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Digitalisation and productivity

A report by the ESCB expert group on productivity, innovation and technological change

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No 339

Contents

Abstract

The productivity-enhancing effects of digitalisation have generated increased interest in the promotion of digital technologies. This report provides different estimations for euro area countries of the impact of digital uptake on productivity at firm level, showing that the adoption of digital technologies could lead to an increase in firms' productivity in the medium term. However, not all firms and sectors experience significant productivity gains from digital adoption, and not all digital technologies deliver significant productivity gains. The report highlights possible factors behind the low productivity benefits of digitalisation in euro area countries. For example, a lack of strong institutions and governance structures may help to explain why digital diffusion is slower than expected, why it is slower in some countries than others and why the expected productivity benefits from digitalisation have not been fully achieved by now. Furthermore, the report suggests that the full benefits of the digital revolution will be reaped by properly supplying skills to firms and also by investing in computerised information in low-productivity firms.

Keywords: digitalisation, productivity, institutions, human capital, complementary investments

JEL codes: D24, E24, E22, J24, O33, O38, C67

Executive summary

Digitalisation is one of the main forces driving structural and organisational changes in the euro area and the global economy. The productivity-enhancing effects of digitalisation have generated increased interest in the promotion of digital technologies. However, euro area countries still lag behind the United States in terms of digital innovation. This could explain why firms in euro area countries are not benefiting much from the changes brought about by digitalisation.

The impact of digitalisation on productivity

Digitalisation is a wide-ranging phenomenon that encompasses numerous technologies and applications. Theoretically, the adoption of digital technologies by both households and firms should have led to large productivity gains through various channels by now, since digital inputs play a key role in aggregate productivity growth. The limited impact of digitalisation on productivity statistics to date is sometimes referred to as the "productivity puzzle".

The level of digital adoption is heterogeneous across countries, while the euro area lags behind the United States on average. Measured by the number of patents related to digital technologies, digital innovation in euro area countries lags behind that in the United States. Moreover, when measuring digitalisation by means of digital activities performed by firms and in particular small and medium-sized enterprises (SMEs), the results indicate that (small) firms have a low level of digital adoption, which could explain why they are not benefiting much from the productivity gains of advanced technologies.

A micro-distributed exercise shows that firms which significantly increase investment in digital technologies improve both labour productivity (LP) and total factor productivity (TFP) five years after adoption compared with firms that rely less on digital technologies. It is interesting to observe that the effect is null and negative for LP and TFP, respectively, in the year of adoption, probably due to the firm's reorganisation of its production process. This exercise is not immune to the fact that the quantification of productivity gains from digitalisation is difficult because of data scarcity and issues in measuring digital technologies and activities.

A second exercise argues that while digital investment boosts average TFP growth at firm level, not all firms and sectors experience significant productivity gains. Digitalisation seems to be a productivity game-changer only for some firms, while it is more like a productivity sideshow for other firms which invest in digital technologies but are not able to adequately reap the productivity benefits from digitalisation.

Complementary investments, labour markets and skills, and productivity gains from digitalisation

Possible factors that could explain the low productivity benefits of digitalisation in euro area countries include institutional factors, skill mismatches on the labour market and complementary investments.

A lack of strong institutions and governance structures may explain why digital diffusion is proceeding at a slower pace than expected. It may also explain why it is slower in some countries than others and why the expected productivity benefits from digitalisation have yet to be fully achieved.

The adoption of new technologies may also affect labour markets. For example, artificial intelligence (AI) is a general-purpose technology that could affect jobs in virtually all occupations. In 16 European countries over the period 2011-19, a positive association is found between AI and changes in employment shares, a relationship that is driven by occupations employing high-skilled and younger workers.

The full benefits of the digital revolution will be achieved by properly supplying skills to firms. To ensure that government efforts to increase firms' adoption of the latest technologies and business practices lead to sustainable productivity gains, such actions should be accompanied by measures to increase the supply and mobility of human science, technology, engineering and mathematics (STEM) capital.

Finally, complementary investments (such as in intangible assets) at firm level have a significant positive impact on productivity growth. Indeed, intangible assets partly reflect the ongoing digitalisation of the corporate sector, which is why their uneven distribution may have contributed to the observed wedge in productivity dynamics across firms. Investment in computerised information at low-productivity firms would need to be coupled with support for firms to develop the complementary skills required to use digital technology. This would boost aggregate productivity growth and contribute to making growth in the euro area more inclusive.

1 Introduction

The digital transition has become a policy priority on the EU agenda, as documented by various initiatives such as the EU's "Digital Single Market" and "NextGenerationEU". Moreover, digital uptake has accelerated because of the coronavirus (COVID-19) pandemic. In addition, the recent popularisation of artificial intelligence (AI) systems like ChatGPT has uncovered the enormous potential for new digital technologies to alter the way we live, produce and work.

The key reason for this interest is the productivity-enhancing effects of digitalisation. Digital technologies can generate productivity gains by improving the efficiency of a firm's processes, enhancing the complementarity between workers and capital and helping to achieve higher rates of automation and robotisation. It is therefore important to have a clearer understanding of how digitalisation affects productivity growth and develop policies that maximise productivity gains.

This report shows that the level of digitalisation in the euro area is still low. To that aim, a group of experts from the European System of Central Banks (ESCB) have been pooling their expertise and sharing macro, sector and firm-level data as part of an Expert Group on Productivity, Innovation and Technological Change.[1] Section 2 shows that the number of triadic patents linked to scientific fields is much lower in the euro area compared with the United States. Furthermore, smaller firms in euro area countries exhibit low levels of digital adoption, including relative to large firms. This could explain why (smaller) firms are not benefiting much in terms of their productivity from the changes brought about by the development of digital activities. Notwithstanding this, a counterfactual exercise in the report shows that without digitalisation-related efficiency increases, productivity growth in the euro area would have been about half of what it was between 1997 and 2018. Input-output linkages tend to be an important transmission channel for digitalisation.

The exact quantification of productivity gains from digitalisation is difficult due to data scarcity; the order of magnitude of estimates in this report indicates that a 1% increase in digital technologies leads to an almost 0.01% increase in total factor productivity (TFP) after five years. Section 2 includes two empirical estimations of the elasticity of productivity to digital uptake, differing in how they measure digital uptake. The first exercise is an event study for France and Austria at firm level and indicates that the effect of a significant increase in digital technology investment at a firm is null for labour productivity (LP) and negative for TFP in the year of investment. However, both LP and TFP increase considerably in subsequent years relative to firms that invested less in digital technologies. In the short term, employment therefore reacts faster than production to the adoption of new technologies, as firms need to hire employees able to perform new tasks (e.g. IT

[1] The ESCB Expert Group on Productivity, Innovation and Technological Change has completed three complementary reports analysing the impact of the COVID-19 pandemic, climate change and monetary policy on productivity growth. See Lalinsky et al. (2024), Bijnens et al. (2024) and Valderrama et al. (2024).

jobs). In the long run, the adoption of new digital technologies has positive effects on productivity.

The second exercise considers sector-level digital intensity and finds that not all firms and sectors experience significant productivity gains. Digitalisation seems to boost productivity only for a minority of selected firms that are able to use digital technologies to become substantially more productive over time. These selected firms are among the most productive, with only 30% of the most productive laggard firms benefiting on average from investing in digital technologies. However, higher digital intensity is not enough to turn highly productive laggard firms into frontier firms. Firms also need more structural innovation compared with their peers, which can be achieved through digital technologies but is not a direct consequence of higher investment in digital technologies. Furthermore, the impact of investment in digital technologies is similar for both laggard and frontier firms, but the latter are better equipped to reap the full benefits of the digital revolution in terms of productivity gains.

The report also explores possible factors behind the low productivity benefits of digitalisation, including the need of institutions, labour markets and skills and complementary investments. A lack of strong institutions and governance structures may help to explain why digitalisation is slower than expected, why it is slower in some countries than others and why the expected productivity benefits from digitalisation have yet to be fully achieved. Recent work on institutions and governance, digitalisation and growth (Labhard and Lehtimäki, 2022) finds empirical evidence for an explanatory role of digitalisation, and its interaction with institutions and governance, in productivity growth.

Specific technologies such as AI are expected to have an impact on labour markets. For 16 European countries over the period 2011-19, Albanesi et al. (2023) find that AI is positively associated with changes in employment shares, driven in particular by occupations employing high-skilled and younger workers.

Evidence from Belgium suggests that availability of skilled workers is crucial to reap the productivity benefits from digitalisation. Stimulating research, innovation and digitalisation in Europe without properly addressing the supply of skilled workers may lead to higher wages for high-skilled workers rather than additional innovation. Bijnens and Dhyne (2021) find a clear positive correlation in Belgium between the share of high-skilled and, more importantly, science, technology, engineering and mathematics (STEM) workers in a firm's workforce on the one hand and its productivity on the other. Increasing the share of high-skilled STEM workers leads to significantly higher productivity gains compared with both non-high-skilled STEM workers and high-skilled non-STEM workers.

Intangible investment can also play an important role. Intangible assets represent a group of corporate expenditure with relevance for the digital transition, including computerised information as well as innovative property, R&D expenditure and patents, some of which constitute new digital technology. Intangible assets can have positive effects on productivity because of their specific properties. Some intangible assets can be scaled at very little or no cost, such as when an existing

corporate database is used for additional business processes, or they can be shared, such as when a new production method resulting from R&D activity is shared against a licence fee, therefore creating important spillovers between firms and sectors.

This paper is organised as follows. Section 2 reviews the literature on the channels of impact of digitalisation on productivity, presents a descriptive analysis of the digital uptake in (selected) euro area countries and provides empirical evidence on the relationship between digitalisation and TFP growth at firm level. Section 3 explores complementary investments, skills and institutions, and the productivity gains from digitalisation. Section 4 concludes and discusses some policy implications.

2 The impact of digitalisation on productivity

2.1 Channels of impact

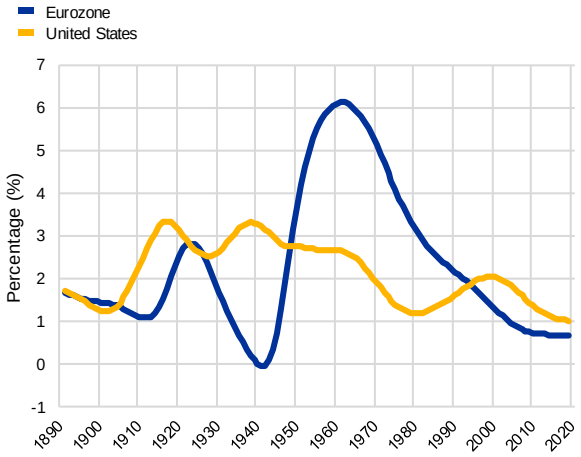
Digitalisation is a broad phenomenon involving many different technologies and applications. Theoretically, the adoption of digital technologies by both households and firms should have led to large productivity gains through various channels by now. From a historical perspective, the impact of the adoption of a general-purpose technology (GPT) on productivity growth has been documented for the Second Industrial Revolution, following the massive adoption of electricity and the significant productivity gains this brought about (Chart 1).[2] However, in spite of the rapid increase in the quality of ICT-based goods and services, aggregate productivity growth in most advanced economies has fallen since the 1970s and has been close to zero since the mid-2000s, with the exception of the United States between 1995 and 2005. The diffusion of a new GPT combined with a sluggish productivity growth rate has led to a "productivity puzzle" (see Adler and Siegel, 2019, for a review of articles on the paradox).

One explanation for this productivity puzzle lies in the lags between implementation and optimal usage of digital technologies by individuals and organisations. It has been shown that previous technological revolutions took time to materialise in productivity statistics and to lead to large productivity gains. Different factors are at play, including the need for successive waves of secondary innovations, each of which corresponds to the adaptation of the GPT to a specific sector of the economy, and the time needed for the development of new physical and organisational infrastructure and skills (David, 1990, in the case of the electricity). It should also be kept in mind that the sources of productivity growth depend on economic practices and institutions, which vary significantly across countries and industries.

[2] Of course, not all GPTs are expected to have exactly the same pattern in terms of their effect on productivity. For instance, Agrawal et al. (2023) show that in order to understand the consequences of GPT diffusion on productivity, one has to understand the commonalities with prior GPTs in terms of co-invention. They show that depending on which firms adopt the new technology and the direction of the co-invention, expected gains from different GPTs can differ significantly.

Chart 1

Average annual growth rate of labour productivity



Source: Bergeaud et al. (2016).

An alternative or complementary explanation is that the productivity gains from ICT and digital goods and services are mismeasured. In this instance, standard indicators of the economy such as gross domestic growth (GDP) underestimate productivity gains because they fail to adequately incorporate the effects of these new technologies. This measurement issue can be caused by incapacity to compute the contribution of new services that are "free" to the user (Brynjolfsson and McAfee, 2014) or the measurement bias of price indices, which can increase if the creative destruction rate of products in the economy is too high (Aghion et al., 2019b). However, the vast majority of quantitative analyses aimed at correcting for these biases conclude that mismeasurement issues are not enough to explain the productivity slowdown (Syverson, 2017).

In order to understand the digitalisation "productivity puzzle", we need to investigate the channels of impact of digital technology adoption on LP, both at macro and micro level. These channels of impact have already been studied previously (see, in particular, Anderton and Cette, 2021, for an extensive literature review).

At macro level, we can decompose the effect of digital technology adoption on LP into two components: an effect on TFP growth and an effect on the growth rate of the capital/labour ratio (capital deepening). Theoretically, these two channels are relevant to explain the effect of a GPT on LP.

The channel of impact of digitalisation on TFP growth depends on the type of industry considered (Wolff, 1991).

First, in ICT-producing sectors, the development of innovations positively affects TFP growth (Fernald, 2015; Aghion et al., 2019a). Nevertheless, the aggregate contribution of productivity gains in the ICT sector has remained limited due to the small share of this industry relative to the economy as a whole. Indeed, Byrne et al. (2013) estimated the ICT sector's contribution to overall LP gains in the

United States at an average of 0.72 percentage points per year from 1995 to 2004, compared with 0.28 from 2004 to 2012, when it reached its highest level. In 2000, the ICT sector represented 11.1% of value added in the United States and 8.5% in EU14 countries according to estimates by the Organisation for Economic Co-operation and Development (OECD).

Second, the impact of digitalisation on TFP growth in ICT-using sectors occurs through a diffusion effect (or network effect). The adoption in recent decades of new communication technologies by a large majority of firms has led to a positive effect on TFP growth through a network effect. For instance, the full potential of a computer is reached once it is connected to an entire network, decreasing communication costs relative to previous technologies. The diffusion of a GPT to the entire economy is a turning point in maximising its effect on productivity growth. This diffusion effect also has an impact on skills, as the broad adoption of digital technologies incentivises firms to hire or train employees that are complementary to the new type of capital. This impact on skills can also lead to suboptimal situations where people are trained on a version of the technology that will not maximise productivity potential in the future.[3] This illustrates the need for adequate policies to maximise the productivity potential of a technology.

The positive effect of the capital/labour ratio (capital deepening) on the growth rate results from a decline in the quality-adjusted price of capital equipment as technology advances. Without changing their planned investment expenditure, ICT-adopting firms increase their capital/labour ratio because of technological progress. Of course, the capital deepening effect is hard to disentangle from the effect on TFP because it requires very precise data on quality-adjusted investment prices.

