999-2003	United States	Specific survey on valve-making plants	New IT investments improve the efficiency of all stages of the production process by reducing setup times, run times, and inspection times. Adoption of new IT-enhanced capital equipment coincides with increases in the skill requirements of machine operators, notably technical and problem-solving skills, and with the adoption of new human resource practices to support these skills.
US-studies	(Aral, Brynjolfsson and Wu, 2012[29])	Three-Way Complementarities:Human Resource Analytics, Performance Pay, and InformationTechnology	Enterprise Resource Planning (ERP), Customer Relationship Management Systens (CRM), Supply Chain Management Systems (SCM).	1995-2002;	United States	Firm-level data; HCM vendor data; Compustat	Human Capital Management software adoption is associated with a disproportionately large productivity premium when it is implemented as a system of organizational incentives, but has little or no benefit when adopted in isolation
US-studies	(Acemoglu et al., 2014[4])	Return of the Solow Paradox? IT, Productivity, and Employment in U.S. Manufacturing	IT intensity as (1) the ratio of sector computer (IT) expenditures to total capital expenditures; and (2) usage of a set of manufacturing technologies	1977, 1982, 1987, 1992, 2002, and 2007;	United States	Plant-level data; US Census Bureau's 1988 and 1993 Survey of Manufacturing Technology (SMT)	IT has no effect on output per worker on the manufacturing sector outside the computer-producing sector.
US-studies	(Bloom, 2017[76])	What Drives Differences in Management?	IT investment (in computers) per employee	2005-2010	United States	Plant-level data; US Census Bureau's Management and Organizational Practices Survey; Business R&D and Innovation Survey	US manufacturing sector, dispersion in IT expenditures per employee explains around 8% of the productivity dispersion, while management quality explains around 17% of the spread in TFP.
US-studies	(Brynjolfsson et al., 2008[25])	Scale Without Mass: Business Process Replication and Sector Dynamics	IT capital comprising computer hardware software	1987-2006	United States	Sector-level (IT) and firm-level data (TFP); Bureau of Economic Analysis's (BEA) "Tangible Wealth Survey"; Compustat	Using case studies, the authors illustrate how IT has enabled firms to more rapidly replicate improved business processes throughout an organization, thereby increasing productivity, market share and market value.

US-studies	(Dinlersoz, 2018[77])	Automation, Labor Share, and Productivity:Plant-Level Evidence from U.S. Manufacturing	Current and future dependenceof operations on technology, as well as about past and future investment in technology.	1991	United States	Plant-level data; U.S. Census Bureau's Survey on Manufacturing Technology 1991.	More automated establishments have lower production labor share and higher capital share, and a smaller fraction of workers in production who receive higher wages. These establishments also have higher labor productivity and experience larger long-term labor share declines.
Cross-country studies	(Basu, 2003[78])	The Case of Missing Productivity Growth	IT capital stock (computer, software, communication equipment)	1995-2000	United States; United Kingdom	Sector-level : Bureau of Labour Statistics; Bank of England	Difference in total factor productivity (TFP) between the United States and the United Kingdom from 1995 onwards can be explained by a combination of unmeasured investments in (intangible) organisational capital and ICTs, and in particular the innovation these investments induce.
Cross-country studies	(Gust and Marquez, 2004[33])	International comparisons of productivity growth: the role of information technology and regulatory practices$	ratio of IT expenditures to GDP	1992 to 1999	13 industrial countries	Country-level; OECD STAN	Burdensome regulatory environments and, in particular, regulations affecting labour market practices have impeded the adoption of information technologies and have slowed productivity growth in a number of industrial countries.
Cross-country studies	(Van Ark and Inklaar, 2006[40])	Catching up or getting stuck? Europe's troubles to exploit ICT's productivity potential	Catching up or getting stuck? Europe's troubles to exploit ICT's productivity potential	2001-2004	France, Germany, Netherlands, United Kingdom, United States	Sector-level; pre-EU KLEMS dataset i.e. the 60 Sector Database of the Groningen Growth and Development Centre (GGDC)	The relationship between ICT investments and productivity is U-shaped, whereby the initial adoption phase is followed by a period of experimentation during which ICT and productivity are negatively related. However, complementary investments eventually lead to gains from ICT in line with its marginal costs.
Cross-country studies	(Van Ark, 2008[79])	The Productivity Gap between Europe and the United States: Trends and Causes	ICT capital	1995-2004	EU, United States	Country-level data: EU KLEMS database	The European productivity slowdown is attributable to the slower emergence of the knowledge economy in Europe compared with the United States, partly due to lower growth contribution from ICT investments.
Cross-country studies	(Bloom, Sadun and Van Reenen, 2012[28])	American do IT better: US Multinationals and the Productivity Miracle"	PC and laptop per worker	1999-2006	EU (France, Germany, Italy, Poland, Portugal, Sweden and the UK)	Firm-level data: UK Census Bureau; CEP Management Survey; Harte-Hanks IT panel	US firms' IT-related productivity advantages are primarlily due to their "tougher" management practices.

