Heliyon 6 (2020) e03935

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Estimating the impact of the Internet of Things on productivity in Europe

Héctor Espinoza [a], Gerhard Kling [b], Frank McGroarty [c,*], Mary O'Mahony [d], Xenia Ziouvelou [c]

[a] Centre for Economic Performance, London School of Economics, London, United Kingdom
[b] University of Aberdeen, Business School, Aberdeen, United Kingdom
[c] Centre for Digital Finance, University of Southampton, Southampton, United Kingdom
[d] King's College London, Business School, London, United Kingdom

ARTICLE INFO

Keywords:
Business
Economics
Industry
Information science
Internet of Things
Productivity
Impact
Evaluation of new technology
Growth accounting

ABSTRACT

The Internet of Things (IoT) refers to interconnected devices and objects that collect and transmit data via the Internet. The IoT is an evolving technology, promising to revolutionise industries, but also demanding far-reaching policy changes (e.g. in terms of data security and privacy), which involve significant resources. This paper reviews the evidence on uptake and the economic impact of the IoT during its early years of inception. It uses a growth accounting framework to evaluate the likely impact of the IoT on productivity. Estimating the effect of new technologies on productivity is an essential step in evaluating the 'economic value-added', justifying resources dedicated to facilitating the adoption of innovations. We find a positive impact of the IoT on productivity, however relatively small, given that the IoT is still at an early stage of development. We present projections on the impact of the IoT under a number of scenarios.

1. Introduction

New technologies promise huge benefits for industries and end-users; however, these alleged benefits need to be assessed against associated costs. Recent policy work has focused on the internet but not the IoT. In particular, previous research has addressed some of the problems in understanding the internet's impact on research productivity and its scientific knowledge value (Bozeman and Rogers, 2002; Vasileiadou and Vliegenthart, 2009) or its role in business creation and entrepreneurship (Batjargal, 2007; Wagner and Cockburn, 2010). This paper contributes to the literature assessing the likely impact of new technologies on productivity, a key driver for economic growth. Specifically, it aims to assess the impact of a new technology, the Internet of Things (IoT)[1].

The IoT refers to interconnected devices and objects that collect, transmit and process data via the Internet (CEBR, 2016; European Commission, 2016). It represents 'an ecosystem in which applications and services are driven by data collected from devices that sense and interface with the physical world' (OECD, 2016, page 9). Several technologies have converged in the last few years to form the IoT. The IoT combines hardware and software technologies (Borgia, 2014; OECD, 2016): '*The hardware consists of the connected devices – which range from simple sensors to smartphones and wearable devices – and the networks that link them, such as 4G Long-Term Evolution, Wi-Fi and Bluetooth. Software components include data storage platforms and analytics programmes that present information to users. However, it is when these components are combined to provide services that real value is created for businesses, consumers and governments*' (Government Office for Science, 2014, page 13).

The IoT is an evolving technology that mainly represents an area for future innovation and development. The IoT market is at an early stage of development, far from its full potential, but step by step it is becoming a reality (Fleisch, 2010; Manyika et al., 2015; Mazhelis et al., 2013). In this scenario, in an era characterised by technology transactions and open innovations (Lichtenthaler and Ernst, 2008; IDC, 2019), some actors are making an effort in investing to foster this technology (Stefan et al., 2014), which promises to be one of the most radical technological changes since the advent of the Internet.[2] It promises a fruitful revolution in our society[3] and the economy.

The present work tries to uncover trends and understand the current state of the IoT, answering the following two questions: what is the link between the Internet of Things and overall IT expenditure? And, what is

* Corresponding author.
E-mail address: f.j.mcgroarty@soton.ac.uk (F. McGroarty).

[1] The term IoT was coined in 1999 by Kevin Ashton (Government Office for Science, 2014), but came into the limelight in 2005 when the ITU published the first report on the subject (Stefan et al., 2014).

[2] Developments and improvements of the Internet have quickly lead to three main revolutions (European Commission, 2016). First, the creation of a word wide web of information (web 1.0). Second, the conception of the universal social-communication technology (web 2.0). Third, the emergence of the Internet of Things (IoT).

[3] The IoT appliances promise better quality of life, fostering efficiency, security and health, for example.

https://doi.org/10.1016/j.heliyon.2020.e03935
Received 25 August 2018; Received in revised form 1 February 2020; Accepted 4 May 2020

the impact of the IoT on productivity? The main reasoning is that if we estimate the percentage of IT that is spent on the Internet of Things, then we should be able to make conjectures about the relationship between the Internet of Things and overall economic productivity.

The methodology used is growth accounting developed by Jorgenson and Griliches (1967), Jorgenson et al. (1987), and Jorgenson et al. (2006), which is a dynamic approach that tries to capture the contributions of different types of inputs to economic growth. Recent research using this method has attempted to capture the contribution of Information and Communications Technology (ICT) capital to GDP or labour productivity growth.[4] Since ICT investments include expenditure on the IoT, we make estimations about the contribution of the IoT to ICT using proxies found in the literature, such as the number of devices connected to the internet, level of adoption of the IoT, and also the level of investment. Other variables needed for this analysis are taken from the EU KLEMS and the Conference Board Total Economy databases, which contain consolidated measures of capital, labour, intermediate inputs, output and total factor productivity up to the year 2014.