Looking more closely at how ICT and digital technologies can boost productivity at firm level can shed light on the macroeconomic mechanisms. On the workers' side, the adoption of digital technologies leads to a boost in workers' efficiency by complementing their tasks (Gal et al., 2019), while non-core occupations are more likely to be outsourced after the arrival of the new technology (Bergeaud et al., 2021). Both of these factors positively affect firms' productivity. Channels of impact through the market have also been documented: digital technologies allow firms to grow more quickly and achieve scale without mass (Haskel and Westlake, 2017), increase competitiveness and market size through the potential of e-commerce (Albani et al., 2019) and access a wider range of imported goods (Malgouyres et al., 2021).

The adoption of digital technologies by firms was contemporaneous with other technological evolutions such as automation. Automation refers to the adoption of modern manufacturing capital (robots, automated machine tools, etc.) that can perform tasks previously performed by human labour only. If these technologies usually include many electronic components and require various digital technologies to work, they cannot be considered as ICT technologies. Consequently, digitalisation

[3] David (1990) shows that the initial adoption of QWERTY keyboards and the training of employees on this technology put society in a suboptimal equilibrium, where the cost to move to a more efficient technology was too high, illustrating a path dependence concern.

and automation should not be considered as close substitutes. Indeed, the first assembly line appeared several decades before the invention of the transistor that fuelled the digital revolution. By contrast, the application of digitalisation to automated production (robotic process automation and intelligent process automation) makes up only a small part of the impact of digitalisation on manufacturing.

The adoption of automation technologies by manufacturing firms also had a positive effect on their productivity, which can make it difficult to identify the productivity effects from digitalisation (Acemoglu et al., 2020, and Aghion et al., 2020, in France; Koch et al., 2021, in Spain). Many firms have adopted both types of technologies in recent decades, making it difficult to disentangle the channels of impact on productivity for each type of technology. Understanding the micro-level productivity effects of digitalisation may therefore not be sufficient due to confounding factors such as the adoption of technologies that are partial complements to digital technologies.

2.2 Uptake of digital technologies in selected euro area countries

This section examines the different degrees of adoption of digital technologies in several euro area countries and also with respect to the United States. This analysis is relevant since the level of digital adoption is heterogeneous across euro area countries, meaning the impact of digitalisation on productivity will be different (Anderton and Cette, 2021).

Two different measures of digitalisation are analysed: (i) digital innovation at country level, measured as the number of triadic ICT-related patents; and (ii) a survey measure of digital adoption at firm level in selected euro area countries related to digital activities performed by small firms (firms with less than 50 employees). Both measures have advantages and disadvantages. Patent counts have the advantage of being a likely predictor of future innovations, while the disadvantages are that the impact of patents is always uncertain and not all innovations (ICT-related or not) are patented. Survey-based digital adoption by firms is a new measure that offers a fresh perspective on these questions but has limited country and year coverage.

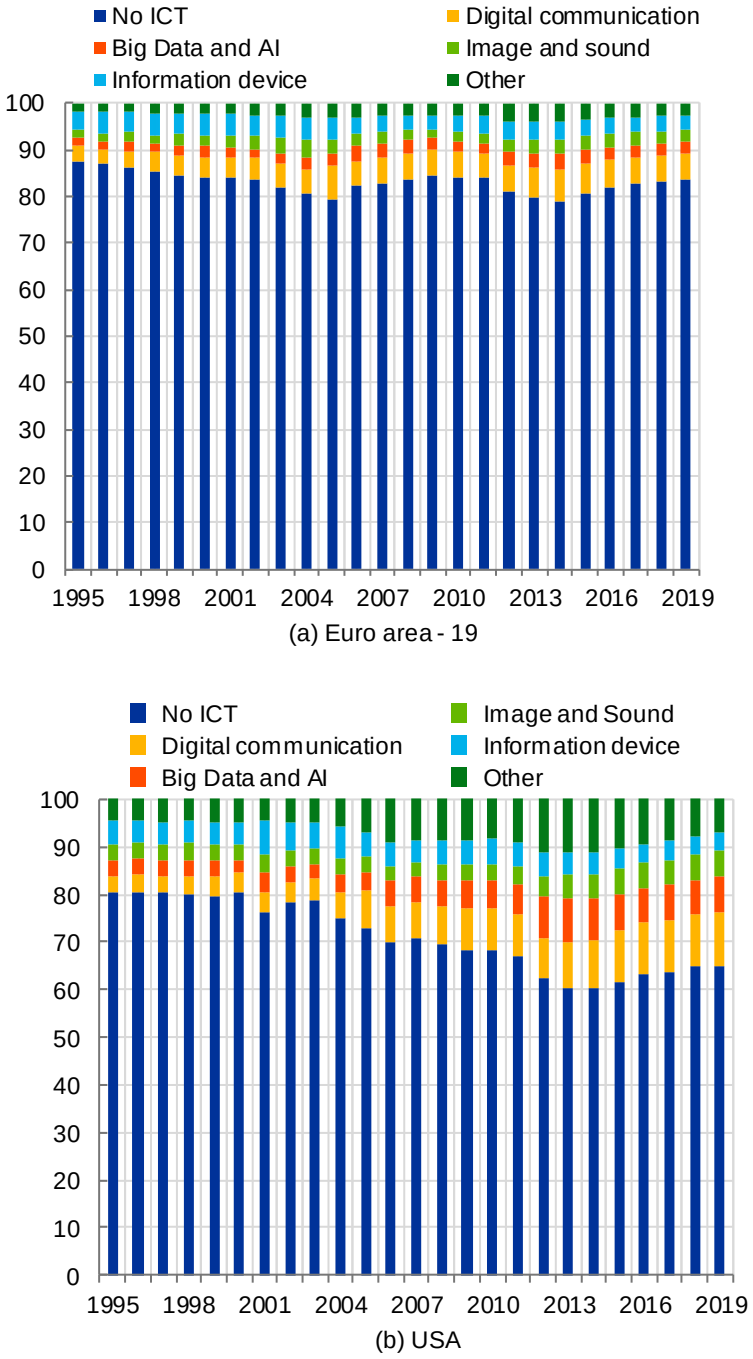
The first measure uses country data from Google Patents on triadic ICT-related patents[4]. Chart 2 shows the evolution of the distribution of triadic patents in euro area countries and the United States, distinguishing between ICT patents (digital communication, big data and AI, image and sound, information device, and other) and non-ICT patents. In euro area countries, the proportion of triadic patents in ICT sectors has remained relatively stable in recent years compared with the United

[4] Triadic patents are a set of patents registered in various countries to protect the same invention (European Patent Office, Japan Patent Office, the US Patent and Trademark Office).

States, where it has increased. This indicates that the use of ICT technologies is still relatively low in euro area countries, lagging behind the United States.

Chart 2

Triadic patents: ICT vs no ICT



Source: Google Patents.

OECD patent data (2023) provide a similar picture. According to this source, the total number of ICT-related triadic patents filed by US firms over the period 2014-18 was 96% higher than the number of triadic patents filed by European firms[5].

The second measure uses data from an ad hoc survey of the financial literacy of small firms (micro, small and medium-sized enterprises, MSMEs, with less than 50 employees) designed by the OECD International Network on Financial Education (OECD/INFE) and conducted in several euro area countries. The survey includes a section with various questions about digital activities performed by firms and the impact of the COVID-19 crisis on the level of firms' digitalisation. The euro area countries included in the survey are France, Germany, Italy[6], the Netherlands, Portugal and Spain (see Appendix A for more details).

More than 50% of small firms have a dedicated website to showcase their products and services, but a lower percentage have a dedicated website to sell their products and services (Chart 3). Digital activities like opening a bank account completely online, signing a financing contract completely online or signing an insurance contract completely online are performed by less than 20% of small firms in Spain, France, the Netherlands and Portugal. The exceptions are Italy (firms with less than ten employees) and Germany (both firms with less than ten employees and firms with 10-49 employees), where opening a bank account completely online is done by more than 40% of firms.

Less than 30% of small firms in the six euro area countries report that sales of products and services through their website are quite large or very large. This proportion is even lower in the case of sales through a shared online platform, except in the Netherlands where this proportion is about 30% in the case of small firms with 10-49 employees (Chart 4). Regardless of firm size, more than 50% of small firms report that digital activities like online payments from customers, online payments to suppliers or online operations on a current account are quite large or very large. Use of social media for business activities such as advertising or networking is relatively low in France and Germany (less than 30% of small firms), while in the rest of the countries, about 40% or more of small firms report that it is quite large or very large.

These numbers confirm that small firms generally are not fully adapting to the changes brought about by digitalisation. The evidence from the survey indicates that small firms in euro area countries show a low level of digitalisation. Regarding the impact of the COVID-19 pandemic on digital activities, the survey shows very small differences between small firms' use of digital activities before the crisis and after. Moreover, relative to large firms, the European Investment Bank's Investment Survey (EIB, 2021) indicates that there is a digital gap between SMEs and large firms in terms of the use of advanced digital technologies (around 60% of SMEs compared with around 80% of large firms). This is likely to have a negative impact on small firms' productivity.

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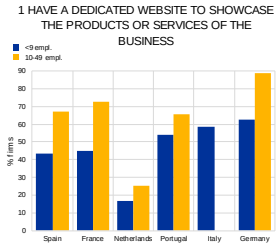
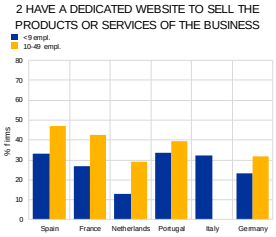
5 More precisely, firms that are located in the European Union.

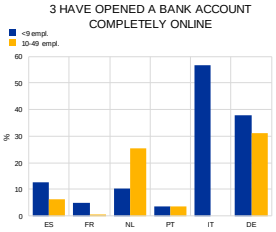
6 In Italy, the survey was only conducted for firms with one to nine employees.

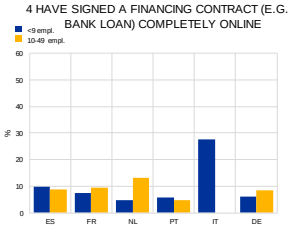
Chart 3

Percentage of firms indicating that they perform the following digital activities, by firm size









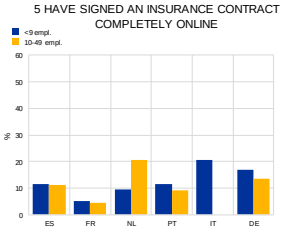
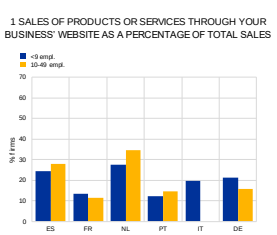
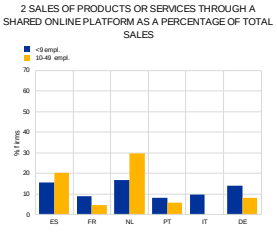
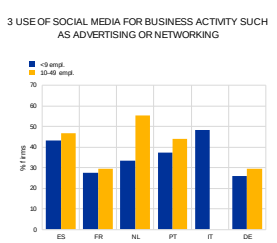


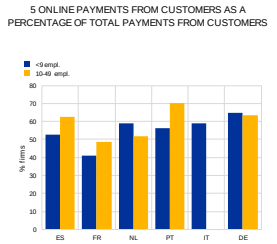
Chart 4

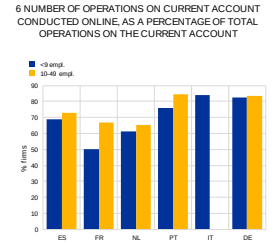
Percentage of firms indicating that the following digital activities are quite large or very large for their business, by firm size











Source: Banco de España. Calculations using the OECD/INFE Survey Instrument to Measure the financial literacy of MSMEs.

2.3 The impact of firms' digital uptake on their productivity: an event study

It is important to understand the impact of digitalisation on firms' outcomes, particularly their productivity, in different European countries. To do so, a micro-distributed exercise was conducted[7] by adapting the methodology of Aghion et al. (2020) to study the effect of digital technology adoption on various firm-level outcomes (value added, employment, LP and TFP). The ability to measure digital technology adoption at firm level is crucial. That is why participation in this exercise was conditional on having access to very detailed balance sheet data at firm level. Sufficiently good data were only available in two countries: France and Austria.[8]

Identifying a relationship between digital technologies and firms' outcomes is complicated for at least two reasons. First, measures of digital technology adoption at firm level are not readily available in balance sheet data. Second, the existence of shocks contemporaneous with a firm's decision to adopt digital technologies (e.g. demand shocks) raises the question of endogeneity bias and implies the use of sophisticated econometric techniques to alleviate these concerns.

This exercise uses the stock of tangible fixed assets identified as "office and IT equipment, and furniture" as a proxy for the stock of digital technologies at firm level. This category includes (i) IT equipment such as computers, scanners, printers and calculators; (ii) office equipment such as staplers, binders and pens; and (iii) furniture such as office desks. Ideally, IT equipment – which we want to measure – would be isolated from office equipment and furniture. Unfortunately, this is not possible in the balance sheet data. Thus, this measure is broader than it should be to identify only digital technologies. Another caveat is that the type of digital technologies (computers vs printers vs tablets, etc.) adopted is not available in these data.

The technique of event studies is used to analyse the response of different firm outcomes to a "digitalisation event". A digitalisation event is defined as a firm's largest relative annual investment in "office and computer equipment, and furniture" – our proxy for digital equipment – over its lifetime. As most firms adjust their quantity of digital technologies every year, the event study design aims to isolate large changes in digital technology investments. The effect is determined by considering as "treated" firms for which this investment event is above a threshold, defined as a percentile of the distribution of investments in digital technology events across all firms. The event study includes controls for time-invariant unobservables as well as industry-by-year fixed effects to address some of the potential correlated demand or supply shocks. The estimated specification is as follows:

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7 See Appendix B for further details regarding the implementation of the micro-distributed exercise.

8 While the German firm-level dataset has a reasonable number of observations in the cross-section, few firms are present across long stretches of consecutive years as required by this analysis, leading to the identification of only 23 events for the analysis. These data limitations kept Germany from providing meaningful economic results.

$$\Delta \log (Y_{it}) = \sum_{k=-3}^{6} \delta_k E_{i,t-k} + \mu_i + \lambda_{st} + \varepsilon_{it}$$

with Yit the outcome of interest, Ei,t−k the investment event occurring in year t, μi the firm fixed effects and λst the industry-by-year fixed effects. This specification allows for delayed responses of outcomes to changes in digital investments. The lead-lag coefficient δk gives the cumulative dynamic response of the outcome Yit at time t + k to the investment event at time t.

A causal interpretation of the estimates requires that the investment event is uncorrelated with the error term, conditional on fixed effects. In the specification presented above, the "lead" coefficients (δk with k < 0) can be used as a pre-trend falsification test. In particular, we expect these coefficients to be statistically insignificant and the point estimates to be close to zero, meaning that firms which relied relatively more on digital technologies followed the same path in terms of outcome (employment, value added, etc.) before the event than firms which relied less on digital technologies. Nevertheless, this may not be sufficient. In particular, the investment event should not be correlated with demand shocks that may happen in the same year. In this situation, firms may invest in new technologies and, at the same time, increase their value added or employment to answer this demand. Aghion et al. (2020) answer this concern by implementing an instrumental variable approach. Here, we will need to keep in mind this potential limitation.