Cross-country studies	(Bartelsman, 2013[35])	ICT, Reallocation and Productivity	N.A.	N.A.,	EU countries	N.A.	Owing to the on-going advances in ICT, much higher growth is technologically feasible, but a considerable amount of churn and reallocation across firms in the market sector is needed.
Cross-country studies	(Hagsten et al., 2013[12])	The Multifaceted Nature of ICT: Final report of the ESSNet on linking of microdata to analyse ICT impact.	Broadband-enabled employees.	2004-2009	EU countries	ESSLait Micro Moments Database	Services (resp. manufacturing) firms in ten (resp. eight) out of 14 countries exhibit a significant relationship between broadband employees and labour productivity.
Cross-country studies	(Evangelista, Guerrieri and Meliciani, 2014[80])	The economic impact of digital technologies in Europe	Composite ICT indicators	2004-2008	EU countries	European Digitalization Development Index	Digitalisation may drive productivity and employment growth. Inclusive policies may contribute to bridge the gap between the most favoured and the disadvantaged parts of the population
Cross-country studies	(Acharya, 2016[81])	ICT use and total factor productivity growth: intangible capital or productive externalities	ICT capital	1973-2004	EU and US	Sector-level data: EU KLEMS	Unmeasured intangible capital accumulation rather than productive externalities were at the core of the US (and to some extent EU) TFP growth in the mid '90s.
Cross-country studies	(Corrado, Haskel and Jona-Lasinio, 2017[30])	Knowledge Spillovers, ICT and Productivity Growth	ICT capital	1998-2007	EU countries	EUKLEMS	The marginal impact of ICT capital is higher when it is complemented with intangible knowledge based capital. More specifically, their study shows that ICT intensive industries have better productivity outcomes in countries that are more KBC intensive, in particular with relative higher investments in organisational capital
Cross-country studies	(Cette, Lopez and Mairesse, 2017[7])	Upstream Product Market Regulations, ICT, R&D and Productivity	ICT capital	1987-2007	EU and US	OECD STAN; EU-KLEMS	ICT capital increases are an important channel to increase sector level MFP when upstream sectors are deregulated.
Cross-country studies	(Bartelsman, Van Leeuwen and Polder, 2017[5])	CDM using a cross-country micro moments database	Enterprise Resource Planning (ERP), Customer Relationship Management Systens (CRM), Supply Chain Management Systems (SCM).	2006-2009;	EU countries	ESSLait Micro Moments Database	Innovative activity contributes to aggregate productivity even while the average effect at the firm level is insignificant. Moreover, the combined use of digital technologies leads to within-firm productivity increases.

Non-US studies	(Bugamelli and Pagano, 2004[32])	Barriers to investment in ICT	ICT capital stock	1995-1997	Italy	Firm-level data: 'Centrale dei Bilanci' (Company Accounts Data Service, CADS); 'Indagine sulle Imprese Manifatturiere' (Survey of Manufacturing Firms, SMF) by Mediocredito Centrale	The ICT marginal product exceeds its user cost, possibly due to the lack of complementary investment in human capital and the lack of a reorganization of the workplace.
Non-US studies	(Wieder et al., 2006[37])	The impact of ERP systems on firm and business process performance	ERP and SCM	2001	Australia	Firm level data; Survey conducted by the Australian Business Journal "BRW"	Except when both technologies were combined, no significant performance differences were found between ERPS adopters and non-adopters, either at the business process level, or at the overall firm level. While it could be confirmed that the longer the experience of firms with ERP, the higher their overall performance, no evidence was found of a similar effect on business process (supply chain) performance.
Non-US studies	(Castiglione, 2012[82])	Technical efficiency and ICT investment in Italian manufacturing firms	ICT investments	1995-2003	Italy	Firm-level survey data from Mediocredito Centrale Capitalia	ICT investments positively and significantly affect firms' technical efficiency.
Non-US studies	(Engelstätter, 2009[39])	Enterprise systems and labor productivity: disentangling combination effects	Share of computer workers, ERP, SCM, and CRM systems	2004; 2006	Germany	Firm-level data; phone interview conducted by Centre for European Economic Research (ZEW).	Replicating Aral, Brynjolfsson and WU (2006) using similar data the authors find a positive correlation between labor productivity and various measures of IT. The authors also show evidence of the complementarity between different measures.
Non-US studies	(Hall, Lotti and Mairesse, 2012[83])	Evidence on the impact of R&D and ICT investment on innovation and productivity in Italian firms	ICT investment expenditure	1995-2006,	Italy	Firm-level data: Unicredit "Survey on Manufacturing Firms"	R&D and ICT are both strongly associated with innovation and productivity, with R&D being more important for innovation, and ICT investment being more important for productivity