Based on an extensive review of the literature presented in sections 2 and 3, we reveal expenditure data that allow a reasonable estimate of IoT as a percent of ICT spend. In section 4, we find a positive impact of the IoT on productivity, which is however relatively small during the early stages of development. We also present projections on the impact of IoT under a number of scenarios and conclude in section 5. Our approach could serve as a starting point for assessing the impact of other new technologies on productivity.

2. Information and communication technologies (ICT) and the economy

To understand the impact of the IoT on the economy, first we take one step back, revisiting the link between ICT and economic performance. In the field of economics this topic has been famously promoted by Robert Solow[5] (Solow, 1987) and has become highly relevant in the last three decades of research; a period that has experienced an IT revolution (Timmer et al., 2010).

Economists have approached the problem from both micro and macro perspectives, mainly using two methodologies. The first is growth accounting,[6] which is a dynamic approach that tries to capture the contributions of different types of assets to output or labour productivity growth. This is usually calculated using aggregate data at country or industry level. The second complementary method is an econometric approach,[7] based on regression analysis that takes into account heterogeneity and time issues to find causal effects (European Commission, 2016; OECD, 2012). However, the econometric approach requires data over longer time periods, which can be challenging when assessing the impact of new technologies. Hence, we follow the growth accounting approach.

In terms of measurement, ICT is represented by proxies (OECD, 2012) such as: i) measures of adoption (e.g. broadband penetration, number of devices per capita), ii) economic measures (e.g. investments in ICT networks), and iii) technical measures (e.g. IPv4[8] per capita, international bandwidth usage). Typically, in aggregate studies, the ICT variable has been represented by investments in computer hardware, communications equipment and software, using various assumptions regarding depreciation and returns to different types of assets (Biagi, 2013; O'Mahony and Timmer, 2009).

Empirical studies have shown a positive effect of ICT on the economy (Biagi, 2013). Estimates of the impact on economic growth suggest that about 20% of GDP growth can be attributed to ICT (Van Ark and O'Mahony, 2016). Using the growth accounting methodology, Van Ark et al. (2008) found that during the period 1995–2004[9] the labour productivity contribution – annual average growth rates in percentage points – from ICT capital per hour in the United States was 0.8 percentage points or 26.7%[10] of labour productivity growth. In the European Union,[11] ICT contributed 0.5 percentage points, representing 33.3%[12] of labour productivity growth. An update of this study (Van Ark and O'Mahony, 2016) for the period 2008–2014,[13] indicates that the contribution to labour productivity growth from ICT capital in the US was 0.4 percentage points, and 0.3 percentage points in the European Union,[14] i.e. since 2008 the ICT capital contribution to growth slowed down considerably in both regions. Timmer et al. (2010) conclude that ICT had a major role in the U.S. productivity acceleration observed in the period 1995–2005, both in terms of Total Factor Productivity (TFP) growth in ICT-producing sectors and capital-deepening in ICT-using sectors. Timmer et al. (2010) also mention that the evidence for Europe is less clear-cut, due to heterogeneity across countries. From a more holistic perspective, it is worth noting that ten Raa and Wolff (2000) have found that there may well be productivity spillovers associated to ICT investment, which means that computers can be engines of growth even during an early stage of development. This can be highly relevant to the IoT and represent an area for further research.

Econometric studies frequently find even larger impacts, suggesting excess returns to ICT on output growth, e.g. O'Mahony and Vecchi (2005) in the context of estimating a production function using industry data for the USA and the UK. Also, econometric studies have focused on the impact of the Internet (Crandall et al., 2007; Czernich et al., 2009; Koutroumpis, 2009), suggesting that the Internet might indeed have had some causal effect on growth.[15] This is a vast literature and there are many more examples confirming or complementing the previous results, for instance Oliner and Sichel (2000), Crepon and Heckel (2002), Van Ark et al. (2002), Qiang et al. (2009).

It is worth noting a recent literature that extends the measurement of productivity to take account of intangible assets, such as research and development, design and economic competences (Corrado et al., 2009). This work points to an important role for intangible assets in explaining cross country productivity performance. Similarly using firm level data, econometric results indicate that intangible assets have a significant positive, association with productivity (Riley, 2011). This literature also suggests that ICT creates complementarities with other assets (Biagi, 2013), so that realising the full potential from ICT requires investment in

[4] Examples are Jorgenson and Stiroh (2000); Oliner and Sichel (2000); Jorgenson et al. (2006); Stiroh (2002).

[5] Robert Solow pointed out the need to do research in the topic to understand the real effects of IT. His motivation was the Solow paradox, described in his own words: 'what everyone feels to have been a technological revolution, a drastic change in our productive lives, has been accompanied everywhere, including Japan, by a slowing-down of productivity growth, not by a step up. You can see the computer age everywhere but in the productivity statistics" (Solow, 1987).

[6] Examples are Jorgenson and Stiroh (2000); Oliner and Sichel (2000); Jorgenson et al. (2006); Stiroh (2002).

