EUROPEAN CENTRAL BANK

EUROSYSTEM

Working Paper Series

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Digitalisation and productivity: gamechanger or sideshow?

No 2794 / March 2023

Abstract

Is digitalisation a massive gamechanger which will deliver huge gains in productivity, or is it more of a sideshow with only limited impacts? We use a large balance sheet panel dataset comprising more than 19 million European firm-level observations to empirically investigate the impact of digitalisation on productivity growth via various previously unexplored channels and mechanisms. Our results suggest that for two otherwise identical firms, the firm that exhibits on average a higher share of investment in digital technologies will exhibit a faster rate of TFP growth, but not all firms and sectors experience significant productivity gains from digitalisation. Digitalisation does not seem to have relatively stronger impacts on the productivity of frontier firms compared to laggards, nor does it help to turn laggards into frontier firms. Overall, firms should not regard digital investment as a 'one-size-fits-all' strategy to improve their productivity. Digital technologies are a gamechanger for some firms. But they seem more like a sideshow for most firms, who attempt to be increasingly digital but are not able to adequately reap its productivity gains.

Keywords: digital technology/transition; productivity growth; technology adoption/diffusion.
JEL codes: D22; D24; D25; O33.

Non-Technical Summary

Although digitalisation promised to be a massive gamechanger that would accelerate firms' productivity and generate value for the economy as a whole, it seems that this has not occurred yet. We are facing a "productivity paradox" whereby rapid advances in digitalisation over the past couple of decades have coincided with a protracted slowdown of aggregate productivity growth, contrary to all expectations.

The transition into a digital economy has been established as a priority by policymakers and international institutions alike, with various policies being implemented with the aim of accelerating digital adoption and thereby boosting productivity. This is the case for the EU's "Digital Single Market" and the "Next Generation EU" policy programs. Hence, our aim is to provide a clearer understanding of the impact of digitalisation on firm level productivity growth.

Using a large panel dataset of 19.3 million firm-level observations of nearly 2.4 million distinct European firms, we show that digitalisation tends to have on average a positive impact on firm-level productivity growth. However, it does not seem to be either a massive gamechanger or a "one-size-fits-all" strategy that manage to deliver productivity gains to all firms alike. The impact of digitalisation on the average firm's TFP growth is relatively small and we find that most firms are not able to benefit from digitalisation at all.

First, we find that firms only in some sectors benefit on average from investing in digital technologies, and that digitalisation is a gamechanger only for a minority of selected firms that manages to use digital technologies to become substantially more productive over time. Second, these selected firms are among the most productive firms in the economy, as only the 30% most productive laggard firms benefit on average from investing in digital technologies. However, it should be noted that a higher digital investment by itself is not enough to turn highly productive laggards into frontier firms. Instead, if firms want to be at the top of the productivity distribution they need to aim for a more structural innovation in comparison to their peers, which can also be enabled by digital technologies, but does not follow directly after an increase in digital investment. Third, the impact of digitalisation is similar for both laggard and frontier firms, but the latter are better equipped to make the full use of digital technologies by tracking and implementing successfully the innovations achieved by other frontier firms. Finally, we find that intangible assets are closely linked with digital technologies and act as a complement to digitalisation to magnify its positive impact on the average firm's TFP growth.

Therefore, firms with a higher level of intangibles are more likely to reap the future benefits from digitalisation.

Overall, digitalisation is a productivity gamechanger only for a minority of firms, while it remains as a sideshow for most firms in the economy. In this way, it should not be seen as a "one-size-fits-all" measure to boost productivity growth. Consequently, investment in digital technologies should be purposefully planned and cautious long-term strategies should be developed to ensure that digital technologies are successfully deployed after their installment. Firms should be particularly aware of this result in light of the rapid and wide-ranging rise in the adoption of digital technologies after the onset of the COVID-19 pandemic.

We conclude that policies aiming to increase the digital-intensiveness of sectors such as the EU's "Digital Single Market" or the "Next Generation EU" programs can be successful in boosting firm-level productivity. However, there are considerably risks that a sub-optimal implementation of these policies hinder their success. This implementation should be carefully considered on a case-by-case basis, with the focus of helping each firm to support the costs of the installation phase of digitalisation and enabling them to use new digital technologies to achieve a higher productivity growth, not immediately but over time.

Finally, and in light of our results, a higher digitalisation can bring about a rise in the natural rate of interest, thereby giving monetary policy more room to manoeuvre. A successful implementation of digital investments is associated with higher productivity. Given that productivity is closely related to potential output and inflation, it affects also the natural rate of interest thereby impacting the structural fundamentals for monetary policy.

1 Introduction

Is digitalisation a massive gamechanger which delivers huge gains in productivity, or is it more of a sideshow with only limited impacts? The role of digitalisation with respect to firms' productivity growth still needs to be clarified. Although digitalisation promises to be a productivity gamechanger, we are still facing a "productivity paradox" whereby rapid advances in digitalisation over the past couple of decades have coincided with a protracted slowdown of aggregate productivity growth (Gordon (2012); Cette et al. 2016). As van Ark (2016) argues, the productivity gains of digitalisation may yet remain to be fully realised because the "Digital Economy" is still in its installation phase. In line with this, if digitalisation is a general purpose technology then its productivity gains will be characteristically slow to materialise (Brynjolfsson et al. (2021)). A related question is whether digitalisation is a 'one-size-fits-all' strategy that firms need to implement which delivers higher productivity and gives them a competitive edge. That is, we try to understand whether digitalisation benefits all firms equally alike or whether, instead, it is a productivity gamechanger only for a minority of firms that are the most capable of reaping the productivity gains of digital technologies and more of a sideshow for the majority.

These questions still remain to be answered. Yet, the secular slow down in aggregate productivity and better understanding in what way digitalisation is able to impact productivity growth are still highly policy relevant issues, with various policy packages being implemented with the aim of accelerating digital adoption and thereby boosting productivity. Examples of these are the EU's "Digital Single Market" and the "Next Generation EU" programs, both with the aim to facilitate the transition to the digital economy and to accelerate digital adoption. Through its effect on firm level TFP growth and thereby on potential output, inflation, and the natural rate, digitalisation can have important implications for monetary policy (Anderton et al. 2020, Anderton and Cette (2021)).

Against this background, our aim is to provide a clearer understanding of the micro-level impact of digitalisation on firm level productivity growth following a systematic approach. Using a large European panel dataset of 19.3 million firm-level observations and nearly 2.4 million distinct european firms, we show that digitalisation accelerates firms' TFP growth on average, although its impact is very heterogeneous. In particular, i) only firms in some sectors seem to benefit from digitalisation, and those who do benefit substantially; ii) only certain laggard firms benefit from digitalisation, namely the 30% most productive laggard firms; iii) the average impact of digitalisation is similar for both laggard and frontier firms, but the latter are better able to track and implement successfully the innovations from their peers; and iv) higher intangibles act as a complement and magnify the impact of digitalisation on the average firm's TFP growth. Although firms in digital-intensive sectors display a higher TFP and faster TFP growth than firms in less digital-intensive sectors, we find that this is mostly explained by differences in both firm and market characteristics across both sectors, and not by the impact of digital investment. While digital technologies enable firms to become more productive, we find that the impact of digital investment is not immediate, suggesting that it takes time for firms to be able to fully reap the benefits associated with digitalisation.

We are not the first to focus on the micro level relationship between digitalisation and productivity. Consistent with our results, various micro-data studies find that digitalisation is associated with firm-level productivity gains (Brynjolfsson et al. 2008; Cette et al. 2018; Gal et al. 2019). These findings are based on proxy variables for digitalisation which try to capture the adoption of digital technology. Digitalisation can be measured by: the computerization of the economy, robotization and the automation of production processes; real investment or the stock of capital in information and communication technologies, in computer software and databases, in research and development; or by internet usage and cloud computing. Under all these approaches, digitalisation has risen substantially since the early 2000s. However, similar to van Ark (2016) we recognize that as digital technology is becoming more and more prevalent in the economy, it is also getting cheaper. In particular, the price of investment in digital capital has decreased considerably over time when compared to the investment price index for the total economy. This decline in the price of digital technology could be one of the main factors contributing to the increase in digital capital investment over the past two decades (Greenwood et al. (1997); Jorgenson (2001); Tambe et al. (2020)). The increase in digital capital can also be thought of as unlocking a broader adoption of digital technologies, thereby facilitating the diffusion of innovations from the frontier to non-frontier firms and enhancing convergence in firm-level productivity.

One contribution of our work is that we account for the (decreasing) price information that is embedded digital investments when we estimate the impact of digitalisation on TFP growth. We do this by measuring digitalisation through two variables, both of which vary at the country-sector-year level. The first reports digital investment intensities (DIIs). These are measured as the ratio between the real investment in Computer Software and Databases (CSD), in Information and Communication technologies (ICT), and in Research and Development (R&D) as a share of total real investment. Our second variable of digitalisation new to the literature and is inspired by the literature on investment-specific technical change. It accounts for the price-related information that can still be present in the DIIs, for example in the case where the fall in prices lead to a wider adoption and even a massification of digital investment that is driven by its availability and not necessarily by business decisions aimed at improving the firm's productivity. In this way, we measure the extent to which the digital investment intensity exceeds, or falls short of, what would be expected from the relative price of digital investment.

We further contribute to the literature by using the richness of our large firm-level data to investigate how digitalisation affects the growth of total factor productivity (TFP) at the firm-level via various previously unexplored channels and mechanisms. To estimate TFP at the firm level, we follow the recent approach developed by Gandhi et al. (2020). We emphasize this because compared to previous methods, this approach is advantageous in that it imposes less restrictions on the functional form of gross output production functions. This allows us to remain agnostic on the way inputs are combined and interacted in the production process (De Roux et al. (2021)). Second, the approach allows to separate the production function coefficients from the elasticities of gross output with respect to each input, with those elasticities being derived at the firm level. And third, the approach tackles weak identification issues that can arise from unknown factor prices at the firm level (Kim et al. (2019); Bond et al. (2020)). Altogether, this approach reduces distortions and possible mismeasurement in estimating firm-level TFP.

As a starting point to estimate the impact of digitalisation on the firms' productivity growth, we augment the econometric specification by Gal et al. (2019) to account also for financial characteristics and market concentration. We confirm that digitalisation is on average positively related to the firms' TFP growth and that the impact on the average laggard firm is relatively small: for two otherwise identical firms at a similar point in time and in the same country, the firm that exhibits a 1pp higher digital investment share will exhibit on average a 0.015 basis points higher TFP growth. For firms that exhibit a digital investment intensity that exceeds by 1pp the DII benchmark that could be justified from the relative price of digital investment, the TFP growth is on average 0.021 basis points higher. Hence, firms in sectors which invest more (less) in digitalisation than what would be otherwise expected given movements in the price of digital technologies seem to be more (less) able to harness its potential productivity benefits.

We find that frontier firms play a significant role in boosting the productivity of laggard firms in the same sector via a technology diffusion channel and that less productive surviving laggards tend to catch up to their peers, which we label as productivity catch-up effects. Our data allow us to include various other explanatory variables which show that TFP growth is higher for larger firms and lower for older firms, while higher market concentration leads to lower TFP growth. Financial factors also have significant impacts on TFP growth, with higher liquidity being associated on average with a lower TFP growth and a higher leverage with a higher TFP growth. These results give us a rough way of gauging the magnitude of the positive effect of digitalisation on improving firms' TFP growth over time. For example, we estimate that the positive impacts of digitalisation on TFP growth would roughly counterbalance the negative impact of an increase in market concentration when both increases are in the magnitude of, respectively, one standard deviation.

We further look more granularly into the impact of digitalisation on firm-level TFP growth, by systematically disaggregating it into different channels. We show that the impact is very heterogeneous across sectors, with the average coefficient of those sectors that exhibit a statistically significant and positive coefficient being 17 times larger than the impact we estimated across all sectors. Furthermore, digitalisation enables only certain laggards to catch up to the productivity frontier. Namely, only the 30% most productive laggard firms benefit from a higher digital investment intensity. However, additional results show that this does not mean that higher digitalisation alone is sufficient to turn top laggard firms into leaders. We further find that the impact of digitalisation is similar for laggard and for frontier firms. And digitalisation does not seem to enhance firm churning into (and out of) the productivity frontier. Finally, we examine whether intangibles improve the firm's TFP growth either directly or via complementarities with digital technologies (Corrado et al. (2021); Brynjolfsson et al. (2021)). For laggard firms we find that it is digital investment, and not intangibles, that increases the average firm's TFP growth. However, intangibles magnify the impact of digitalisation, indicating a positive complementarity between the two factors for laggards. For frontier firms digitalisation and intangibles are both important factors which boost TFP growth, with complementarities arising between these factors.

Overall, our results suggest that digitalisation does not tick all of the productivity boxes. Digitalisation seems to be a productivity gamechanger only for some firms, but it is more like a productivity sideshow for other firms who invest in digital technologies but are not able to adequately reap the productivity gains from digitalisation. Nevertheless, digitalisation is like other general purpose technologies in the sense that it takes time to deliver on its potential productivity gains. In this way, if adopted successfully, it could become a gamechanger in the future, and particularly so given the rapid and wide-ranging rise in the use of digital technologies during the COVID-19 pandemic (Amankwah-Amoah et al. (2021)).

The paper is structured as follows. Section 2 describes how we estimate firm-level productivity, while Section 3 presents our measures of digitalisation. In Section 4 we specify and estimate our benchmark econometric model relating firm level TFP growth and digitalisation. Section 5 empirically assesses along which dimensions of heterogeneity and through which channels the productivity gains from digitalisation materialize. Finally, Section 6 summarises the main conclusions of our analysis.

