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Keywords: Digital, productivity, organisation

JEL classification: O33, O40, D22

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Are digital-using UK firms more productive?

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Abstract

One possible explanation for the productivity slowdown in advanced economies coinciding with widespread digital adoption is that firms need time to change organisational structures or processes to use the new technologies effectively. Using a unique UK firm-level data set, we explore the links between a large set of digital inputs and investments and productivity. We found that large firms are more digital-intensive than small ones and that digital adopters do have higher productivity than non-adopters, but the nature of the digital variables matters. Those reflecting in-house capabilities are positively related to firm-level total factor productivity (TFP) while those indicating bought-in ones are negatively related. This finding that firms' capabilities matter for the impact of digital adoption on productivity takes advantage of the wide range of digital variables we were able to use, and points to the need for future research on the role of digital technology in driving productivity to take account of organisational capabilities.

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Introduction

A large and growing literature addresses two trends in productivity: one is a slowdown in productivity growth in many developed economies from the mid-2000s (Lafond et al 2021); and a second is evidence of a growing productivity gap between frontier firms and the rest (Andrews, Criscuolo & Gal 2019, Haldane 2017). One of the reasons these phenomena call for investigation is that they have emerged during a period when there has been continuing digitalisation of production, reflected for example in rapid increases in data usage and cloud services, and a proliferation of digital platform

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business models (eg Coyle & Nguyen 2018). This might have been expected to increase firm-level and aggregate productivity.

At least two types of resolution to the puzzle have been suggested, some with conflicting implications. One is that there are fewer new ideas or important innovations, as compared with previous periods of high productivity growth (Bloom et al 2021, Gordon 2017). An alternative is that there are intangible aspects of digital adoption, such as the time needed by most firms to achieve productivity gains, for example because of necessary organisational changes (Tambe et al. 2020). In this case, a small number of firms might record productivity improvements, but the gains would take time to spread to most firms in the economy. While the first, pessimistic, type of explanation has attracted considerable attention, it simply relocates the productivity puzzle: why are firms undertaking substantial investment and organisational change, including extended supply chains and a shift to platform and ecosystem models, for little apparent return?

We therefore explore further in this paper the alternative approach, the role of digital adoption and its link to productivity outcomes in firm-level data. Our contribution is to explore the role of a range of specific digital inputs to productivity by assembling the most comprehensive database to date on UK firms' purchases of inputs and investments, and specifically a wide range of digital measures, such as internet access, orders via website, ICT specialists, cloud computing, among others. We have linked for the first time three sets of data on firms' activities – the Annual Business Survey, Annual Purchases Survey, and E-Commerce survey -, in total comprising around 11,000 firms; and are therefore able to include a wide range of inputs to estimate production functions that are able to account for the contribution of the adoption of different digital technologies to firm-level productivity. We also construct a number of novel digital capital stock measures in our estimation of total factor productivity. We use an instrumental variables approach in our production function estimation.

We find that larger firms broadly speaking are both more digital-intensive and more productive. However, there are important differences among firms. Particularly, having key digital capabilities available in-house, as opposed to purchasing in digital services from external suppliers, seems to be an important indicator. For example, the employment of in-house ICT specialists is the most significant "digital" variable, positively associated to firm productivity, while the use of CRM software, cloud computing and 3D printing also play a role. However, other digital variables available in our data set are negatively related to productivity. These are the (extensive margin) measures of external purchases of various services such as software support, web solutions and data protection. These may signal an important difference between having in-house capabilities and needing to purchase services from external suppliers.

Our findings therefore support the interpretation that organisational factors internal to the firm, as well as specific employee skills, are key to deriving a productivity advantage from adopting digital technologies, and thus help explain the gap between leader and laggard firms. A growing body of literature has converged on the role of organisational capacity in taking advantage of digital technologies. For example, while the use of cloud computing can help reduce the cost and expand the opportunities for digital production processes, firms that use cloud computing will be differently structured in terms of the internal division of labour compared with both firms that do all their computing in-house and firms that are not digital-intensive at all; Coyle & Nguyen (2018) found that cloud-using firms tended either to be large businesses or digitally-native start-ups. Bloom, Sadun and Van Reenen (2012) found that technology is used more productively by better managed firms; Schneebacher (2021) found that online sales increased more during the pandemic in better managed UK firms; Corrado et al (2021) found a link between investment in intangible assets such as data and software and productivity. This interpretation focusing on the organisation of the firm is consistent with approaches in the institutional and management literature. This emphasises either transactions costs (Williamson 1985, 2000) or core competencies (Prahalad & Hamel 1990), or combining internal elements in the 'eclectic' or 'OLI' (ownership, location, internalisation) framework, which similarly identifies the advantages to retaining some production activities in-house for reasons such as learning-by-doing, transactions costs, or tacit knowledge.

Thus, for non-digital-intensive firms, the transition to being digital-intensive and highly productive will be costly in organisational terms, in line with the argument that there is a productivity J-curve in adopting digital technologies. As Brynjolfsson et al. (2021) observe, there is a substantial historical literature on the long lags between the invention and widespread adoption and productivity impacts of new technologies (David, 1990, is the canonical reference). They therefore construct a measure of intangible capital stocks using stock market valuations to illustrate the role of organisational change: whenever the intangible stock is growing faster than the tangible stocks included in growth accounting approaches, the estimated TFP growth will be reduced. In addition to applying only to listed firms, this assumes market valuations accurately reflect the likely impact of digital adoption. The advantage of our data and approach is that we cover a wider range of firms, not just publicly listed ones, and are able to consider separate indicators of different digital measures and construct digital capital stocks.

Our approach

Much of the literature on the puzzle of slower productivity growth has used an aggregate growth accounting approach to decomposing contributions to output growth and estimating total factor productivity (TFP) as a residual. For example, Goodridge et al (2017) consider the role of output mismeasurement and omission of intangibles in UK productivity growth, finding that the puzzle is mainly due to slower TFP growth. Riley et al (2018) calculate an industry sector decomposition, again finding that slower TFP growth is the main culprit. This literature has over time introduced more careful definition and measurement of the contributory variables, including adjusting for labour skills (Black & Lynch 1996), introducing intangible capital (Corrado et al. 2020) or materials inputs (Baptist & Hepburn 2013).

Any additional accounting for inputs will, however, reduce estimated TFP, which is the residual ('the measure of our ignorance' as Abramowitz (1956) termed it). An omitted input implies an upward bias on TFP estimates. For instance, if the equation estimated on the basis of a standard Cobb-Douglas production function is

$$\ln Y_{it} = a_{it} + b_{ki} \ln k_{it} + b_{li} \ln L_{it}$$

but there are omitted inputs M_i such that the correct specification would be

$$\ln Y_{it} = a_{it} + \beta_{ki} \ln k_{it} + \beta_{li} \ln L_{it} + \beta_{mi} \ln M_{it}$$

then the estimated coefficients b_k and b_l will be biased with

$$b_k = \beta_k / (\beta_k + \beta_l) \text{ and } b_l = \beta_l / (\beta_k + \beta_l)$$

and the residual TFP will be biased upwards. In empirical applications, the character of the bias will depend on the calculation of factor shares, the correlations between included and omitted variables, and on the construction of the output measure.

Additionally, growth accounting assumes perfect competition and constant returns to scale (Barro 1998). Given that the economy seems characterised by increasing concentration and extensive economies of scale – particularly in the context of digital markets – it is increasingly difficult to interpret the growth accounting empirics. For example, it is not valid to assume that observed factor prices reflect social marginal product. Barro additionally shows that estimated TFP growth will overstate 'true' TFP growth if factor composition shifts over time toward higher quality. In either case, growth accounting approaches seem likely if anything to deepen the productivity puzzle.

At the same time, we might have a prior that economies where firms spend on innovation – including process innovations such as digital organisation of production – experience a high social return (Jones & Summers 2020). There is also mounting evidence on the specific role of digital inputs. For example, Tambe et al (2020) find that high productivity US firms are those with a high level of digital capital. They calculate that digital capital accounts for 25% of total US firm capital and is highly concentrated among a small number of firms. Li & Hall (2020) link the use of data and intangibles to firm-level productivity differences. Bessen (2020) finds a strong link between firms' proprietary IT, rising industry concentration, and higher productivity among the leading firms, a finding affirmed by Pelzman (2020). The implication of this literature is that a minority of firms have to date developed the capability to use digital technology effectively, increasing their productivity advantage, and gaining market share. This minority at the frontier have been dubbed 'superstar' firms (Autor et al. 2020). Using digital technologies effectively requires not only that the relevant investments and purchases of IT equipment and services are made, but also that firms make investments in organisational capital and how they use the knowledge flows enabled by digital technology (e.g. Brynjolfsson & Hitt 2000, Li & Hall 2020). This is likely to require acquisition of certain types of human capital and management know-how, and organisational change. Unlike physical or software technology purchases, these practices do not diffuse easily from firm to firm and may therefore help explain growing productivity dispersion. It should be noted (as Pelzman (2020) emphasises) that the findings in this literature tell a consistent but not necessarily a causal story about drivers of firm-level productivity; there are likely to be common forces operating on productivity and market structure.

Much of the evidence on firm-level productivity in the literature concerns the US, or, as in Andrews et al. (2019) and Cathles et al. (2020), a number of OECD countries. We extend Cathles et al. (2020), and Andrews et al. (2019) who look across a number of countries, by focusing on UK firms and considering a large number of digital inputs. As far as we are aware, this is the first study to consider such a wide range of inputs. For the UK, where the aggregate evidence is that the productivity gap is wider than for other comparable economies, we take a production function estimation approach to the largest UK dataset to date, incorporating a wide range of inputs and using TFP estimates based on digital capital stocks as well as physical stocks.

Data

For the empirical analysis, we merged several firm-level datasets compiled and administered by the Office for National Statistics (ONS). These are the Annual Business Survey (ABS), the Annual Purchases Survey (APS) and the E-Commerce Survey (E-Com).

The ABS the main structural business survey in the UK, covering around 62,000 businesses annually. It mainly provides financial information on firms, including investment and ownership data. The APS is the primary source of information on business expenditure on energy, services, goods and materials. It has been running since 2015 with a sample size of around 33,000 firms. Finally, E-Com is an annual survey and the main instrument to measure firms' use of and expenditure on different information and communication technologies (ICT). It has been running since 2000 with a sample size of around 11,000 businesses per year, and currently in the process of being revised for future years.

The merging process involving the three mentioned databases had led to a bias towards larger firms, since only large firms are reliably surveyed every year and across all surveys. Indeed, the ABS data had in 2018 an average gross value added (GVA) of around £18 million and a mean employment of 293 workers, with a total number of firms above 44,000. By merging ABS with APS, the sample sharply drops to 8,250 firms in 2018, with mean GVA rising to over £64 million, and an average of 1,011 employees per firm. Finally, after merging with E-Com, the final dataset contains around 2,000 large firms per year for the period from 2015 to 2018. It is therefore not representative of the universe of UK businesses. The sample is biased toward large firms - in terms of employment, gross value added and turnover - and survivors. On the other hand, the sample is likely to account for a large proportion of total output. In 2018, the average firm in our fully merged dataset had around 1,900 employees, with total output of £267 million and gross value added (GVA) of around £119 million (both in basic prices). Total employment costs amounted to around £64 million. The average firm has spent around £1.3 million per year on telecommunication services, £2.7 million on programming services, and £1.6 million on information services. Further detail is provided in the Appendix, where Table A.1 shows the variables we use in the estimation.