[7] Examples are Czernich et al. (2009) and Koutroumpis (2009).

[8] Note that the Internet Protocol version 4 already has a successor, the IPv6. From a technical point of view the latter is key to further IoT development. However, the transition to IPv6 protocol has been slow (OECD, 2016, page 4), and is speeding up only in past months.

[9] Calculations based on EU KLEMS database.

[10] This is the contribution of ICT capital (0.8) divided by labour productivity growth (3.0) in the United States.

[11] EU refers to Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Spain, and the United Kingdom.

[12] This is the contribution of ICT capital (0.5) divided by labour productivity growth (1.5) in the European Union.

[13] Using the Conference Board Total Economy Database.

[14] Refers to pre-2004 membership of EU.

[15] According to this research broadband penetration has a positive effect on GDP growth. A 10% increase in broadband penetration -on average-increases GDP by 0.25 percentage points (Biagi, 2013).

complementary assets, such as human, organizational and managerial capital.

3. The Internet of Things in numbers

Preliminary statistics[16] show the level of investment in this technology, the use and adoption of the IoT, and the potential effects on the economy for the next few years. Below we present some of the major findings.

3.1. IoT investment

The optimism and confidence about the IoT are not yet matched by investment (The Economist, 2013). According to The Economist (2013), in 2012 only around 30% of organisations have seen double-digit growth in IoT investment (see Table 1). Since then, IoT investment has increased as organisations move from the research stage (i.e. pilots) to the planning stage (The Economist, 2017). The International Data Corporation (IDC) Spending Guide (2019) forecasts worldwide spending on the Internet of Things (IoT) to grow 15.4% in 2019, reaching $745 billion. For the medium term, the forecast predicts nearly $1 trillion in 2022.

Reports by Vodafone (2016 and 2019)[17], estimate that companies that are adopters of the IoT[18] invest 24% of their average IT budgets[19] on the IoT, on par with cloud computing or data analytics. In a new update to the Worldwide Semi-annual Internet of Things Spending Guide, the International Data Corporation (IDC, 2019) forecasts that The United States and China will be the global leaders for IoT spending in 2019 at $194 billion and $182 billion respectively. This is close to a half of global spending. In the case of Europe, availability of data is very limited compared to the US, making an analysis for this region more difficult. According to IDC (2019), Germany will be leading in Europe in 2019, with spending exceeding $35 billion, followed by France and the U.K. each spending over $25 billion.

3.2. Connected devices

The number of objects connected to the internet today is large, and the evidence suggests that it will continue growing exponentially in the next few years. IDC, 2014, Cisco (Cisco counter) estimated that 14 billion of devices were connected to the internet,[20] and industry analysts estimate that the number of connected devices could be anywhere from 20 billion to 100 billion by 2020 (Government Office for Science, 2014; Cisco, 2016).[21] For example, Gartner (2017) estimates that there will be 20 billion devices connected by 2020. Business Insider Intelligence asserts that there will be a total of 23.4 billion IoT devices connected by 2019 (Greenough, 2014). ABI Research contends that more than 35 billion networked devices will be in use by 2019 (ABI Research, 2013), whereas Cisco projects that 40 billion intelligent things will be connected and communicating by 2019 (Evans, 2013). In line with, Morgan Stanley forecasts 75 billion networked devices by 2020 (Danova, 2013), and Huawei expects 100 billion IoT connections by 2025 (Huawei, 2015). There is a lot of variance among these projections (in part due to different assumptions); however, the key point is that all of them suggest rapid growth. Moreover, disaggregating the data projections by region we observe that Asia/Pacific, North America and Western Europe are leading the IoT business in terms of the number of connected devices (see Table 2).

3.3. Adoption

Preliminary figures show that the global level of adoption of the IoT was relatively low in 2015, but it has been increasing in recent years. According to the IoT business index developed by The Economist (2013), only 17% of the organisations are currently using the IoT in their products or services, and 21% of organisations are using this technology for their internal operations (see Table 3)[22]. These figures represent the early stage of the IoT during its incubation period. It is likely that a significant number of organisations are currently at the research stage and are planning to use the IoT in the near future.

4. Economic impact

4.1. Previous studies on economic impact

As the IoT is a relatively new phenomenon, researchers mostly try to evaluate how they expect the value of the IoT to develop in the near future. The McKinsey (2015) suggested that the financial impact of IoT on the global economy may be as much as $3.9 to $11.1 trillion by 2025, the largest of which will be felt in the manufacturing and health care industries. McKinsey (2015) estimated the economic impact by examining applications that exist currently, are evolving, or are likely to have significant adoption in 2025, in nine different settings. They measured both direct financial impact, such as potential savings from improved machine utilization, and non-financial factors,[23] such as consumer time saved or improved health. It should be noted that these estimates of economic impact are not equivalent to industry revenue or GDP figures and, therefore, diverge from other market projections (McKinsey, 2015). Cisco analysts also estimated that IoT will create $14.4 trillion in net profit between 2013 and 2022, which amounts to an increase in global corporate profits by roughly 21 percent (Cisco, 2013a, b). The $14.4 trillion does not include potential Value at Stake[24] from the consumer or public sectors, or from societal benefits. Furthermore, Cisco (2013a), b calculated the Value at Stake by taking a bottom-up approach considering the value created by more than 50 use cases in the private sector only and consolidating them into the 21 most material and value-generating examples. Other industry analysts such as General Electric, Accenture (in collaboration with World Economic Forum in 2015), ABI research or Business Insider derived similar forecasts.