2 Measurement of total factor productivity (TFP)

We follow Gandhi et al. (2020) (GNR) to estimate and measure firm level TFP.[1] The starting point is our assumption on the form of the production function, which we allow to vary across the different sectors of the economy:[2]

$$y_{icst} = f^s \left(k_{icst}, l_{icst}, m_{icst}\right) + tfp_{icst}. \tag{1}$$

The term y_{icst} stands for (log) total revenues, k_{icst} for (log) tangible fixed assets, l_{icst} for the (log) number of employees, and m_{icst} for the (log) expenditures on materials. Subscripts denote a firm i that operates in country c, sector s, and at a given year t.[3] Our interest lies on the term tfp_{icst}, which measures the Hicks-neutral log-TFP. The GNR procedure consists of estimating tfp_{icst} in two steps: First, estimate the output elasticity with respect to intermediate materials. We do so based on a nonparametric regression (i.e., sieve estimation). The idea is to use this information to identify the part of the production function that is related to intermediate inputs.

1. The GNR methodology is being increasingly used in the empirical literature. See, for example: (1) Chan et al. (2019) use Danish data to assess the impact of firms' productivity shocks on workers' labour earnings; (2) Bonfim and Nogueira (2021) use Portuguese data to examine the role of corporate reorganization as a source of labour insurance in bankruptcies; or (3) Liu (2019) use both Chinese and Korean data to assess the extent to which industrial policies aimed at reducing distortions should be targeted to upstream sectors.

2. When estimating equation 1, we pool all firms in our sample that belong to the same 4-digit industry across countries and over time, implying that the functional form of the production function is restricted to be the same across all firms in a given 4-digit sector.

3. Firms' balance sheet information is deflated using the relevant 2-digit sector-specific price indices for the different variables, countries and over time. All deflators are publicly available at the OECD's Structural Analysis Database (STAN).

The second step of the GNR approach consists of estimating the remaining parameters of the production function in another nonparametric regression. By iterating on these two steps, we estimate the parameters of the sector specific production functions. This in turn allows us to compute the TFP for the firms in our data.[4]

We apply the GNR approach to firm level balance sheet data from Bureau van Dijk's Orbis. The raw data originates from balance sheets and income statements filed by companies to local business registers and encompasses more than 200 million firm-level observations. One important advantage of ORBIS is that it provides data for both listed and private/non-listed companies.We retrieve the data for firms operating in Europe between 2000 and 2019 and clean it according to Kalemli-Ozcan et al. (2015) to ensure the representativeness of the data across the different countries. In addition, we limit our sample to firms that provide at least one reporting spell of three or more consecutive years, which is needed for the GNR approach to account for the lack of price information at the firm level. We 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.[5] Finally, we exclude from the analysis those sectors that have less than one thousand firm-level observations. Our final sample comprises 19.3 million firm-level observations from almost 2.4 million distinct firms that operate in 13 European countries. We observe each firm on average for about 8.1 years. To our knowledge, we are the first to apply the GNR method on such a large scale to multiple European countries simultaneously.

Table 1 reports the country composition of our firm-level data alongside some descriptives such as the number of employees for the average firm or the median firm's operating revenues and its TFP levels (in logs). The median firm in our sample has yearly operating revenues equal to €640.5 thousand (in 2015 euros) and a log-TFP of 10.23. The median firm in our data has 5 employees. As the firm's employment distribution is right-skewed, we prefer to show the average firm's employment levels. The over-representation of large firms in the data is particularly important for countries where regulations exempt smaller firms from reporting their financial information to the administrative authorities.[6] There is also some country heterogeneity across

4. The GNR approach is quite flexible, restricting the gross output production function only to be partially separable in TFP. As such, it can either entail the usual Cobb-Douglas specification for the firm's production function, as described in De Roux et al. (2021), or a more complex production function under a translog specification, allowing for more flexibility in the way inputs interact.

5. We drop firms in agriculture, forestry, and fishing (2-digit NACE codes 1-8), mining (9), financial and insurance activities (64-66), real estate (68), education and health (85-88), and in non-market services sectors including arts, recreation, and personal services (90-99).

6. In our data, the average firm in Belgium has 98 employees, while in Austria or Germany it has more than

Table 1: Country coverage and median firm's TFP by country

Country	Observations	Firms	Years in Sample	Revenues (log)	Employees	tfp
Austria	12,953	2,535	5.1	17.69	322.1	10.75
Belgium	198,536	18,904	10.5	16.43	98.7	10.94
Estonia	293,981	31,884	9.2	12.16	12.0	9.68
Finland	597,480	70,836	8.4	13.41	21.8	10.45
France	3,081,537	432,535	7.1	13.55	32.2	10.49
Germany	182,902	23,570	7.8	17.44	367.4	10.81
Italy	5,132,502	629,570	8.2	13.85	23.4	10.42
Latvia	14,056	2,436	5.8	11.39	25.4	9.00
Norway	306,362	64,013	4.8	13.82	24.7	10.38
Portugal	1,800,582	229,465	7.9	12.28	13.1	9.42
Slovenia	427,750	53,434	8.0	12.51	14.6	10.13
Spain	6,057,186	677,260	8.9	13.15	19.2	10.08
Sweden	1,240,585	154,363	8.0	13.21	10.4	10.50
Full Sample	19,346,412	2,390,805	8.1	13.37	25.5	10.23

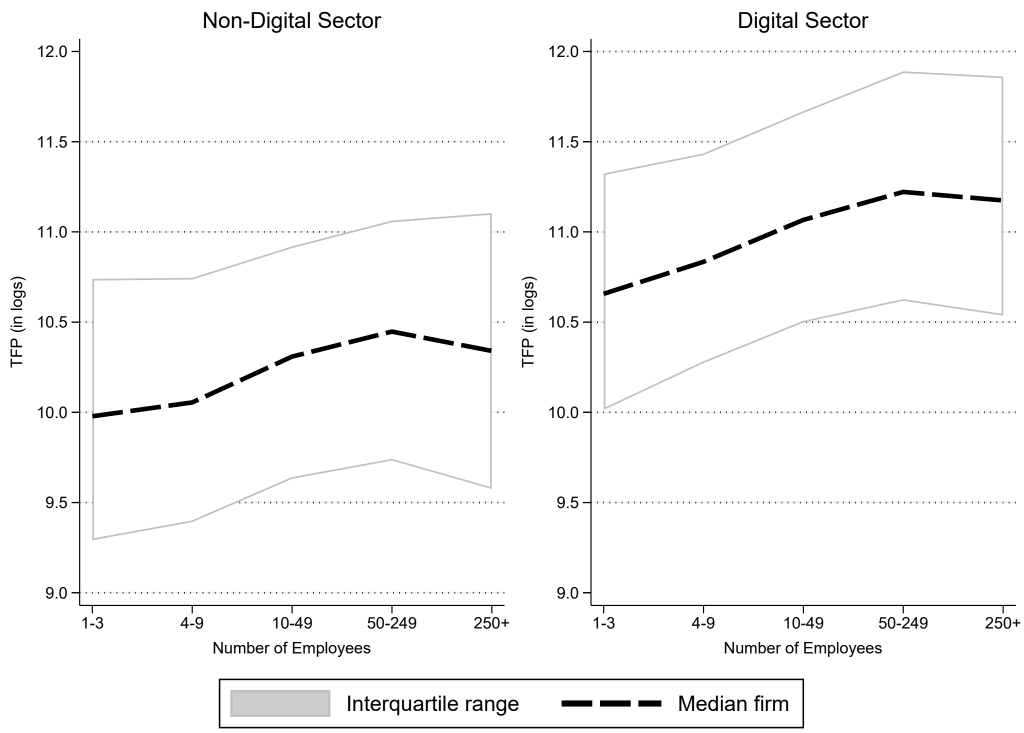
Notes: (1) the cleaning procedure follows Kalemli-Ozcan et al. (2015) alongside some additional filters needed for the implementation of the GNR procedure. The sample gathers data from 2000 to 2019, with the exception of firms in Sweden (2000-16) and Portugal (2000-18); (2) the average number of years in the sample is calculated as the ratio between the number of firm-level observations and the number of unique firms in the sample; (3) revenues correspond to the median firm's total operating revenues; (4) the number of employees corresponds to the average firm of the economy; (5) tfp is calculated following the GNR procedure and is shown for the median firm; and (6) all monetary variables are deflated using the appropriate price indices in 2015 euros.

the median firm log-TFP, with the median firms in Latvia, Portugal and Estonia exhibiting the lowest and those in Belgium, Germany, and Austria exhibiting the highest log TFP levels.

We observe that firm-level tfp differs along the firm size distribution and between sectors' average digital intensities. Figure 1 establishes both of these facts in our data, with the latter achieved by separating firms in digital intensive sectors from firms in non-intensive (i.e., non-digital) sectors, as in Calvino et al. (2018). First, larger firms are relatively more productive than smaller firms: the median large firm (more than 250 employees) is 39% more productive than the median micro firm (between 1 and 9 employees) in the non-digital sector and is 55% more productive than the median micro firm in the digital sector. Second, firms in digital sectors are relatively more productive than firms in non-digital sectors. The median micro firm in the non-digital sectors records a log-TFP of around 10.01, while the median micro firm in the digital

300 employees. By contrast, the median firm in Belgium has 32 employees, in Austria it has 137 employees, and in Germany it has 111 employees. For further considerations on the coverage and representativeness of the data, refer to Bajgar et al. (2020).

Figure 1: Interquartile range and median firm's TFP by employment for (non-)digital sectors.



Notes: (1) (non-)digital sectors defined following Calvino et al. (2018), i.e. a high a low or high digital intensity in 2013-15. Our data have 16,782,960 observations in non-digital sectors and 2,563,452 observations in digital sectors; (2) tfp is calculated following the GNR procedure and is shown for firms in the interquartile range and for the median firm; and (3) all monetary variables are deflated using the appropriate price indices in 2015 euros.

sectors has a log-TFP of 10.73. Moreover, the median large firm records a log-TFP of 10.34 in the non-digital sectors and a log-TFP of 11.17 in the digital sectors. These figures imply that both the median micro firm and the median large firm in the digital sector are at least twice more productive than their median non-digital counterparts. Finally, the distribution of TFP in the digital sector has stochastic dominance over the distribution of TFP in the non-digital sector. This implies that firms in the digital sector are in general more productive than firms in the non-digital sector for all parts of the distribution.

Table 2 presents the summary statistics for TFP growth and the other main variables used in our analysis, again conditioning on digital versus non-digital sectors. $\Delta tfp_{t,t-j}$ measures the growth rate of firm level TFP between year $t-j$ and year t. The median firm in our data registers a positive yearly TFP growth of around 0.15%. The average firm registers instead a negative yearly TFP growth of around -0.31%. Moreover, the firm-level TFP growth distribution exhibits considerable volatility, with the interquartile range comprising more than 20 percentage

Table 2: Summary Statistics

	Variable	mean	s.d.	p10	p25	p50	p75	p90
Non-Digital Sectors	tfp	10.16	1.13	8.93	9.44	10.12	10.82	11.45
	$100 \times \Delta tfp_{t,t-1}$	-0.33	35.65	-27.44	-10.39	0.11	10.02	26.23
	$100 \times \Delta tfp_{t,t-5}$	-2.66	47.75	-45.75	-19.48	-0.75	16.41	38.85
	ln (Revenues)	13.60	1.74	11.60	12.42	13.43	14.61	15.90
	Employees	23	340	1	2	5	13	34
	ln (K/Employees)	9.20	1.79	6.95	8.10	9.24	10.37	11.37
	Firm's Age	15.76	13.19	3.15	6.30	12.69	21.45	31.74
	Liquidity Ratio	1.55	3.55	0.21	0.50	0.92	1.51	2.74
	Gearing (%)	1.165	1.796	0.000	0.047	0.412	1.434	3.454
Digital Sectors	tfp	10.88	1.07	9.65	10.23	10.84	11.49	12.17
	$100 \times \Delta tfp_{t,t-1}$	-0.16	45.80	-40.48	-15.92	0.52	16.03	39.36
	$100 \times \Delta tfp_{t,t-5}$	-3.07	65.57	-69.48	-30.54	-0.84	26.64	60.49
	ln (Revenues)	13.15	1.78	11.16	11.96	12.94	14.12	15.48
	Employees	40	765	1	2	4	12	38
	ln (K/Employees)	8.73	1.91	6.39	7.49	8.69	9.96	11.15
	Firm's Age	13.23	10.17	3.08	5.90	10.98	18.02	25.85
	Liquidity Ratio	2.21	4.44	0.43	0.83	1.26	2.10	3.95
	Gearing	1.012	1.702	0.000	0.010	0.290	1.173	3.057

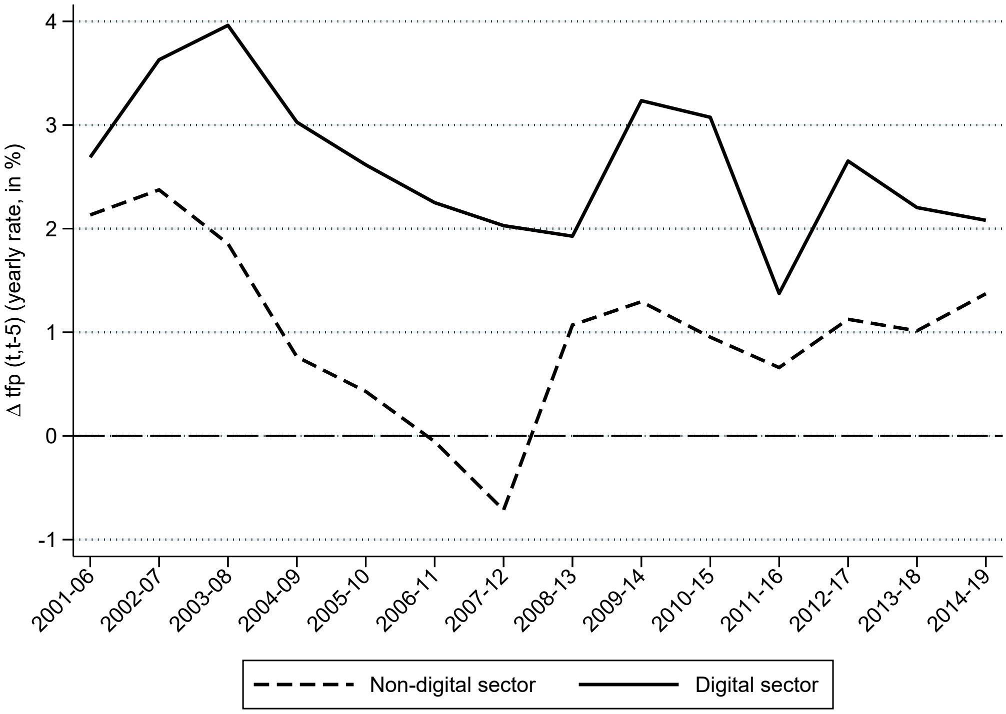
Notes: (1) (non-)digital sectors defined following Calvino et al. (2018). Digital sectors are those with a high digital intensity in 2013-15. Our data have 16,782,960 observations in non-digital sectors and 2,563,452 observations in digital sectors; (2) ln (K/Employees) is the log of the capital-labour ratio, where capital is measured using the level of tangible fixed assets held by the firm; (3) the liquidity ratio is measured as the ratio between the current assets of the firm excluding stocks and the firm's current liabilities; (4) gearing is defined as the percent share of non-current liabilities and loans out of the amount of the firm's shareholder funds; and (5) all monetary variables are deflated in 2015 euros.