The micro-distributed exercise requires a balanced panel of firms to compare the evolution of outcomes between firms that rely more – treated – and firms that rely less – untreated – on digital technology adoption, without considerations of entry and exit of firms over time. In France, this condition leads to 3,593 firms that are present for at least ten consecutive years between 2000 and 2020. In Austria, it leads to only 93 firms that are present for at least seven consecutive years between 2008 and 2019. The whole population of firms is a priori taken into account (manufacturing and services). The reduced sample size for Austria raises some concerns that are discussed below. The threshold in terms of relative investment in digital technologies defining the treated group is set at p90 in France, where we have numerous firms to study, and at p75 for Austria, where the number is limited, leading to 359 and 23 treated firms in France and Austria respectively.

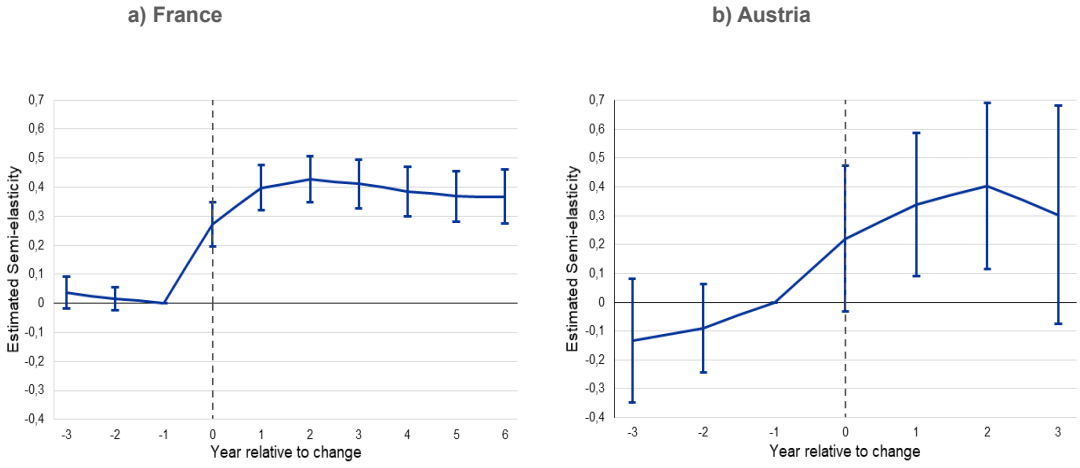
Chart 5 confirms that there are no significant differences in the pre-event trend between treated and non-treated firms in both countries. In order to be able to interpret the results, it is important to check that firms which relied relatively more on digital technologies showed the same value added path before the event than firms which relied relatively less on digital technologies.

After the event, firms that invested relatively more in digital technologies experienced a greater increase in value added, both in France and Austria. The semi-elasticity of firm value added to the investment event increases over time, from +0.28 in the investment year to +0.38 after six years in France, and from a non-significant +0.10 in the investment year to +0.39 after three years in Austria. Standard errors are bigger for Austria, probably due to the small sample size.

Empirically, the average log change in the balance sheet value of digital technologies after the event in France is close to 1.5, such that the semi-elasticities should be divided by 1.5 to be interpreted as elasticities. For France, the estimated elasticities at time t=0 and t=6 are +0.19 and +0.25 respectively.

Chart 5

Firm-level event studies for value added

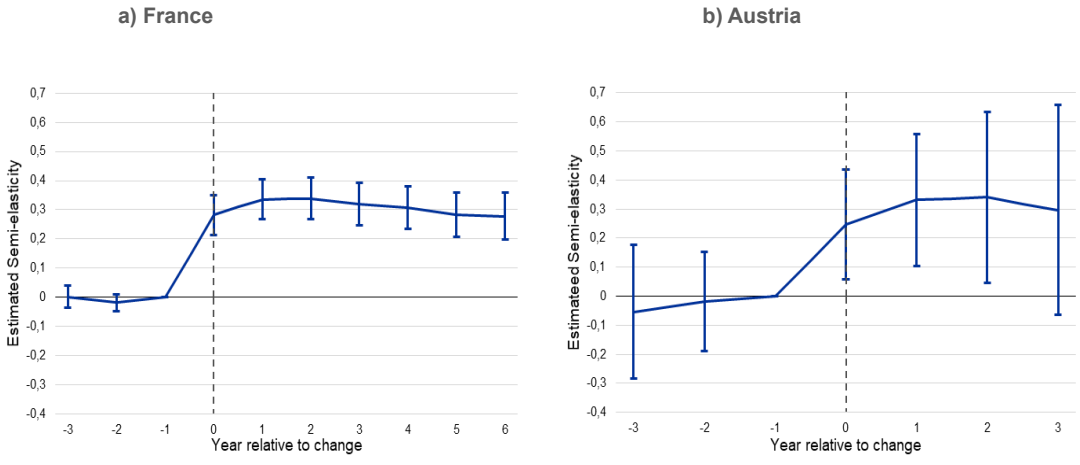


Sources: Fiben dataset for France; dataset for Austria described in Beer et al. (2021).
Note: Treated = top 10% - controlling for four-digit industry-by-year FE + firm FE.

Chart 6 shows similar results for employment: firms that invested relatively more in digital technologies had higher employment, both in France and in Austria. The semi-elasticity of firm employment to the investment event is stable over time in France, at around +0.3, while it increases in Austria from +0.2 in the year of investment to +0.4 three years after. For France, elasticities are thus close to +0.2. By comparison, Aghion et al. (2020) found the elasticity of firm employment to modern manufacturing capital for manufacturing firms to be close to +0.4 in France.

Chart 6

Firm-level event studies for employment

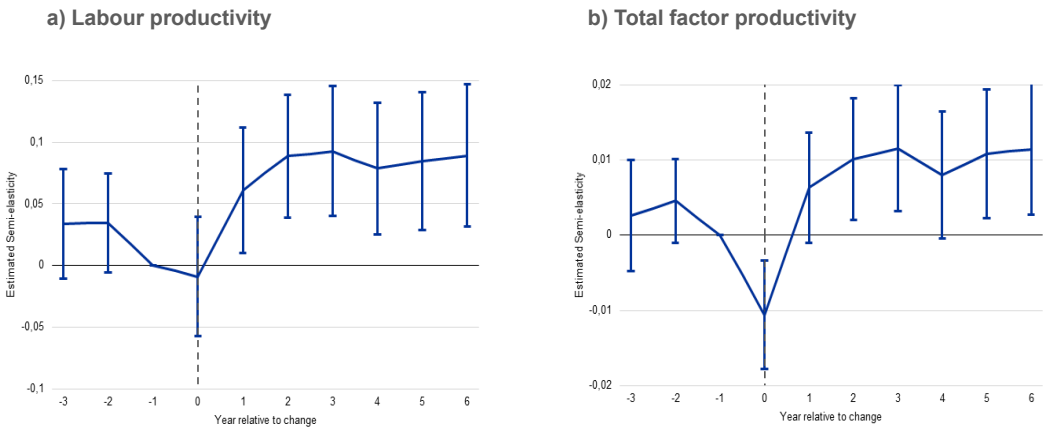


Sources: Fiben dataset for France; dataset for Austria described in Beer et al. (2021).
Note: Treated = top 10% - controlling for four-digit industry-by-year FE + firm FE.

Although the results in terms of value added and employment are informative, the goal of this exercise is to focus on firms' productivity. Chart 7 presents estimations considering LP (panel a) and TFP (panel b) as firm-level outcomes in France. First, we observe that the pre-trends are not as clean as for value added or employment, with a less clearly estimated zero. Still, we observe common trends between the two groups (firms that rely more and less on digital technologies).

Chart 7

Firm-level event studies for productivity in France



Source: Fiben dataset (France).
Note: Treated = top 10% - controlling for four-digit industry-by-year FE + firm FE.

Chart 7 reports an increase in productivity, measured as both LP and TFP, following a digitalisation event at firm level. Interestingly, firms that adopted more digital technologies were similar in terms of LP and did not increase their TFP as much as firms that invested less in these technologies in the year of investment. Then, after one year, firms that relied more on digital technologies had a greater increase in both LP and TFP. Given the fact that the average log change in the balance sheet value of the stock of digital technologies after the event in France is close to 1.5, the estimated elasticities at time t=6 for LP and TFP are +0.06 and +0.007 respectively.[9] One could argue that these estimated elasticities are small, but it is important to keep in mind that they are micro-based elasticities at firm level, which means that spillover and general equilibrium effects are not taken into account at all (Box 1 shows the importance of input-output links when studying macro effects). It should also be taken into account that the time period of this exercise is 2000-20, so before the last generation of innovations in AI, and in particular generative AI. The impact of these technologies should not be underestimated.

These results suggest that digitalisation boosts the productivity of firms in the medium term, but there are implementation costs in the short run. In the short run, the adoption of these new technologies implies structural changes in the production process, explaining the one-year lag observed empirically. Indeed,

9 In order to estimate micro elasticities at firm level, very detailed balance sheet data providing the stock of capital by type (land, building, ICT, etc.) are needed. Given data limitations in the United States, to our knowledge there are no estimates of elasticities of digital investments to productivity at firm level. Jorgenson et al. (2005) estimate elasticities at industry level.

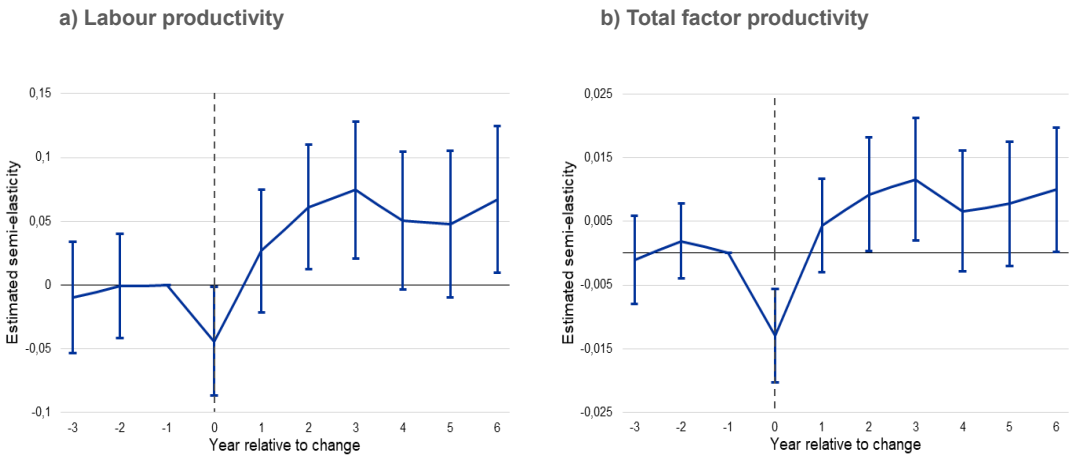
employment reacts faster than production because firms need to hire employees able to perform new tasks (IT department jobs). David (1990) rationalises the lag between technology adoption and productivity by the fact that processes within the firm have to evolve to unleash the productivity potential of digital technologies.

Unfortunately, the productivity results for Austria are not robust and, consequently, are not presented in this report. Several factors may explain this. First, as mentioned above, the sample size for Austria is limited (only 93 firms), leading to imprecise estimates, especially for productivity variables. Second, our measure for digital technologies at firm level suffers from some caveats, as previously mentioned. In addition to "IT equipment", the measure includes "office equipment" and "furniture". This may lead to the identification of investments that are not only related to digital technology adoption but also capture contemporaneous demand shocks. For instance, a firm facing a positive demand shock may scale up and, consequently, invest in new IT equipment, new furniture and new office equipment.

For France, we conducted a robustness check to alleviate the potential concern that these investment events were only driven by contemporaneous demand shocks. To do so, we identified "automation events" at firm level as the largest relative annual investment in industrial equipment (as in Aghion et al., 2020). We then restricted our treated sample to firms for which the two events are not contemporaneous and the largest digitalisation event does not correspond to the largest automation event. The intuition is the following: if there were only a contemporaneous demand shock, the firm would increase all its types of capital and not only digital technologies. Thus, firms for which the two events are not simultaneous are less likely to have experienced a contemporaneous demand shock. Chart 8 reports estimations for LP (panel a) and TFP (panel b) for this subsample of firms. We observe that the results are very similar to the ones presented for the whole sample in Chart 7, with a positive correlation between digitalisation and productivity. In fact, the majority of firms (267 out of 359 treated firms) experienced non-simultaneous investment events and belong to this subsample. This last result tends to support the fact that the effect previously identified between digitalisation and increased productivity is causal.

Chart 8

Firm-level event studies for productivity in France for a subsample of non-simultaneous investment events



Source: Fiben dataset (France).
Note: Treated = top 10% - controlling for four-digit industry-by-year FE + firm FE.

2.4 Sector digital intensity and firm TFP growth

An alternative approach to the analysis of the impact of digitalisation on firms' TFP growth is the use of sector data on digital investments. As mentioned before, balance sheet data do not disentangle between office and IT equipment. One way around this drawback is to consider the average level of digital investment for the country, sector and year in which the firm operates.

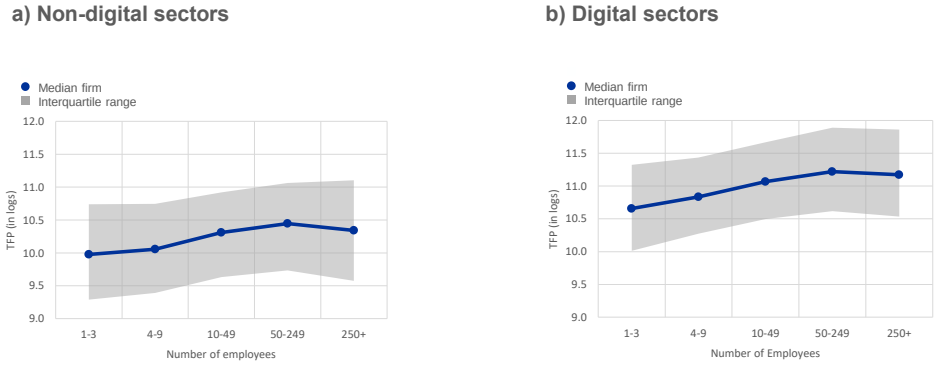
In this section, the empirical framework follows Anderton et al. (2023) and allows the impact of digitalisation to be separated from other possible determinants of productivity growth at firm level. These include technological diffusion from the productivity frontier to non-frontier firms, the catch-up effect whereby low-productivity firms tend to grow faster than their more productive counterparts, the role of market concentration in shaping TFP growth and the fact that firms have heterogeneous characteristics, which is tackled by including as controls the firm's employment levels and age and, on the financial side, the firm's leverage and liquidity ratio.[10]

At first glance, digitalisation seems to be a game-changer for TFP growth at firm level. Not only are firms in digital sectors unconditionally more productive than firms in non-digital sectors (Chart 9), but firms in digital sectors also improve on average their TFP at a faster pace than their less digital-intensive peers and seem to be relatively more insulated from downturns (Chart 10). However, the better than average performance of firms in the digital sector may be driven not by digitalisation itself, but by composition effects caused by distinct firm characteristics.