One question is how to distinguish between investment in capital stocks and intermediate expenditures on inputs. The distinctions are not analytically precise, yet more intermediate purchases imply more specialisation and a changing structure of production. For example, firms can either invest in durables such as servers or instead purchase expensed cloud computing services, with differing implications for uses of other factors and organisation. Similarly, labour is distinguished from capital, but firms clearly accumulate firm-specific shared 'stocks' of human capital know-how even though individual employees can leave at any time. Nor are the boundaries between different types of intangibles clear; for example, what is the boundary between organisational capital as opposed to management as a labour service of a certain quality?

For our production function estimation, we nevertheless needed to create stocks from some of the flow variables, including total physical and intangible capital stocks by firm and year. Using the Perpetual Inventory Method (PIM) and information on annual expenditure on physical capital (land, vehicles, machinery), statisticians from the ONS have created total physical capital stocks in the ABS. However, since those are only available until 2014, we carried them forward using firm's annual net expenditure on "land and existing buildings" (wq_531), "vehicles" (wq_532) and "other fixed capital" (wq_533), using depreciation rates by industry from the EUKLEMS database. We used a similar method to create stocks for other types of capital using APS expenditure data on R&D, programming services, information services, telecommunication services, and education & training services.[5] Again, we used depreciation rates from EUKLEMS and assumed an average life of the investment of 5 years.

Another data issue is the interpretation of the questions in E-Com and their implications. Many of the survey questions provide extensive margins only (does the firm use the technology or not?) These are therefore dummy variables in the regressions reported below. Several questions ask whether the business purchases digital services from external providers. It is apparent from the results that, in some of these cases, use of purchased services may in fact signal a less productive business. Moreover, examining the E-Com questions and responses, we could check that most negative responses to questions on use of purchased services correspond to firms with bought-in digital services. Hence, we can indeed make a more direct productivity comparison between firms with in-house and bought-in digitalisation. This is a feature rather than a bug in the sense that it sheds light on how firms use different digital technologies. We discuss this further below.

[5] We did not adjust value added for these capitalised intermediate services but note that most of the E-Comm variables could not be capitalised given their yes/no characteristic.

Descriptive results[6]

ICT purchases are consistently growing with firm size. An example of this is the upward trend by firm size on both purchased and own-account computer software, as seen in Tables 1 and 2, based on ABS data. Table 1 shows that in 2018, the largest firms in our data set spent on average almost GBP 400,000 on own-account software, compared to the GBP 150 average expenditure by the smallest firms (0-9 employees). Similarly, Table 2 shows that those figures for purchased computer software are around GBP 750,000 for the largest firms, but only GBP 280 for the smallest.

Table 1: Weighted investment in computer software developed in-house, by year and firm size 2015-2018. Means and frequencies (GBP thousands)

Year	Indicator	Employment sizeband						Total
		0-9	10-19	20-49	50-99	100-249	250+	
2015	mean	0.21	0.55	1.02	5.86	15.06	391.6	1.94
	freq.	1890527	132862.7	70507.32	22420.81	12205.16	8370.61	2136894
2016	mean	0.06	0.52	1.37	5.44	10.75	390.36	1.64
	freq.	2081564	136054.5	71718.76	22923.03	12479.16	8374.1	2333114
2017	mean	0.16	1.46	3.11	6.23	24.69	411.08	2.13
	freq.	2102587	137454.5	73369.53	23181.97	12660.31	9229.56	2358483
2018	mean	0.15	0.81	1.56	5.97	28.98	393.73	1.85
	freq.	2151712	138487.9	73324.93	23768.37	12814.57	8632	2408740

Notes: Investment defined as expected asset lifespan of >1 year. Variable weighted by the ABS A-weight variable (number of respondents in the firm's band, divided by the number of firms in the universe of that band).

Source: Own calculations based on Annual Business Survey, Office for National Statistics

Table 2: Weighted investment in purchased computer software, by year and firm size 2015-2018. Means and frequencies (GBP thousands)

Year	Indicator	Employment sizeband						Total
		0-9	10-19	20-49	50-99	100-249	250+	
2015	mean	0.48	2.63	6.78	16	41.82	618.54	3.64
	freq.	1890527	132862.7	70507.32	22420.81	12205.16	8370.61	2136894
2016	mean	0.66	4.25	5.69	17.48	50.58	743.5	4.12
	freq.	2081564	136054.5	71718.76	22923.03	12479.16	8374.1	2333114
2017	mean	0.43	3.22	6.71	22.28	65.93	651.05	3.9
	freq.	2102587	137454.5	73369.53	23181.97	12660.31	9229.56	2358483
2018	mean	0.28	4.91	7.6	26.35	43.44	751.13	3.95
	freq.	2151712	138487.9	73324.93	23768.37	12814.57	8632	2408740

Notes: Investment defined as expected asset lifespan of >1 year. Variable weighted by the ABS A-weight variable (number of respondents in the firm's band, divided by the number of firms in the universe of that band).

[6] Tables 1, 2 and 4 are based only on data from ABS. Tables 3 and 5 are based on the merged ABS plus APS dataset.

Source: Own calculations based on Annual Business Survey, Office for National Statistics

Mean expenditure on scientific R&D followed an upward trend from 2015-2018 (the period covered by APS data), as observed in Table 3. The largest firms (250 employees or more) account for most R&D spending while average expenditure declined between 2015 to 2018. At the same time, expenditure increased for medium-sized firms (100-249 employees) between 2015 to 2017 but dropped sharply in 2018. Other types of ICT expenditures do not exhibit a clear trend over this period.

Table 3: Weighted expenditure on scientific research and development services, by year and firm size 2015-2018. Means and frequencies (GBP thousands)

Year	Indicator	Employment sizeband						Total
		0-9	10-19	20-49	50-99	100-249	250+	
2015	mean	1.46	0.27	9.53	3.46	15.07	347.11	38.31
	freq.	15947.49	18309.69	10640.47	4560.38	2820.3	5876.08	58154.4
2016	mean	0	0.27	2.65	0.57	26.55	322.63	51.2
	freq.	7125.61	15531.43	6344.56	2978.35	1807.65	6112.72	39900.32
2017	mean	0.58	0.87	3.86	9.41	133.99	278.35	62.37
	freq.	10653.17	10876.01	4374.49	2413.22	1908.72	7289.46	37515.08
2018	mean	0.73	0.05	0.39	3.12	35.85	307.46	83.49
	freq.	4127.55	7139.47	3407.61	1690.61	1192.41	6309.34	23867

Notes: Variable weighted by the ABS A-weight variable (number of respondents in the firm's band, divided by the number of firms in the universe of that band).

Source: Own calculations based on ABS and APS.

Looking at the ratio of firms' ICT purchases relative to total purchases, their "digital intensity", by firm size and over time presented in Table 4 (ABS data), no clear pattern is distinguished for digital intensity across firm sizes, but ratios for each size band remain stable over time, except for the largest firms in 2018, when digital intensity rose considerably to 14.1%. In Table 5, using APS data on ICT services expenditure, there seems to be a clearer positive relation between firm size and digital intensity when moving from micro enterprises to medium-sized firms (50-99 employees), but that ratio tends to be slightly lower for larger firms with 100 employees or more.

Table 4: Weighted ICT purchases, % total purchases (ABS), by year and firm size (means and frequencies)

Year	Indicator	Employment sizeband						Total
		0-9	10-19	20-49	50-99	100-249	250+	
2015	mean	0.07	0.063	0.08	0.068	0.058	0.054	0.07
	freq.	1564866	126614.7	68119.97	21953.42	11963.47	8257.783	1801775
2016	mean	0.067	0.094	0.061	0.071	0.092	0.06	0.069
	freq.	1543676	124832	67051.69	21530.96	11823.46	8223.841	1777138
2017	mean	0.071	0.068	0.071	0.071	0.057	0.065	0.071
	freq.	1588363	125547.4	68526.57	21753.1	11972.18	9069.509	1825232
2018	mean	0.069	0.078	0.061	0.076	0.058	0.141	0.07
	freq.	1587660	127667.4	68932.15	22193.03	12186.35	8501.319	1827141

Notes: Variable weighted by the ABS A-weight variable (number of respondents in the firm's band, divided by the number of firms in the universe of that band).

Source: Own calculations based on ABS.

Table 5: Weighted ICT services, % total expenditure on services (APS), by year and firm size (means and frequencies)

Year	Indicator	Employment sizeband						Total
		0-9	10-19	20-49	50-99	100-249	250+	
2015	mean	0.088	0.169	0.155	0.169	0.152	0.132	0.142
	freq.	13857.14	18228.99	10580.9	4545.951	2818.901	5857.906	55889.79
2016	mean	0.102	0.138	0.149	0.164	0.131	0.14	0.135
	freq.	7124.612	15453.99	6329.482	2973.945	1804.59	6110.138	39796.76
2017	mean	0.086	0.146	0.183	0.184	0.124	0.125	0.131
	freq.	10129.63	10796.28	4373.492	2409.802	1908.724	7285.462	36903.39
2018	mean	0.154	0.149	0.16	0.196	0.126	0.143	0.152
	freq.	4127.55	7139.475	3407.613	1690.608	1192.414	6302.044	23859.71

Notes: Variable weighted by the ABS A-weight variable (number of respondents in the firm's band, divided by the number of firms in the universe of that band).

Source: Own calculations based on ABS and APS.

We next looked at the correlation between basic ICT usage and labour productivity. For that purpose, we produced bin scatter plots, joined by a fitted line between both variables, in which we grouped equal-sized bins, taking the average ICT usage and labour productivity per bin. (This is the case with all the scatter plots. Firm-level plots were not possible because they would have been disclosive of individual firms.) Each dot in the scatter plot represents one bin. This correlation is indeed strongly positive across all firms for ratios provided by the E-Com survey, such as the proportion of employees with internet access, and taking orders via a website (Figures 1, 2). Apparent 'outliers' do not change the sign of the relationships in the figures.