points. We find that the negative skewness of the TFP growth distribution is characterised by the impact of small firms. When we use employment as weights, the average yearly TFP growth amounts to 3.1%. This implies that on average, larger firms improve their TFP by more than smaller firms every year.[7]

The distinction between digital versus non-digital sectors as in Calvino et al. (2018) is also quite relevant when assessing the dynamics of firm-level TFP growth. TFP of the median firm in the digital sectors increases by 0.52% per year, but over 5-year periods it decreases by -0.84% (≈ -0.17% per year). By contrast, the TFP of the median firm in the non-digital sectors increases by 0.11% per year, but decreases by -0.75% over 5-year periods (≈ -0.15% per year). This implies that in the short run, the median firm in the digital sectors becomes more productive than its counterpart in the non-digital sectors. However, it faces a slightly higher risk in the medium-run, decreasing by more its productivity over a 5-year period. This higher risk faced by firms

7. This is also the case when we condition on firms that are in the data over periods of five years. In this case, the 5-year weighted-average TFP growth amounts to 6.8% (≈ 1.3% per year).

Figure 2: Average $\Delta tfp_{t,t-5}$ in (non-)digital sectors (yearly rates, in %).



Notes: (1) (non-)digital sectors defined following Calvino et al. (2018). Digital sectors are those with a high digital intensity in 2013-15; and (2) average TFP growth rates are weighted by the firms' employment levels at year $t-5$, and presented in yearly rates.

in the digital sector is a prevalent feature in our data. First, the distribution of TFP growth is considerably more volatile in the digital sector than in the non-digital sector. Second, the higher volatility of the digital sector is particularly salient at the top of the TFP growth distribution: We observe that 10% of firms in the digital sector increase their productivity levels by more than 39% per year and by more than 60% over 5-years periods. By contrast, the 10% firms that improve the most their productivity in the non-digital sector register only TFP growth levels of 26% per year and of 38% over periods of five years. The performance of very large firms is also particularly relevant to characterise productivity dynamics across both sectors. In particular, the average TFP growth of firms with 250+ employees in the digital sector stands at 4.4% per year and at 13.6% over periods of five years, and at 2.8% per year or at 5.0% over 5-year periods in the non-digital sector.

Figure 2 develops on this and shows how average $\Delta tfp_{t,t-5}$ evolved over time (employment weighted and in terms of its average yearly growth rate). Firms in digital sectors consistently record a stronger average TFP growth than firms in non-digital sectors. Firms in both the digital and non-digital sectors were negatively affected by the global financial crisis and by the European sovereign debt crisis: for firms in digital sectors the average TFP growth decreased from around 4% per year during the 2003-08 period to 2% per year in 2007-12; while for firms in non-digital sectors it decreased from 2% to -0.6% respectively. It therefore seems that firms in the digital sectors were more insulated from the effects of the two crises in terms of their productivity dynamics. The data also unveils a long-term slowdown in productivity growth, with the average $\Delta tfp_{t,t-5}$ during the latest economic expansion being about 1 percentage point lower than at its 2003-08 levels for both sectors.

Given these inherent differences in TFP growth rates, we return to Table 2 and check whether firms in both the digital and non-digital sectors differ along other basic characteristics. Firms in the non-digital sectors record higher operating revenues and higher capital-labour ratios than firms in the digital sectors. Regarding the employment distribution of firms across sectors, the median firm in the non-digital sectors is slightly larger than the median firm in the digital sectors, but large firms in the digital sectors tend to be larger than those in the non-digital sectors. These large digital sector firms record on average higher TFP growth rates than large firms in non-digital sectors. Firms in digital sectors are also younger than those in non-digital sectors. Regarding their financials, digital sector firms record higher liquidity ratios and are slightly less leveraged in terms of their debt-to-equity ratio (i.e., gearing) when compared to their non-digital sector counterparts.

These inherent differences in basic firm-level characteristics need to be accounted for when analyzing TFP, which calls for a systematic approach. The distinction of firms in digital versus non-digital sectors stresses that digitalisation may be connected with considerable differences in TFP and TFP growth. However, the distinction is based on the binary classification by Calvino et al. (2018), which distinguishes sectors with low digital intensities from sectors with high digital intensities. This brings about the implication that the sectors composing the digital sector partition are the same over time. Furthermore, it tempts both researchers and policymakers to reduce the discussion on how digitalisation impacts TFP growth to the extensive margin of digitalisation (i.e., whether or not a firm should become digital at all), while disregarding that firms have different incentives on how much to invest in digital technologies. We address this issue in the next section, where we develop measures that allow us to take into account the variation in the extent to which sectors invest in digital technologies.

3 Investment in digital technologies

Our aim is to go beyond a binary separation of sectors into digital versus non-digital. When assessing how digitalisation is connected to firm level TFP growth we intend to make use of the fact that in Europe digital investment differs considerably across sectors, countries, and over time. In the spirit of Greenwood et al. (1997) theory of investment-specific technological change, firms' investment in digital technologies increased over time simultaneously as these technologies became more accessible and relatively cheaper when compared to other investment goods. This is particularly interesting because it opens up the possibility to extend our previous assessment to incremental changes in digitalisation. We can then estimate whether firms in a given country-sector group are over- or under-investing in digital technologies, given the relative investment price of digital technologies at any given moment in time.[8]

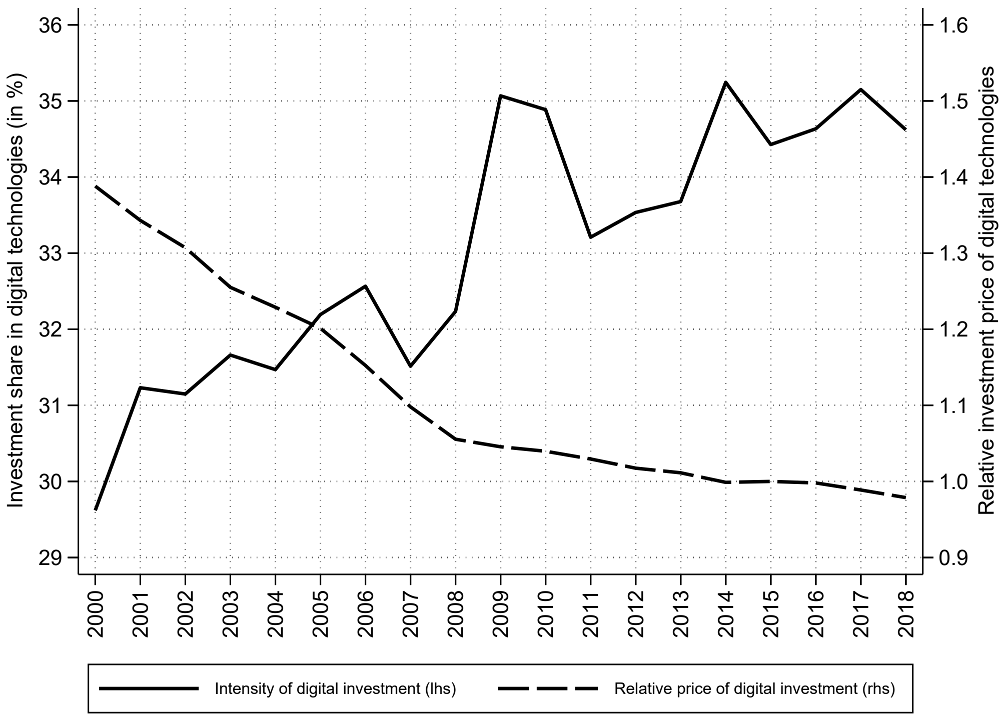
3.1 Measurement of digital investment.

We consider as investment in digital technologies the investment in information and communications technology (ICT) and the investment in intellectual property products (IPP). ICT comprises computer hardware and telecommunications equipment and it proxies for the tangible component of digitalisation. By contrast, investment in intellectual property products encompass the investment in computer software and databases (CSD) and expenditures in Research and Development (R&D). The investment in CSD proxies for the intangible component of digitalisation (Colecchia and Schreyer (2002) and Calvino et al. (2018)). It is established that investments in ICT and CSD enhance productivity through the implementation of new production methods, product customization, the automation of routine tasks, or the improvement of business and organizational processes (Anderton et al. (2020)). We add, as another intangible component of digitalisation also R&D because it is strongly connected to technological innovation (Hall et al. (2013), Corrado et al. (2017) and Mohnen et al. (2018)) and complementary to the other types of digital investment.

We retrieve data for investment in ICT, in CSD, and in R&D from the ESA 2010 National Accounts, which provides yearly information on the cross-classification of investments across the different countries and sectors. To construct investment intensities we also retrieve yearly

8. Some other approaches to measure digitalisation are the usage of data on computer capital (Brynjolfsson et al. (2008)), robotization (Zator (2019)), or specific technologies such as cloud computing, customer relationship management or high-speed broadband (Gal et al. 2019). Anderton et al. (2020) provides a more comprehensive survey on the different ways to measure digitalisation.

Figure 3: Intensity of digital investment and relative price of digital investment.



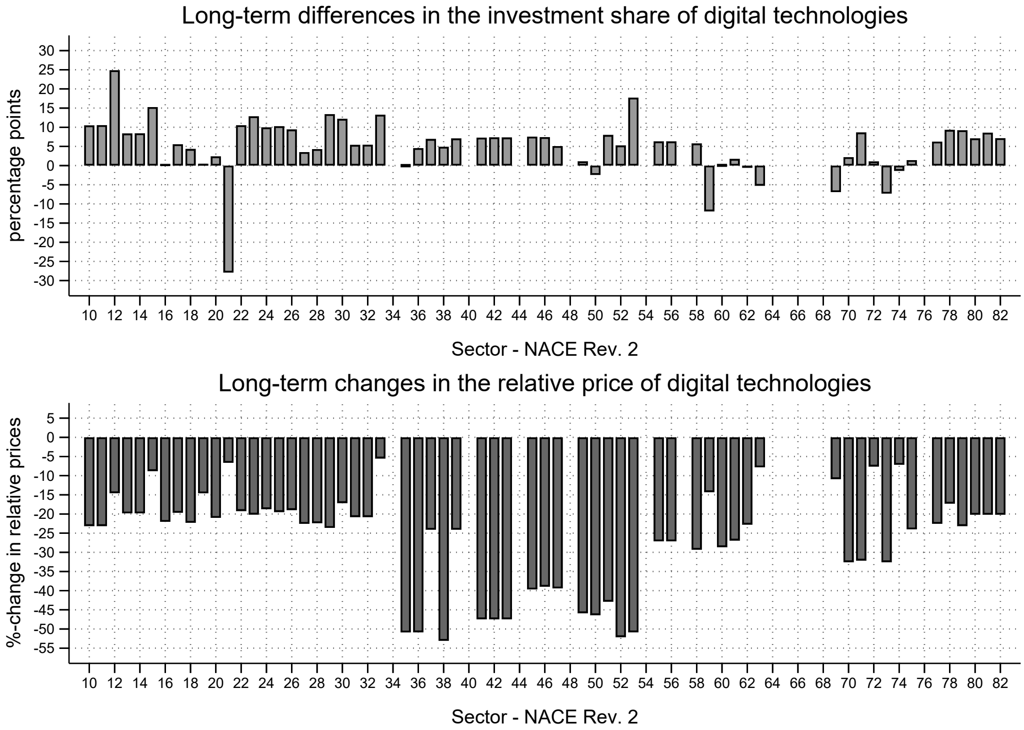
Notes: (1) The investment share in digital technologies is constructed as the ratio between the real investment in digital technologies (i.e., ICT equipment, computer software and databases, and R&D expenditures) and the real total investment for each country, sector, and year; (2) the relative investment price of digital technologies is the ratio between the price level of investment in digital technologies and the price level of total investment. The price level of investment in digital technologies is constructed as a Törnqvist index of the price levels of ICT equipment, computer software and databases, and R&D; and (3) the yearly time series are a weighted average of the country-sector data aggregated using employment as weights.

data on total investment for each country and sector. We then measure the digital investment intensity (DII) as the ratio between the real investment in digital technologies and the real total investment. This yields data for about 12 thousand country-sector-year cells.[9]

Figure 3 shows the time evolution of the average intensity of investment in digital technologies in our data between 2000 and 2018. It unveils a clear pattern of digitalisation in Europe, with the investment share of digital technologies consistently increasing over time. The intensity of investment in digital technologies increased from 29.6% in 2000 to 34.6% in 2018. Alongside

9. We gathered the data on digital technology investment intensities for the thirteen countries, see Table 1, for 61 sectors of economic activity, and over the period 2000-18 (19 years). This implies that there is a possible total of 15,067 country-sector-year combinations. Due to data availability restrictions across the different countries, sectors, and years, we end up with information on digital investment intensities for 11,953 cells, with Austria, Latvia, Norway and Portugal having considerably less information available than the remaining countries in our sample.