Non-US studies	(Akerman, Gaarder and Mogstad, 2013[18])	The skill complementarity of broadband internet	Broadband subscription	2001-2007	Norway	Firm-level data; Annual Community Survey on ICT Usage of Firms by Statistics Norway	Broadband internet complements skilled workers in executing non-routine abstract tasks, and substitutes for unskilled workers in performing routine tasks.
Non-US studies	(Pellegrino, 2017[84])	Diagnosing the Italian Disease	IT capital	1984-2006	Italy	Sector-level: EU KLEMS	Italy's slowdown was likely caused by the failure of its firms to take full advantage of the ICT revolution. While many institutional features can account for this failure, a prominent one is the lack of meritocracy in the selection and rewarding of managers. Familyism and cronyism are the ultimate causes of the Italian disease.
Non-US studies	(Dhyne et al., 2018[19])	IT and Productivity: A firm level analysis	IT purchases by firms	2002-2013	Belgium	Firm-level data; VAT transaction data obtained from tax authorities.	Using VAT transaction data between Belgium firms, this paper looks at the various dimensions of sector and firm level heterogeneity in returns of IT capital. IT investments are found to be more productivity-enhancing in the manufacturing sector and in large firms.
Non-US studies	(Chevalier and Luciani, 2018[58])	Computerization, labor productivity and employment: impacts across industries vary with technological level	Office and computing machinery investment	1994-2007	France	Sector and firm-level data (BRN and DADS), manufacturing sector	For the whole IT-using manufacturing sector, computerization is associated with positive but fragile effects on labor productivity, and to unambiguous declines in employment.
Non-US studies	(DeStefano, Kneller and Timmis, 2018[6])	Broadband infrastructure, ICT use and firm performance: Evidence for UK firms	ADSL broadband	1999-2005	United Kingdom	Ci Technology Database (CiTDB)	ICT causally affects firm size (captured by either sales or employment) but not productivity.
Non-US studies	(Mohnen, Polder and Van Leeuwen, 2018[31])	R&D and Organizational Innovation: Exploring Complementarities in Investment and Production	ICT investment (hardware only)	2008-2014	Netherlands	Firm-level data, Dutch Investment Survey	Investments in ICT, R&D and organisational capital are complementary, in the sense that investing in one increases the probability of investing in another one because joint investments lead to higher TFP growth than individual investments.

Other	(Brynjolfsson and Hitt, 2000[26])	Beyond Computation: Information Technology, Organizational Transformation and Business Performance	N.A.	N.A.	N.A.	N.A.	Relying primarily on case studies, but also on preliminary research the authors document that computerization without changes in work practices usually fails at delivering an increase in efficiency. For example, technology aiming at facilitating the interactions between a firm and its suppliers will be efficient only if the entire supply chain is reorganised accordingly.
Other	(Dedrick, Gurbaxani and Kraemer, 2003[21])	Information Technology and Economic Performance: A Critical Review of the Empirical Evidence	N.A.	1987-2002	N.A.	N.A.	In a conclusive review of over 50 scholarly studies on ICT and productivity published between 1987 and 2002, the authors find that "the productivity paradox as first formulated has been effectively refuted.
Other	(Syverson, 2011[2])	What Determines Productivity?	N.A.	N.A.	N.A.	N.A.	Provides a literature review of IT-related productivity gains.