Figure 1

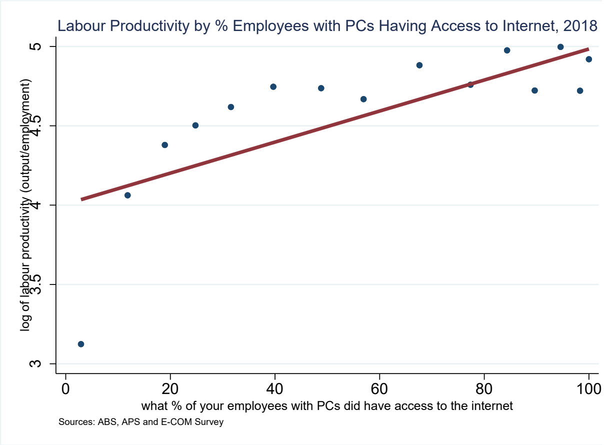


Figure 2

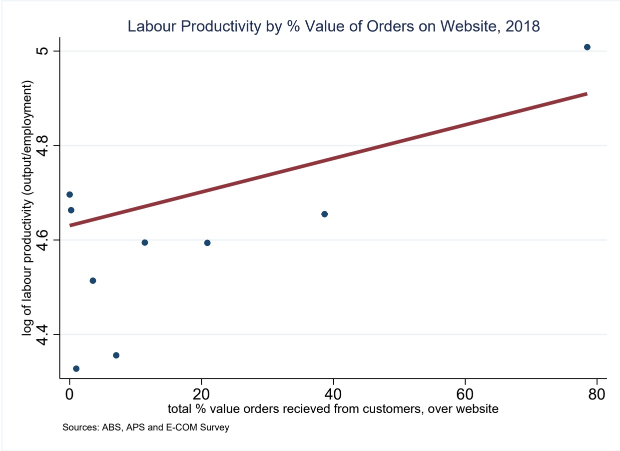
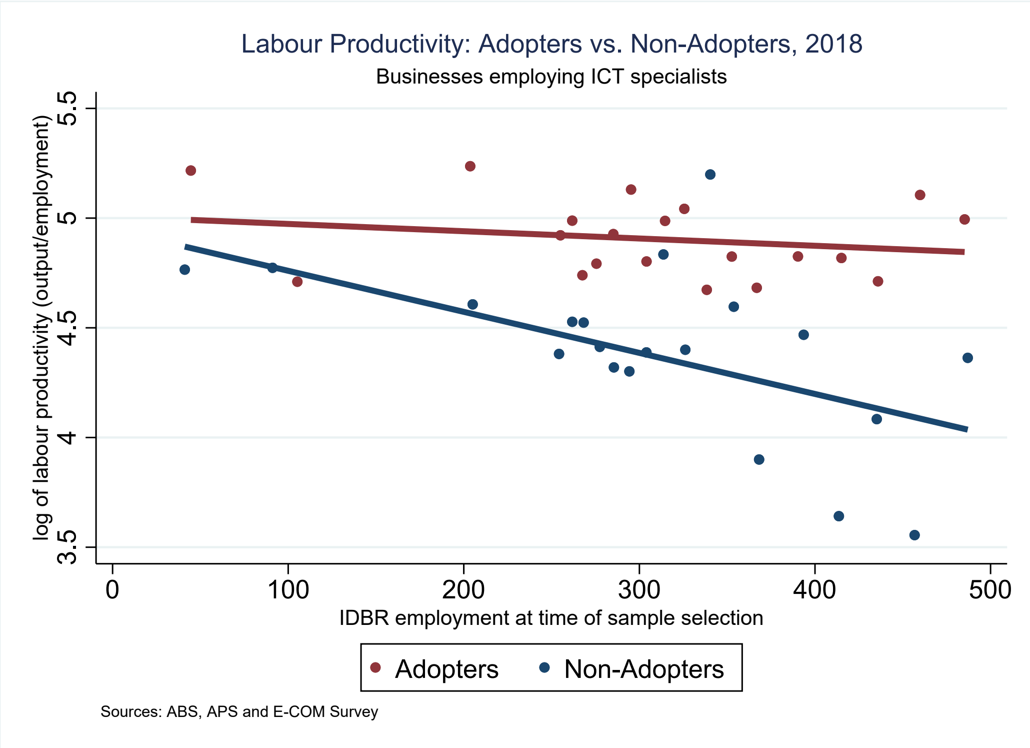
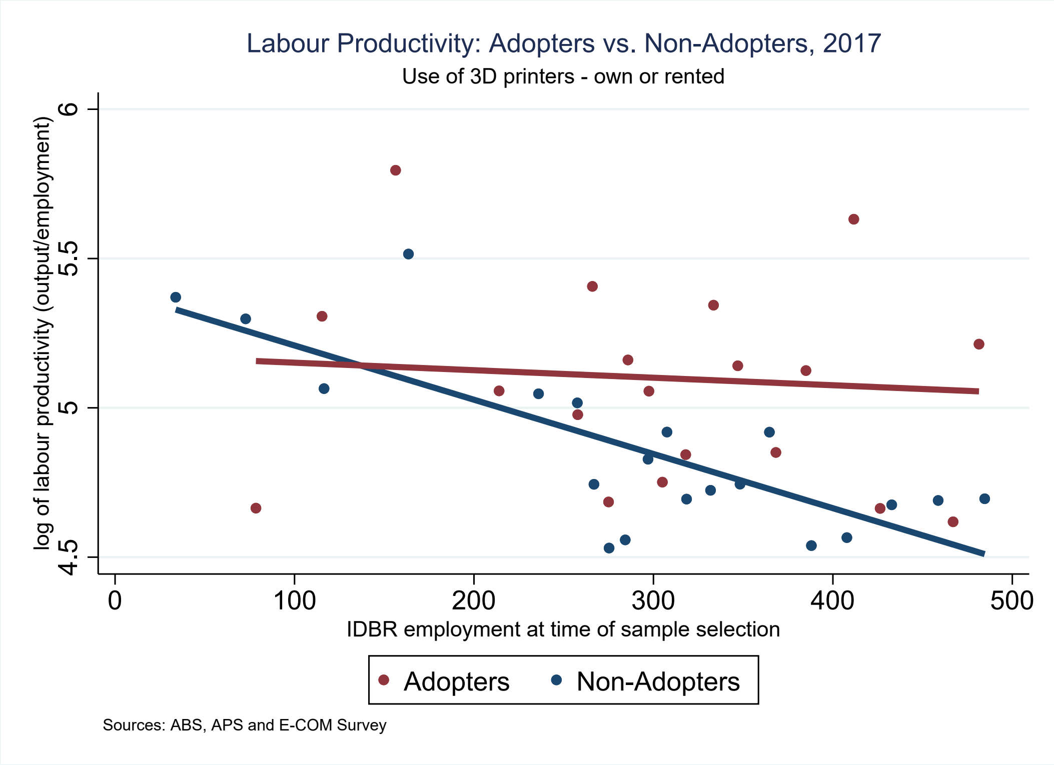
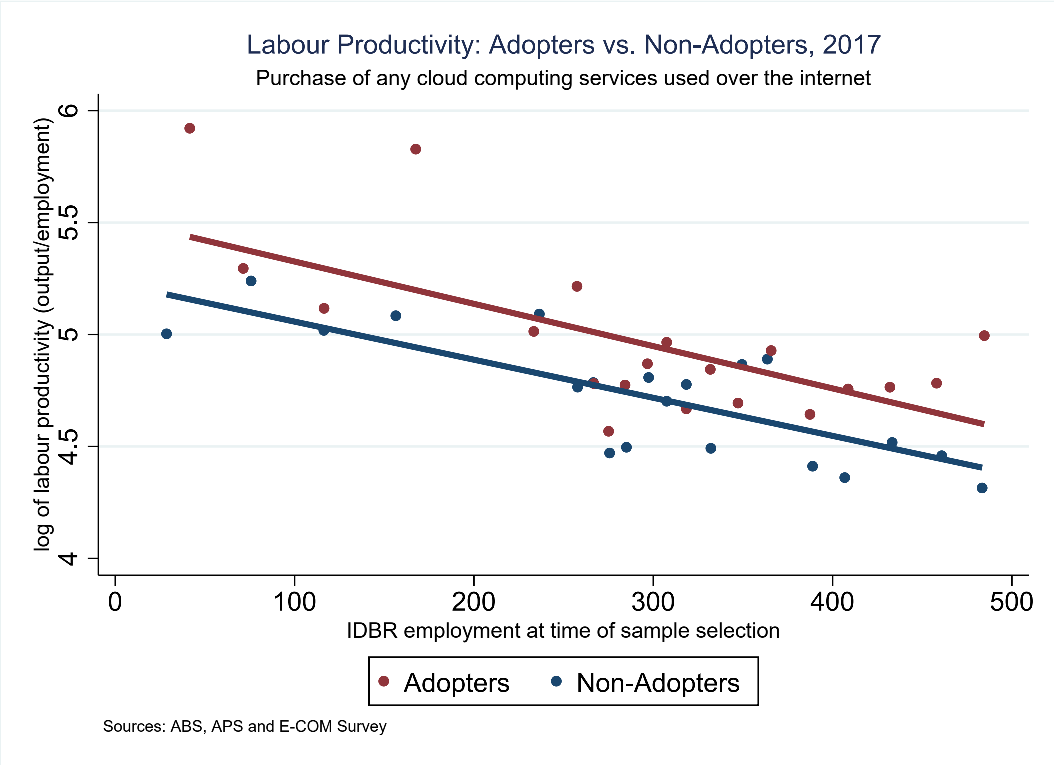


Figure 3: E-Com digital activities where adopters are higher productivity



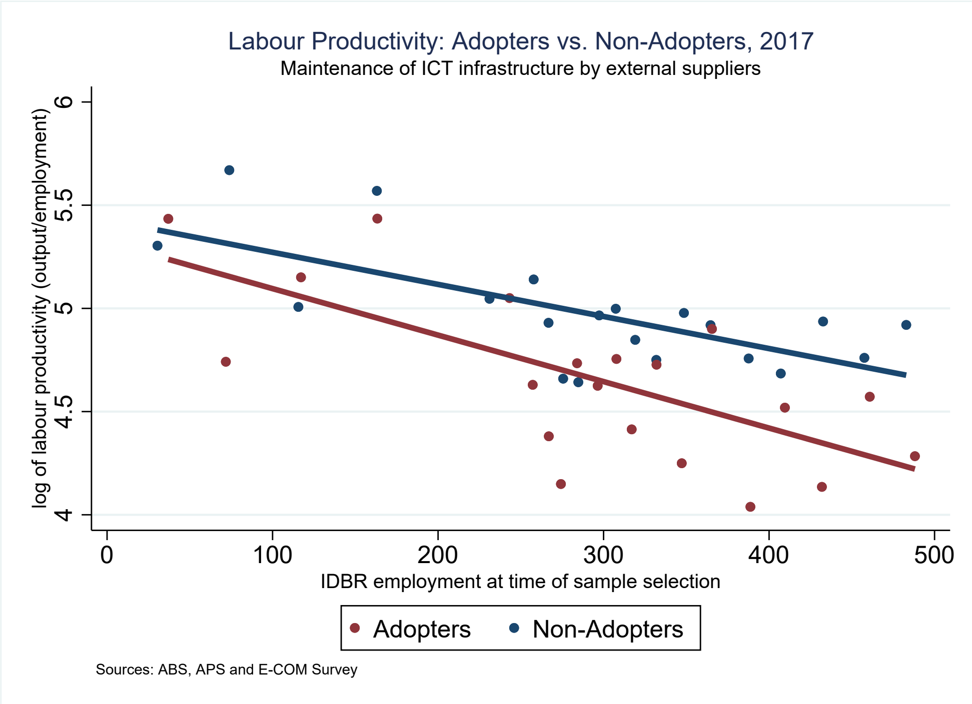


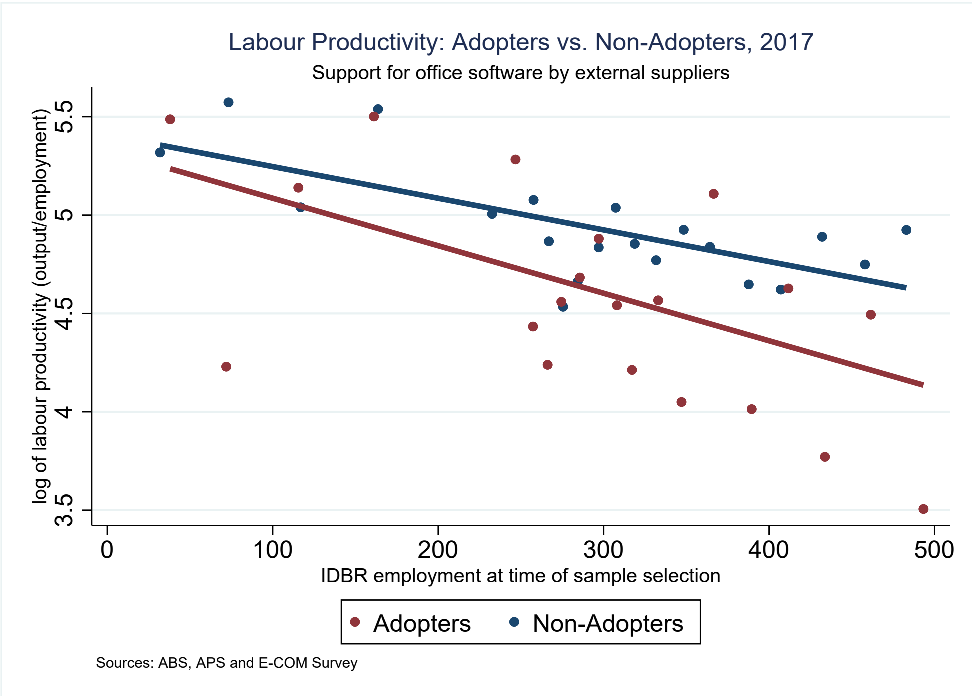
Labour Productivity: Adopters vs. Non-Adopters, 2017
Use of 3D printers - own or rented
log of labour productivity (output/employment)
4.5
5
5.5
6
0
100
200
300
400
500
IDBR employment at time of sample selection
Adopters
Non-Adopters
Sources: ABS, APS and E-COM Survey