Figure 4: Long-term changes in the intensity and relative investment price of digital technologies.



Notes: (1) See the notes of Figure 3; and (2) long-term variations are measured between 2000 and 2018, and are defined as the difference in the share of digital investment or in terms of the percentage changes in the relative investment price of digital technologies.

the acceleration of the digitalisation process in Europe, Figure 3 shows that digital technologies became relatively cheaper over time. We compute the relative price of investment in digital technologies in two steps. First, we construct the price deflator of digital technologies as a Törnqvist index for the basket composed of investment in ICT equipment, computer software and databases, and R&D expenditures. We divide this price deflator for digital technologies by the price deflator for total investment. Both deflators are normalized to year 2015, which implies that the relative price of digital capital equals unity in 2015. Compared to 2015, the relative price of investment in digital technologies was 39% higher in 2000 and 2% lower in 2018.

We show the long-term differences (2000 to 2018) in the investment share of digital technologies by sector of economic activity in Figure 4. Digital investment is on average more prominent in manufacturing than in services. Between 2000-2018, in manufacturing the intensity of digital investment increased from 41.1% to 50.5%. In services, it increased from 21.5% to 25.3%.[10]

10. Within manufacturing, the intensity of digital investment increased in all sub-sectors except for the manufacture of basic pharmaceutical products and pharmaceutical preparations (NACE Rev 2 sector 21). Within

These patterns are slightly more heterogeneous across countries. For example, countries such as Estonia, Germany, France and Spain observed a strong increase in the investment share of digital technologies over time, whilst Finland and Sweden recorded the opposite. Figure 4 shows that the decrease in the relative price of digital investment occurred across all sectors. The long-term decrease in the relative price of digital technologies was also common to the majority of countries and sectors, although with the exception of Belgium and Latvia where it remained broadly stable over time.

3.2 Accounting for the price information in digital investment intensities.

Part of the increase in the investment intensity of digital technologies can be explained by the decrease in the relative price of digital technologies. 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 opens up the question on whether it would be possible to i) account for how relative price effects impact digital investment intensities; and to ii) assess whether some sectors exhibit digital investment intensities that are higher or lower than expected given the relative price of digital technologies in these sectors. To embed these questions into our analysis, we construct a second measure of digitalisation according to

$$\text{DII}_{c,s,t} = \beta \times \text{Relative Price of Digital Investment}_{c,s,t-1} + \delta_{c,t} + \delta_s + \varepsilon_{c,s,t}, \tag{2}$$

We allow for country-specific time effects and level differences across the different sectors of economic activity. Equation (2) is consistent with a framework in which firms take the information available on prices during the previous year in order to undertake their investment decisions during the year. The identifying assumption is that the average firm in a given country, sector and year cell is a price taker regarding its investment decisions. Under this assumption, so is the sector on aggregate.

We are interested in the residuals of equation (2), $\hat{\varepsilon}_{c,s,t}$. These are our second measure of digitalisation. We interpret this indicator as the intensity of digital investment that is not induced by variations in the relative price of digital technologies. When these residuals are

services, the intensity of digital investment increased in all but five sub-sectors: Water transport (NACE Rev 2 sector 50); motion picture, video and television programme production, sound recording and music publishing activities (59); information service activities (63); legal and accounting activities (69); and advertising and market research (73).

Table 3: Regression results of equation (2).

	(1)	(2)	(3)	(4)
$\hat{\beta}$	-0.074***	-0.102***	-0.142***	-0.139***
ln (Real Value Added$_{c,s,t-1}$)		0.052***		0.014**
Sector Fixed Effects			✓	✓
Country-Year Fixed Effects			✓	✓
# Obs	10,545	10,544	10,545	10,544
R^2	0.007	0.134	0.610	0.611

Notes: regressions weighted by employment and standard errors corrected for heteroskedasticity. ** describe 5%-significance levels and *** describe 1%-significance levels.

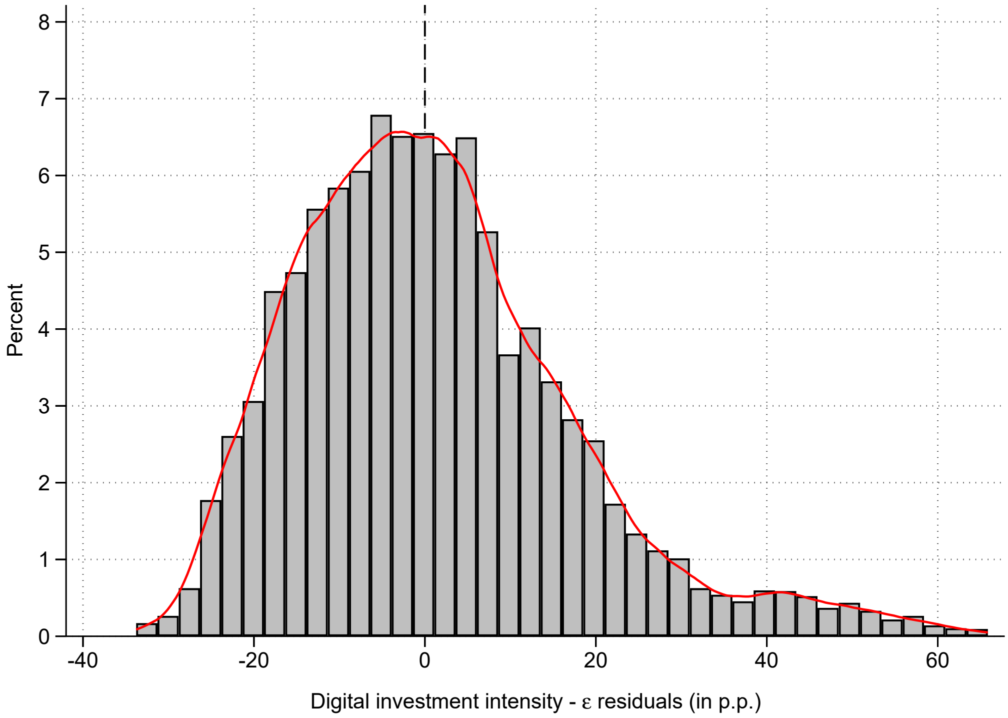
positive (negative), the digital investment intensity in a given country-sector-year cell is then above (below) what would be expected given the relative price of digital technologies in the previous period. Or in other words: it measures the extent to which the digital investment intensity exceeds, or falls short of, what would be expected from the relative price of digital investment. As a robustness check, we consider in Table 3 alternative specifications of equation 2 taking into account also the log-level of real activity in the previous period for each country-sector cell. We find that country-sector cells with relatively higher real value added in the previous period report on average higher digital investment intensities. However, this variable does not add considerable explanatory power when added to our benchmark specification with sector and country-year fixed effects.

Table 3 shows the regression results of equation (2), with a focus on the coefficient measuring the co-movement between digital investment intensities and the relative price of investment in digital technologies. As expected, country-sector-year cells that exhibit relatively higher prices of investment in digital technologies report on average lower digital investment intensities. Our benchmark measure of digitalisation, which we label as $\hat{\epsilon}$-residuals, is measured by extracting the residuals from the empirical specification (3).[11] The $\hat{\epsilon}$-residuals are positively correlated with the DIIs, with a correlation of 0.678. This means that there is significant price information across the different country-sector-year cell DIIs, which we filter out when obtaining the $\hat{\epsilon}$-residuals.

We present in Figure 5 the empirical distribution of these digital investment intensity residuals. Our aim is to better understand their underlying variability, so we group the residuals

11. Since including the lagged log value added as a regressor yields only a marginal gain to the explanatory power of the empirical model, we decided to remain parsimonious and to exclude it from our benchmark measure.

Figure 5: Empirical distribution of digital investment intensity residuals



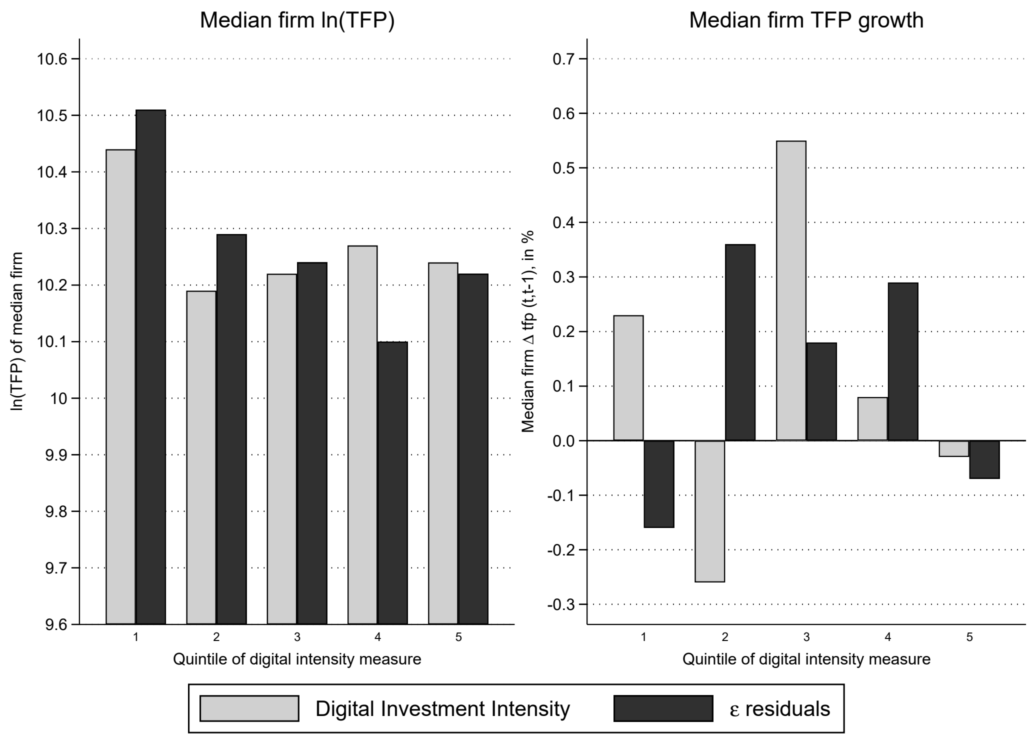
Variable	mean	s.d.	p10	p25	p50	p75	p90
$\hat{\varepsilon}$	1.09	16.42	-17.72	-10.61	-0.87	9.90	21.60

Notes: (1) digital investment intensity residuals $\hat{\varepsilon}$ are constructed as the residuals of equation (2) when estimated with model (3) in Table 3.

into cells without employing the weighting scheme that we used when estimating equation 2. In particular, the residuals span between -34 and 66 percentage points. The distribution is broadly centered around zero and it is positively skewed, implying that the majority of sectors have negative residuals and that some country-sector-year cells observe relatively large positive residuals. That is, they exhibit digital investment shares that are particularly large when compared to the relative price of digital technologies in the previous period. This implies that firms in these cells exhibited a larger investment in digital technologies that would be otherwise expected by the relative price these firms faced when investing in these technologies. There is some persistence in the degree of digitalisation for the average country-sector group: the autoregressive coefficient of a simple AR(1) model for $\hat{\varepsilon}$ stands at around 0.65.[12]

12. The AR(1) specification is based on $\hat{\varepsilon}_{c,s,t} = \alpha + \rho \times \hat{\varepsilon}_{c,s,t-1} + \nu_{c,s,t}$ and is estimated by Pooled OLS and weighted by the employment in each cell. The autoregressive coefficient increases to 0.77 when we include country-

Figure 6: Median firm's tfp and $\Delta tfp_{t,t-1}$ by degree of digital investment intensity.



Notes: (1) digital investment intensity residuals $\hat{\varepsilon}$ are constructed as the residuals of equation (2) when estimated with model (4) in Table 3; and (2) quintile 1 (or 5) corresponds to the 20% of sectors with the lowest (or highest) degree of digital investment intensity.

We have argued in the previous section that firms in the digital sector were both more productive and that they exhibited faster TFP growth than firms in the non-digital sector, when both sectors were defined according to the time-invariant classification from Calvino et al. (2018). However, the relationship between digitalisation and TFP is less clear once we account for the variability of digitalisation measures over time. Figure 6 shows the median firms' tfp levels and $\Delta tfp_{t,t-1}$ by degree of digital investment intensity in their country-sector-year cells. There is no clear relationship between digitalisation and tfp. The median firm in cells at the lowest quintile of digital investment intensity have the highest tfp levels, with the median firms in the remaining quintiles of digital investment intensity being broadly comparable to each other. This occurs also when we consider a partition along different levels of $\hat{\varepsilon}$. Similarly, there is no clear relationship between digitalisation and firm-level TFP growth. The median firm's TFP

year and sector fixed effects in the regression specification. Amongst the most digital intensive country-sector cells when defined in terms of their over-investment in digital technology, we have for example the information and communication sectors in Estonia and Slovenia. On the other end, examples of the least digital intensive country-sector cells are the legal and accounting sector and the management consultancy sector in Spain.

growth varies across the different quintiles of digital investment intensity but again without a clear pattern.

These figures contrast with the earlier descriptive results showing that digital intensive firms are more productive and increase their productivity faster than their less digital intensive counterparts. In the next section we disentangle the impact of digitalisation on firm-level TFP growth, by also taking into account that firms face different market conditions and differ regarding their micro level characteristics.