10 See Appendix C for more details of the empirical specification.

Chart 9

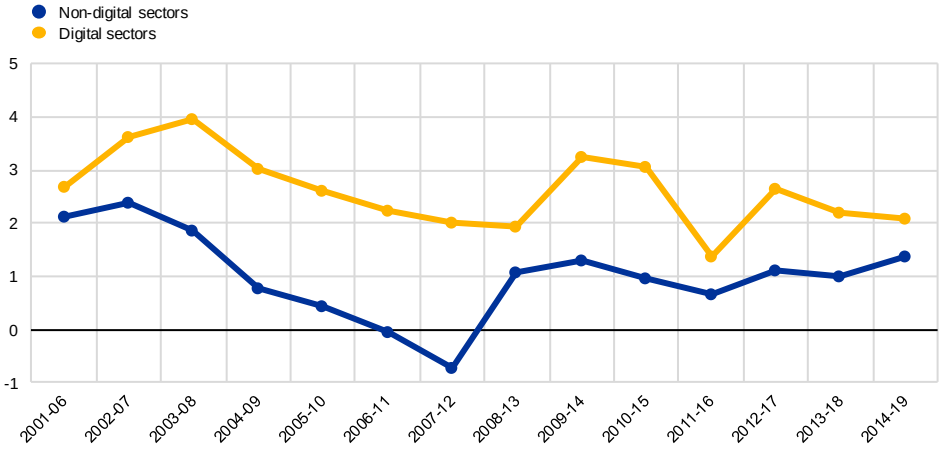
Interquartile range and median firm's TFP by size in (non-)digital sectors



Source: Anderton et al. (2023).

Chart 10

Average annualised five-year firm-level TFP growth rates in (non-)digital sectors



Source: Anderton et al. (2023).

The measures of digitalisation reflect digital investment intensities, i.e. the share of digital investment out of total investment for all firms in a given country, sector and year. Digital investment comprises both tangible (ICT equipment) and intangible (computer software and databases, and R&D expenditures) components. Furthermore, in order to account for how the relative price of digital technologies affects digital investment intensities and to assess whether some sectors exhibit digital investment intensities that are higher or lower than expected given the relative investment price of digital technologies, Anderton et al. (2023) use as a measure of digitalisation the intensity of digital investment that is not induced by variations in the relative price of digital technologies.

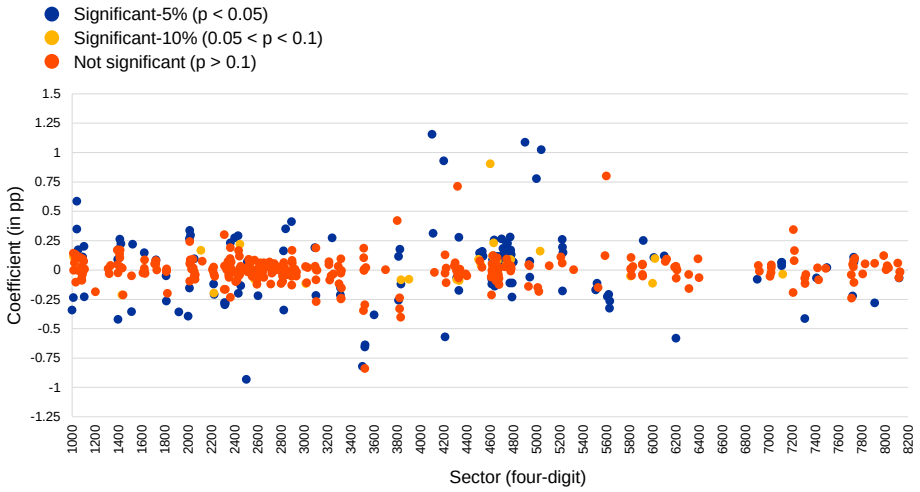
The benchmark empirical results indicate that, quantitatively, digitalisation boosts the average firm's productivity growth (Table C.1 in Appendix C). The estimates suggest that a 1 percentage point increase in digital investment intensity in the country, sector and year in which the firm operates is associated with an

acceleration in the average non-frontier firm's TFP growth by roughly 0.02 percentage points.[11] However, the magnitude of the impact of digital investment seems rather small, corroborating the notion that the productivity gains from digitalisation are relatively low, as is also the case for the aggregate economy (Anderton and Cette, 2021). Therefore, while digitalisation is shown to increase TFP growth on average, it does not seem to be a game-changer for firms' productivity.

Furthermore, the impact of digitalisation is very heterogeneous across sectors, and only in a few sectors do firms benefit significantly from it (Chart 11). We find that the average coefficient of sectors with a statistically significant and positive coefficient is 17 times larger than the average impact estimated across all sectors**.** Thus, only in some sectors do firms benefit on average from investing in digital technologies, and digitalisation is a game-changer only for a minority of selected firms. In this regard, the analysis unveils that the most productive 30% of non-frontier firms benefit the most from higher digital investment in terms of their TFP growth, controlling for the size of the firm and for other characteristics such as age, financials and sector (Chart 12). The firms closest to the frontier are a minority that manage to use these digital technologies in innovative and even disrupting ways to become substantially more productive over time. Indeed, these firms already have internal processes that are highly productive, and digitalisation is another advantage that gives them a competitive edge vis-à-vis their competitors.

Chart 11

Sector-specific impact of digitalisation on the average non-frontier firm's TFP growth (ε-residuals)

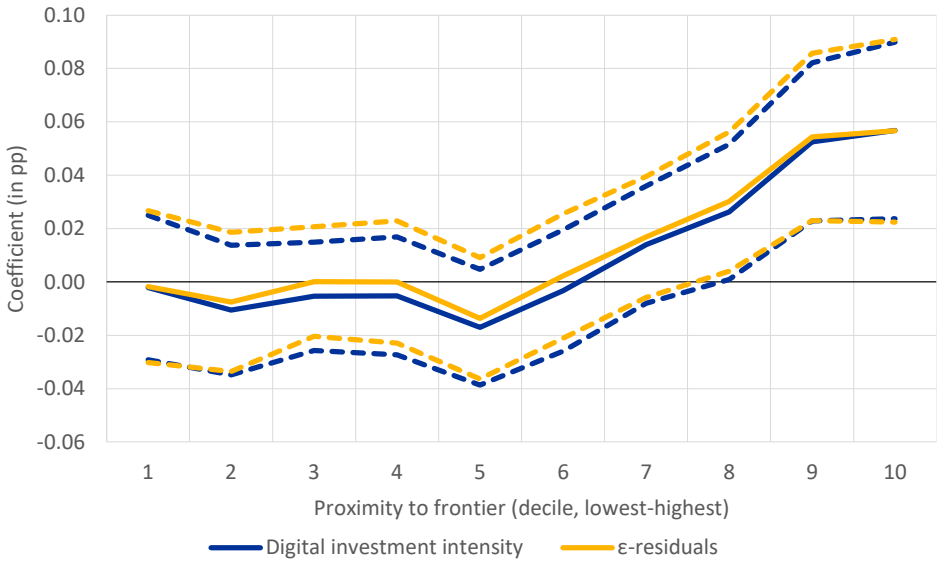


Source: Anderton et al. (2023)

[11] By comparison, the event studies regarding TFP at firm level in France estimated that a 1% increase in digital technologies led to a 0.007% increase in TFP after six years.

Chart 12

Marginal impact of digitalisation on non-frontier firms' TFP growth by proximity to frontier decile



Source: Anderton et al. (2023).

However, higher digital investment by itself is not enough to turn highly productive non-frontier firms into frontier firms. The reason is that frontier firms also benefit from digital technologies and are particularly adept at making full use of digital technologies by tracking and successfully implementing the innovations achieved by other frontier firms. Indeed, Chart 12 shows that TFP gains are larger the closer the firm is to the TFP frontier of the country and sector.

Overall, the results of Anderton et al. (2023) suggest that digitalisation does not tick all of the productivity boxes. While digital investment boosts TFP growth at firm level on average, not all firms and sectors experience significant productivity gains. Digitalisation seems to be a productivity game-changer only for some firms, while it is more like a productivity sideshow for other firms which invest in digital technologies but are not able to adequately reap the productivity benefits from digitalisation. Therefore, firms should not simply regard digitalisation as a game-changer or as a "one-size-fits-all" strategy that can deliver productivity gains for all firms alike.

Box 1

The impact of digitalisation on productivity and the role of input-output linkages

Prepared by Elisabeth Falck, Oke Röhe and Johannes Strobel (Deutsche Bundesbank) based on analyses presented in Deutsche Bundesbank (2023)

Despite the rapid spread of digital technologies, there is still an active debate about the extent to which digital transformation has contributed to aggregate labour productivity (LP) growth in advanced economies. The majority of existing studies on this topic focus on the role of

digital investments as a transmission mechanism.[12] Recent analyses, however, suggest that production networks may play a key role in the diffusion of technologies.[13] Since digital goods are significant intermediate inputs, this raises the question of how important input-output linkages are for the productivity-enhancing impact of digitalisation.[14]

The multi-sector dynamic stochastic general equilibrium model MuSe captures sectoral production linkages, enabling analysis of their macroeconomic implications.[15] In the MuSe model, sectoral output is used not only for consumption or investment purposes, but also as an intermediate input in various sectors of the economy.[16] Moreover, there is only limited substitutability between different intermediate inputs, and the bundle of intermediate inputs may vary across economic sectors.

In the MuSe model, digital transformation is triggered by total factor productivity (TFP) growth in digital sectors. An increase in sectoral TFP, ceteris paribus, lowers the marginal costs of firms in digital sectors, as production now takes place with smaller factor inputs.[17] The prices of digital goods fall as a result. This, in turn, stimulates demand for these goods for consumption and investment purposes and as intermediate inputs. As far as possible, products from non-digital sectors are replaced by comparatively cheaper digital goods. However, demand for other goods also increases due to complementarities. The growth in production in non-digital sectors calls for increased use of factors of production, which, when viewed in isolation, drives up factor prices, marginal costs and output prices.

The role of digitalisation in LP growth is assessed in counterfactual analyses. The model specification used here covers 19 economic sectors and was specified for each of the three largest euro area economies as well as the United States.[18,19] Under the reference scenario, TFP paths for all sectors, which were estimated in a separate analysis and span the period 1997-2018, are fed into the MuSe model.[20] The development of TFP in the "digital sectors" thereby serves as an

12 See, inter alia, Byrne et al. (2013), Cette et al. (2015) and Anderton and Cette (2021).

13 For a more detailed discussion of the prominent role of input-output linkages, see, inter alia, Foerster et al. (2022) and vom Lehn and Winberry (2022).

14 In the United States, Germany, France and Italy, at least 50% of the goods produced in digital sectors (NACE divisions C26-C27 and section J) are used as production inputs (World Input Output Database, vintage of 2000).

15 MuSe is a variant of the environmental multi-sector DSGE model EMuSe, which does not include an environmental module. A detailed description can be found in Hinterlang et al. (2021, 2022, 2023).

16 The MuSe model is an extension of prototypical models, where production is usually used only for consumption or investment purposes, as capital and labour are the only factors of production. See, inter alia, Christiano et al. (2018).

17 The transmission channel of TFP growth in digital sectors described here is transferable to the other sectors depicted in the model.

18 The model bundles NACE divisions C26-C27 (manufacture of computer, electronic and optical products and electrical equipment) and section J (information and communication) into one sector. The other sectors in the model are NACE divisions C10-C12, C13-C15, C16-C18, C20-C21, C22-C23, C24-C25, C28, C29-C30 and C31-C33 as well as sections D-E, F, G, H, I; K, M, N and R-S. For a detailed description of the NACE classification, see Eurostat (2008).

19 External trade links are excluded for the purposes of simplification. The production structure of the countries under review is modelled using country-specific datasets from the World Input-Output Database (WIOD). For more information on the WIOD, see Timmer et al. (2015).

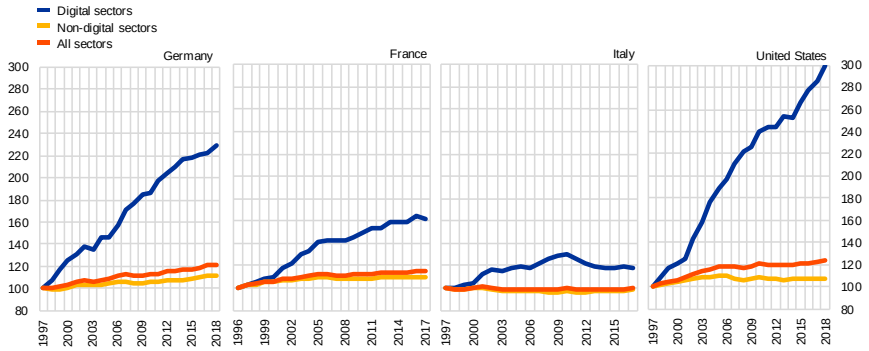
20 The TFP calculations are based on data from the EU KLEMS database. To obtain precise estimates of TFP a two-step approach is used, which extends standard growth accounting techniques by additionally controlling for the degree of utilisation of the factors of production; see Deutsche Bundesbank (2021, 2023). For Italy, the TFP series end in 2017.

indicator for the efficiency gains made possible by digitalisation (Chart A).[21,22] Under the counterfactual scenario, it is assumed that TFP in digital sectors is constant. The contribution of digital sectors to LP growth is then calculated as the difference between the two scenarios.

Chart A

Total factor productivity between 1997 and 2018*

(1997=100, log scale)



Sources: EU KLEMS, European Commission and Bundesbank calculations.
Notes: * Calculated using a prototypical Solow decomposition and an econometric model to adjust for changes in the degree of capacity utilisation. 1 NACE divisions C26-C27 (manufacture of computer, electronic and optical products as well as electrical equipment) and NACE section J (information and communication). 2 NACE sections D, E, F, G, H, I, K, M, N, R-S and NACE section C (excluding divisions C26-C27 and C19). 3 Digital and non-digital sectors. 4 Series for Italy end in 2017.

The MuSe model replicates the actual path of LP in the countries under review quite well (Chart B).[23] This is noteworthy given that LP developments in this group of countries varied substantially in some cases. LP rose considerably more strongly in the United States than in the euro area countries. Among the latter, productivity growth in Germany and France was more dynamic than in Italy.

Without TFP growth in digital sectors, LP growth would be considerably weaker. Digital sectors cumulatively contributed about 70% of aggregate LP growth in the United States between 1997 and 2018 (Chart B). Put differently, around seven-tenths of productivity growth would be lost without TFP growth in these sectors, despite the fact that they account for a relatively small share of aggregate gross value added. In Germany and France, LP growth would have been about 50% and 40% lower without digitalisation-related efficiency increases respectively.[24] Aggregate LP in Italy would have stagnated. Overall, the simulation results highlight the high impact of TFP growth in

21 Here, the digital sectors comprise the economic sectors “Manufacture of computer, electronic and optical products” (NACE division C26), “Manufacture of electrical equipment” (NACE division C27) and “Information and communication” (NACE section J).

22 The simulation results are driven exclusively by the interplay between TFP paths in the individual sectors.

23 We also performed a simulation exercise for the Spanish economy (see Deutsche Bundesbank, 2023). For Spain, however, the model deviates noticeably in some parts from the actual path of LP. One reason for this is probably the fact that LP in Spain increased considerably as a result of the disproportionately large reduction in labour input in the wake of the global financial and economic crisis and the subsequent sovereign debt crisis. However, this dramatic development is not triggered by TFP and therefore cannot be inferred from the model. See also Deutsche Bundesbank (2021).