Labour Productivity: Adopters vs. Non-Adopters, 2017
Purchase of any cloud computing services used over the internet
log of labour productivity (output/employment)
4
4.5
5
5.5
6
0
100
200
300
400
500
IDBR employment at time of sample selection
Adopters
Non-Adopters
Sources: ABS, APS and E-COM Survey

Figure 4: E-Com digital activities where adopters have lower productivity





Next, we used the merged ABS, APS and E-COM datasets to estimate the total factor productivity (TFP) of firms over the 2015-2018 period, using all of our capital stock variables, calculated as described in the Appendix. For completeness, we estimated two types of TFP: firstly, a baseline TFP, resulting from retrieving a residual by regressing gross value added against the ABS capital stock, employment and production costs; and secondly, a TFP controlling additionally for the capital stock variables computed from the APS dataset as described above. Furthermore, we experimented by running the TFP estimations with both 2nd and 3rd degree of polynomial approximation in the first stage regressions. We used several estimation approaches, including those most widely used in the literature, such as Levisohn & Petrin (2003) and Olley & Pakes (1996), and Wooldridge (2009) with and without the application of system Generalised Method of Moments (GMM). Unless otherwise stated, we report results for the Wooldridge GMM method below (an instrumental variables approach using lagged values as instruments). There were few differences in results between the methods of estimation.

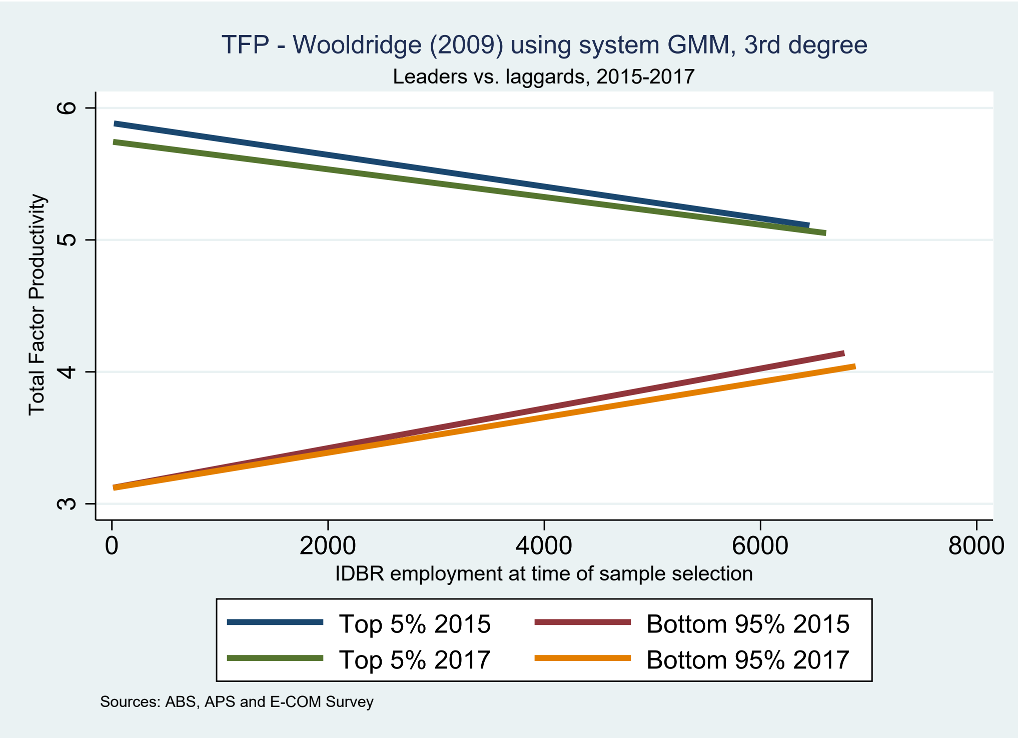
Our findings based on this unique UK dataset confirm that it is the largest firms (by number of employees) which are on average the most productive. Following Andrews, Criscuolo & Gal (2019) for their cross-country panel, we divided our UK merged sample (ABS, APS and E-Com) of firms in 2015 and 2017 into a top 5% by level of TFP ('leaders') and a remainder ('laggards') for each year. Thus, the output from this exercise is a graph consisting of four series relating TFP and firm size for 'leaders' and 'laggards' in each of those two years. We again omitted a small number of very large firms lying above the 95th percentile of employment in 2017 (6,880 workers) to prevent these significant outliers from driving the results. Up to 10% of firms with non-missing TFPs in 2015 and 2017 were dropped from this exercise, following the criterion above. Keeping them would have complicated the identification of productivity gaps between firms and years.[7]

Figure 5 shows the relationship between TFP and firm size within each group: for the majority 'laggards' there is a positive relationship between firm size and productivity, i.e. larger firms in terms of employment tend to be more productive. However, for the top 5% by TFP it is negative: smaller firms in the most productive 5% are more productive than larger firms in that group. This outcome is in line with the findings from Kara and Rincon-Aznar (2017), which show a negative relationship between TFP growth and employment growth in the UK for the 44 years until 2016, denoting a potential trade-off between these two variables. The patterns observed in Figure 5 may complement their findings in the sense that the negative relationship between productivity and employment might be mostly driven by firms lying within the productivity frontier. In contrast to the finding Andrews et al (2019) for the period 2001-2015 (for firms across the OECD), we did not find that the TFP gap between leaders and laggards increased significantly between 2015 and 2017: there were declines in both groups, albeit with modest differences depending on the estimation method (their definition of

[7] This analysis comprises all firms in our merged ABS, APS and E-Com sample for 2015 and 2017, without distinguishing between sectors. Sampling weights are not utilised for the calculation of the series.

the leaders' group is also slightly different from ours). In the Appendix, we present an equivalent 'leaders vs. laggards' analysis, considering the TFP estimated by controlling for digital capital stock from APS. There, we do find an increase in the TFP gap between leaders and laggards between 2015 and 2017, but only for firms with up to 3,000 workers. For even larger firms, the gap shrinks instead. It should be noted that every analysis that includes the digital capital stock from the APS is limited by the number of available observations by firm.

Figure 5: Productivity 'leaders' and 'laggards' by firm size



Estimation results

Turning to the estimated production function, we looked at the relationship between firm-level TFP and a wide range of digital inputs from the E-Com survey. We used both the baseline TFP figures described above and the TFP figures controlling for the capital stocks calculated from APS data. We also estimated regressions using the entire panel structure of the dataset as well as separate cross-sections for 2015 and 2017.

The panel data results (Table 6) show mostly insignificant coefficients on the digital variables, with one exception: the baseline TFP regression shows a consistently positive and significant coefficient on the employment of ICT specialists, meaning that firms employing ICT specialists are on average 12.5% more productive than firms without them. With the alternative TFP measure, the sign remains positive but statistical significance is lost. This alternative TFP regression does however have a significant and positive coefficient on the use of CRM software (see Appendix). Consistent with our interpretation of the E-Com variables involving external purchases of some services as a marker of lower digital intensity, the signs on these are often negative (albeit insignificant) in the regressions.

The results from cross-section regressions display more consistent patterns (Tables 7 and 8). One reason to prefer these specifications is that they will abstract from any possible change in mark-ups over the period, which have risen across many sectors of the economy (Van Reenen 2018). Several of the digitalisation variables – share of employees with internet access, employment of ICT specialists, use of CRM, use of cloud services – are consistently positive and significant for both TFP measures. For instance, in 2015, firms using CRM tended to have a 17.7% larger TFP than non-users, and cloud service users were on average 14.6% more productive than firms not adopting that technology.

Conversely, purchases of external security and data protection services are consistently negative and significant for both 2015 and 2017. Revising the characteristics of the merged dataset, we can conclude, for instance, that in 2017, firms externally purchasing the ICT maintenance service tended to be 13.1% less productive than firms with an in-house ICT maintenance service. Similarly, firms purchasing external office software support in 2017 are found to be 15.4% less productive than firms doing office software support on their own. In the case of the use of 3D printers, the coefficient is positive and significant, meaning that 3D printer users in 2017 had a 12.7% larger TFP than non-users. When taking instead the estimated TFP controlling for the digital capital stock (APS dataset), the signs pattern described prevails, but with a lower significance. In addition to TFP, we also used labour productivity as the dependent variable in both years (see Appendix) and our findings remained while other E-Com variables (use of business management software and web solutions purchased from external suppliers) had negative and significant coefficients.

There is a consistent message that not all digitalisation variables in our data from E-Com can be interpreted in the same way; several of them involving external purchases correlate with lower productivity possibly because they indicate lower in-house digital capabilities. As mentioned earlier, for E-Com questions on external purchases of digital services, most firms comprising the control group were firms that have developed those technologies in-house, which facilitates the comparison. This is a key finding, extending the earlier literature, and points to the need for further empirical work to take into consideration the organisational literature.