4 Impact of digitalisation on firm-level TFP growth

Our starting point are previous findings which suggest that investment in digital technologies can be an important driver of productivity growth (Jorgenson (2001), Syverson (2011), Gal et al. (2019)). To validate this using our own data, we build upon and extend the empirical framework of Gal et al. (2019):

$$
\begin{aligned}
\Delta tfp_{i,c,s,t} = & \beta_{dig} \times Dig_{c,s,t-1} && \text{(Digitalisation)} \\
& + \beta_{ftfp} \times \Delta ftfp_{s,t} && \text{(Frontier growth)} \\
& + \beta_{gap} \times Gap_{i,c,s,t-1} && \text{(Distance to frontier)} \\
& + \beta_{x} \times X_{i,c,s,t-1} && \text{(Firm-level controls)} \\
& + \beta_{hhi} \times \text{HHI}_{c,s,t-1} && \text{(Market concentration)} \\
& + \delta_{c,t} + \delta_{s} && \text{(Fixed Effects)} \\
& + \nu_{i,c,s,t}. && \text{(Residual)} \qquad (3)
\end{aligned}
$$

On the left-hand-side, $\Delta tfp_{i,c,s,t} = \ln(\text{TFP}_{i,c,s,t}) - \ln(\text{TFP}_{i,c,s,t-1})$ measures the (log) TFP growth rate of firm i, with TFP estimated as in Gandhi et al. (2020). We measure digitalisation as the digital investment intensities or the digital investment $\hat{\varepsilon}$-residuals described in Section 3, which vary at the country-sector-year level.[13] Compared to Gal et al. (2019), whose measures

13. The usage of digital technologies can impact the firm's output elasticities with respect to the different factors of production (Acemoglu and Restrepo (2018)). This can lead to measurement error in the estimation of firm-level TFP, which could be corrected by augmenting the Gandhi et al. (2020) methodology to estimate TFP while accounting for the usage of digital technology in a fashion similar to De Loecker (2013). However, firm level data on the usage of digital technologies is limited or restricted to detailed sectors (Bartel et al. (2007)), or samples are small and cover restricted time periods (Bresnahan et al. 2002, Cusolito et al. 2020). We acknowledge this caveat, but prioritize our scope on a large firm-level balance sheet data from 13 European countries, given that

of digitalisation vary on the country-level, we thus add more layers of variation to identify the impact of digitalisation on firm TFP growth.

There are however other channels that can drive the TFP growth at the firm level. One such factor is technological diffusion from frontier firms to laggard firms (Andrews et al. 2015, Akcigit and Ates 2021). We follow Gal et al. (2019) and capture this force via the contemporaneous (log) TFP growth for frontier firms, β_{ftfp}. We define the technological frontier as the 5% most productive firms in their respective disaggregate (4-digit) sector and for each year. We then measure the average (log) TFP for frontier firms for each sector and year and we construct $\Delta ftfp_{s,t}$ as the yearly log difference of that average. Similar to the aforementioned authors, to avoid endogeneity we estimate equation (3) only for laggard firms (i.e., those firms in the sample who are not among the 5% most productive firms in their respective sector).

Another factor that can affect firms' TFP growth is related to how fast laggard firms catch up to the frontier. Firm TFP growth depends on how far away the respective firm is from the productivity frontier (Cette et al. 2018). We control for this by including the (lagged) distance of the TFP level of each laggard firm to the TFP of its frontier, $Gap_{i,c,s,t-1}$. We interpret β_{gap} as reflecting "up-or-out" dynamics: firms needing to catch up to the productivity frontier in order to survive and be able to compete in their market.

We go beyond Gal et al. (2019) by also taking into account the role of market concentration for TFP growth (Olmstead-Rumsey 2022). To do so, using our own firm-level data we construct time varying Herfindahl-Hirschman indices at the disaggregated (4-digit) sector and country level. We prefer it to be at the country level because this is arguably the most relevant geographical unit to measure market concentration for most firms.[14]

We take into account that firms have heterogeneous characteristics by including as controls the firm's (log) employment level to proxy for size, the firm's age (Haltiwanger et al. 1999), how leveraged the firm is (i.e., gearing), and the firm's liquidity ratio (Levine and Warusawitharana 2021).[15] Finally, our specifications include country-year and (4-digit) sector fixed effects. This is to allow for country-specific trends or for technological shifts across the different sectors that

we observe digital investment data at the sectoral rather than the firm level.

14. The Herfindahl-Hirschman index is constructed by gathering the information of all firms in our data, both laggards and frontier firms, by country, sector, and year.

15. The liquidity ratio measures whether a company has sufficient short term assets to cover its short term liabilities. Our indicator for gearing is a debt-to-equity ratio that compares non current liabilities and loans with the firm's shareholder funds. We include these two measures simultaneously to have a better sense of the firm's liquidity and indebtedness conditions.

are not otherwise explained for by the channels we consider in our empirical framework.

Table 4 shows the results for the estimation of equation 3.[16] Starting point is column 1, which isolates the impact of technological diffusion from the frontier to laggard firms, the convergence of laggard firms depending on where they stand in the productivity distribution, and firm-level controls for the size and age of the firm (these are the baseline controls in Gal et al. 2019). We find that a one percentage-point (pp) higher growth of frontier TFP is associated with a 0.15pp-0.16pp higher TFP growth for the average laggard firm. While this confirms previous findings on technological diffusion from frontier to laggard firms, we note that our estimates are slightly lower than previous ones in the literature (around 0.22pp in Gal et al. 2019 and 0.27pp in Andrews et al. 2015). Regarding the catching up process of laggard firms, a one percentage point larger distance of a laggard's (log) TFP to the frontier is associated with a 0.20pp higher TFP growth on average. This estimate lies in the mid-range of those from previous evidence. For example, Andrews et al. (2015) find a convergence coefficient of around 0.29pp for the distance to the national frontier, while Cette et al. (2018) unveil a time-varying coefficient of around 0.09pp-0.14pp using French data, and Gal et al. (2019) find a convergence coefficient of around 0.11pp for firms with ten or more employees. We control for the firms' heterogeneity in size by including the firm's employment (log) level. Doing so we find that a 1% increase in the firm's employment is associated on average with a 0.05pp higher TFP growth. Consistent with Alon et al. (2018) we find that a one year increase in the firm's age is associated with a 0.08pp-0.10pp lower firm TFP growth.

In the second column of Table 4 we add our Herfindahl-Hirschman index to measure market concentration in the previous year. In addition, the regression includes the firm's lagged indebtedness and liquidity ratio. We find that a 1pp increase in the HHI is associated with a TFP growth that is 0.026pp lower on average. That is, higher market concentration forms stricter barriers to entry and reduces the TFP growth of incumbent firms, à la "winner-takes-(almost)-all" dynamics. Turning to the firms' financial information, we find that a 1pp higher (lagged) short-run liquidity ratio is associated to a 0.14pp lower TFP growth of the average firm. We view this negative impact of a higher liquidity ratio on the firm's TFP growth as resulting from costs associated with this higher liquidity risk: the firm then incurs costs to insure itself against

16. To further improve our data's representativeness, we construct inverse probability sampling weights for each country, sector, firm size class, and year cell. To do so, we follow Gal (2013) and calculate the ratio between the number of firms in the population (taken from the OECD Structural and Demographic Business Statistics database) and the number of firms in our sample.

Table 4: Benchmark results: Marginal impact of digital investment on the firm's TFP growth

	(1)	(2)	Digital Investment Intensity (3)	(4)	$\hat{\varepsilon}$-Residuals (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)
$\beta_{\text{employment}}$	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)
$\beta_{\text{liquidity ratio}}$		-0.145^{***}		-0.152^{***}		-0.160^{***}
		(0.020)		(0.021)		(0.022)
β_{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

Notes: (1) all specifications include country-year and sector fixed effects; (2) digital investment intensity is measured as the investment share of digital technologies and $\hat{\varepsilon}$ are constructed as the digital investment intensity residuals following equation (2) and estimated with model (3) in Table 3; (3) all specifications are estimated after excluding frontier firms - the 5% most productive firms in each disaggregated (4 digit) sector and year; (4) firms are weighted by their inverse share in the population of firms at the country, sector (2 digit), firm size, and year cell level; (5) standard errors are clustered at the country-sector (4 digit) level; and (6) (*) describe 10%-significance, (**) describe 5%-significance, and (***) describe 1%-significance levels.

the risk of not having enough liquidity to meet their short-term debt obligations. Alternatively, these firms could be more averse to debt-financed investment and thus be reluctant to invest, via debt, in ex-post productive projects. By contrast, we find that a higher (lagged) indebtedness is positively related to TFP growth: a 10pp increase in gearing is associated to a 0.005pp higher TFP growth of the average firm. This is consistent with Levine and Warusawitharana (2021) who find that book leverage and debt growth are associated with higher firm TFP growth.[17]

Our main interest lies on the coefficient β_{dig}, which unveils the average impact of digitalisation on firm-level TFP growth. We lag our digitalisation variables to measure the impact of digitalisation after its installment (i.e. during the deployment) phase. This follows van Ark

17. Although we account for the firm's financial information, we do not explicitly tackle the impact of financial constraints, as in Ferrando and Ruggieri (2018). The Gandhi et al. (2020) methodology to estimate firm-level TFP relies on the optimality of the firm's first order conditions in the input markets and, in this way, does not take into account possible non-linearities in TFP stemming from financial constraints (see also Shenoy (2021)).

(2016) and is similar in spirit to the standard "time to build" assumption on the accumulation of physical capital. In this way, we embed in a simple reduced form the notion that the impact of digitalisation depends also on the managerial quality of the firm (Bloom et al. 2012, Anderton et al. 2020) and we allow firms the time to better embed digitalisation in their production process before assessing its impact on their TFP growth.

The benchmark specifications accounting for the impact of digital investment on firm-level TFP are shown in columns (3) and (4) of Table 4. Column (3) corresponds to the reduced form model and accounts for technological diffusion, catching up dynamics, the age and the size of the firm. In addition, column (4) controls for market concentration and the firm's financials. Both columns confirm that digitalisation brings about benefits to the average laggard firm's TFP growth. Quantitatively, our estimates suggest that a 1pp higher digital investment intensity is associated with an acceleration of the average laggard firm's TFP growth by 0.012pp, which is rather small. This impact is 21% larger when we account also for market concentration and for the firm's financial information, with the acceleration in the average firm's TFP growth then amounting to 0.015pp.[18] While our measures of digitalisation are defined at the country-sector-year cell level, our empirical model implies that for two otherwise identical firms, the firm that exhibits a 1pp higher share of investment in digital technologies will exhibit a 0.015pp faster TFP growth.

In the last two columns of Table 4, we re-assess the impact of digitalisation on TFP growth by using as digitalisation measure our non-price induced digital investment intensity residuals from Section 3. A 1pp increase in $\hat{\varepsilon}$ is associated with a 0.019pp higher TFP growth of the average firm over the next year. Or put differently, for firms in sectors where the DII exceeds by 1pp the DII benchmark that could be justified from the relative price of digital investment, the TFP growth is 0.019pp higher. This impact is 10% higher in the full model, when we account also for market concentration and for the firm's financial information, being around 0.021pp in this case. Independently of the empirical specification used, the impact of digitalisation on the average firm's TFP growth is considerably larger when assessed with the non-price induced $\hat{\varepsilon}$-residuals than when we consider both quantity and price effects of digital investment with the raw digital investment shares.[19] We view the lower TFP growth impact of digitalisation from the

18. We note that this difference in the impact of digital technology is mostly driven by the different sample compositions and by data availability on the firm's financial information.

19. The difference stands between 40%-50% when comparing β_{dig} in (3) and (5) or in (4) and (6). The sample composition has an important effect here as well, although the difference still stands at around 12% both when

specifications in (3) and (4) as resulting from, indeed, price effects. As the relative price of digital investment declines, this fosters a relatively more widespread adoption of digital technology. In turn, the increased competition increases the need for firms to invest in digital technologies although they won't be able to fully reap the benefits. Overall, our findings corroborate the notion that digitalisation brings about productivity gains at the firm level, albeit these are relatively low - as is the case for the aggregate economy (Anderton and Cette (2021)).

However, we emphasize that despite the low marginal effect on the TFP growth of laggard firms, a strong investment in digital technologies can still be associated with a sizeable boost to the firm's TFP growth. For example, a one standard deviation increase in the digital investment intensity (around 18pp) would be associated with an increase in the average firm's TFP growth by 0.22pp per year in specification (3) and by 0.27pp per year in (4). Similarly, a one standard deviation increase of the $\hat{\varepsilon}$-residuals (15.4pp) would correspond to a boost to the average firm's TFP growth by 0.30pp per year in specification (5) and by 0.33pp in (6). To substantiate the potential importance of digitalisation, we do a simple exercise and compare the impact of digitalisation to that of market concentration. A one standard deviation increase in both digital intensities and market concentration yields an overall decline in the laggard firm's TFP growth of only 0.04pp in (4) and 0.01pp in (6). This is because the impact of higher digitalisation nearly completely offsets the negative impact of higher market concentration.

Such large changes in the digitalisation intensity are however not regularly observed in our data. For only 25% of the firms in our sample we observe that the respective country-sector digital investment intensity increases by 1.5pp or more on a yearly basis (or 1.3pp for $\hat{\varepsilon}$). By contrast, for 25% of firms the respective country-sector digital investment intensity declines by around 0.5pp (or 1.4pp in $\hat{\varepsilon}$). Therefore, while digitalisation is shown to increase TFP growth on average, it does not seem at first sight a gamechanger to improve firms' productivity over time. While the average impact of digitalisation is relatively small, it may be that some firms are reaping the full benefits of digitalisation, while others consider it more of a sideshow. To shed light on this, our next step is to systematically investigate patterns of heterogeneity in the productivity gains from digitalisation.

we estimate (3) on the sample of (5) and (4) on the sample of (6).

Table 5: Marginal impact of digitalisation in digital and non-digital intensive sectors

	Digital Investment Intensity		$\hat{\varepsilon}$-Residuals	
	(3)	(4)	(5)	(6)
β_{dig}	0.020**	0.022**	0.022*	0.024**
	(0.010)	(0.010)	(0.011)	(0.012)
$\beta_{\text{dig-CCMS}}$	0.003	0.007	0.017	0.019*
	(0.013)	(0.013)	(0.012)	(0.011)
# Obs. (in mio.)	14.059	11.664	13.067	10.868
R^2	0.154	0.151	0.154	0.151

Notes: all specifications build on those in Table 4 to add a dummy variable to isolate digital intensive sectors, and are labelled with the same number to allow for an easier comparison. See Table 4 for further details. (*) describe 10%, (**) 5%, and (***) 1%-significance levels.