IDC (2014) assessed each of the major regions around the world and showed that while every region in the world has begun implementing IoT solutions, developed regions are leading and will continue to lead the way to the massive growth of IoT by 2020 (see Table 4) The IDC worldwide IoT revenue forecast includes two major revenue categories

[16] Estimations have proved to be not an easy task due to problems of measurement.

[17] Vodafone's fourth annual 'IoT Barometer' report is a global survey involving more than 1,096 companies across Australia, Brazil, Canada, China, Germany, India, Ireland, Italy, Japan, Netherlands, South Africa, South Korea, Spain, Turkey, UAE, UK and US.

[18] Overall, it is estimated that 34% of organisations have adopted the IoT.

[19] ICT investment has three components (OECD, 2016): software, IT equipment, and communications equipment. According to Gartner (2016) worldwide IT spending is forecast to total $3.54 trillion dollars in 2016, just a 0.6 percent increase over 2015 spending of $3.52 trillion dollars. The International Data Corporation (2016) states that the total IT spending on hardware, software and services will reach $2.3 trillion in 2016. Including telecom services, total ICT spending will increase by 2% to $3.8 trillion.

[20] Cisco is counting the number of objects connected to the internet. A similar number was found by the online statistics portal Statista (www.statista.com).

[21] To calculate projections analysts usually consider the total number of 'things' in the world, the proportion of connected things, a decline in hardware, software and connectivity costs, and a very elastic price-elasticy of demand.

[22] As a reference point, we observe that in the UK the adoption of the IoT stood at 30% in 2015 (Cebr, 2016).

[23] McKinsey also translated these non-financial impacts into economic value by gauging the value of time saved, improved health, extended life spans, etc.

[24] Value at Stake is the potential bottom-line value that can be created, or that will migrate among private-sector companies and industries, based on their ability to harness the Internet of Things over the next decade (Cisco, 2013a, b).

Table 1. Survey results by approximately what percentage has your organisation increased its investment in the IoT this year compared to last year (% of respondents) [301].

Over 100%	3
Between 75% and 100%	1
Between 50% and 75%	4
Between 25% and 50%	9
Between 10% and 25%	13
Between 5% and 10%	17
Between 1% and 5%	15
Under 1%	7
We have yet to make any investment	22
Don't know	10

Source: The Economist (2013),[30].

Table 2. Worldwide IoT installed base, connected devices by region, in billions, 2013–2020.

Region	2013	2014	2015	2016	2017	2018	2019	2020
Asia/Pacific	2.8	3.6	4.4	5.4	6.4	7.6	8.9	10.1
Central/Eastern Europe	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.8
Latin America	0.2	0.2	0.3	0.2	0.4	0.4	0.5	0.6
Middle/East Africa	0.3	0.4	0.4	0.5	0.5	0.7	0.7	0.8
North America	3.1	3.8	4.5	5.2	5.9	6.5	7	7.5
Western Europe	2.4	3.1	3.7	4.5	5.4	6.3	7.3	8.3
Total	9.1	11.4	13.7	16.3	19.2	22.2	25.2	28.1

Source: IDC (2014). Note that totals are in line with more recent projections, for example Statista in 2019: https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/.

Table 3. Levels of adoption of the IoT.

	To what extent (%) is your organisation using, or planning to use, the IoT…	
	in products or services	in internal operations
Non-existent	26	24
In research	40	36
In planning	17	20
Early implementation	12	16
Extensive	5	5

Source: IoT business index, The Economist (2013).

Table 4. Worldwide IoT revenue, in US$ billions.

Region	2013	2014	2015	2016	2017	2018	2019	2020
Asia/Pacific	600.3	729.5	881.8	1056.9	1287.6	1605.9	2027.2	2602.6
Central/Eastern Europe	57.9	69	81.9	96.4	115	140	172.9	217.1
Latin America	37.5	42.5	47.2	51.5	56.7	62.9	69.4	76.3
Middle/East Africa	56.2	63.7	70.8	77.2	85.1	94.4	104.1	114.4
North America	667.9	775.5	892.7	1016.8	1168.8	1363.2	1608	1922.1
Western Europe	507.7	612.1	737.1	880.9	1069.2	1325.8	1667	2132.8
Total	1927.5	2292.3	2711.5	3179.7	3782.4	4592.2	5648.6	7065.3

Source: IDC (2014).

the IoT system shipment revenue and the IoT stack revenue per installed device.

4.2. The growth accounting approach

As outlined in previous sections, data on the IoT is scarce with the vast majority of studies based on surveys and predictions conducted by non-academic actors. Quite often, the methodology of these forecasts is not disclosed or underreported. The underlying data is not publicly available, making it impossible to validate or replicate these studies. We propose a more rigorous approach based on growth accounting, which can estimate the impact of the IoT on GDP and productivity.