Table 6: Panel regression results (fixed effects at firm level, Wooldridge GMM)

Dependent Variable	TFP - Wooldridge (2009) using system GMM 3rd degree																							
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
% internet access	-0.0186	-0.0178																						
	(0.0262)	(0.0256)																						
% orders via website			0.00567	0.00812																				
			(0.0129)	(0.0132)																				
have a website					-0.00168	0.00708																		
					(0.0777)	(0.0784)																		
ICT especialists							0.118**	0.118**																
							(0.0588)	(0.0584)																
use of CRM									0.0106	0.00581														
									(0.0320)	(0.0322)														
cloud computing											-0.000778	-0.00452												
											(0.0278)	(0.0277)												
ICT maintenance (external)													-0.0452	-0.0477										
													(0.0290)	(0.0292)										
office software support (external)															-0.00932	-0.0102								
															(0.0340)	(0.0339)								
management software (external)																	-0.0123	-0.0127						
																	(0.0246)	(0.0251)						
web solutions (external)																			0.00463	0.00275				
																			(0.0264)	(0.0266)				
security data protection (external)																					-0.0234	-0.0264		
																					(0.0201)	(0.0203)		
3D printing																							0.00635	0.0291
																							(0.0545)	(0.0562)
constant	3.520***	4.757***	3.443***	4.676***	3.449***	4.680***	3.350***	4.588***	3.483***	4.070***	3.448***	4.695***	3.462***	4.737***	3.450***	4.691***	3.455***	4.692***	3.445***	4.686***	3.457***	4.696***	3.447***	4.685***
	(0.102)	(0.393)	(0.0101)	(0.374)	(0.0756)	(0.384)	(0.0487)	(0.376)	(0.0200)	(0.265)	(0.0189)	(0.377)	(0.00930)	(0.383)	(0.00660)	(0.375)	(0.0138)	(0.375)	(0.0158)	(0.376)	(0.00812)	(0.375)	(0.00201)	(0.371)
Firm Size, Sector, Region and Year FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	7767	7767	7767	7767	7767	7767	7767	7767	6115	6115	7767	7767	7767	7767	7767	7767	7767	7767	7767	7767	7767	7767	7767	7767
N_g	3877	3877	3877	3877	3877	3877	3877	3877	2874	2874	3877	3877	3877	3877	3877	3877	3877	3877	3877	3877	3877	3877	3877	3877
r2	0.000181	0.0104	0.0000436	0.0103	0.000000115	0.0102	0.00191	0.0121	0.0000438	0.0112	0.000000263	0.0102	0.000737	0.0110	0.0000218	0.0102	0.0000730	0.0103	0.00000962	0.0102	0.000288	0.0106	0.00000720	0.0103
sigma	0.970	1.129	0.968	1.126	0.968	1.126	0.962	1.119	0.920	1.078	0.968	1.127	0.968	1.128	0.968	1.126	0.968	1.126	0.968	1.126	0.968	1.126	0.968	1.125
sigma_u	0.866	1.041	0.863	1.037	0.864	1.038	0.857	1.030	0.826	0.999	0.864	1.038	0.863	1.039	0.864	1.038	0.864	1.038	0.864	1.038	0.863	1.038	0.864	1.037
sigma_e	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.405	0.405	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.437
rho	0.797	0.850	0.796	0.849	0.796	0.849	0.794	0.848	0.806	0.859	0.796	0.849	0.796	0.850	0.796	0.849	0.796	0.849	0.796	0.849	0.796	0.849	0.796	0.849

Standard errors in parentheses

* p<0.10 ** p<0.05 *** p<0.01

Table 7 Cross-section regression results 2015 (Wooldridge GMM)

Dependent Variable	TFP - Wooldridge (2009) using system GMM 3rd degree																					
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
% internet access	0.131***	0.149***																				
	(0.0255)	(0.0265)																				
% orders via website			0.0650***	0.0437***																		
			(0.0138)	(0.0149)																		
have a website					0.173	0.0977																
					(0.173)	(0.149)																
ICT especialists							0.419***	0.287***														
							(0.0604)	(0.0630)														
use of CRM									0.176***	0.163***												
									(0.0479)	(0.0469)												
cloud computing											0.217***	0.137***										
											(0.0411)	(0.0414)										
ICT maintenance (external)													0.0207	0.0235								
													(0.0447)	(0.0433)								
office software support (external)															0.0426	0.0313						
															(0.0595)	(0.0562)						
management software (external)																	-0.0363	-0.0428				
																	(0.0381)	(0.0377)				
web solutions (external)																			0.0121	-0.0158		
																			(0.0390)	(0.0367)		
security data protection (external)																					-0.0844**	-0.0608
																					(0.0398)	(0.0395)
constant	2.941***	2.058***	3.403***	2.522***	3.283***	2.422***	3.102***	2.420***	3.436***	2.041***	3.311***	2.466***	3.445***	2.497***	3.444***	2.506***	3.472***	2.540***	3.445***	2.527***	3.486***	2.544***
	(0.101)	(0.239)	(0.0228)	(0.243)	(0.172)	(0.274)	(0.0573)	(0.246)	(0.0413)	(0.382)	(0.0345)	(0.240)	(0.0210)	(0.247)	(0.0195)	(0.246)	(0.0274)	(0.244)	(0.0304)	(0.244)	(0.0232)	(0.243)
Firm Size, Sector and Region FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	1850	1850	1850	1850	1850	1850	1850	1850	1212	1212	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850
r2	0.0206	0.178	0.0108	0.159	0.00109	0.155	0.0360	0.170	0.0125	0.169	0.0161	0.161	0.000138	0.155	0.000414	0.155	0.000487	0.156	0.0000528	0.155	0.00255	0.156
r2_a	0.0200	0.161	0.0103	0.141	0.000545	0.138	0.0355	0.152	0.0117	0.142	0.0156	0.143	-0.000403	0.137	-0.000127	0.137	-0.0000536	0.138	-0.000488	0.137	0.00201	0.138
ll	-2235.7	-2073.6	-2244.8	-2094.8	-2253.9	-2098.8	-2221.0	-2082.9	-1358.6	-1254.1	-2239.9	-2092.6	-2254.8	-2099.0	-2254.5	-2099.0	-2254.5	-2098.5	-2254.9	-2099.1	-2252.5	-2097.8

Standard errors in parentheses

* p<0.10 ** p<0.05 *** p<0.01

Table 8 Cross-section regression results 2017 (Wooldridge GMM)

Dependent Variable	TFP - Wooldridge (2009) using system GMM 3rd degree																							
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
% internet access	0.128***	0.123***																						
	(0.0299)	(0.0328)																						
% orders via website			0.0474***	0.0400**																				
			(0.0158)	(0.0198)																				
have a website					-0.118	-0.243																		
					(0.203)	(0.192)																		
ICT especialists							0.370***	0.261***																
							(0.0523)	(0.0534)																
use of CRM									0.202***	0.177***														
									(0.0451)	(0.0455)														
cloud computing											0.141***	0.0574												
											(0.0426)	(0.0422)												
ICT maintenance (external)													-0.135***	-0.141***										
													(0.0415)	(0.0396)										
office software support (external)															-0.165***	-0.168***								
															(0.0536)	(0.0517)								
management software (external)																	-0.0411	-0.0423						
																	(0.0395)	(0.0394)						
web solutions (external)																			-0.0342	-0.0543				
																			(0.0396)	(0.0383)				
security data protection (external)																					-0.237***	-0.225***		
																					(0.0389)	(0.0394)		
3D printing																							0.120**	0.0857
																							(0.0602)	(0.0702)
constant	2.906***	2.391***	3.369***	2.880***	3.519***	3.051***	3.104***	2.807***	3.362***	3.259***	3.305***	2.875***	3.450***	2.947***	3.439***	2.936***	3.428***	2.905***	3.425***	2.911***	3.501***	3.012***	3.389***	2.889***
	(0.119)	(0.330)	(0.0222)	(0.325)	(0.202)	(0.366)	(0.0480)	(0.324)	(0.0306)	(0.490)	(0.0360)	(0.326)	(0.0231)	(0.325)	(0.0204)	(0.326)	(0.0309)	(0.326)	(0.0311)	(0.324)	(0.0248)	(0.323)	(0.0204)	(0.324)
Firm Size, Sector and Region FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	2193	2193	2193	2193	2193	2193	2193	2193	1183	1183	2193	2193	2193	2193	2193	2193	2193	2193	2193	2193	2193	2193	2193	2193
r2	0.0167	0.104	0.00465	0.0934	0.000471	0.0926	0.0255	0.102	0.0153	0.132	0.00514	0.0915	0.00505	0.0959	0.00553	0.0963	0.000506	0.0912	0.000346	0.0915	0.0167	0.105	0.00201	0.0915
r2_a	0.0163	0.0889	0.00419	0.0779	0.0000153	0.0770	0.0250	0.0865	0.0144	0.105	0.00469	0.0759	0.00460	0.0804	0.00508	0.0808	0.0000497	0.0756	-0.000110	0.0759	0.0162	0.0898	0.00155	0.0759
ll	-2867.1	-2764.8	-2880.4	-2778.0	-2885.0	-2779.0	-2857.2	-2767.6	-1413.2	-1338.4	-2879.9	-2780.3	-2880.0	-2775.0	-2879.5	-2774.5	-2885.0	-2780.7	-2885.2	-2780.3	-2867.1	-2763.7	-2883.3	-2780.3

Standard errors in parentheses
* p<0.10 ** p<0.05 *** p<0.01

We also applied an Instrumental Variables (IV) approach, following Cathles et al. (2020), by instrumenting each of the E-Com survey digitalisation dummies by the share of firms (excluding the firm of interest) adopting that specific digital technology at the year, industry and TFP quintile level. In the case of ratio variables like internet access and orders via website, we consider the average share at the levels mentioned above. This approach not only confirms the signs obtained in the baseline cross-section regressions, but also the size and significance of the coefficients are larger. Taken together this provides us with strong support for our main findings on the relationships between firm productivity and digitalisation.

To explore this relation even further, we created the following three variables: 1) a dummy which indicates if a firm has only adopted one type of digitalisation (single_digital); 2) a dummy indicating if a firm has adopted more than one type (multiple_digital); and 3) a variable (digital) which counts the number of digital technologies adopted by a firm, ranging from 0 to 6. We only take into account the six digital technologies, which had a positive and significant effect on TFP in the previous estimates. These are:

a. share of employees with internet access above 50%.
b. percentage of orders via website above 50%.
c. employment of ICT specialists.
d. use of CRM.
e. use of cloud computing.
f. use of 3D printers.

Tables 9 and 10 show the results for 2015 and 2017, respectively. Consistently across years (and estimation methods), adopting multiple digital technologies has a strongly positive and significant relation with TFP at firm level, as does the number of these technologies used.

Table 9 Multiple digital adoption (Wooldridge GMM, 2015)

Dependent Variable	TFP - Wooldridge (2009) using system GMM 3rd degree			
Column	(1)	(2)	(3)	(4)
single_digital	0.237*	0.118		
	(0.126)	(0.123)		
multiple_digital	0.562***	0.373***		
	(0.115)	(0.115)		
digital			0.176***	0.132***
			(0.0177)	(0.0189)
constant	2.961***	2.400***	3.001***	2.449***
	(0.113)	(0.240)	(0.0522)	(0.238)
Firm Size, Sector and Region FE	No	Yes	No	Yes
N	1850	1850	1850	1850
r2	0.0367	0.172	0.0604	0.184
r2_a	0.0357	0.154	0.0599	0.167
F	25.38	13.49	98.86	14.27
ll	-2220.3	-2080.2	-2197.3	-2066.6

Standard errors in parentheses
* p<0.10 ** p<0.05 *** p<0.01

Table 10 Multiple digital adoption (Wooldridge GMM 2017)

Dependent Variable	TFP - Wooldridge (2009) using system GMM 3rd degree			
Column	(1)	(2)	(3)	(4)
single_digital	0.103	0.0678		
	(0.126)	(0.123)		
multiple_digital	0.390***	0.259**		
	(0.119)	(0.121)		
digital			0.145***	0.112***
			(0.0175)	(0.0196)
constant	3.075***	2.101***	3.025***	2.122***
	(0.117)	(0.366)	(0.0497)	(0.369)
Firm Size, Sector and Region FE	No	Yes	No	Yes
N	2193	2193	2193	2193
r2	0.0195	0.0984	0.0395	0.110
r2_a	0.0186	0.0825	0.0391	0.0951
F	20.83	7.608	68.54	8.554
ll	-2863.9	-2772.0	-2841.4	-2757.3

Standard errors in parentheses
* p<0.10 ** p<0.05 *** p<0.01

Conclusions

Using a unique UK firm-level data set, enabling us to explore the links between a large set of digital inputs and investments and productivity, we found that large firms are more digitally intensive than small ones and that the use of multiple in-house digital technologies strongly positively linked to TFP. As in other research, we found that digital adopters have higher productivity than non-adopters. In addition, we found that some digital variables are positively related to productivity (TFP), and others negatively related. The difference is driven by the use of in-house as opposed to bought-in capabilities. This new finding takes advantage of the wide range of digital variables we were able to use, and points to the need for future research on the role of digital technology in driving productivity to take specific account of organisational capabilities.