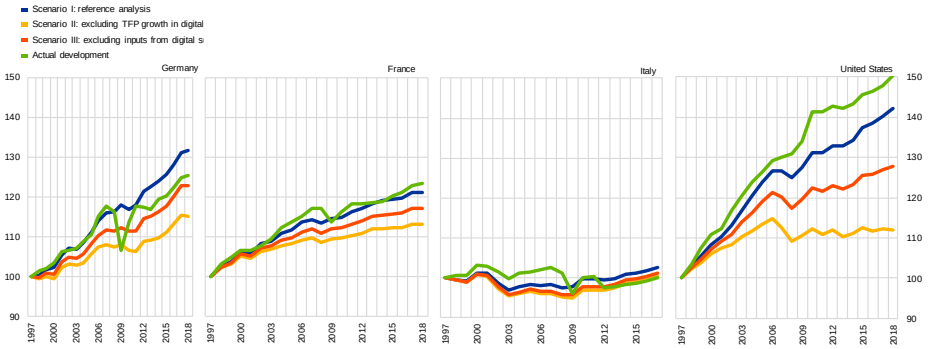
24 One could wonder to what extent we can reconcile the large productivity impact of digitalisation found by this model with the small elasticities estimated in Section 2.3. However, these two exercises are very different, in the sense that the micro-distributed exercise estimates the effect of an investment in digital technologies on LP for incumbent firms. This does not take account of entry and exit and other equilibrium effects. These reasons may explain the significant differences between micro estimates and macro effects on LP.

digital sectors, indicating that less dynamic TFP growth in digital sectors – alongside a consistently weak impetus from other economic sectors – would have significant consequences.

Chart B

Role of digital sectors in aggregate labour productivity*

(1997=100, log scale)



Sources: EU KLEMS, World Input-Output Database and Bundesbank calculations.
Notes: * The simulations are based on a multi-sector DSGE model. The simulation period covers the years 1997 to 2018 for Germany, France, Spain and the United States and 1997 to 2017 for Italy. The digital sector comprises NACE divisions C26-C27 (manufacture of computer, electronic and optical products and electronic equipment) and NACE section J (information and communication). NACE sections C (excluding divisions C26-C27 and C19), D-E, F, G, H, I, K, M, N and R-S are also covered. 1 Depicts LP developments based on the sectoral TPF paths and a model version with 19 sectors. 2 Aggregate hourly LP of the 19 sectors on which the reference analysis is based.

Input-output linkages prove to be an important transmission channel for digitalisation. To highlight the specific importance of input-output linkages for the transmission of digitalisation, a further scenario assumes that digital goods are used exclusively for consumption or investment purposes and not as intermediate inputs.[25] According to the simulation results, digital inputs play a key role in aggregate productivity growth (Chart B). Productivity gains in the United States, Germany and France in particular would have been significantly lower under scenarios where digital inputs were disregarded, but the transmission channel was still important in Italy as well.

[25] To this end, digital goods are excluded from the intermediate input bundles of all sectors.

3 Institutions, skills and complementary investments and productivity gains from digitalisation

Section 2 provided evidence of the productivity effects of digitalisation. However, as stated by the literature and also by some of the analyses presented here, firms and countries need to invest in complementary capabilities in order to reap the full benefits of digitalisation. This section focuses on the role of quality institutions, investment in intangible assets and worker skills.

3.1 Institutions, technology diffusion and productivity[26]

This subsection focuses on institutions and governance as one example of the complementary capital required for digital technology to display the associated productivity gains.[27] As noted by Anderton et al. (2020a) and also in the introduction to this report, digital technology, like other GPTs, requires a sufficiently high stock of complementary capital, including specialised physical, human and managerial capital, to be fully operational. Like other GPTs, digital technologies may therefore be subject to implementation lags (in the case of electricity, it took more than 30 years for the diffusion midpoint to be reached), and the benefits may take longer to fully materialise.

Theoretically, institutions and governance might be expected to support technology diffusion, raising efficiency and reducing uncertainty – especially if they interact. This was emphasised, for example, by North (1991), who pointed out that institutions play a substantial role in shaping modern economies and are important (positive or negative) drivers of growth. Institutions, therefore, should be taken into account when modelling growth, even if they may be considered "background forces" supporting the basic neoclassical model rather than core elements.

New evidence from Labhard and Lehtimäki (2022) suggests that quality institutions/governance support digitalisation diffusion and thereby EU productivity growth. The effects of institutions and governance and their interaction with digitalisation are more significant when looking at TFP than GDP per employee (Table 1 below). When split between the long run and the short run, the effects of digitalisation and institutions/governance are far more important in the long run (Table D.1 in Appendix D).[28] This implies that there are potential long-term

[26] Acknowledgements: this section has been prepared in collaboration with J. Lehtimäki (University of Turku).

[27] Somewhat related to this is the political environment, as stressed for example by Milner (2006).

[28] Similar effects were observed for the EU by Labhard and Lehtimäki (2022) in their study looking at economic growth effects of digital technologies and institutions and governance.

productivity-enhancing effects to be gained from developing institutions and governance as well as from introducing digital technologies, which might not be evident in the short run.

The COVID-19 pandemic might have affected the potential links between institutions and productivity as well as accelerated the diffusion of digital technology. The approach adopted in this section is based on annual data and so only reveals effects with a delay. However, the acceleration in digitalisation during the pandemic appears to have been concentrated on connectivity (see https://digital-strategy.ec.europa.eu/en/policies/desi), and so is captured by the measures of digitalisation used in this approach (internet and broadband).

Table 1

Effects of institutions and governance on productivity (summary of results)

	Real GDP per employee				Total factor productivity			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
PMG estimation (long run)								
Institutions								
WGI total	+/-	+/-	+***	+/-	+***	+***	+***	+***
Digitalisation*WGI total	..	..	-***	+/-	..	..	+***	+***
PMG estimation (short run)								
Institutions								
WGI total	+***	+/-	+/-	+/-	+/-	+/-	+**	+/-
Digitalisation*WGI total	..	..	+/-	+/-	..	..	-**	+/-
Fixed effects estimation								
Institutions								
WGI total	+/-	+/-	+/-	+/-	+*	+**	+*	+**
Digitalisation*WGI total	..	..	+/-	+/-	..	..	+/-	+/-

Source: Authors' calculations.
Notes: Signs and significance of the effects of institutions and governance, including the interaction with digitalisation, on productivity growth, based on pooled mean group (PMG) and fixed effects (FE) estimates. *** significant at 1% level, ** significant at 5%, * significant at 10%. The shaded estimates and associated standard errors pertain to the coefficients that capture the effects of institutions and governance, and the interaction with digitalisation, and signal productivity-enhancing effects and are significant. The exact specifications are detailed in equation (1) (PMG) and equations (2) and (3) in section 4 and of Labhard and Lehtimäki (2022).

3.2 Complementary worker skills and the impact of digitalisation on the labour market

The recent emergence of AI has revived the debate about the potential impact of technologies on jobs. AI breakthroughs include advancements in robotics, supervised and unsupervised learning, natural language processing, machine translation and image recognition, among many other activities that enable automation of human labour in non-routine tasks, both in manufacturing and also services (e.g. medical advice or writing code). AI is thus a GPT that could affect work in virtually every occupation.

AI-enabled automation may lead to a displacement of workers, i.e. replace existing jobs, but could also create new jobs through reinstatement and through employment gains stemming from higher productivity. The overall

impact on wage inequality depends on the changes in the relative shares of jobs along the skill distribution.

The existing evidence on the overall effect of new technologies on employment is mixed. Much of the recent literature, focusing on the United States, estimates that automation has a positive net effect on the total number of jobs but tends to reduce the number of low-skill jobs. By contrast, some recent work for France highlights that the introduction of automation can also have a positive effect on the employment of unskilled industrial workers. The benefit for low-skilled workers is mostly driven by aggregate productivity gains in the French manufacturing sector that are shared between workers and firm owners, as shown in Aghion et al. (2022).

For Europe, ongoing work by Albanesi et al. (2023) examines the link between labour market developments and new technologies such as AI[29] in 16 European countries over the period 2011-19. The work uses data at the three-digit occupation level according to the International Standard Classification of Occupations and two proxies for potential AI-enabled automation, borrowed from the literature. These proxies are (i) the so-called occupational AI impact (AIOI) created by Felten et al. (2018) and Felten et al. (2019), which links advances in specific AI applications to workplace tasks and occupations; and (ii) a measure of the exposure of tasks and occupations to AI constructed by Webb (2020), using information on job task descriptions and the text of patents.

Albanesi et al. (2023) find a positive association between AI-enabled automation and changes in employment shares in the pooled sample of European countries, regardless of the proxy used. In Chart 13, the horizontal dotted line displays the estimated coefficient for the whole sample. According to the AI exposure indicator proposed by Webb, on average in Europe, moving one decile up along the distribution of exposure to AI is associated with an increase in the sector-occupation employment share of 1.04%, while using the measure by Felten et al., the estimated increase in the sector-occupation employment share is 1.7%. The positive association supports the idea that in Europe, automation enabled by the adoption of AI would not result in lower aggregate employment.

Technology-enabled automation may also induce changes in the relative shares of employment along the skill distribution and thus affect earnings inequality. The literature on job polarisation shows that medium-skilled workers in routine-intensive jobs will be replaced by computerisation. By contrast, it is often argued that AI-enabled automation is more likely to complement or replace jobs in occupations that employ high-skilled workers.

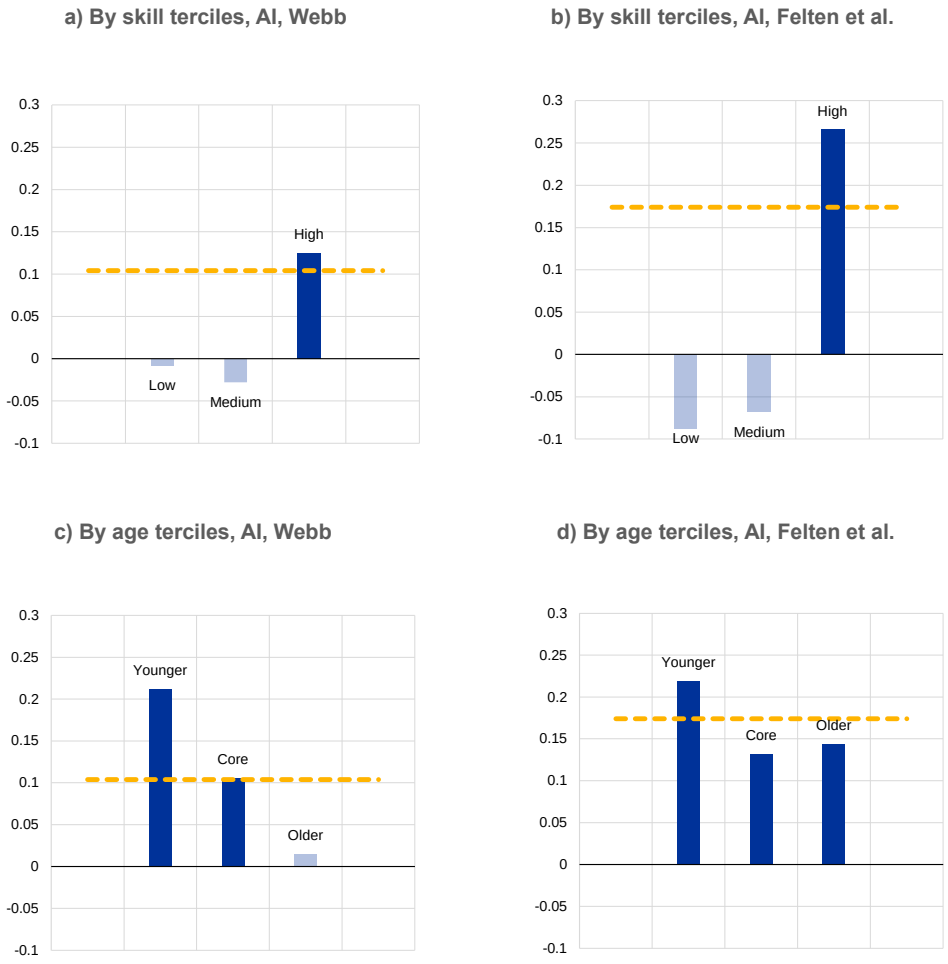
Albanesi et al. (2023) rank the sector-occupation cells within each country by age and skill terciles in the initial year of the sample. They name this first tercile “younger”, the second “core” and the third “older”. Similarly, with skills, each tercile consists of these sector-occupation cells whose average educational attainment is in the low, medium and high tercile, respectively, of a country’s education distribution.

[29] Albanesi et al. (2023) also provide results for software-enabled automation.

The height of the green bars in panels a) and b) of Chart 13 displays the estimated coefficients of the association between changes in employment and AI-enabled automation for the terciles of occupations that employ low, medium and high-skilled workers. Significant coefficients are plotted in dark shaded colour.

Chart 13

Exposure to AI and changes in employment share, by skill and age



While there is no significant change in employment associated with AI for the low and medium skill terciles, for the high skill tercile there is a positive and significant association: moving one decile up along the distribution of exposure to AI is estimated to be associated with an increase in the sector-occupation employment share of 1.25%, using Webb's AI exposure indicator, and 2.66%, using the measure proposed by Felten et al. These estimates show that the positive relationship between AI-enabled automation and employment growth uncovered for the pool of countries is driven by jobs that employ high-skilled workers.

Panels c) and d) in Chart 13 show the estimates by age groups, according to which AI-enabled automation appears to be more favourable for those occupations that employ relatively younger workers. Regardless of the AI

indicator used, the magnitude of the coefficient estimated for the younger group is twice that of the rest of the groups. AI-enabled automation in Europe is thus associated with employment increases, particularly for occupations with relatively higher skills and younger workers.

Across countries, one would expect the impact of these technologies to vary depending on their distribution of employment across sectors and occupations that are differently exposed to the technologies. However, Albanesi et al. (2023) report that while there is heterogeneity in the magnitude of the estimates, the relationship between AI and employment also tends to be positive at country level.

Box 2

The return on human (STEM) capital in Belgium (Bijnens and Dhyne, 2021)

Prepared by Gert Bijnens

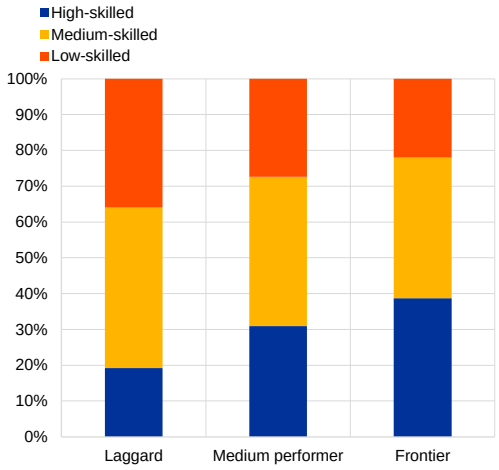
Human capital, especially related to science, technology, engineering and mathematics (STEM) fields, will become even more relevant as digitalisation accelerates. The NextGenerationEU recovery package rightly places significant emphasis on research, innovation and digitalisation. The need for skilled people to deliver on these promises, however, has received little attention. Stimulating demand for innovation without addressing the supply of skilled workers may simply result in higher wages for the high-skilled rather than additional innovation. While the number of tertiary education graduates in Belgium has risen steadily over the past decades and is above the EU28 average, the number of such graduates in STEM fields is below the EU28 average. At the same time, Belgian firms have a greater need for ICT specialists, for instance. The combination of these factors has led to a steep increase in the number of firms with hard-to-fill vacancies for such jobs. If firms cannot find the human capital they need to implement and take advantage of new digital technologies, this is likely to have an impact on productivity.