5 Heterogeneity in the productivity gains from digital investment and its main channels

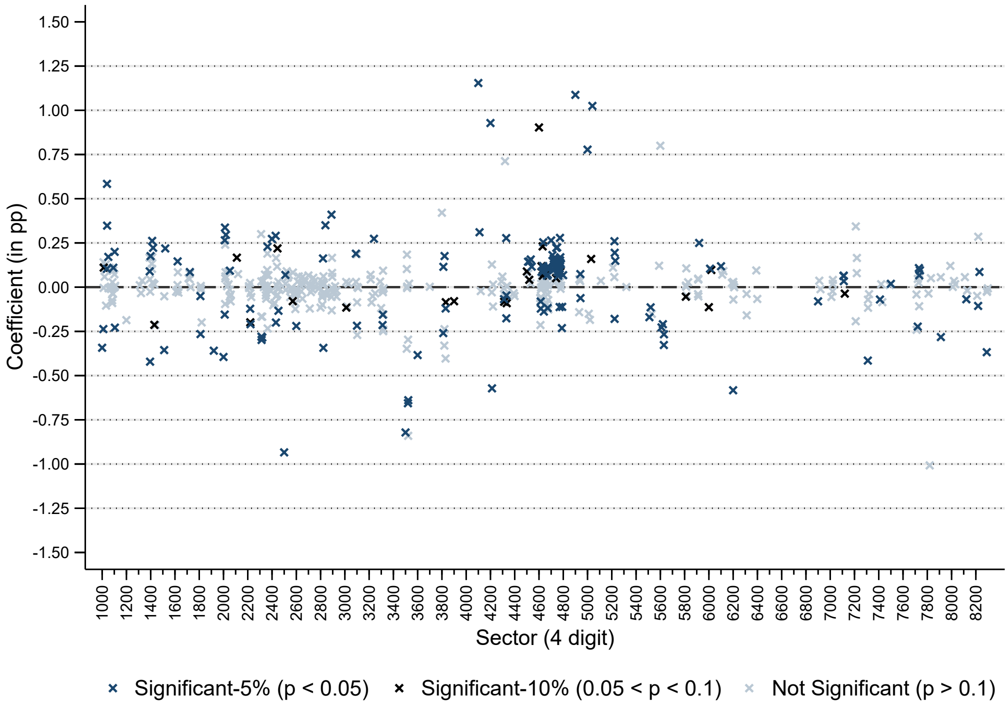
5.1 Is the impact of digitalisation common across sectors?

To understand who are the firms for which digitalisation is a gamechanger (and not a sideshow), we start by disaggregating the impact of digitalisation across sectors. We first modify equation (3) to differentiate the impact of digitalisation across digital versus non-digital intensive sectors as defined by Calvino et al. (2018):

$$\begin{aligned}\Delta tfp_{i,c,s,t} =& \beta_{dig} \times Dig_{c,s,t-1} + \beta_{dig-CCMS} \times Dig_{c,s,t-1} \times \mathbb{1}_{CCMS} \\ & + \beta_{ftfp} \times \Delta ftfp_{s,t} + \beta_{gap} \times Gap_{i,c,s,t-1} + \beta_{hhi} \times \text{HHI}_{c,s,t-1} \\ & + \beta_x \times X_{i,c,s,t-1} + \delta_{c,t} + \delta_s + \nu_{i,c,s,t}, \end{aligned} \tag{4}$$

where $\mathbb{1}_{CCMS}$ is a dummy variable taking a value of unity if firm i belongs to a sector that Calvino et al. (2018) identify as digital intensive, and zero otherwise. Table 5 shows the results from this specification. To summarize, the impact of digitalisation on the average laggard's TFP growth seems to be only slightly larger in magnitude for firms in digital intensive sectors, with the coefficient $\beta_{dig-CCMS}$ not being in general statistically different from zero across most specifications. Specification (6) is the exception, as it finds that a 1pp increase in $\hat{\varepsilon}$-residuals increases the average laggard's TFP growth by 43 basis points in digital intensive sectors, higher than the 24bp estimated for non-digital intensive firms.

Figure 7: Sector-specific coefficient on digitalisation ($\hat{\varepsilon}$-residuals)



Notes: Coefficients estimated from equation (5) with digitalisation measured by the $\hat{\varepsilon}_{c,s,t}$-residuals and embedding the same controls as specification (6) in Table 4.

However, and as we mentioned in previous sections, the Calvino et al. (2018) approach does not properly account for all idiosyncrasies, and in this case also sectoral, that affect how digitalisation is related to firm TFP growth. We therefore modify our empirical framework in (4) to isolate the impact of digitalisation on the average laggard firm's TFP growth for each disaggregated (4-digit) sector:

$$\begin{aligned}\Delta tfp_{i,c,s,t} =& \beta_{dig,s} \times Dig_{c,s,t-1} \times \mathbb{1}_s + \beta_{ftfp} \times \Delta ftfp_{s,t} + \beta_{gap} \times Gap_{i,c,s,t-1} \\ &+ \beta_x \times X_{i,c,s,t-1} + \beta_{hhi} \times \mathrm{HHI}_{c,s,t-1} + \delta_{c,t} + \delta_s + \nu_{i,c,s,t}\end{aligned} \tag{5}$$

where $\mathbb{1}_s$ is a dummy that equals one if firm i belongs to sector s, and zero otherwise.

We plot the resulting coefficients measuring the sector-specific impacts of digitalisation on the average laggard's productivity growth in Figure 7. Clearly, there is a certain degree of volatility in the benefits of digitalisation across sectors, although the coefficients remain mostly within a range between -0.50 and +0.50. A simple equal-weighted average across sectors of the estimated sectoral coefficients would yield an increase in firm-level TFP growth by 0.35pp following a 1pp increase in the $\hat{\epsilon}$-residuals.[20] A higher investment in digital technologies does not benefit firms in all sectors in the same way. In 349 sectors (69% of the total 503 sectors we include), the average firm records a neutral impact of digital technology on their productivity growth: for them β_{dig} is statistically insignificant and close to zero. Instead, for 95 sectors digitalisation is associated with a considerable positive impact on the average firm's TFP growth (+0.34pp on average across these sectors).[21] This is about 17 times larger than the average impact we reported for the average firm in our total sample according to specification (6) in Table 4. For firms in these sectors, digital technologies are a true gamechanger, allowing firms to become considerably more productive over time. By contrast, in 59 sectors the impact of digitalisation is negative and amounts to around -0.30pp on average, showing that firms in some sectors do not benefit directly from a stronger investment in digital technologies and incur in productivity losses when increasing this investment.[22] These sectors are still in the installation phase of digital technologies, for which its productive use is not yet apparent or easy to implement. Therefore, firms in these sectors should consider digital technologies only as a sideshow.

5.2 Digitalisation enables (certain) laggards to catch up...

Another important channel to consider is whether digitalisation benefits all, or instead only some laggards, depending on their distance to the productivity frontier. To assess this, we modify our regression framework to include the interaction between our measures of digitalisation and firm i's TFP gap to the frontier:

$$\begin{aligned}\Delta tfp_{i,c,s,t} =& \beta_{dig} \times Dig_{c,s,t-1} + \beta_{ftfp} \times \Delta ftfp_{s,t} + \beta_{gap} \times Gap_{i,c,s,t-1} \\ &+ \beta_{dig-gap} \times Gap_{i,c,s,t-1} \times Dig_{c,s,t-1} + \beta_x \times X_{i,c,s,t-1} \\ &+ \beta_{hhi} \times \text{HHI}_{c,s,t-1} + \delta_{c,t} + \delta_s + \nu_{i,c,s,t}. \end{aligned} \tag{6}$$

We collect the results in Table 6 (for brevity, we focus on the digitalisation coefficients). A 1pp higher digital investment intensity leads to an acceleration of the TFP growth by 0.134pp.

20. The unweighted average of all the sectoral coefficients estimated in analogy to specification (6) in Table 4, i.e. using equation (5) with the estimated $\hat{\varepsilon}_{c,s,t}$-residuals but including the firms' financial information and the HHI on top of the other controls. Using the sectors' DIIs, a higher digitalisation is associated with a 0.2pp higher TFP growth on average across sectors.

21. This includes for example the professional, scientific and technical activities sector, office administration and support activities, and the construction of buildings and civil engineering sectors.

22. This is the case, for example, in the waste collection, travel agency and tour operator activities, and in the electricity and gas sectors.

Table 6: Marginal impact of digitalisation on the ability of laggards to catch up with the frontier

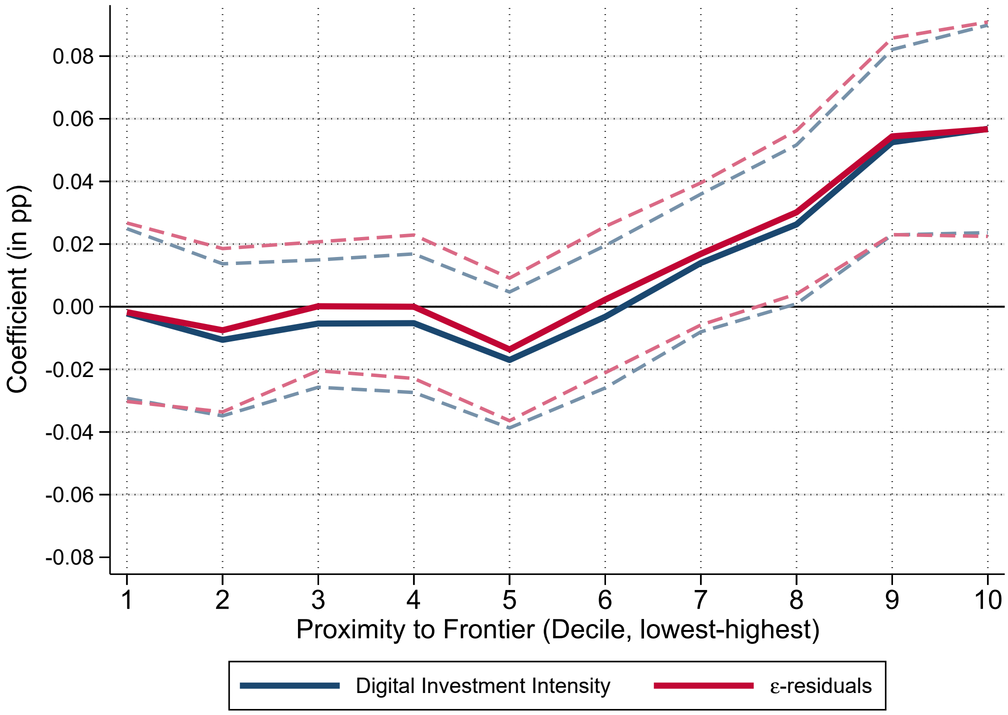
	Digital Investment Intensity		$\hat{\varepsilon}$-Residuals	
	(3)	(4)	(5)	(6)
β_{dig}	0.137***	0.134***	0.039*	0.041*
	(0.026)	(0.026)	(0.022)	(0.022)
$\beta_{\text{dig-gap}}$	-0.001***	-0.001***	-0.0001	-0.0001
	(0.0002)	(0.0002)	(0.0001)	(0.0001)
# Obs. (in mio.)	14.059	11.664	13.067	10.868
R^2	0.156	0.153	0.154	0.151

Notes: Specifications build on those in Table 4 according to equation (6), but we only show the digitalisation coefficients for brevity. All other coefficients are well in line with those reported in Table 4. (*) describe 10%, (**) 5%, and (***) 1%-significance levels.

This is, however, only for the most productive laggards. For laggard firms further away from the frontier, the boost from digital technology is lower. This implies that the most productive laggard firms are those that are able to fully reap the benefits from digitalisation, while less productive firms are less able to benefit from digital investment. By contrast, a 1pp increase in $\hat{\varepsilon}$ implies that the most productive laggards improve their TFP growth by 0.041pp. For this measure, however, the benefits from digitalisation are more common across most firms. Still, when comparing these results with those in Table 4, the marginal benefit from digitalisation for the average firm is about half of the benefit for the more productive laggards as reported here. This suggests that digital investment does not allow all laggards to improve their productivity in the same way.

To further highlight this result, we consider that the impact of digitalisation may not be linear in the gap to the productivity frontier. To further investigate this we estimate our benchmark regression, equation (3), by decile of the firm's proximity to the productivity frontier. Figure 8 plots the resulting coefficients and unveils that the 70% least productive laggards in their sectors do not benefit from digitalisation. Instead, the benefits of investing in digital technologies are concentrated on the 30% most productive laggards in their sectors of activity. That is, only the most productive laggards are effectively able to productively use digital technologies to accelerate their TFP growth and thereby become more productive over time, with $\hat{beta}_{\text{dig}}$ for these firms being between two to three times larger than the impact that we measured for the average laggard firm in Table 4. Independently on the sector of activity, the most productive laggard in each sector could consider the investment in digital technologies as a gamechanger that boosts

Figure 8: Marginal impact of digitalisation on laggards' TFP growth by proximity to frontier decile

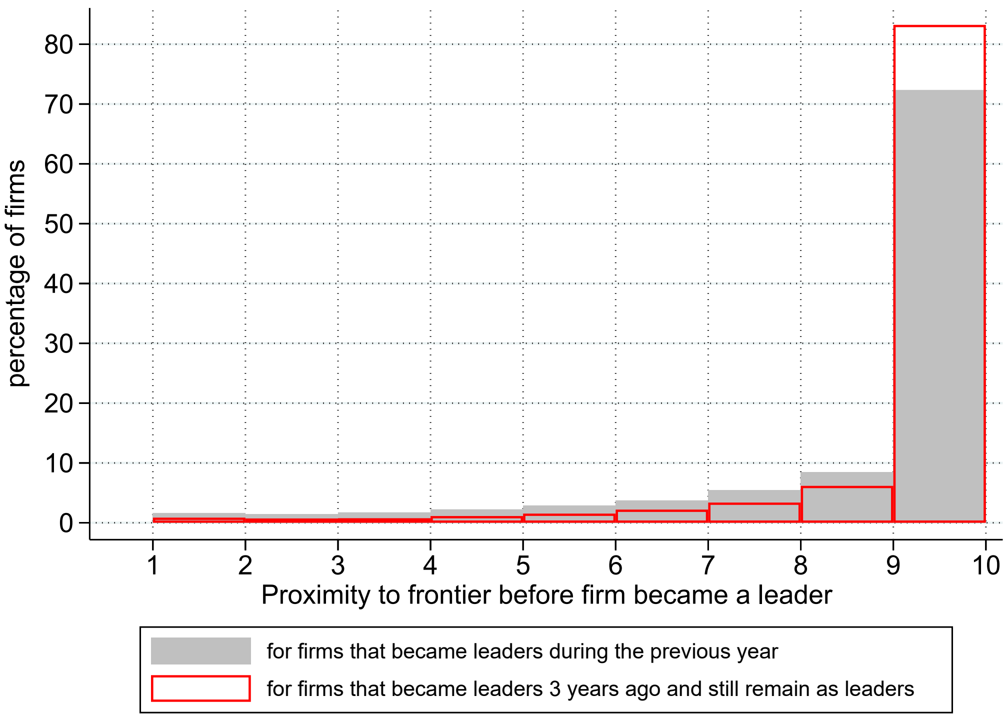


Notes: Coefficients estimated based on 3 for each decile of the firms proximity to the productivity frontier. We do so essentially by estimating specifications (4) and (6) in Table 4 for each decile of proximity to the productivity frontier. Deciles of proximity to the productivity frontier are constructed yearly. Dashed lines show the 95%-CIs.

their future productivity. They do so by embedding digital technologies in production methods that are already optimised and more productive than their sectoral peers.