Growth accounting has been theoretically motivated by the seminal contribution of Jorgenson and Griliches (1967) and put in a more general input-output framework by Jorgenson et al. (1987). In its value-added form, it uses a production function framework standard in economics which relates value added growth to input growth and technical progress. Under the assumptions of competitive factor markets, full input utilization and constant returns to scale, the growth accounting decomposes the value-added growth into the growth of inputs (divided into labour and capital) and a residual productivity term known as total factor productivity (TFP)[25], as follows:

[25] Eq. (1) is the general form for a growth accounting relationship. In practice, the growth rates can be defined relative to base year or using logs and the shares can be constant or vary through time (see Chambers, 1988). For more details on the calculations in this paper see the appendix of O'Mahony and Timmer (2009), which contains additional mathematical derivations.

$$y_t = v_l l_t + v_{ict} kict_t + v_{nict} knict + tfp_t \quad \text{[Equation 1]}$$

where at any period *t*, *y* represents value added growth, *kict* the growth in ICT capital, *knict* the growth in non-ICT capital, v_l, v_{ict} and v_{nict}, the shares of labour, ICT capital and non-ICT capital in nominal value added and *tfp* stands for total factor productivity growth. The impact of ICT in this framework is through its treatment as an investment in capital assets, comprising computer hardware, software and communications equipment. ICT capital is built up from real investments in these components assuming a depreciation rate so that capital in period *t* is undepreciated capital in the previous period plus investment in the current period (the perpetual inventory method). In Eq. (1), the contribution of ICT capital to output growth is then calculated by weighting its growth by its share of nominal value added, v_{ict}. The latter in turn is based on ICT capital's share in total capital which depends on user costs of capital calculated as the rate of return minus depreciation minus capital gains. Imposing constant returns to scale in the production function implies that the share of total capital can be estimated as one minus labour's share (the ratio of the wage bill to value added). ICT's contribution to output growth is then estimated by its share of total capital times aggregate capital share times the growth in real ICT capital. An analogous calculation estimates the contribution of ICT to labour productivity growth by using ICT divided by numbers of hours worked.

The above sketch makes clear that a number of components are involved in the growth accounting calculation. Two important components stand out, the deflators to derive real investment and capital gains in the user cost formula, and the depreciation rate. The high contributions of ICT capital in the previous literature depends on both. The quality adjusted price of the ICT components has been declining rapidly since its first inception, in particular for hardware taking account that a computer today is much more powerful than one purchased a decade ago. These prices are often measured using hedonic regression methods. The depreciation assumed for ICT assets are generally much higher than for other assets – this increases the depreciation term in the user cost formula, raising the share of ICT in total capital. Put simply, the rental price of these assets has to reflect both their high depreciation and capital losses in the face of rapidly falling prices. This relatively high rental price implies a much higher contribution from ICT capital than a calculation that is based on its capital share using asset prices.

Calculating the exact contribution of IoT is difficult as it is made up of expenditures on all three components that are separately tabulated in official statistics[26], hardware (such as chips and sensors), software (i.e. the service enabler) and communications equipment (i.e the network operator). Ideally, we would estimate separate deflators and depreciation rates for this type of spend. Therefore, we base on our estimates on the share of IoT in existing ICT spending.

Consolidated growth accounting calculations based on Eq. (1) are available for the period 2010–2014 (i.e. early years of IoT development) and are shown in Table 5. Labour productivity growth is divided into contributions from four components (right-hand side of equation 1): growth in ICT capital per hour worked, growth in non-ICT capital per hour worked, growth in labour composition (which takes account of e.g. the skill makeup of the workforce) and growth in total factor productivity, which together sum to 100.

We then calculate how much of the contribution of ICT capital per hour is due to IoT – see summary in Table 5. Using the result that the average IoT expenditure of early adopters has soared from 0 (before the IoT era in 2008) to a third of IT expenditure in the US by year 2016, where the IoT is booming, can give an indication of its contribution to GDP during its early years.

United States, contribution of inputs in percentage points (in parentheses) to labour productivity growth, derived from Eq. (1):

Labour productivity growth (0.77) = Percentage points contributions of:

ICT capital (0.11) + *Non-ICT capital* (0.17) + *Labour* (0.15) + *tfp* (0.34)

The equation above shows that the contribution to labour productivity growth from ICT capital in the US was 0.11 percentage points during the period 2008–2014 (figures based on Van Ark and O'Mahony, 2016). Based on the numbers, if we assume about 30% of organisations have adopted the technology and this accounts for one third of ICT expenditures, then an estimate for the US would be the product of these two numbers times the contribution of ICT to current labour productivity growth which equals 0.01 percentage points (i.e. (30/100)*(1/3)*0.11 = 0.01).

In the European Union countries for which data are available the ICT contribution to labour productivity growth was a little lower at 0.09 percentage points (see formula below). With an IoT investment likely closer to the 24% average global investment, a similar calculation suggests a very modest 0.006 percentage points contribution from IoT in that region (i.e. 0.24*(1/3)*0.09 = 0.007). These estimates are likely to be an upper bound as firms adopting now are likely to be the larger firms that account for much more than 30% share of investment, and the calculation uses investment rates rather than changes in capital stock (that are affected by depreciation).