We make use of linked employer-employee data and focus on the full Belgian universe of firms with ten employees or more. We studied approximately 1.5 million workers and 20,000 firms over the period 2000-18. The human capital of a firm is proxied by the skills of its workforce. The skill level of an employee is based on educational attainment and categorised as high (tertiary education), medium (upper secondary education and post-secondary non-tertiary education) and low (lower secondary education or below). Firms are divided into productivity groups based on their position within the productivity distribution of their industry. We focus on the top performers or “frontier firms” (top 10%), medium performers (40-60%) and low performers or “laggards” (bottom 10%). Productivity is measured via labour productivity (LP) (euro per hour worked).

The productivity gap between a frontier and laggard firm has increased simultaneously with the human capital gap. A frontier firm is more than twice as productive as a medium performer and almost five times as productive as a laggard firm. On average, the share of high-skilled workers as a percentage of total workers in a frontier firm is currently close to 10 percentage points higher than in a medium performer and 20 percentage points higher than in a laggard firm (Chart C). The larger share of high-skilled workers in frontier firms is mainly compensated by a smaller share of low-skilled workers. Close to 10% of the Belgian population aged 18-25 does not hold a secondary education certificate and is not in further training or education. We find that job opportunities for the lowest-skilled workers are mainly available in the least productive firms.

Chart C

Human capital profile of a typical firm

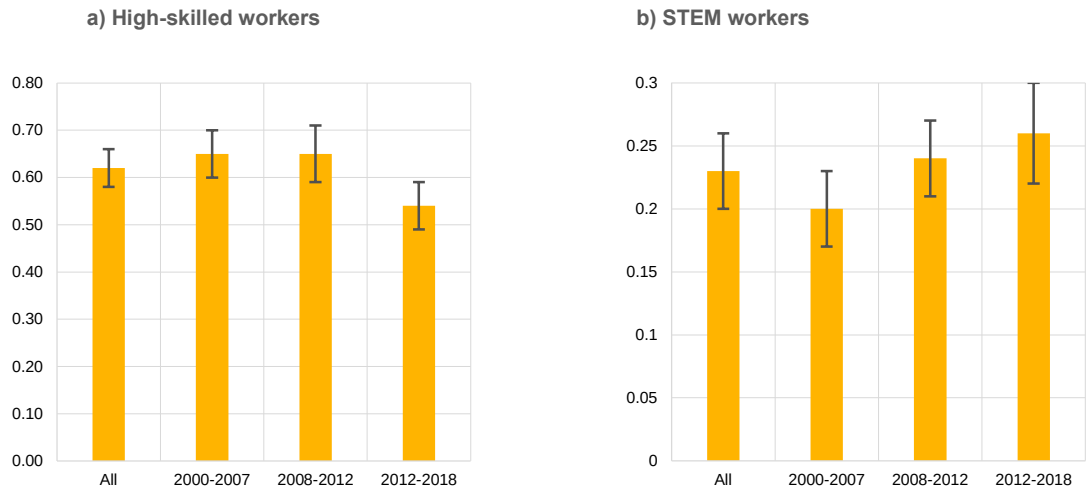


Note: Employment share of high, medium and low-skilled employees for laggard firms, medium performers and frontier firms, using simple averages across all two-digit sectors and over time.

The impact on productivity of increasing the share of high-skilled workers has decreased over time. A 10 percentage point increase in a firm's share of high-skilled workers is correlated with an increase in productivity of 2% (for knowledge-intensive services), 6% (for manufacturing) and 7% (for less knowledge-intensive services). For all sectors combined, a 10 percentage point increase in the share of high-skilled workers was linked to an increase in productivity of 6.5% for the period 2000-07 and 5.5% for the period 2012-18 (Chart D, panel a). The reason for this declining marginal productivity of skills could be that the overall number of high-skilled workers is increasing and the additional benefits of continuing to add high-skilled workers decrease the more high-skilled workers a firm already employs.

Chart D

Elasticity of firm-level productivity as a function of the share of high-skilled and STEM workers



Notes: Based on regressing firm-level LP on the share of high-skilled workers (panel a) and STEM workers (panel b), while controlling for a wide array of firm characteristics and fixed effects. The brackets mark the 95% confidence intervals.

Increasing automation and digitalisation requires workers with STEM skills. Although Belgium performs relatively well with respect to tertiary education graduates, its performance is poorer with respect to STEM graduates. For the manufacturing industry and less knowledge-intensive services, we observe a clear, positive link between productivity and the share of STEM workers. For knowledge-intensive services, only laggard firms employ a smaller proportion of STEM workers, and we see little difference between frontier firms and medium performers.

The impact of STEM workers on productivity is increasing. For STEM workers (high, medium and low-skilled), we find that a 10 percentage point increase in their share of a firm's workforce is linked to a 2.5% (manufacturing) or 4% (less knowledge-intensive services) increase in the firm's productivity. But more importantly, unlike the impact of high-skilled workers, which has decreased over time, the impact of STEM workers on productivity is increasing (Chart D, panel b). The average impact on productivity across all sectors combined of a 10 percentage point increase in the share of STEM workers has risen from 2.0% (2000-07) to 2.6% (2012-18). This could be linked to the increasing importance of digital technology for productivity.

Increasing the share of high-skilled STEM workers leads to significantly higher productivity gains, not only compared with non-high-skilled STEM workers, but also compared with high-skilled non-STEM workers. For a typical manufacturing firm, the gains from increasing the share of high-skilled STEM workers by 10 percentage points is linked to an increase in productivity of about 20% or approximately 3 to 4 times more than the gains from a 10 percentage point increase in the share of high-skilled non-STEM workers. The growing difficulty that Belgian firms experience in recruiting specialists with ICT skills is therefore likely to have a significant negative impact on productivity.

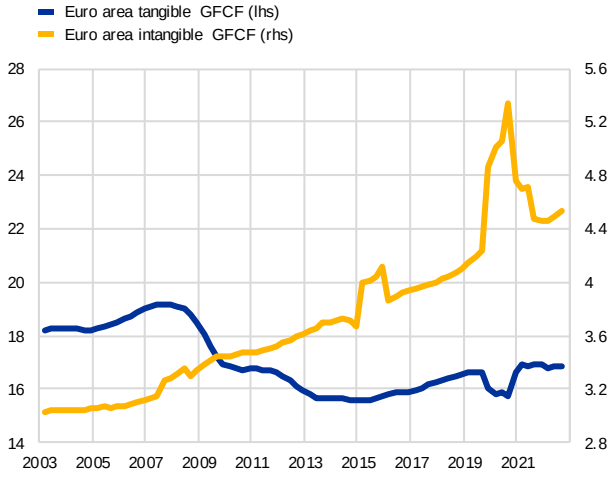
3.3 Complementary investment in intangible assets

The rise in intangible investment reflects, among other things, the digital transformation of the euro area economy. Intangible assets are a heterogeneous group of corporate expenditures with threefold relevance for the digital transition. First, they contain computerised information, i.e. software (both standard and tailor-made), and databases. Second, they include innovative property, R&D expenditure and patents, some of which constitute new digital technology.[30] Third, they may be needed to reap the benefits of new digital technologies. One example of the latter is AI, which requires access to databases. Euro area total investment in intangible assets is recorded in quarterly national accounts. Overall, it has increased much more than investment in tangible assets over the last two decades (Chart 14), and this has been the case across all countries. Positive effects of investment in intangible assets on TFP can be expected, among other things, due to two specific properties of intangible capital which set it apart from tangible capital. First, some intangible assets can be scaled at very little or no cost. An existing corporate database, for example, can be used for additional business processes, whereas expanding tangible capital requires additional investment. Second, whereas tangible investment, e.g. in equipment for production, is typically used by the investor only, some intangible assets, e.g. a new production method resulting from R&D activity, can be shared (for example, against a licence fee). Therefore, intangible assets may not only support a firm's TFP growth, but also have significant potential to create spillovers between firms and sectors.

[30] Another group of intangible assets relevant for the digital transition, which are typically not recorded on corporate balance sheets and are therefore excluded from our analysis, are economic competencies. These comprise brand names, trademarks, firm-specific human capital (for which digital skills matter; see Box 2) as well as managerial skills and organisational know-how.

Chart 14

Euro area (excluding Ireland) tangible and intangible gross fixed capital formation (as a percentage of GDP)



Sources: Eurostat and own calculations.
Note: Numbers exclude Ireland, for which there have been huge intangible investments reflecting the activity of multinational enterprises.

This section discusses how the increasing importance of intangible investment may have affected aggregate TFP dynamics in the euro area. TFP dynamics across firms are uneven in the euro area. In line with previous papers such as Andrews et al. (2019) and Anderton and Cette (2021), we document how the wedge in TFP levels between high-productivity firms (frontier firms) and low-productivity firms (laggards) has been widening over the sample period 2003-19. In other words, firms with much lower than average levels of TFP have seen lower TFP growth than the average firm, while firms with above-average TFP levels at the beginning of the sample have also seen above-average TFP growth (Appendix E). The fact that the wedge is particularly large in ICT-producing/using manufacturing industries[31] compared with non-ICT-using industries indicates that digitalisation may have played an important role in giving rise to these divergences.

For this purpose, the analysis uses a micro dataset from Orbis and iBACH. The dataset includes six euro area countries (Germany, France, Italy, Spain, Belgium and Portugal) over the period 2003-19 and the two-digit sector level. In the empirical specification, TFP growth of a firm is regressed on its intangible intensity, measured as the share of intangible assets in total assets in the previous period, as well as the intangible intensity of the sector at the regional level, to capture possible spillovers between firms.

The analysis suggests that, controlling for other factors, intangible capital has contributed to an increase in the TFP wedge across firms in the euro area. While, on average, higher intangible intensity significantly boosted TFP growth over the sample period, its productivity benefits were significantly lower for laggard firms (see fourth and fifth set of rows in Table 2). There is large cross-country variation in the effect (see first row in Table 2). There is also evidence of positive spillover

31 This classification is based on Calvino et al. (2018).

effects from high sectoral intangible intensity, with at least weak significance in four of the six countries (see second set of rows in Table 2).

Table 2

Panel regression of TFP growth on intangible investment and controls across six euro area countries

	DE	IT	FR	ES	PT	BE	Pooled
IKa-lag	0.141***	0.305***	0.235***	0.0406***	0.370***	0.227***	0.258***
	(-0.0476)	(-0.0138)	(-0.0151)	(-0.011)	(-0.0368)	(-0.0617)	(-0.00971)
IKa region-lag	0.0602	0.730***	0.0135	-0.257***	0.845***	-0.015	0.0649***
	(-0.102)	(-0.0471)	(-0.0177)	(-0.0536)	(-0.105)	(-0.135)	(-0.0188)
Laggard	-0.242***	-0.381***	-0.254***	-0.443***	-0.531***	-0.189***	-0.538***
	(-0.0165)	(-0.00633)	(-0.00441)	(-0.0158)	(-0.025)	(-0.017)	(-0.00408)
IKa-lag x laggard	-0.151	-0.160***	-0.130***	-0.263***	-0.108	0.198	-0.239***
	(-0.17)	(-0.0332)	(-0.018)	(-0.0381)	(-0.0767)	(-0.169)	(-0.0177)
IKa region-lag x laggard	-0.163	-1.315***	-0.139***	-1.265***	-1.414***	-0.257	0.702***
	(-0.262)	(-0.103)	(-0.0267)	(-0.097)	(-0.244)	(-0.285)	(-0.0238)
Market concentration	-0.0373	-0.00813	0.123***	0.514***	0.0574**	0.0828***	0.356***
	(-0.0251)	(-0.0146)	(-0.00827)	(-0.0199)	(-0.0291)	(-0.0258)	(-0.0207)
TFP distance to frontier	-9.77e-07***	-2.36e-05***	-1.15e-05***	-6.04e-06***	-9.45e-06***	-7.99e-07***	-9.44e-06***
	(-0.000000162)	(-0.000000824)	(-0.000000299)	(-0.000000267)	(-0.00000184)	(-0.000000118)	(-0.000000686)
TFP growth at frontier	0.0243***	0.0282***	0.0454***	0.0174***	0.0163***	0.0279***	0.0448***
	(-0.00211)	(-0.00099)	(-0.00173)	(-0.00131)	(-0.00191)	(-0.00444)	(-0.00163)
Return on assets	0.738***	1.188***	0.000137	0.223	0.708***	1.044***	0.000611
	(-0.127)	(-0.0533)	(-0.000117)	(-0.152)	(-0.163)	(-0.105)	(-0.000631)
Value added growth	0.448***	0.362***	0.491***	0.323***	0.220***	0.0856***	0.345***
	(-0.019)	(-0.0128)	(-0.0115)	(-0.0179)	(-0.0145)	(-0.0173)	(-0.00845)
Constant	0.344***	0.358***	0.283***	0.249***	0.195***	0.117***	0.424***
	(-0.0452)	(-0.0101)	(-0.00646)	(-0.00757)	(-0.0132)	(-0.0352)	(-0.0155)
Observations	126,028	2,273,330	977,983	1,471,797	289,993	54,753	3,722,087
R-squared	0.092	0.127	0.104	0.093	0.096	0.086	0.077
Number of panels	22,519	481,705	221,398	333,244	76,239	9,496	811,357
Size class	YES	YES	YES	YES	YES	YES	YES

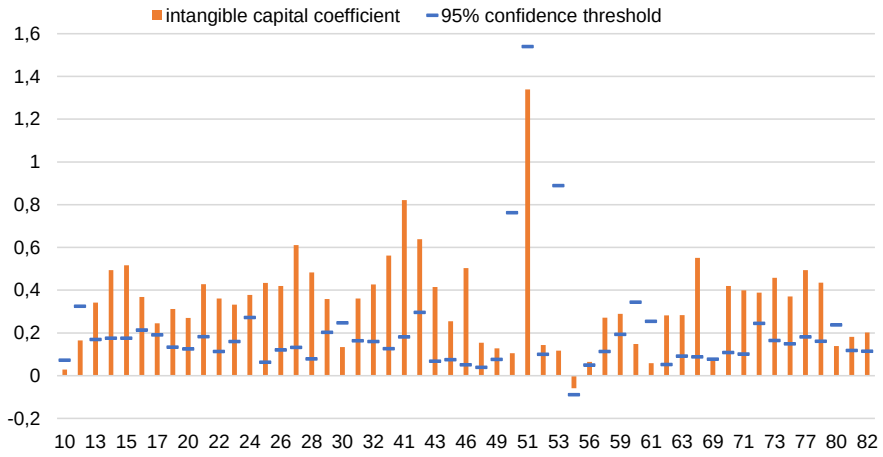
Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Sources: Eurostat and own calculations.