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Appendix

Data

Table A.1: Input variables and sources

Buildings	ABS
Land	ABS
Other capital equipment	ABS
Gross value added	ABS
Employment costs	ABS
Telecommunication services	APS
Computer programming, consultancy and related services	APS
Information services; data processing, web hosting and IT infrastructure provisioning	APS
Scientific research and development services	APS
Cloud computing services	E-Com
Employ ICT specialists	E-Com
Percentage of employees with PCs connected to the internet	E-Com
CRM	E-Com
Percentage of value of orders received via website	E-Com
Use external suppliers for: maintenance of ICT infrastructure; for support of office software; development of business management software/systems; support of business management software/systems; development of web solutions; support for web solutions; security and data protection	E-Com

3D printing (own or rented printers)	E-Com
3D printing (by other businesses)	E-Com
Have a website	E-Com

Table A.2: Summary statistics of main variables (in GBP thousands, except employment)

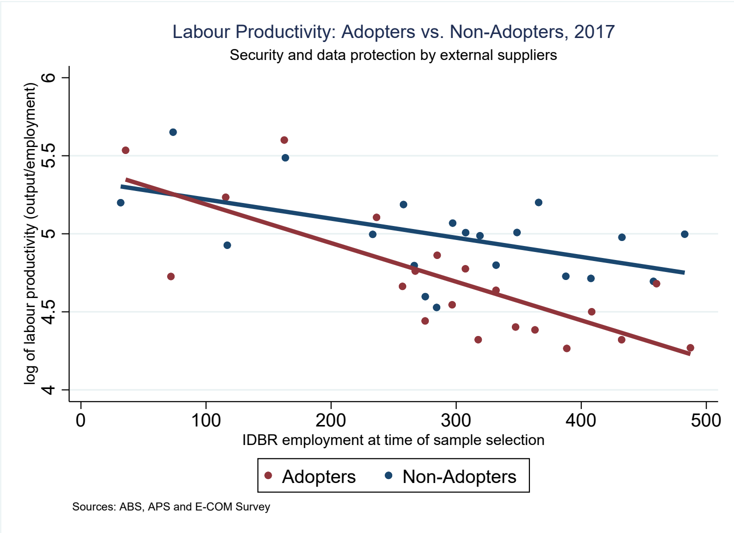
Variable	2015	2016	2017	2018	Source
ABS Employment	2611	2164	2028	1930	ABS
APS Employment	2617	2164	2028	1929	APS
Gross Wages	65969	55378	53568	53999	ABS, Q446
Total Capex Acquisitions	26914	26401	22273	24154	ABS, Q600
Total Cost of Energy	9067	7214	7256	7812	ABS, Q427
Total Cost of Materials	57851	54710	56087	60224	ABS, Q402
Total Employment Costs	77665	65271	63413	63734	ABS, Q252
Total Production Costs	334670	302640	292588	309625	ABS, Q499
Net Capex Land	1392	1347	1051	820	ABS, Q531
Net Capex Vehicles	1955	2629	1781		ABS, Q532
Net Capex Other	13849	10916	10751		ABS, Q533
Total Capital Stock (land + vehicles + other machinery)	69118	55896	57090	80010	calculation
GVA Basic Prices	147918	124386	119832	119338	ABS, Q613
Output Basic Prices	296624	257044	253917	266748	ABS, Q614
Intermediate Consumption (output less GVA, basic prices)	148705	132657	134085	147411	calculation
Production Value	313746	277936	275343	289505	ABS, Q610
GVA Market Prices	155330	135202	130356	128958	ABS, Q611
Telecoms Expenditure	1895	1259	1167	1227	APS, Q61
Programming Expenditure	2834	2460	2330	2733	APS, Q62
Information Expenditure	1565	1794	1449	1599	APS, Q63
R&D Expenditure	790	219	221	279	APS, Q72
Education Expenditure	327	309	276	310	APS, Q85
Stock Telecoms Expenditure	2390	3690	4818	6053	calculation
Stock Telecoms Expenditure (Missing Values Filled)	2390	3667	4735	5980	calculation
Stock Programming Expenditure	4608	7231	9982	12057	calculation
Stock Programming Expenditure (Missing Values Filled)	4608	7313	9857	12007	calculation

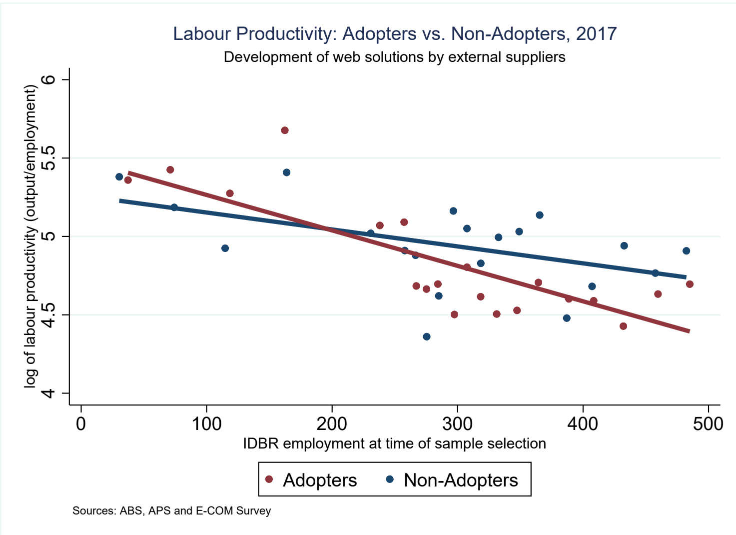
Stock Information Expenditure	1473	2325	3101	3754	calculation
Stock Information Expenditure (Missing Values Filled)	1473	2725	3239	3810	calculation
Stock R&D Expenditure	814	864	735	1059	calculation
Stock R&D Expenditure (Missing Values Filled)	814	1069	884	1042	calculation
Stock Education Expenditure	853	1325	1692	1976	calculation
Stock Education Expenditure (Missing Values Filled)	853	1400	1765	2094	calculation

For the ABS capital stock, average annual flows were carried backwards for 10 years, based on average annual depreciation rates from EUKLEMS. As for the APS capital stock, the construction started in 2014, using the average of each ICT variable until 2018, but using just the first lag to fill each capital stock.

Further results

Figure A.1: E-Com digital activities with no clear relation with productivity (adopters vs. non-adopters of digital technology)





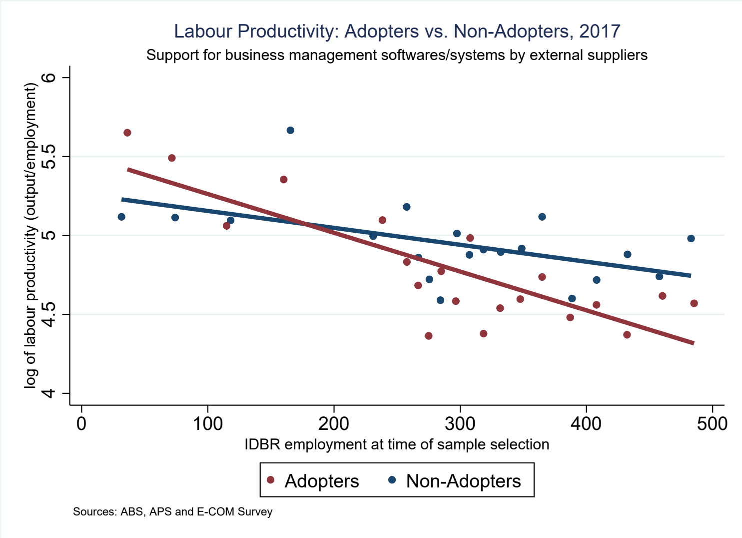


Figure A.2: Productivity 'leaders' and 'laggards' by firm size (TFP controlling for APS capital stock)

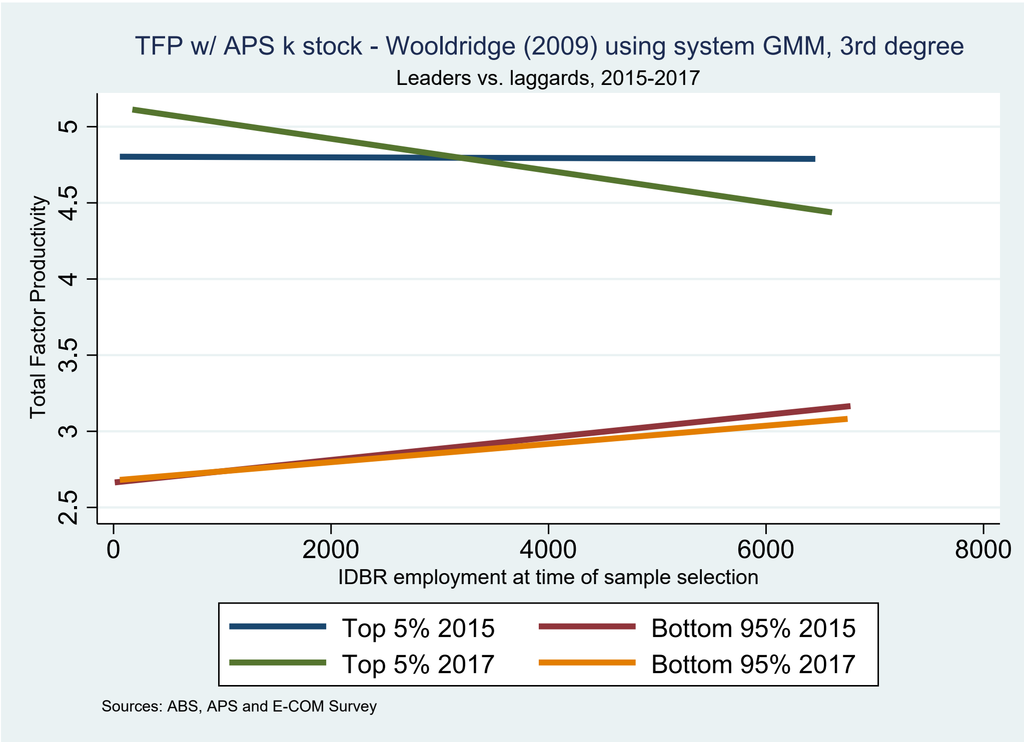


Table A.3: Panel regression results, TFP with APS capital stock (fixed effects at firm level, Wooldridge GMM)