European Union10[27], contribution of inputs in percentage points (in parentheses) to labour productivity growth, derived from Eq. (1):

Labour productivity growth (1.05) = Percentage points contributions of:

ICT capital (0.09) + *Non-ICT capital* (0.32) + *Labour* (0.25) + *tfp* (0.39)

Looking ahead, the double-digit projected rates of growth of the IoT are similar to the growth in ICT investment in the period of most rapid ICT expansion, from 1995 to 2005. In that period the percentage point contribution of ICT capital to labour productivity growth was a much larger 0.6 percentage points. If we assume that 50% of US ICT spend is likely to be devoted to the IoT then this suggests a contribution of about 0.3 percentage points once the technology reaches full adoption. In the same period in the EU countries for which data is available, the contribution to labour productivity growth of ICT capital per hour was a smaller 0.45 percentage points. Using the same 50% assumption on the share of IoT would give a percentage point contribution of 0.23.

These calculations may understate the relative magnitude for the EU countries for two reasons. First there is evidence that these countries have been catching up with the US in terms of ICT spend as a share of total investment. Secondly the IoT is more concentrated in the public sector than earlier ICT innovations and Europe tends to invest more in public infrastructure than the US. It is important to emphasise that these estimates are quite large, about equivalent to the contribution of labour force skills to labour productivity growth. They also do not take into account spillovers from the IoT, as discussed above. The research on intangible investments, referred to above, suggests the need to take account of complementary investments when evaluating the impact of ICT. A similar argument is likely to prevail for IoT so that just focusing on the direct investments in IoT, rather than the investment in design, research and development and organisational changes associated with this technology, will underestimate its contribution to labour productivity growth. The estimates are also focused on the production side so do not

[30] The inaugural IoT business index is based on a survey of 779 executives from around the world, conducted by The Economist Intelligence Unit in June 2013. Survey respondents were asked to indicate the extent to which their companies currently make use of the IoT in their external products and services, and separately in their internal operations and processes (The Economist, 2013)).

[26] The national accounts investment data that underlie the EU KLEMS estimates categorise ICT into these three groups.

[27] EU-10 comprises Austria, Belgium, Finland, France, Germany, Italy, the Netherlands, Spain, Sweden and the United Kingdom. Estimates for each EU country are weighted by their shares in value added.

Table 5. Contribution of inputs to labour productivity growth.

	United States	EU-10*
Average annual percent change in:		
Labour productivity	0.77	1.05
Percentage points contributions of:		
ICT capital per hour worked	0.11	0.09
Of which IoT	*0.010*	*0.006*
Non-ICT capital per hour worked	0.17	0.32
Labour composition	0.15	0.25
Total Factor productivity	0.34	0.39
IoT	*0.010*	*0.006*
percent contributions		
ICT capital per hour worked	13.9	8.4
Non-ICT capital per hour worked	22.4	30.6
Labour composition	19.4	23.7
Total Factor productivity	44.3	37.3

Notes: Using updates of EU KLEMS for European countries (www.euklems.net) and the Conference Board growth accounting and total factor productivity database for the United States. * EU-10 comprises Austria, Belgium, Finland, France, Germany, Italy, the Netherlands, Spain, Sweden and the United Kingdom. Estimates for each EU country are weighted by their shares in value added.

Table 6. Sensitivity analysis, IoT contribution to labour productivity growth under a number of scenarios.

	ICT capital contribution	% of ICT spend devoted to IoT	IoT contribution
United States			
Scenario 1	0.6	0.4	0.24
Scenario 2	0.6	0.5	0.3
Scenario 3	0.6	0.6	0.36
European Union			
Scenario 1	0.45	0.4	0.18
Scenario 2	0.45	0.5	0.225
Scenario 3	0.45	0.6	0.27

Source: author's own calculations.

include any contributions to consumer welfare from the IoT which arise due to e.g. more intelligent activities within the household, which previous studies such as the McKinsey report suggest to be significant.

Alternative scenarios are shown in Table 6. Changing the percentage of the ICT spend devoted to the IoT (ranging from 0.4 to 0.6), we compute the IoT contribution to labour productivity growth. In line with projections, we observe that an increase in spending tend to be associated with a larger contribution in the US, however these calculations also suggest that the European Union could obtain significant benefits from the IoT in the near future.

5. Conclusion

Using a growth accounting methodology, we find a positive impact of the IoT on productivity. However, the impact is relatively small, given that the IoT is at an early stage of development. This result applies to the United States and the European Union, places where the IoT has been fostered in recent years. Forward projections suggest that in about a decade, the IoT might account for a much larger share of labour productivity growth.