There are very good reasons for a firm to invest in and adopt digital technologies in their production. Some examples are to keep or increase their customer base by advertising their goods or services, to reduce inefficiencies by passing physical processes to digital and allowing for some cost reduction, to avoid losing market shares versus their competitors, or in a final attempt to survive by focusing on a different market. These reasons are broadly the same for all firms, independently on their initial productivity. But what about the less productive firms? We estimate that these firms are not able to benefit from their investments in digital technologies, implying that digitalisation only acts as a sideshow for these firms. This means that less productive laggards should focus first on optimising their production process first by other means in an attempt to become as productive as their more productive peers, and only then to invest in digital technologies. This suggests that the synergies from digital investment

Figure 9: New frontier firms by proximity to frontier before the firm became a leader



Notes: The proximity to frontier before the firm became a productivity leader is measured in deciles, with the lowest decile corresponding to the lowest productive firms in the economy and with the highest decile corresponding to the most productive laggards. Deciles of proximity to the productivity frontier are constructed yearly for each sector.

occur mostly when firm has already an efficient production process in place. This allows the most productive laggards to leverage digitalisation as a way to obtain a competitive edge over their peers.

5.3 ...but does not necessarily make laggards into leaders.

In light of these results, highly productive laggards could believe that increasing their digital investments might make them go the extra mile to get into the productivity frontier. Figure 9 shows the distribution of new leaders by their proximity to the frontier before these firms became leaders (in deciles). Highly productive laggards are more likely to make it to the frontier than their peers: 70% of new leaders were in the top 10% most productive laggards. This is the case also for the most successful new leaders, with 80% of the firms that managed to become leaders and to remain at the productivity frontier for more than three consecutive leaders after becoming new leaders, stemming from the top 10% most productive laggards.

We have seen that on average the most productive laggards are the ones benefiting the most from digital investments. These firms are also the most likely to become new productivity leaders in the future. These results together raise the question whether digitalisation helps today's laggard firms to become the productivity leaders of tomorrow. To test this directly, we modify the model in equation (3) to include interactions with a dummy variable that reflects whether a given (laggard) firm has transitioned into the productivity frontier at each time t.

In particular, our empirical approach follows

$$\begin{aligned}\Delta tfp_{i,c,s,t} =& \beta_{dig} \times Dig_{c,s,t-1} + \beta_{dig-entry} \times Dig_{c,s,t-1} \times \mathbb{1}\left[\text{New Leader}_{i,c,s,t}\right] \\ &+ \sum_k \boldsymbol{\beta_k} \times Controls^k_{i,c,s,t-1} + \sum_k \boldsymbol{\beta}_k \times Controls^k_{i,c,s,t-1} \times \mathbb{1}\left[\text{New Leader}_{i,c,s,t}\right] \\ &+ \delta_{c,t} + \delta_{c,t} \times \mathbb{1}\left[\text{New Leader}_{i,c,s,t}\right] + \delta_s + \delta_s \times \mathbb{1}\left[\text{New Leader}_{i,c,s,t}\right] + \nu_{i,c,s,t}. \end{aligned} \tag{7}$$

The coefficient of interest is $\beta_{dig-entry}$, which measures the specific marginal impact of digitalisation for new productivity leaders. We condition the analysis on the most productive firms, as these are the ones that benefit the most from digitalisation and are the most likely to transition into the frontier. We set the lower threshold to be either the median or the 70th percentile of the productivity distribution of laggard firms and we show the results in Table 7.

Although the investment in digital technologies helps those laggards who are already highly productive to improve their productivity even further, we find that digital investments by themselves are however not able to make laggards into leaders. Among the 30% most productive laggards, a 1pp increase in DIIs implies a 0.03pp increase in the average laggard's TFP growth over the following year, while a 1pp increase in $\hat{\varepsilon}$ is associated with a 0.04pp higher TFP growth. By contrast, digital investment seems not to improve, and it even slows down to some extent, the TFP growth of new productivity leaders. A 1pp increase in DIIs is associated with a non-significant decrease in new leaders TFP growth by 0.02pp, while a 1pp increase in $\hat{\varepsilon}$ is associated with a 0.03pp decrease in the new productivity leaders TFP growth among those that have risen from being in the top 30% laggards during the previous year. This implies that digitalisation is not necessarily a gamechanger for highly productive firms to become the productivity leaders in their sector. Installed digital technologies could be at some point an enabler for large productive innovations, thereby allowing firms to become leaders. By contrast, recent digital investments do not seem to help firms in jumping this hurdle, although they allow highly productive laggards to become even more productive over time.

Table 7: Marginal impact of digitalisation on the TFP growth of new productivity leaders.

	DIIs		$\hat{\varepsilon}$-Residuals	
Lower TFP threshold:	50%	70%	50%	70%
β_{dig}	0.025***	0.032***	0.032***	0.041***
	(0.007)	(0.008)	(0.007)	(0.009)
$\beta_{\text{dig-entry}}$	-0.043**	-0.056***	-0.055***	-0.069***
	(0.018)	(0.018)	(0.018)	(0.018)
$\beta_{\text{dig}} + \beta_{\text{dig-entry}}$	-0.019	-0.024	-0.023	-0.028*
	(1.43)	(2.36)	(2.13)	(3.09)
# Obs. (in mio.)	6.761	4.807	6.165	4.285
R^2	0.230	0.247	0.229	0.248

Notes: Coefficients estimated taking the model described in equation (7) with either digital investment intensities or with the estimated $\hat{\varepsilon}_{c,s,t}$-residuals from equation (2) both used to measure digitalisation. We include the firms' financial information and the sector HHI in the estimation. The distribution of proximities to the productivity frontier are calculated yearly by sector. Standard errors are clustered at the country-sector (4 digit) level. For the marginal impact of digitalisation on the TFP growth of new productivity leaders, we opted to show instead the F-statistic on whether this impact is equal to zero. (*) describe 10%, (**) 5%, and (***) 1%-significance levels.

5.4 Do frontier firms benefit more from digitalisation?

So far, we have mostly focused on the productivity gains that laggard firms can obtain by investing in digital technologies. In this section, we will focus instead on the most productive firms in their own sectors, the frontier firms. We are interested in understanding whether the productivity gains from digitalisation are larger (or smaller) for frontier firms compared to what we observed for laggards. Digital transformation is in principle most suitable for frontier firms, who one might consider to be the most effective from a managerial (or even from an organisational) perspective. As such, frontier firms should be the most able to cope with the challenges that digitalisation brings about and to fully reap its benefits. However, also for frontier firms there can be inefficiencies in the adoption of digital technologies, with firms needing time to test and adapt their best practices in order to become more productive by embedding digital technologies in their production processes.

We adapt slightly our benchmark regression (3). First, we only consider frontier firms, and thus we do not account for the distance to the frontier as a control variable. Second, we modify the frontier growth control to be firm-specific. This means that for a given firm i, the frontier growth control accounts for the average TFP growth of all other frontier firms in the same sector of activity as this firm, which we label as $-i$. In this specification, we only consider firms that were at the frontier for two consecutive years and sectors with 5 or more frontier firms.

Table 8: Marginal impact of digital investment on frontier firms' TFP growth

			Digital Investment Intensity		$\hat{\varepsilon}$-Residuals	
	(1)	(2)	(3)	(4)	(5)	(6)
β_{dig}			0.022***	0.017**	0.023***	0.019**
			(0.008)	(0.007)	(0.009)	(0.008)
$\beta_{\text{ftfp}(-i)}$	0.335***	0.340***	0.336***	0.340***	0.319***	0.327***
	(0.022)	(0.024)	(0.022)	(0.024)	(0.021)	(0.023)
$\beta_{\text{employment}}$	1.899***	1.784***	1.899***	1.787***	1.842***	1.742***
	(0.139)	(0.132)	(0.139)	(0.132)	(0.136)	(0.130)
β_{age}	-0.007	-0.000	-0.007	-0.001	-0.007	0.001
	(0.007)	(0.008)	(0.007)	(0.008)	(0.007)	(0.008)
β_{hhi}		-0.013		-0.013		-0.015*
		(0.010)		(0.010)		(0.009)
$\beta_{\text{liquidity ratio}}$		-0.022		-0.022		-0.015
		(0.022)		(0.022)		(0.030)
β_{gearing}		0.213***		0.216***		0.210***
		(0.065)		(0.065)		(0.063)
# Obs. (in mio.)	0.531	0.472	0.526	0.469	0.488	0.437
R^2	0.081	0.080	0.081	0.080	0.077	0.078

Notes: (1) all specifications include country-year and sector fixed effects; (2) digital investment intensity is measured as the investment share of digital technologies and $\hat{\varepsilon}$ are constructed as the digital investment intensity residuals following equation (2) and estimated with model (3) in Table 3; (3) technological diffusion from other frontier firms is measured for each frontier firm as the average TFP growth for all other frontier firms in the same sector; (4) firms are weighted by their inverse share in the population of firms at the country, sector (2 digit), firm size, and year cell level; (5) standard errors are clustered at the country-sector (4 digit) level; and (6) (*) describe 10%-significance, (**) describe 5%-significance, and (***) describe 1%-significance levels.

These changes imply that our empirical specification to estimate the marginal impact of digital investment on frontier firms' TFP growth is given by

$$\begin{aligned}\Delta tfp_{i,c,s,t} =& \beta_{dig} \times Dig_{c,s,t-1} + \beta_{ftfp(-i)} \times \Delta ftfp_{-i,s,t} + \beta_x \times X_{i,c,s,t-1} \\ &+ \beta_{hhi} \times \text{HHI}_{c,s,t-1} + \delta_{c,t} + \delta_s + \nu_{i,c,s,t}. \end{aligned} \tag{8}$$

We display the results in Table 8. First, consider the baseline factors contributing to the TFP growth of frontier firms, which are very similar to those that we observed for laggard firms: (i) larger firms display a faster TFP growth; (ii) market concentration entangles a small drag to the firms' productivity growth; and (iii) a higher gearing is linked to a faster TFP growth, reflecting that frontier firms are successful in taking risks and turning debt into productive activities.

Now focus on the parameters related to digitalisation. For the frontier firms, β_{dig} is estimated to be around 0.02pp, with broadly the same magnitudes that we have estimated for laggards.

This implies that the impact of digitalisation is not particularly stronger for frontier firms. Instead, digitalisation impacts TFP growth in a broadly similar way across the average laggard and the average frontier firms. The technological diffusion channel is however stronger across frontier firms: We find that the average frontier firm is able to increase its TFP growth by 0.33pp for each 1pp increase in the TFP growth of the other frontier firms. This is more than twice the technological diffusion rate we observed for laggards. This implies that frontier firms are more able to rapidly embed innovations by their competitors and to become more productive as a consequence. Therefore, if a frontier firm makes an innovation enabled by digital technologies, it is also more likely that other frontier firms pick this innovation up quite quickly, while this would take longer for laggards to implement. To summarise, frontier firms do not directly benefit more from digitalisation than laggard firms. But they are able to better track and implement successfully the innovations performed by their peers than the average laggard firm.

5.5 Digitalisation and churning at the frontier

We have discussed so far the marginal impact of digitalisation on the firm's TFP growth depending on whether the firm was a laggard, a leader, or a previous laggard that became a leader. A related question is whether, from a macro-level perspective, digitalisation accentuates or deters churning into (or out of) the frontier. To answer this we measure churning rates at the productivity frontier for each country-sector-year cell. The entry rate is defined as the share of laggards that manages to become a productivity leader. Conversely, the exit rate is measured as the share of frontier firms that become laggards.