Consistent with the findings in Section 2 of this report, we observe that intangible intensity contributes significantly more to TFP growth in ICT-intensive manufacturing sectors. To be more certain that the positive impact of intangible assets on TFP growth is related to digitalisation, the empirical specification is run separately for each NACE2 sector covered by the analysis (Chart 15). It turns out that the positive effect of intangible capital on TFP growth is most pronounced in the manufacturing of machinery and equipment, construction, wholesale trade, air transport and a few business services such as advertising and market research. The manufacturing sectors where there is a strong impact from intangible assets are all ICT-producing or ICT-using sectors, with the exception of clothing and footwear manufacturing. Furthermore, in these very sectors, laggard firms benefit much less from intangible assets than the average firm.

Chart 15

Impact of intangible intensity on TFP growth across NACE2 sectors (percentage points)



Sources: Eurostat and own calculations.

There is stronger evidence of gains from intangible investment in computerised information than research and development. When looking at intangible assets, it is also relevant to acknowledge whether firm-specific deployment of digital technology or something else has boosted TFP growth in the sample. Unfortunately, as mentioned above, the breakdown of firm-specific intangible investment into software and databases and R&D or other innovative property is not available in the balance sheet data. However, a very rough proxy of this breakdown is generated by applying the country/sector-specific shares of computerised information and innovative property for the respective year to the intangible investment of each firm in the country/sector, i.e. assuming that they are the same across all firms in the sector. With that, instead of total intangible assets, it is possible to estimate the separate effects of innovative property (RD) and software and databases (SOFT) on firm TFP growth, keeping the control variables. The results in Table E.1 of Appendix E indicate at least mildly significant effects of computerised information in all countries but Germany, and the effects are clearly larger than for innovative property, except for Belgium.[32] Furthermore, for all countries where significant effects are found, these are noticeably reduced for laggard firms. This may be related to the lack of complementary skills in these firms, such as digital skills of the workforce and management and organisational skills, which prevent them from deriving the benefits from these digital technologies.

Overall, investment in intangible assets, also reflecting the ongoing digitalisation of the corporate sector, has had a significant positive impact on TFP growth, while the uneven distribution of intangible assets may have contributed to the observed wedge in TFP dynamics across firms. Investment in computerised information at low-TFP firms would need to be coupled with support for firms to develop the complementary skills required to use digital technology. This

[32] This also relates to the fact that R&D may take more time to result in deployment of an innovation at firm level that increases productivity.

would boost aggregate TFP growth and contribute to making growth in the euro area more inclusive.

4 Conclusions and policy discussion

This report provides empirical evidence that the adoption of digital technologies leads to an increase in firms' productivity in the medium term. This is true for digital technologies in general, but also for specific technologies like AI. However, not all firms and sectors experience significant productivity gains from digital adoption, and not all digital technologies deliver similar productivity gains.

The report includes different estimations of the productivity effects of digital uptake at firm level. Studies differ in terms of approach and, most importantly, in how they measure firm-specific digitalisation, given the scarcity of available data. The order of magnitude of estimates in this report indicates that a 1% increase in digital technologies leads to an almost 0.01% increase in TFP level after five years. Similarly, a 1 percentage point increase in digital investment is associated with an acceleration in the average firm's TFP growth by roughly 0.02 percentage points. This average impact is, however, different across countries, sectors and firms because it depends on complementary investments.

Indeed, the productivity gains from digital technologies could be larger than they have been until now. Institutions, policies and worker skills should be adapted in order to promote and ease the diffusion of digital technologies among firms (and especially among small firms); research in innovation should be encouraged, among other things.

A lack of strong institutions and governance structures may help to explain why digital diffusion is proceeding slower than expected, why it is slower in some countries than others and why the expected productivity benefits from digitalisation have yet to be fully achieved. It is therefore worth working towards strong institutional and governance structures in EU countries, inter alia, to enhance the productivity benefits of digital technologies. This can be achieved, for example, in the context of country monitoring and surveillance mechanisms.

Results for Belgium suggest that, to ensure government efforts to increase firms' adoption of the latest technologies and business practices lead to sustainable productivity gains, such actions should be accompanied by measures to increase the supply and mobility of human (STEM) capital. Indeed, the full benefits of the digital revolution will be reaped by properly supplying skills to firms.

Investment in computerised information at low-TFP firms would need to be coupled with support for firms to develop the complementary skills required to use digital technology. This would boost aggregate TFP growth and contribute to making growth in the euro area more inclusive.

The effects of digitalisation on productivity, which have been described in this report, can affect monetary policy via a number of channels. Because productivity is an important determinant of the potential growth, it contributes

significantly to the size of the output gap and, therefore, to the assessment of inflationary pressures. An underestimation of the effect of digitalisation on potential output could lead to an overestimation of the risks of inflationary pressures and contribute to an overly restrictive monetary policy stance. Productivity growth also affects monetary policy indirectly, through its effect on the natural rate of interest. Depending on the future impact of digitalisation on productivity, monetary policy will have more or less room for manoeuvre: if productivity growth were to rise with increasing digitalisation in the following years, it would raise the natural rate of interest and give monetary policy more room for manoeuvre. That is why it is crucial to understand these channels of impact and how to maximise them.

Appendix

A Description of the OECD/INFE survey to measure the financial literacy of micro, small and medium-sized enterprises

The Survey Instrument to Measure the Financial Literacy of MSMEs was designed by the OECD/INFE through an iterative process in 2017 and 2018 and was revised after a pilot test in seven volunteering countries in 2018-19. The questionnaire was ultimately revised again in 2020 to take into account the implications of the COVID-19 crisis for small enterprises and so that it could be used under the circumstances of limited physical contact (by telephone or online). Country participation in the data collection was voluntary and included G20 countries (Brazil, China, France, Germany, Italy, Mexico, Russia, Saudi Arabia and Turkey) and non-G20 countries (Georgia, the Netherlands, Peru, Portugal and Spain). The euro area countries included in the survey are France, Germany, Italy, the Netherlands, Portugal and Spain. The OECD required around 1,000 completed surveys for each country. The survey includes a series of questions aimed at measuring enterprises' financial literacy (financial knowledge, attitudes and behaviour), their ownership of financial instruments, and the impact of the COVID-19 crisis on their activity and on their level of digitalisation.[33] The target population of the survey are owners of independent for-profit businesses employing fewer than 50 employees, who are involved in taking financial decisions for the business. Financial decisions for the business may include decisions around taking a loan for the business, looking for sources of funding, paying taxes and solving cash flow issues.

The survey includes a section with various questions about firms' digital activities and the impact of the COVID-19 crisis on their level of digitalisation.

There are two groups of questions about various digital activities that are analysed in this report. The first group includes questions about digital activities that the firm performed or did not perform before the COVID-19 pandemic at the end of 2019 and at the time of the survey. The responses to these questions were "yes" or "no". The activities are the following: (i) have a dedicated website to showcase the products or services of the business, (ii) have a dedicated website to sell the products or services of the business, (iii) have opened a bank account completely online, (iv) have signed a financing contract (e.g. a bank loan) completely online, and (v) have signed an insurance contract completely online.

The second group includes questions about how large some digital activities were for the firm before the COVID-19 pandemic at the end of 2019 and at the time of the survey. The responses to these questions were "very small", "quite small", "quite large" and "very large". The activities are the following: (i) sales of products or

[33] The survey questionnaire and methodology can be found here: https://www.oecd.org/financial/education/2020-survey-to-measure-msme-financial-literacy.pdf.

services through the business' website as a percentage of total sales; (ii) sales of products or services through a shared online platform (e.g. Amazon) as a percentage of total sales; (iii) online payments from customers as a percentage of total payments from customers; (iv) online payments to suppliers as a percentage of total payments to suppliers; (v) use of social media (e.g. Facebook) for business activity such as advertising or networking; (vi) number of operations on current account conducted online, as a percentage of total operations on the current account.

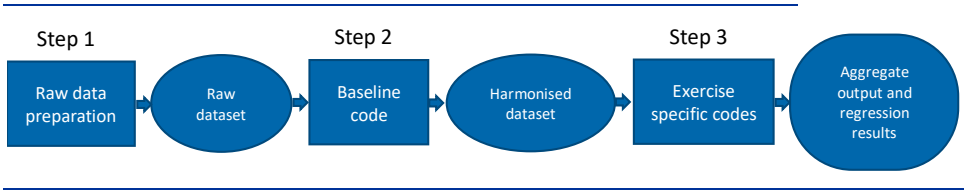
B Appendix for Section 2.3

The results of the analysis based on firm-level data presented in this report relied on a micro-distributed approach to the country-specific, and frequently confidential, individual data. A common code was distributed to national central banks' representatives, who then directly or indirectly executed it on their respective national firm-level datasets. This method ensured high coverage and cross-country comparability, while preserving confidentiality of the data used.

The approach was motivated by the established CompNet (The Competitiveness Research Network) infrastructure, and the code largely followed the experience with micro-distributed exercises used for regular updates of the CompNet dataset of micro-aggregated indicators (mostly the code for the eighth vintage of the dataset).

The process of data collection and analysis was divided into three main steps. In the first step, data providers from contributing countries prepared their data in line with the agreed variable definitions.

Chart B.1



In the second step, a baseline code was run on the raw firm-level datasets. It first read the available data, verified whether the data met expected properties and renamed all variables in line with a key common across countries. The code then eliminated false observations and outliers and created various ratios, growth rates and a number of non-parametric variables, such as labour, financial indicators or trade indicators. Finally, the baseline code calculated several types of TFP and related parametric indicators and completed the preparation of the harmonised firm-level dataset that served as input for the various exercises.

In the third step, the data providers executed the exercise-specific modules on their harmonised datasets and shared the aggregate results and regression outputs with the teams that prepared the exercises - partial analyses. In total, there were eight separate exercises with different numbers of participating countries depending on the availability of the data required. The results of seven exercises, which presented a reasonable outcome from a sufficient number of countries, are a crucial part of the results presented in the reports drawn up by the WGF Expert Group on Productivity. More precisely, one of them is presented in this report, three in the report on the workstream on monetary policy and productivity (Valderrama et al., 2023), and three in the report on the workstream on COVID-19 and productivity (Lalinsky et al., 2023) (see Table B.1 below for more details).

Table B.1
Micro-distributed exercises

Report	Exercise	Countries
The impact of the COVID-19 pandemic and policy support on productivity	Intensive productivity growth and productivity-enhancing reallocation	12
	Distribution of pandemic subsidies and guaranteed loans across firms	7
	Pandemic support, indebtedness and zombification	10
The impact of monetary policy on productivity	Role of market power and concentration in the transmission of monetary policy to productivity	8
	Effects of monetary policy on the allocation of input factors	8
	Effects of monetary policy on zombie margins	8
Digitalisation and productivity	The impact of firms' digital uptake on their productivity	2

C Appendix for Section 2.4

Anderton et al. (2023) use firm-level balance sheet data from Bureau van Dijk's Orbis for firms operating in Europe between 2000 and 2019. TFP is estimated for gross output production functions following Gandhi et al. (2020) (henceforth GNR). The GNR approach tackles the weak identification issues that can arise from the unknown factor prices at firm level using a dynamic structure that requires firms to be in the dataset for at least three consecutive years, thereby reducing distortions and possible mismeasurements in estimating revenue-based firm-level TFP (i.e. "TFPR"). They ensure the representativeness of the data across different countries by following Kalemli-Özcan et al. (2015). They also exclude specific sectors of the economy for which the estimation of TFP via a gross output production function approach is more likely to suffer from mismeasurement (e.g. agriculture, mining, financial services, education and health). Sectors that have less than one thousand firm-level observations are also excluded from the analysis. They end up with 19.3 million firm-level observations from almost 2.4 million distinct firms that operate in 13 European countries, with each firm being in the data for an average of about 8.1 years.

To gauge the impact of digitalisation on TFP growth, Anderton et al. (2023) use a firm-level model to disentangle the impact of investment in digital technologies on

firms' TFP growth. Their empirical framework builds on Gal et al. (2019) by allowing for time variation in digitalisation measures and for the impact of market concentration and firms' financial information on TFP growth:

$$\Delta tfp_{icst} = \beta_{dig} Dig_{cst-1} + \beta_{ftfp} \Delta ftfp_{st} + \beta_{gap} Gap_{icst-1} + \beta_x X_{icst-1} + \beta_{hhi} HHI_{cst-1} + \delta_{ct} + \delta_s + \varphi_{icst}$$

where Δtfp_{icst} is the (log) TFP growth rate of a firm i in sector s, country c and year t. Their main interest lies in the marginal impact of digitalisation on the average laggard firm. They follow van Ark (2016) and measure the impact of digitalisation after its instalment phase on firms' TFP growth. In this way, they embed in a simple reduced form the notion that the impact of digitalisation also depends on the managerial quality of the firm (Bloom et al., 2012; Anderton et al., 2020a) and they allow firms to better embed digitalisation in their production process before assessing its impact on TFP growth.

This empirical framework allows the impact of digitalisation Dig_{cst-1} to be separated from other channels that are usually considered as determinants of productivity growth at firm level: (1) the technological diffusion from the productivity frontier $\Delta ftfp$ to laggard firms (Akcigit and Ates, 2021); (2) the catch-up effect whereby low-productivity firms tend to grow faster than their more productive counterparts, which also accounts for the "up-or-out" dynamics whereby low-productivity firms must improve their productivity in order to survive (Cette et al., 2018) – Gap_{icst-1}; (3) the role of market concentration in shaping TFP growth (Olmstead-Rumsey, 2020), for which time-varying Herfindahl-Hirschman indices at the country-sector level are constructed – HHI_{cst-1}; and (4) the fact that firms have heterogeneous characteristics, which is tackled by including as controls (X_{icst-1}) the firm's employment levels and age (Haltiwanger et al., 1999) and, on the financial side, its leverage and liquidity ratio (Levine and Warusawitharana, 2021). Finally, country-year (δ_{ct}) and sector fixed effects (δ_s) are included.

The measures of digitalisation reflect digital investment intensities, i.e. the share of digital investment out of total investment for all firms in a given country, sector and year cell. Digital investment comprises both tangible (ICT equipment) and intangible (computer software and databases, and R&D expenditures) components.

However, part of the increase in the investment intensity of digital technologies can be explained by the decrease in the relative price of these technologies over time. From a partial equilibrium perspective, the decline in the price of digital technologies would make them more attractive as an investment opportunity for price-taking firms making investment decisions. This, however, raises the question of whether it would be possible to account for how relative price effects influence digital investment intensities and whether some sectors exhibit digital investment intensities that are higher or lower than expected given the relative investment price of digital technologies.

$$DII_{cst} = \beta \left(\frac{P^{I,dig}_{cst-1}}{P^{I}_{cst-1}} \right) + \delta_{ct} + \delta_s + \varepsilon_{cst}$$

This is consistent with a framework in which firms take the information available on prices during the previous year as given to undertake their investment decisions at a given point in time. The preferred measure of digitalisation is the residuals from this equation $\hat{\varepsilon}_{cst}$, which can be interpreted as the intensity of digital investment that is not induced by variations in the relative price of digital technologies.

Table C.1 shows the benchmark empirical results for the marginal impact of digitalisation on the average laggard firm's TFP growth.