Dependent Variable	TFP w/ APS k stock - Wooldridge (2009) using system GMM 3rd degree																							
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
% internet access	-0.00523	-0.000726																						
	(0.0174)	(0.0168)																						
% orders via website			0.00466	0.0120																				
			(0.0188)	(0.0200)																				
have a website					-0.00662	0.0267																		
					(0.0651)	(0.0667)																		
ICT especialists							0.0613	0.0579																
							(0.0417)	(0.0413)																
use of CRM									0.0779*	0.0614														
									(0.0450)	(0.0458)														
cloud computing											-0.00829	-0.0121												
											(0.0336)	(0.0315)												
ICT maintenance (external)													0.00971	0.0176										
													(0.0302)	(0.0282)										
office software support (external)															0.0420	0.0482								
															(0.0483)	(0.0446)								
management software (external)																	-0.0260	-0.0176						
																	(0.0256)	(0.0261)						
web solutions (external)																			0.0239	0.0273				
																			(0.0261)	(0.0258)				
security data protection (external)																					-0.0212	-0.0171		
																					(0.0243)	(0.0245)		
3D printing																							-0.0280	0.00635
																							(0.0678)	(0.0684)
constant	2.944***	2.693***	2.920***	2.684***	2.930***	2.660***	2.871***	2.644***	2.890***	2.472***	2.930***	2.698***	2.921***	2.685***	2.916***	2.683***	2.939***	2.692***	2.909***	2.670***	2.932***	2.682***	2.925***	2.692***
	(0.0677)	(0.181)	(0.0162)	(0.167)	(0.0640)	(0.183)	(0.0360)	(0.170)	(0.0303)	(0.105)	(0.0232)	(0.168)	(0.0103)	(0.167)	(0.00960)	(0.168)	(0.0149)	(0.167)	(0.0165)	(0.171)	(0.00973)	(0.168)	(0.00197)	(0.167)
Firm Size, Sector, Region and Year FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	2998	2998	2998	2998	2998	2998	2998	2998	2473	2473	2998	2998	2998	2998	2998	2998	2998	2998	2998	2998	2998	2998	2998	2998
N_g	1198	1198	1198	1198	1198	1198	1198	1198	856	856	1198	1198	1198	1198	1198	1198	1198	1198	1198	1198	1198	1198	1198	1198
r2	0.0000224	0.0291	0.0000404	0.0294	0.00000170	0.0292	0.000532	0.0296	0.00318	0.0315	0.0000472	0.0292	0.0000527	0.0293	0.000688	0.0300	0.000461	0.0293	0.000355	0.0296	0.000392	0.0294	0.000246	0.0291
sigma	0.808	0.885	0.807	0.885	0.807	0.886	0.806	0.883	0.791	0.938	0.808	0.885	0.807	0.885	0.808	0.884	0.807	0.884	0.808	0.886	0.807	0.884	0.808	0.884
sigma_u	0.735	0.820	0.735	0.820	0.735	0.821	0.733	0.818	0.713	0.873	0.735	0.821	0.735	0.821	0.735	0.820	0.734	0.819	0.735	0.821	0.734	0.819	0.735	0.820
sigma_e	0.335	0.332	0.335	0.332	0.335	0.332	0.335	0.332	0.343	0.341	0.335	0.332	0.335	0.332	0.335	0.332	0.335	0.332	0.335	0.332	0.335	0.332	0.335	0.332
rho	0.828	0.859	0.828	0.859	0.828	0.859	0.827	0.859	0.812	0.868	0.828	0.859	0.828	0.859	0.828	0.859	0.828	0.859	0.828	0.859	0.828	0.859	0.828	0.859

Standard errors in parentheses

* p<0.10 ** p<0.05 *** p<0.01

Table A.4: Cross-section regression results 2015, TFP with APS capital stock (Wooldridge GMM)

Dependent Variable	TFP w/ APS k stock - Wooldridge (2009) using system GMM 3rd degree																					
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
% internet access	0.0601*	0.0724**																				
	(0.0327)	(0.0358)																				
% orders via website			0.00391	0.00374																		
			(0.0148)	(0.0168)																		
have a website					-0.178	-0.135																
					(0.278)	(0.252)																
ICT especialists							0.256***	0.200**														
							(0.0833)	(0.0871)														
use of CRM									0.0692	0.126**												
									(0.0557)	(0.0569)												
cloud computing											0.104**	0.0467										
											(0.0478)	(0.0497)										
ICT maintenance (external)													0.000600	-0.0220								
													(0.0496)	(0.0472)								
office software support (external)															0.0227	-0.00158						
															(0.0650)	(0.0625)						
management software (external)																	-0.0570	-0.0521				
																	(0.0438)	(0.0435)				
web solutions (external)																			-0.0301	-0.0730		
																			(0.0469)	(0.0452)		
security data protection (external)																					-0.102**	-0.0839*
																					(0.0438)	(0.0429)
constant	2.678***	2.268***	2.909***	2.491***	3.087***	2.633***	2.690***	2.444***	2.910***	1.862***	2.843***	2.477***	2.912***	2.506***	2.908***	2.490***	2.944***	2.549***	2.931***	2.533***	2.953***	2.540***
	(0.129)	(0.245)	(0.0265)	(0.234)	(0.277)	(0.325)	(0.0805)	(0.241)	(0.0482)	(0.656)	(0.0408)	(0.235)	(0.0243)	(0.232)	(0.0225)	(0.236)	(0.0341)	(0.233)	(0.0403)	(0.229)	(0.0277)	(0.227)
Firm Size, Sector and Region FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	1151	1151	1151	1151	1151	1151	1151	1151	810	810	1151	1151	1151	1151	1151	1151	1151	1151	1151	1151	1151	1151
r2	0.00560	0.127	0.0000505	0.120	0.00122	0.121	0.0141	0.128	0.00214	0.172	0.00456	0.121	0.000000145	0.120	0.000146	0.120	0.00151	0.121	0.000407	0.122	0.00465	0.123
r2_a	0.00473	0.0980	-0.000820	0.0908	0.000349	0.0915	0.0133	0.0987	0.000902	0.132	0.00370	0.0916	-0.000870	0.0910	-0.000724	0.0908	0.000640	0.0920	-0.000463	0.0931	0.00378	0.0938
ll	-1266.2	-1191.3	-1269.4	-1195.9	-1268.8	-1195.4	-1261.3	-1190.8	-856.7	-781.0	-1266.8	-1195.3	-1269.5	-1195.8	-1269.4	-1195.9	-1268.6	-1195.1	-1269.2	-1194.4	-1266.8	-1193.9

Standard errors in parentheses

* p<0.10 ** p<0.05 *** p<0.01

Table A.5: Cross-section regression results 2017, TFP with APS capital stock (Wooldridge GMM)

Dependent Variable	TFP w/ APS k stock - Wooldridge (2009) using system GMM 3rd degree																							
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
% internet access	0.0287	0.0328																						
	(0.0504)	(0.0539)																						
% orders via website			0.0268	0.0391																				
			(0.0221)	(0.0279)																				
have a website					-0.825	-0.689																		
					(0.543)	(0.525)																		
ICT especialists							0.129	0.104																
							(0.0952)	(0.0930)																
use of CRM									0.112	0.185**														
									(0.0835)	(0.0839)														
cloud computing											0.00875	-0.0582												
											(0.0774)	(0.0829)												
ICT maintenance (external)													0.00910	-0.0299										
													(0.0610)	(0.0635)										
office software support (external)															-0.0936	-0.134*								
															(0.0781)	(0.0780)								
management software (external)																	-0.0893	-0.0833						
																	(0.0678)	(0.0699)						
web solutions (external)																			0.0234	0.0680				
																			(0.0651)	(0.0610)				
security data protection (external)																					-0.160***	-0.145**		
																					(0.0599)	(0.0591)		
3D printing																							0.0883	0.111
																							(0.100)	(0.115)
constant	2.811***	3.412***	2.899***	3.567***	3.733***	4.286***	2.812***	3.463***	2.863***	3.271***	2.916***	3.554***	2.920***	3.567***	2.943***	3.566***	2.978***	3.629***	2.908***	3.537***	2.987***	3.610***	2.911***	3.466***
	(0.202)	(0.530)	(0.0357)	(0.522)	(0.542)	(0.682)	(0.0896)	(0.508)	(0.0685)	(0.289)	(0.0701)	(0.523)	(0.0399)	(0.525)	(0.0335)	(0.521)	(0.0594)	(0.517)	(0.0536)	(0.512)	(0.0413)	(0.517)	(0.0318)	(0.532)
Firm Size, Sector and Region FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	622	622	622	622	622	622	622	622	439	439	622	622	622	622	622	622	622	622	622	622	622	622	622	622
r2	0.00129	0.168	0.00229	0.170	0.0206	0.178	0.00342	0.168	0.00416	0.201	0.0000258	0.167	0.0000336	0.166	0.00257	0.171	0.00328	0.169	0.000215	0.168	0.0107	0.174	0.00164	0.168
r2_a	-0.000320	0.118	0.000680	0.120	0.0190	0.129	0.00181	0.118	0.00189	0.131	-0.00159	0.117	-0.00158	0.117	0.000958	0.121	0.00167	0.119	-0.00140	0.118	0.00915	0.125	0.0000256	0.118
ll	-709.2	-652.6	-708.9	-651.7	-703.1	-648.5	-708.6	-652.4	-534.9	-486.6	-709.6	-652.7	-709.6	-653.0	-708.8	-651.3	-708.6	-652.1	-709.6	-652.5	-706.3	-650.0	-709.1	-652.4

Standard errors in parentheses

* p<0.10 ** p<0.05 *** p<0.01

Table A.6: Cross-section regression results 2015, labour productivity (Wooldridge GMM)

Dependent Variable	Labour productivity (GVA/employment)																					
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
% internet access	0.443***	0.368***																				
	(0.0244)	(0.0269)																				
% orders via website			0.0367**	0.0774***																		
			(0.0172)	(0.0180)																		
have a website					0.143	0.101																
					(0.143)	(0.144)																
ICT especialists							0.674***	0.631***														
							(0.0718)	(0.0721)														
use of CRM									0.259***	0.277***												
									(0.0560)	(0.0516)												
cloud computing											0.192***	0.236***										
											(0.0471)	(0.0448)										
ICT maintenance (external)													-0.136***	-0.0922*								
													(0.0518)	(0.0494)								
office software support (external)															-0.101	-0.0938						
															(0.0682)	(0.0626)						
management software (external)																	-0.146***	-0.0932**				
																	(0.0435)	(0.0419)				
web solutions (external)																			-0.185***	-0.129***		
																			(0.0441)	(0.0419)		
security data protection (external)																					-0.258***	-0.192***
																					(0.0453)	(0.0427)
constant	2.113***	2.508***	3.823***	3.719***	3.712***	3.610***	3.286***	3.482***	3.715***	2.937***	3.728***	3.619***	3.894***	3.769***	3.870***	3.730***	3.930***	3.763***	3.958***	3.819***	3.952***	3.801***
	(0.0945)	(0.259)	(0.0262)	(0.255)	(0.142)	(0.283)	(0.0685)	(0.259)	(0.0470)	(0.381)	(0.0393)	(0.255)	(0.0239)	(0.259)	(0.0224)	(0.258)	(0.0311)	(0.258)	(0.0335)	(0.257)	(0.0268)	(0.257)
Firm Size, Sector and Region FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	2078	2078	2078	2078	2078	2078	2078	2078	1349	1349	2078	2078	2078	2078	2078	2078	2078	2078	2078	2078	2078	2078
r2	0.162	0.278	0.00236	0.192	0.000506	0.183	0.0619	0.230	0.0165	0.271	0.00847	0.195	0.00397	0.185	0.00157	0.184	0.00537	0.185	0.00841	0.187	0.0160	0.191
r2_a	0.161	0.265	0.00188	0.177	0.0000250	0.168	0.0615	0.216	0.0158	0.250	0.00799	0.180	0.00349	0.169	0.00109	0.169	0.00489	0.170	0.00793	0.172	0.0155	0.176
ll	-2756.9	-2601.0	-2937.7	-2719.0	-2939.6	-2729.9	-2873.7	-2668.4	-1829.1	-1627.1	-2931.3	-2714.5	-2936.0	-2728.0	-2938.5	-2728.5	-2934.5	-2727.6	-2931.3	-2725.2	-2923.4	-2719.3