This positive effect is in line with previous research and analyses, which consistently unveil the potential benefits of the IoT at different levels (see for example Jorgenson et al., 2006; OECD, 2016; Cebr, 2016) and across all industries (Government Office for Science, 2014; OECD, 2016). Accordingly, in the consumer side of the economy the IoT would foster security (e.g. the smart home that incorporates home automation components), and health (e.g. wearable fitness and health monitoring devices and network enabled medical devices). In addition, impacting consumers and producers the IoT would promote efficiency (e.g. networked vehicles, intelligent traffic systems, and sensors embedded in roads and bridges move us closer to the idea of "smart cities", which help minimize congestion and energy consumption). Finally, from the producer perspective, the IoT stimulates productivity and economic growth in general as the IoT technology offers the possibility to transform agriculture, industry, and energy production and distribution by increasing the availability of information along the value chain of production using networked sensors.

Nevertheless, more IoT investment is required to reach the full potential (OECD, 2016; The Economist, 2013; European Commission, 2016), and several challenges must be addressed, such as privacy and security measures to protect the data generated by the IoT (Want et al., 2015), better infrastructure to further develop the technology[28] (Internet Society, 2015), cooperation among actors to promote the best policies and regulations[29] (Vermesan and Friess, 2014), and development of IoT skills that are key to operate this radical technological change (Government Office for Science, 2014; Internet Society, 2015) to name a few. However, none of the above are likely to outweigh the potential benefits of the IoT.

[28] For instance, a smooth transition to IPv6 is frequently mentioned in the literature, or good and trusty alternatives of data storage.

[29] Understanding that the IoT involves cities, countries, citizens and governments.

Declarations

Author contribution statement

Héctor Espinoza, Mary O'Mahony: Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Gerhard Kling, Frank McGroarty, Xenia Ziouvelou: Conceived and designed the analysis; Wrote the paper.

Funding statement

This work was supported by the EU/FIRE IoT Lab project – STREP ICT-610477.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