Table C.1

Benchmark results for the marginal impact of digital investment on the average laggard firm's TFP growth

			Digital investment intensity		ε-residuals	
	(1)	(2)	(3)	(4)	(5)	(6)
β_{dig}			0.012*	0.015**	0.019***	0.021***
			(0.007)	(0.007)	(0.007)	(0.007)
β_{ftfp}	0.161***	0.151***	0.160***	0.149***	0.157***	0.148***
	(0.013)	(0.011)	(0.013)	(0.012)	(0.013)	(0.012)
β_{gap}	0.204***	0.199***	0.205***	0.200***	0.205***	0.200***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.010)	(0.010)
$\beta_{employment}$	4.983***	4.770***	5.005***	4.798***	5.035***	4.808***
	(0.184)	(0.182)	(0.188)	(0.185)	(0.194)	(0.189)
β_{age}	-0.101***	-0.082***	-0.099***	-0.081***	-0.098***	-0.080***
	(0.010)	(0.011)	(0.010)	(0.011)	(0.010)	(0.011)
β_{hhi}		-0.023**		-0.026**		-0.024**
		(0.011)		(0.012)		(0.012)
$\beta_{liquidity\ ratio}$		-0.145***		-0.152***		-0.160***
		(0.020)		(0.021)		(0.022)
$\beta_{gearing}$		0.048*		0.054**		0.052*
		(0.026)		(0.027)		(0.027)
# Obs. (in mio.)	14,773	12,193	14,059	11,664	13,067	10,868
R^2	0,153	0,150	0,154	0,151	0,154	0,151

Source: Anderton et al. (2023).

D Appendix for Section 3.1

The approach in Section 3.1 is similar to that in recent work on institutions and governance, digitalisation and growth. It is adapted from Labhard and Lehtimäki (2022), who aim to find empirical evidence for an "explanatory" role of digitalisation and institutions/governance, and their interaction, for growth.[34] This appendix describes the application of that approach to productivity, relating productivity to digitalisation and institutions/governance as well as controlling for other factors.

The results reported are for TFP and real GDP per employee for the EU, based on fixed effects (FE) or pooled mean group (PMG) estimates. The productivity data are from the World Bank and the Penn World Tables. The data for the control variables are from the World Bank and the Atlas of Economic Complexity. The data for digitalisation and institutions/governance are taken from the World Development Indicators ("internet users" and "broadband connections") and the World Governance Indicators respectively.

The key caveats of the approach used in this section are related to the data. The data for digitalisation only capture internet and broadband, and only the extensive margin of adoption.[35] They therefore do not take into account different intensities of use or more recent technologies with the potential for an even greater transformative impact, such as AI and intelligent process automation, the internet of things and digital twins, distributed ledger technology, and edge and quantum computing.

For the (PMG) specification disentangling short-run and long-run effects, all of the six relevant terms capturing long-run effects are significant, as highlighted in Table D.1 below in the upper panel, columns 5-8. This includes the two terms capturing the interaction with digital technologies. The evidence is less clear for the short run, however, with only one coefficient significant. In the FE estimates, which do not distinguish between short and long run, the two interaction terms are not significant.[36]

[34] The role of institutions and governance in diffusion is examined by Baccianti et al. (2022).

[35] A recent paper looking at diffusion of a greater array of digital technologies is Hoffreumon and Labhard (2022), albeit also only at the extensive margin.

[36] The results are more mixed for real GDP per employee, as can be seen from the tables in this appendix. In either case, the results appear to be robust to different sets of control variables. Further results will be made available in a working paper version of the analysis.

Table D.1
Results from the pooled mean group specification

	Real GDP per employee				Total factor productivity			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
LONG-RUN EFFECTS								
Digitalisation								
Internet use	0.187***		0.516***		-0.460***		-0.751***	
	(0.039)		(0.053)		(0.051)		(0.072)	
Broadband use		-0.059		0.296		-0.006***		-0.010**
		(0.047)		(0.571)		(0.001)		(0.001)
Institutions								
WGI total	0.055	0.356	0.472***	1.020	0.334***	0.199***	0.193***	0.118**
	(0.045)	(0.232)	(0.047)	(1.976)	(0.035)	(0.035)	(0.053)	(0.042)
Digitalisation*WGI total			-0.478***	-0.245			0.305***	0.005**
			(0.034)	(0.475)			(0.047)	(0.001)
Controls								
ECI	0.189***	-0.834	0.061**	-2.121	0.316***	0.246***	0.294***	0.089**
	(0.037)	(0.679)	(0.025)	(4.406)	(0.042)	(0.032)	(0.048)	(0.035)
Labour force	-1.398***	0.931	0.094	4.187	-0.043	0.242**	-0.518***	-0.923**
	(0.132)	(1.237)	(0.080)	(8.559)	(0.107)	(0.096)	(0.141)	(0.123)
Human capital	0.210***	0.274	0.192***	-0.080	0.145***	0.058**	0.159***	0.058**
	(0.019)	(0.192)	(0.019)	(0.556)	(0.022)	(0.025)	(0.024)	(0.021)
Convergence								
Productivity(-1)	-0.137***	-0.009	-0.167***	0.003	-0.267***	-0.337***	-0.242***	-0.308**
	(0.043)	(0.008)	(0.049)	(0.003)	(0.040)	(0.037)	(0.046)	(0.052)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SHORT-RUN EFFECTS								
Digitalisation								
Internet use	0.026		-0.100		0.129		0.533***	
	(0.062)		(0.176)		(0.093)		(0.219)	
Broadband use		0.001		0.002		0.004***		0.008*
		(0.002)		(0.003)		(0.001)		(0.004)
Institutions								
WGI total	0.063***	0.030	-0.076	0.081	-0.000	0.001	0.168**	0.005
	(0.023)	(0.028)	(0.083)	(0.062)	(0.046)	(0.048)	(0.083)	(0.065)
Digitalisation*WGI total			0.140	0.001			-0.295**	-0.003
			(0.129)	(0.003)			(0.125)	(0.003)
Controls								
ECI	-0.001	0.014	0.010	0.004	-0.056***	-0.058**	-0.054**	-0.050*
	(0.016)	(0.018)	(0.018)	(0.022)	(0.021)	(0.026)	(0.023)	(0.028)
Labour force	-0.492***	-0.747***	-0.613***	-0.666***	-0.003	0.164	0.070	0.350*
	(0.118)	(0.120)	(0.104)	(0.134)	(0.112)	(0.172)	(0.117)	(0.212)
Human capital	0.038**	0.037*	0.039**	0.047*	0.020	0.035	0.012	0.006
	(0.016)	(0.020)	(0.016)	(0.025)	(0.031)	(0.045)	(0.028)	(0.031)
Constant								
	1.422***	-0.125	1.513***	0.024	-0.486***	-0.454***	-0.296***	0.131
	(0.430)	(0.109)	(0.441)	(0.017)	(0.072)	(0.048)	(0.066)	(0.094)
R^2 adjusted								
	0.46	0.48	0.50	0.49	0.43	0.48	0.53	0.58

Source: Authors' calculations.
Notes: Pooled mean group estimates of the relationship between real GDP per capita growth (dependent variable) and technology, institutions, governance and control variables. *** significant at 1% level, ** significant at 5%, * significant at 10%. The shaded estimates and associated standard errors pertain to the coefficients that capture the effects of institutions and governance, and the interaction with digitalisation, and are significant. The exact specification is detailed in equation (1) in Section 4 of Labhard and Lehtimäki (2022).

Table D.2
Results from the fixed effects specification

	Real GDP per employee				Total factor productivity			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Productivity(-1)	-0.028	-0.060**	-0.029	-0.058*	-0.232***	-0.171***	-0.231***	-0.173**
	(0.023)	(0.030)	(0.024)	(0.030)	(0.066)	(0.039)	(0.065)	(0.039)
Digitalisation								
Internet use(-1)	-0.052**		-0.043**		-0.037		-0.022	
	(0.020)		(0.021)		(0.025)		(0.021)	
Broadband use(-1)		-0.073**		-0.091**		-0.016		0.009
		(0.030)		(0.044)		(0.039)		(0.043)
Institutions								
WGI total(-1)	-0.001	0.016	0.002	0.012	0.040*	0.037**	0.045*	0.043**
	(0.012)	(0.013)	(0.016)	(0.015)	(0.021)	(0.015)	(0.025)	(0.017)
Digitalisation*WGI total(-1)			-0.006	0.015			-0.011	-0.020
			(0.012)	(0.022)			(0.015)	(0.028)
Controls								
ECI(-1)	-0.017**	-0.024***	-0.019**	-0.022***	0.045***	0.025**	0.042***	0.022
	(0.007)	(0.007)	(0.008)	(0.008)	(0.010)	(0.011)	(0.012)	(0.013)
Labour force(-1)	-0.016	0.040	-0.012	0.035	-0.087***	0.023	-0.077***	0.030
	(0.026)	(0.028)	(0.025)	(0.028)	(0.027)	(0.030)	(0.024)	(0.031)
Human capital(-1)	-0.008	-0.010	-0.008	-0.009	0.000	-0.001	-0.001	-0.002
	(0.005)	(0.007)	(0.006)	(0.007)	(0.006)	(0.007)	(0.007)	(0.007)
Constant								
	0.453*	0.743**	0.469	0.726**	0.219**	0.046	0.215**	0.046
	(0.270)	(0.344)	(0.284)	(0.350)	(0.092)	(0.078)	(0.089)	(0.078)
R^2 adjusted								
	0.44	0.52	0.43	0.52	0.35	0.36	0.35	0.36

Source: Authors' calculations.
Notes: Fixed effects (country and time) estimates of the relationship between productivity growth (dependent variable) and changes in technology, institutions and governance and control variables. White diagonal standard errors and covariance (corrected for degrees of freedom) in parentheses. *** significant at 1% level, ** significant at 5%, * significant at 10%. The shaded estimates and associated standard errors pertain to the coefficients that capture the effects of institutions and governance, and the interaction with digitalisation, and are significant. The exact specifications are detailed in equations (2) and (3) in Section 4 of Labhard and Lehtimäki (2022).

E Appendix for Section 3.2

The analysis is based on a quasi-panel of a micro dataset merged from Orbis and iBach databases for six euro area countries (Germany, France, Italy, Spain, Belgium and Portugal), using standard data-cleaning procedures as outlined by Kalemli-Özcan et. al. (2015) and Gal (2013), including some imputation and cleaning of datasets with implausible or missing key variables. Firm-specific TFP is estimated using the two-step methodology proposed by Ackerberg et al. (2015).

The empirical specification is the following: TFP growth of firm i is regressed on its intangible intensity IKai, i.e. the share of intangible assets in total assets, in the previous period[37], as well as the intangible intensity of the sector at the regional level[38] $\overline{IKa}$i to reflect possible spillovers between firms. Given the observed wedge between laggards and the average firm, the empirical specification includes a

[37] While contemporaneous variables and longer lags also showed weak significance in a few cases, using the first lag seems to strike the best balance between avoiding endogeneity issues and chasing noise.

[38] NUTS 3 where available, otherwise NUTS 2.

dummy li that takes on the value 1 for firms in the lowest decile of the TFP level distribution, and interaction terms between the two measures of intangible capital and the laggard dummy. Sector and size-class dummies as well as some firm/sector control variables Xit are included.

$$gTFP_{it} = \beta_1 \cdot IKa_{i,t-1} + \beta_2 \cdot l_i + \beta_1 \cdot IKa_{it} \cdot l_i + \beta_1 \cdot \overline{IKa}_{s,t-1} + \beta_1 \cdot \overline{IKa}_{s,t-1} \cdot l_i + \sum_n \beta_n \cdot X_{it} + \varepsilon_{it}$$

The controls include sectoral mark-ups over wages, a proxy for pricing behaviour and sectoral market concentration, sectoral value added growth as a proxy for demand conditions affecting TFP, and firm-specific EBITDA over total assets (ROA) as a proxy for firms' financial position.

Furthermore, to be more certain that the positive impact of intangible assets on TFP growth is related to digitalisation, the above regression is run separately for each NACE2 sector covered by the analysis.

Table E.1

Panel regression of TFP growth on different intangible assets and controls across six euro area countries

	DE	IT	FR	ES	PT	BE	Pooled
IKa R&D-lag	0.266*	0.787***	0.400***	0.0103	-0.137	0.485***	0.406***
	(-0.14)	(-0.0514)	(-0.0938)	(-0.0303)	(-0.115)	(-0.128)	(-0.0393)
IKa Soft&db-lag	0.0537	0.202***	0.231***	0.0397**	0.591***	-0.058	0.247***
	(-0.0729)	(-0.0197)	(-0.0174)	(-0.0174)	(-0.0573)	(-0.144)	(-0.0132)
IKa region - lag	0.0942	0.723***	0.00544	-0.240***	0.799***	0.0517	0.0467**
	(-0.107)	(-0.0495)	(-0.0178)	(-0.0524)	(-0.108)	(-0.138)	(-0.0192)
Laggard	-0.246***	-0.403***	-0.251***	-0.456***	-0.548***	-0.196***	-0.554***
	(-0.0174)	(-0.00658)	(-0.00455)	(-0.0155)	(-0.0259)	(-0.0182)	(-0.00529)
IKa R&D-lag x laggard	-0.292	0.784***	0.256***	0.0835	0.476**	-0.113	-0.0105
	(-0.37)	(-0.103)	(-0.0975)	(-0.0988)	(-0.218)	(-0.414)	(-0.0671)
IKa Soft&db-lag x laggard	0.118	-0.461***	-0.154***	-0.469***	-0.284***	0.491**	-0.259***
	(-0.233)	(-0.0506)	(-0.0195)	(-0.0577)	(-0.104)	(-0.233)	(-0.021)
IKa region-lag x laggard	-0.158	-1.271***	-0.150***	-1.242***	-1.310***	-0.28	0.781***
	(-0.282)	(-0.107)	(-0.0271)	(-0.0989)	(-0.25)	(-0.298)	(-0.025)
Market concentration	-0.0888***	0.0502***	0.122***	0.519***	0.00943	0.0875***	0.346***
	(-0.0294)	(-0.0155)	(-0.00829)	(-0.0205)	(-0.0305)	(-0.0288)	(-0.0258)
TFP distance to frontier	-8.33e-07***	-2.61e-05***	-1.17e-05***	-5.91e-06***	-9.98e-06***	-7.87e-07***	-1.10e-05***
	(-0.000000153)	(-0.000000827)	(-0.000000309)	(-0.000000261)	(-0.00000204)	(-0.000000116)	(-0.00000103)
TFP growth at frontier	0.0249***	0.0280***	0.0474***	0.0172***	0.0141***	0.0262***	0.0405***
	(-0.00217)	(-0.001)	(-0.0018)	(-0.00137)	(-0.00197)	(-0.005)	(-0.00133)
Return on assets	0.762***	1.180***	0.000133	0.216	0.699***	1.030***	0.000564
	(-0.139)	(-0.0553)	(-0.000111)	(-0.149)	(-0.166)	(-0.114)	(-0.000585)
Value added growth	0.410***	0.333***	0.496***	0.318***	0.237***	0.0662***	0.333***
	(-0.0207)	(-0.0129)	(-0.0121)	(-0.0178)	(-0.0161)	(-0.0178)	(-0.00923)
Constant	0.343***	0.362***	0.286***	0.248***	0.215***	0.111***	0.462***
	(-0.0458)	(-0.00966)	(-0.00673)	(-0.00741)	(-0.0149)	(-0.0337)	(-0.0244)
Observations	103,836	2,104,769	942,820	1,390,915	278,852	49,191	3,479,468
R-squared	0.089	0.128	0.106	0.092	0.098	0.084	0.078
Number of panels	18,974	456,298	215,466	318,983	73,767	8,730	773,235
Size class	YES	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Sources: Eurostat and own calculations.

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