Standard errors in parentheses
* p<0.10 ** p<0.05 *** p<0.01

Table A.7: Cross-section regression results 2017, labour productivity (Wooldridge GMM)

Dependent Variable	Labour productivity (GVA/employment)																							
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
% internet access	0.425***	0.338***																						
	(0.0234)	(0.0235)																						
% orders via website			0.0106	0.0576***																				
			(0.0188)	(0.0210)																				
have a website					0.0900	0.303**																		
					(0.138)	(0.129)																		
ICT especialists							0.480***	0.518***																
							(0.0648)	(0.0566)																
use of CRM									0.211***	0.230***														
									(0.0551)	(0.0529)														
cloud computing											0.211***	0.251***												
											(0.0500)	(0.0470)												
ICT maintenance (external)													-0.236***	-0.160***										
													(0.0484)	(0.0441)										
office software support (external)															-0.177***	-0.142***								
															(0.0604)	(0.0548)								
management software (external)																	-0.0776*	-0.0246						
																	(0.0450)	(0.0426)						
web solutions (external)																			-0.143***	-0.0595				
																			(0.0454)	(0.0419)				
security data protection (external)																					-0.344***	-0.258***		
																					(0.0461)	(0.0444)		
3D printing																							0.251***	0.203***
																							(0.0594)	(0.0670)
constant	2.254***	3.131***	3.919***	4.333***	3.840***	4.148***	3.534***	4.226***	3.813***	4.077***	3.778***	4.412***	4.005***	4.493***	3.964***	4.424***	3.971***	4.425***	4.011***	4.450***	4.063***	4.549***	3.896***	4.415***
	(0.0881)	(0.404)	(0.0259)	(0.415)	(0.137)	(0.413)	(0.0605)	(0.418)	(0.0393)	(0.467)	(0.0428)	(0.411)	(0.0262)	(0.413)	(0.0240)	(0.415)	(0.0343)	(0.415)	(0.0354)	(0.416)	(0.0269)	(0.417)	(0.0241)	(0.413)
Firm Size, Sector and Region FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	2435	2435	2435	2435	2435	2435	2435	2435	1306	1306	2435	2435	2435	2435	2435	2435	2435	2435	2435	2435	2435	2435	2435	2435
r2	0.124	0.252	0.000161	0.189	0.000183	0.187	0.0285	0.214	0.0103	0.215	0.00767	0.195	0.0102	0.189	0.00424	0.187	0.00123	0.185	0.00413	0.185	0.0235	0.197	0.00573	0.188
r2_a	0.124	0.240	-0.000249	0.176	-0.000228	0.174	0.0281	0.201	0.00951	0.193	0.00727	0.182	0.00981	0.177	0.00383	0.175	0.000817	0.172	0.00372	0.173	0.0231	0.185	0.00532	0.175
ll	-3519.9	-3327.7	-3680.7	-3426.4	-3680.6	-3429.4	-3645.6	-3388.3	-1871.5	-1720.2	-3671.5	-3417.2	-3668.4	-3425.6	-3675.7	-3428.3	-3679.4	-3432.2	-3675.8	-3431.3	-3651.9	-3413.2	-3673.9	-3427.6

Standard errors in parentheses

* p<0.10 ** p<0.05 *** p<0.01

Table A.8: IV *cross-section regression results 2015 (Wooldridge GMM)*

Dependent Variable	TFP - Wooldridge (2009) using system GMM 3rd degree																					
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
% internet access	0.829***	2.012***																				
	(0.0723)	(0.242)																				
% orders via website			0.421***	-8.964																		
			(0.0427)	(10.05)																		
have a website					8.563*	-25.22																
					(4.380)	(34.04)																
ICT especialists							2.936***	5.871***														
							(0.247)	(0.878)														
use of CRM									1.645***	5.181***												
									(0.213)	(1.352)												
cloud computing											4.652***	12.64**										
											(0.667)	(5.250)										
ICT maintenance (external)													-0.826**	-5.069								
													(0.349)	(6.014)								
office software support (external)															-1.140**	-2.651*						
															(0.456)	(1.360)						
management software (external)																	-0.735***	-16.97				
																	(0.250)	(42.38)				
web solutions (external)																			-1.051*	4.078*		
																			(0.548)	(2.159)		
security data protection (external)																					-3.952***	-30.10
																					(0.872)	(43.83)
constant	0.223	-3.648***	3.132***	0.815	-4.898	26.12	1.000***	0.610	2.476***	4.098***	0.439	-1.852	3.715***	6.107	3.668***	3.166***	3.851***	13.08	4.071***	-0.880	5.043***	17.72
	(0.284)	(0.888)	(0.0375)	(2.804)	(4.283)	(31.20)	(0.215)	(0.674)	(0.142)	(1.004)	(0.440)	(2.466)	(0.107)	(4.283)	(0.0850)	(0.504)	(0.136)	(26.42)	(0.324)	(1.916)	(0.355)	(22.42)
Firm Size, Sector and Region FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	1850	1850	1850	1850	1850	1850	1850	1850	1202	1202	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850
idstat	241.0	71.70	167.4	0.806	6.376	0.589	126.5	46.15	75.16	14.74	49.79	5.578	30.31	0.824	31.23	6.492	44.29	0.161	12.73	4.378	24.00	0.474
idp	2.38e-54	2.50e-17	2.77e-38	0.369	0.0116	0.443	2.39e-29	1.09e-11	4.34e-18	0.000123	1.71e-12	0.0182	3.68e-08	0.364	2.29e-08	0.0108	2.83e-11	0.689	0.000359	0.0364	0.000000962	0.491
widstat	303.5	78.35	188.0	0.813	5.549	0.598	143.1	43.81	102.8	14.46	49.67	5.398	28.26	0.790	30.38	6.124	45.03	0.157	12.85	4.340	23.18	0.461

Standard errors in parentheses
* p<0.10 ** p<0.05 *** p<0.01

Table A.9: IV *cross-section regression results 2017 (Wooldridge GMM)*

Dependent Variable	TFP - Wooldridge (2009) using system GMM 3rd degree																							
Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
% internet access	0.892***	1.907***																						
	(0.0666)	(0.222)																						
% orders via website			0.367***	-10.43																				
			(0.0428)	(11.31)																				
have a website					-1.563	-2.120																		
					(3.602)	(2.949)																		
ICT especialists							3.427***	6.176***																
							(0.309)	(0.886)																
use of CRM									2.064***	23.11														
									(0.282)	(20.90)														
cloud computing											5.280***	69.73												
											(0.893)	(154.4)												
ICT maintenance (external)													-2.610***	-10.34										
													(0.571)	(6.943)										
office software support (external)															-3.055***	-10.05								
															(0.785)	(6.857)								
management software (external)																	-0.413	-11.81						
																	(0.271)	(31.93)						
web solutions (external)																			-0.667	2.307				
																			(0.441)	(2.019)				
security data protection (external)																					-5.894***	68.67		
																					(1.181)	(134.8)		
3D printing																							0.876***	27.79
																							(0.160)	(33.68)
constant	-0.0713	-3.468***	3.130***	0.549	4.923	3.569*	0.615**	0.369	2.258***	4.917	-0.296	5.875	4.290***	5.779**	4.046***	4.069**	3.642***	8.287	3.802***	0.916	5.799***	-24.35	3.291***	2.713
	(0.262)	(0.891)	(0.0370)	(2.586)	(3.502)	(1.995)	(0.261)	(0.855)	(0.172)	(5.042)	(0.631)	(10.56)	(0.192)	(2.811)	(0.161)	(1.767)	(0.157)	(16.67)	(0.262)	(1.213)	(0.482)	(53.09)	(0.0294)	(2.054)
Firm Size, Sector and Region FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	2203	2203	2203	2203	2203	2203	2203	2203	1180	1180	2203	2203	2203	2203	2203	2203	2203	2203	2203	2203	2203	2203	2203	2203
idstat	247.8	72.59	206.2	0.860	2.514	2.246	122.2	49.80	77.49	1.205	36.00	0.204	27.84	2.252	19.75	2.217	46.06	0.135	15.33	2.043	25.42	0.260	91.08	0.679
idp	7.65e-56	1.60e-17	9.42e-47	0.354	0.113	0.134	2.14e-28	1.70e-12	1.33e-18	0.272	1.97e-09	0.651	0.000000132	0.133	0.00000883	0.136	1.15e-11	0.713	0.0000904	0.153	0.000000462	0.610	1.38e-21	0.410
widstat	285.4	74.57	223.5	0.875	2.396	2.303	149.7	48.78	81.86	1.171	33.63	0.199	28.02	2.205	19.28	2.150	50.08	0.133	15.62	1.980	24.27	0.259	138.4	0.664

Standard errors in parentheses

* $p<0.10$ ** $p<0.05$ *** $p<0.01$

Table A.10: Multiple digital adoption, TFP with APS capital stock (Wooldridge GMM, 2015)

Dependent Variable	TFP w/ APS k stock - Wooldridge (2009) using system GMM 3rd degree			
Column	(1)	(2)	(3)	(4)
single_digital	0.154	0.0712		
	(0.181)	(0.178)		
multiple_digital	0.267	0.189		
	(0.168)	(0.167)		
digital			0.0866***	0.0745***
			(0.0218)	(0.0239)
constant	2.669***	2.452***	2.682***	2.470***
	(0.167)	(0.251)	(0.0646)	(0.238)
Firm Size, Sector and Region FE	No	Yes	No	Yes
N	1151	1151	1151	1151
r2	0.00694	0.124	0.0178	0.132
r2_a	0.00521	0.0945	0.0170	0.103
F	2.359	5.000	15.78	5.393
ll	-1265.5	-1193.0	-1259.1	-1188.3

Standard errors in parentheses
* p<0.10 ** p<0.05 *** p<0.01

Table A.11: Multiple digital adoption, TFP with APS capital stock (Wooldridge GMM, 2017)

Dependent Variable	TFP w/ APS k stock - Wooldridge (2009) using system GMM 3rd degree			
Column	(1)	(2)	(3)	(4)
single_digital	-0.197	-0.153		
	(0.265)	(0.225)		
multiple_digital	-0.00291	0.0412		
	(0.263)	(0.234)		
digital			0.0558*	0.0616*
			(0.0304)	(0.0330)
constant	2.940***	3.253***	2.760***	3.140***
	(0.261)	(0.418)	(0.0917)	(0.421)
Firm Size, Sector and Region FE	No	Yes	No	Yes
N	622	622	622	622
r2	0.00462	0.170	0.00811	0.174
r2_a	0.00140	0.119	0.00651	0.125
F	6.045	.	3.384	.
ll	-708.2	-651.6	-707.1	-650.0

Standard errors in parentheses
* p<0.10 ** p<0.05 *** p<0.01