The average share of laggards that manage to become leaders in a given year stands at 2.5% in Calvino et al. (2018)'s digital-intensive sectors and at 2.8% in non-intensive sectors. Amongst the 50% most productive laggards, 3.7% become leaders in the digital sector and 4.1% in the non-digital sector every year. The lower entry rate for the digital sector is mirrored by a lower exit rate: 20.1% of the frontier firms become laggards in any given year for the digital sector, and 23.5% for the non-digital sector. In this sense, leaders are more likely to remain at the frontier in digital sectors. This unconditional result does not necessarily mean that digitalisation decreases churning at the frontier by itself, but it implies that firms in digital sectors share features that decrease churning at the frontier. In order to test the macro impact of digitalisation on churning

Table 9: The impact of digitalisation on firm churning into and out of the productivity frontier

	Entry into frontier		Exit from frontier	
Digitalisation measure	(DIIs)	($\hat{\varepsilon}$-residuals)	(DIIs)	($\hat{\varepsilon}$-residuals)
β_{dig}	-0.019**	-0.016*	0.020	-0.007
	(0.009)	(0.008)	(0.031)	(0.031)
Technological diffusion (frontier)	-0.030**	-0.033**	0.099**	0.099*
	(0.014)	(0.015)	(0.047)	(0.052)
β_{emp}	3.420***	4.023***	-0.391	-0.284
	(0.725)	(0.800)	(0.908)	(0.968)
β_{age}	-0.050	-0.077	-0.091	-0.093
	(0.047)	(0.053)	(0.062)	(0.063)
β_{hhi}	0.017	0.005	-0.099***	-0.109***
	(0.017)	(0.017)	(0.028)	(0.031)
# Observations	11,622	9,935	8,990	8,042
R^2	0.311	0.302	0.468	0.482

Notes: Observations are defined as country, sector (2 digits), and year cells. Each cell is aggregated from our firm-level data, with each firm being attributed an inverse sampling weight to make it representative to the full population of firms in its cell. The dependent variable for entry into frontier is the share of laggard firms that became leaders in a given sector, country and year. Correspondingly, for exit it is the share of frontier firms that left the frontier. All estimations include country-year and sector fixed effects and control for the cell-specific technological diffusion from frontier firms, for the employment size and the age of the average firm in the cell (both lagged), and for the lagged market concentration (HHI) in the cell. The technological diffusion from the frontier is measured differently across models. For the entry into the frontier, technological diffusion is measured as the average TFP growth of frontier firms in a given country-sector-year cell, which is defined at the sector-year level. For the exit from the frontier, technological diffusion is firm-specific, and measured for each frontier firm as the average TFP growth by all other frontier firms in the same sector-year cell that stayed at the frontier between years $t-1$ and t. This measured is then aggregated as the average across all frontier firms in a given sector-year cell. Standard errors are corrected for heteroskedasticity. * describe 10%-significance, ** describe 5%-significance, and *** describe 1%-significance levels.

at the frontier, we estimate the following regression at the country, sector, and year cell level:

$$\begin{aligned}\text{Churning}_{c,s,t} =& \beta_{dig} \times Dig_{c,s,t-1} + \beta_{ftfp} \times \Delta ftfp_{s,t} + \beta_{\text{emp}} \times \text{Avg. Employment}_{c,s,t-1} \\ &+ \beta_{\text{age}} \times \text{Avg. Age}_{c,s,t-1} + \beta_{hhi} \times \text{HHI}_{c,s,t-1} + \delta_{c,t} + \delta_s + \nu_{c,s,t} \end{aligned} \tag{9}$$

We separate our churning measure in entry rates into the frontier versus exit rates out of the frontier. Digitalisation is the sector level digital investment intensity and defined as before by using either DIIs or the $\hat{\varepsilon}$-residuals. For the regressions on the exit rates, the technological diffusion from the frontier is replaced by the average technological diffusion from other frontier firms that remained at the frontier between years $t-1$ and t in a given sector (as introduced in equation (8)), and is aggregated as an average across all frontier firms in a given country-sector-year cell: $(1/N_{\text{front,s,t}}) \sum_{i=1}^{N_{\text{front,s,t}}} \Delta ftfp_{-i,s,t}$ where $N_{\text{front,s,t}}$ is the number of frontier firms in a given sector-year cell. Firm employment and firm age stand for their averages in each cell. The HHI corresponds to the market concentration at the cell level.

Table 9 reports the estimation results. They suggest that digitalisation decreases the share of firms that manage to get into the frontier: a 1pp increase in our measures of digitalisation is associated with a 2 basis points lower entry rate. This is consistent with the results displayed in Table 7, since digitalisation enables highly productive firms to become more productive over time while it does not seem to help the TFP growth of new leaders. Second, our results suggest that digitalisation and exit rates out of the frontier are broadly unrelated, meaning that firms do not exit the productivity frontier because of their investments in digital technologies or their lack of success in becoming more productive by making use of these technologies.

Regarding other factors affecting entry rates into the frontier, we find that a stronger growth of TFP at the frontier makes it more difficult for firms to get into the frontier. Intuitively, this is because leaders innovate at a faster speed. Also, in sectors where the average firm is larger, highly productive laggards are also more likely to get to the frontier. Regarding exit rates, we find that a faster TFP growth by those frontier firms that managed to remain at the frontier increases the amount of exits from the frontier, as this implies that it is more difficult for firms in these cells to keep up with their peers. A larger average firm size increases churning via an increase in entry rates, with larger firms being more likely to benefit from economies of scale. A higher market concentration intuitively implies that firms hold a stronger market power, thus leading to lower exit rates and to a reduced churning overall.

5.6 Digitalisation and intangible assets

As a last channel, we disentangle the impact of digitalisation and investments in intangible assets on the firm's TFP growth. Intangibles represent a broad category of assets that is closely linked with digital technologies. On the one hand, they provide information on an important subset of digital investment that comprises R&D, CSD, and other IPP items. On the other hand, they additionally entail some non-measurable information about firms' specific characteristics, such as their organisational strategy or managerial skills. In this way, intangible assets can contribute to the firm's TFP growth either directly or as complements to digital technologies (Corrado et al. (2021), Brynjolfsson et al. (2021)).[23]

23. There are some issues with the measurement of intangible assets (Haskel and Westlake (2018), Criekingen et al. (2021)), which are not addressed explicitly in the paper as we rely on the data on intangible assets provided by BvD-Orbis. One example reflects the usage of digital technology: while the usage of new computer software

Fortunately, we can measure intangibles for a subset of our firm-level data. Specifically, we measure the intangible-to-total assets ratio, which we express in percentages. In contrast to our measures of digitalisation, the intangible asset ratio varies at the firm-year level. We incorporate it in our analysis as a complement to our measures of digitalisation, as this allows us to further consider firm-specific variations in the usage of digital technologies. To measure the joint impact of digitalisation and intangibles on the average firm's TFP growth, we augment our benchmark regression (3) to include the (lagged) intangible asset ratio and an interaction with our measure of digitalisation. This means that our empirical specification is

$$\begin{aligned}\Delta tfp_{i,c,s,t} =& \beta_{dig} \times Dig_{c,s,t-1} + \beta_{intangibles} \times \frac{\text{Intangibles}_{i,c,s,t-1}}{\text{Total Assets}_{i,c,s,t-1}} \\ &+ \beta_{dig-intangibles} \times Dig_{c,s,t-1} \times \frac{\text{Intangibles}_{i,c,s,t-1}}{\text{Total Assets}_{i,c,s,t-1}} + \beta_{ftfp} \times \Delta ftfp_{s,t} \\ &+ \beta_{gap} \times Gap_{i,c,s,t-1} + \beta_x \times X_{i,c,s,t-1} + \beta_{hhi} \times \text{HHI}_{c,s,t-1} \\ &+ \delta_{c,t} + \delta_s + \nu_{i,c,s,t} \qquad (10)\end{aligned}$$

We present the results in Table 10.[24] For laggard firms we find that most of the positive impact of intangibles on the average firm's TFP growth stems from digital investment. However, intangibles as a whole can act as complements to digital investment and can further magnify the impact of digitalisation. We deduce this from the regression using the $\hat{\varepsilon}$-residuals to measure digitalisation and including all firms (even those with no intangible assets), as it showcases a positive complementarity between the two factors. This result is driven by the stronger TFP impact of digitalisation for laggards with a strictly positive intangible asset ratio. The measured direct marginal impact of digitalisation on the laggard firm's TFP growth is around 2.3 times higher for firms exhibiting a positive level of intangible assets in comparison to the average laggard in the full sample. This further suggests that digitalisation is more likely to be a gamechanger for firms that record a positive intangible asset ratio, and to be a sideshow for firms that do not record any intangibles.

Digitalisation and intangibles are jointly important to boost the average frontier firm's TFP growth, with complementarities arising between the two factors. While digitalisation still improves the TFP growth for the average frontier firm directly, the increased contribution of

is measurable, searching databases is not measurable.

24. For robustness, we also consider the role that the intangible asset ratio has at the productivity frontier, by correspondingly augmenting equation (8) accordingly.

Table 10: Complementarities between digital investment and intangibles for firm TFP growth.

	Laggards				Frontier	
Digitalisation measure:	DIIs		$\hat{\varepsilon}$-Residuals		DIIs	$\hat{\varepsilon}$-Residuals
β_{dig}	0.014**	0.040***	0.017**	0.039***	0.013**	0.015*
	(0.007)	(0.009)	(0.007)	(0.010)	(0.007)	(0.008)
$\beta_{\text{intangibles}}$	-0.003	0.016	0.004	0.006	0.003	0.023***
	(0.012)	(0.013)	(0.005)	(0.006)	(0.017)	(0.007)
$\beta_{\text{dig-intangibles}}$	0.0004	-0.0003	0.0011***	0.0003	0.0008	0.0011*
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0006)	(0.0006)
Intangibles > 0	✗	✓	✗	✓	✗	✗
# Obs. (in mio.)	11.622	6.325	10.832	5.860	0.467	0.436
R^2	0.152	0.169	0.151	0.168	0.080	0.078

Notes: The estimated coefficients take the model described in equation (3) for laggards and in equation (8) for frontier firms, augmented to include the ratio between intangible assets and total assets (lagged one year) and its interaction with our measures of digitalisation. We include the firms' financial information and the sector HHI in the estimation. The specifications with intangible assets > 0 exclude from the estimation all firms that do not report a positive amount for intangible assets. (*) describe 10%, (**) 5%, and (***) 1%-significance levels.

intangibles reflects that these firms focus on being the best at managing and using the available resources at their disposal. Moreover, its complementarity with digitalisation showcases that digital investment needs to be complemented by other improvements in the way firms do business so that their benefits are fully maximised.

6 Conclusion

The expected large productivity gains of digitalisation are not yet fully apparent, particularly against the background of the "productivity paradox" whereby rapid advances in digitalisation over the past couple of decades have coincided with a protracted slowdown of aggregate productivity growth. This begs the question as to whether digitalisation is a massive gamechanger which will deliver huge gains in productivity, or if it is more of a sideshow with only limited impacts on productivity.

We find that digitalisation tends to have on average a positive impact on firm-level TFP growth. However, the impact of digitalisation on productivity is very heterogenous across firms. First, there is an important component associated with sectoral heterogeneity, with the average firm in most sectors not being able to reap the productivity benefits from digital investment. Second, only the 30% most productive laggard firms benefit from digitalisation. However, an increase in digital investment by itself is not enough for highly productive laggards to turn into frontier firms. Instead, laggard firms are required to make significant innovations to boost their TFP enough to be able to jump the productivity frontier hurdle. Third, the impact of digitalisation is broadly similar for laggard and for frontier firms alike, but the latter are better able to track and implement successfully the innovations from their peers. Finally, the impact of digitalisation to firm-level TFP growth seems stronger for digital investment than for intangibles as a whole, although an increase in intangibles can lead to a higher TFP growth, and particularly so for frontier firms. This is because intangibles gather information on non-tangible best practices and act as complements to digital technologies, magnifying the impact of digitalisation on the average firm's TFP growth.

Overall, our results suggest that digitalisation does not currently tick all of the productivity boxes. Given this, the investment in digital technologies should be carefully planned, and digitalisation should not be thought of as a 'one-size-fits-all' measure to be adopted by all firms equally. Digitalisation seems to be a productivity gamechanger for firms in specific sectors and who already exhibit relatively high productivity levels, while it may be more like a sideshow for most firms. The latter may be investing in digital technologies as a means either to remain in the market and not to become outdated, but are not very successful in using digital technologies to generate innovations. Without a clear plan or without a specific innovation as to how to optimally use digital investment on a case by case basis, these firms do not seem able to adequately reap the productivity gains from digitalisation. Nevertheless, digitalisation - like other general purpose technologies which took time to deliver their potential productivity gains - still has the potential to become a future productivity gamechanger. This is particularly so given the rapid and wide-ranging rise in the use of digital technologies during the COVID-19 pandemic.

The increasing digitalisation of the economy and its positive (but somewhat ambiguous) effect on firm level TFP growth can have important implications for monetary policy (Anderton et al. (2020), Anderton and Cette (2021)). First, the average positive impact of digital technologies on firm level productivity growth can lead towards a rise in the natural rate of interest, thereby giving monetary policy more room to manoeuvre. Our results suggest that policies which incentivise and accelerate digital adoption and (or) increase the digital-intensiveness of sectors will bring about faster productivity growth. This is the case for the EU's "Digital Single Market" and the "Next Generation EU" programs, both of which aim to facilitate the transition to the digital economy and to accelerate digital adoption. If well implemented, and in light of our results, these programs have the potential of boosting potential output by improving firm-level productivity growth. Furthermore, policies that incentivise firms to become more digital over time should be designed in a way that can help laggard firms (particularly low-productivity laggards) to fully reap the productivity gains from higher digital investments on a case by case basis. While some features of digital technology can be applied broadly as a general-purpose technology, these will not suffice to transform laggards into productivity leaders, as firms may need to embed new digital technologies in unique ways in their daily operations. This result is particularly important for the calibration and implementation of future fiscal stimulus programs aimed at facilitating the digital transition for European firms.

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Acknowledgements

We would like to thank seminar participants for their kind, helpful, insightful and constructive comments on earlier versions of this paper, which was presented at the European Central Bank; at the G7 Central Bank Digitalisation Working Group; at the 2021 EEFS Conference, with special thanks to Jean Baptiste Habyarimana and Usman Khalid for their helpful written comments; and at GREDEG (Université Côte-d'Azur), in which we are indebted to Lionel Nesta, Flora Bellone, and Sarah Guillou for their insightful suggestions. Any errors and omissions are the sole responsibility of the authors. The views expressed in this paper are those of the authors and do not necessarily reflect the views of OFCE, the European Central Bank, the Deutsche Bundesbank, or any other Eurosystem Central Bank.

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PDF ISBN 978-92-899-5990-2 ISSN 1725-2806 doi:10.2866/719620 QB-AR-23-031-EN-N