ABI Research, 2013. More than 30 Billion Devices Will Wirelessly Connect to the Internet of Everything in 2020. Press release. May 9 2013.
Batjargal, B., 2007. Internet entrepreneurship: social capital, human capital, and performance of Internet ventures in China. Res. Pol. 36, 605–618.
Biagi, F., 2013. ICT and Productivity: A Review of the Literature. European Commission, Institute for Prospective Technological Studies. Digital Economy Working Paper.
Borgia, E., 2014. The Internet of Things vision: key features, applications and open issues. Comput. Commun. 54, 1–31.
Bozeman, B., Rogers, J.D., 2002. A churn model of scientific knowledge value: internet researchers as a knowledge value collective. Res. Pol. 31, 769–794.
Cebr, 2016. The Value of Big Data and the Internet of Things to the UK Economy. Report for SAS. Centre for Economic and Business Research, London. Retrieved from: https://www.sas.com/content/dam/SAS/en_gb/doc/analystreport/cebr-value-of-big-data.pdf.
Chambers, R.G., 1988. Applied Production Analysis: A Dual Approach. Cambridge University Press, Cambridge.
Cisco, 2013a. The Internet of Everything. Global Public Sector Economic Analysis.
Cisco, 2013b. Embracing the Internet of Everything to Capture Your Share of $14.4 Trillion. Cisco White Paper.
Cisco, 2016. Internet of things at a glance. Cisco. Avalaible in. www.cisco.com.
Corrado, C., Hulten, C., Sichel, D., 2009. Intangible Capital and US economic growth. Rev. Income Wealth 55 (Number 3).
Crandall, R., Lehr, W., Litan, R., 2007. The effects of broadband deployment on output and employment: a cross-sectional analysis of U.S. Data. Issues in Economic Policy 6.
Crepon, B., Heckel, T., 2002. Computerization in France: an evaluation based on individual company data. *Review of Income and Wealth* - International Association for Research in Income and Wealth 48 (1), 77–98.
Czernich, N., Falk, O., Kretschmer, T., Woessmann, L., 2009. Broadband Infrastructure and Economic Growth. CESifo Working Paper, No. 2861.
Danova, T., 2013. Morgan Stanley: 75 billion devices will Be connected to the internet of things by 2020. Business Insider. (Accessed 2 October 2013).
Evans, D., 2013. Thanks to IoE, the Next Decade Looks Positively 'Nutty'. Cisco Blog, February 12, 2013.
European Commission, 2016. Advancing the Internet of Things in Europe. Staff Working Document.
Fleisch, E., 2010. What is the internet of things? An economic perspective. Auto-ID Labs White Paper.
Gartner, 2016. Gartner Says Worldwide IT Spending Is Forecast to Grow 0.6 Percent in 2016, 18. Press release, January, p. 2016.
Gartner, 2017. Press release. Available in. https://www.gartner.com/newsroom/archive/.
Government Office for Science, 2014. The Internet of Things: Making the Most of the Second Digital Revolution. UK Government Chief Scientific Adviser Report.
Greenough, J., 2014. The Enterprise Internet of Things Report: Forecasts, Industry Trends, Advantages, and Barriers for the Top IoT Sector. Business Insider.
Huawei, 2015. Global Connectivity Index. Huawei Technologies Co., Ltd.
IDC, 2014. Worldwide and Regional Internet of Things (IoT) 2014-2020 Forecast: A Virtuous Circle of Proven Value and Demand. IDC Market Analysis Report.
IDC, 2019. Worldwide Semi-annual Internet of Things Spending Guide.
Internet Society, 2015. The Internet of Things (IoT): an Overview. White Paper.
Jorgenson, D.W., Gollop, F.M., Fraumeni, B., 1987. Productivity and US Economic Growth. Harvard University Press, Cambridge MA.
Jorgenson, D., Griliches, Z., 1967. The explanation of productivity change. Rev. Econ. Stud. 34 (99), 249–280.
Jorgenson, D., Ho, M., Stiroh, K., 2006. Projecting productivity growth: lessons from the US growth resurgence. In: The New Economy and beyond, Chapter 2 Edward. Elgar Publishing.
Jorgenson, D., Stiroh, K., 2000. Raising the speed limit: U.S. Economic growth in the information age. Brookings Pap. Econ. Activ. 31 (1), 125–236. Economic Studies Program, The Brookings Institution.
Koutroumpis, P., 2009. The economic impact of broadband on growth: a simultaneous approach. Telecommun. Pol. 33 (issue 9), 471–485.
Lichtenthaler, U., Ernst, H., 2008. Opening up the innovation process: the role of technology aggressiveness. R D Manag. 39 (Issue 1), 38–54.
Manyika, J., Chui, M., Bisson, P., Woetzel, J., Dobbs, R., Bughin, J., Aharon, D., 2015. The internet of things: mapping the value beyond the hype. McKensey Global Institute Report.
Mazhelis, O., Warma, H., Leminen, S., Ahokangas, P., Pussinen, P., Rajahonka, M., Siuruainen, R., Okkonen, H., Shveykovskiy, A., Myllykoski, J., 2013. Internet-of-ThingsMarket, Value Networks, and Business Models: State of the Art Report. University of JYVÄSKYLÄ, Department of Computer Science and Information Systems.
McKinsey, 2015. The Internet of Things: Mapping the Value beyond the Hype. McKinsey Global Institute. June 2015.
OECD, 2012. ICT investments and productivity: measuring the contribution of ICTs to growth. OECD Journal.
OECD, 2016. The Internet of Things: seizing the benefits and addressing the challenges. Background report for Ministerial Panel 2, 2.
Oliner, S., Sichel, D., 2000. The resurgence of growth in the late 1990s: is information technology the story? J. Econ. Perspect. 14 (4), 3–22. American Economic Association.
O'Mahony, M., Timmer, M., 2009. Output, input and productivity measures at the industry level: the EU KLEMS database. Econ. J. 119 (issue 538), F374–F403.
O'Mahony, M., Vecchi, M., 2005. Quantifying the impact of ICT capital on output growth: a heterogeneous dynamic panel approach. *Economica*, London School of Economics and Political Science 72 (288), 615–633.
Qiang, C., Rossotto, C., 2009. Economic impacts of broadband. In: Information and Communications for Development 2009: Extending Reach and Increasing Impact. World Bank, Washington, DC, pp. 35–50.
Riley, R., 2011. Skills and Economic Performance: the Impact of Intangible Assets on UK Productivity Growth. Evidence Report 39. UKCES.
Solow, R., 1987. We'd Better Watch Out. New York Times Book Review, p. 36. July 12.
Stefan, D., Comes, C., Munteanu, A., Nistor, P., Stefan, A., Glova, J., Sabol, T., Vajda, V., 2014. Business models for the internet of things environment. Emerging Markets Queries in Finance and Business 15, 1122–1129, 2014.
Stiroh, K., 2002. Information technology and the U.S. Productivity revival: what do the industry data say? American Economic Review, American Economic Association 92 (5), 1559–1576.
ten Raa, T., Wolff, E., 2000. Engines of growth in the US economy. Struct. Change Econ. Dynam. 11 (4), 473–489. Elsevier, December.
The Economist, 2013. The Internet of Things Business index: a Quiet Revolution Gathers Pace. Report from The Economist Intelligence Unit.
The Economist, 2017. He Economist Intelligence Unit IoT Business Index. The Economist Intelligence Unit.
Timmer, M., Inklaar, R., O'Mahony, M., Van Ark, B., 2010. Economic Growth in Europe, A Comparative Industry Perspective. Cambridge University Press.
Van Ark, B., Inklaar, R., Mcguckin, R., 2002. Changing Gear – Productivity, ICT and Service Industries: Europe and the United States. Research Memorandum GD-60. University of Groningen.
Van Ark, B., O'Mahony, M., Timmer, M., 2008. The productivity gap between Europe and the United States: trends and causes. J. Econ. Perspect. 22 (number 1), 25–44.
Van Ark, B., O'Mahony, M., 2016. Productivity growth in Europe before and since the 2008/2009 economic and financial crisis. In: Chapter 4Jorgenson, D., Fukao, K., Timmer, M. (Eds.), The World Economy Growth or Stagnation?.
Vasileiadou, E., Vliegenthart, R., 2009. Research productivity in the era of the internet revisited. Res. Pol. 38, 1260–1268.
Vermesan, O., Friess, P., 2014. Internet of Things Applications - from Research and Innovation to Market Deployment. River Publishers Series in Communications.
Vodafone, 2016. The IoT Barometer 2016 Report.
Vodafone, 2019. The IoT Barometer 2019 Report.
Wagner, S., Cockburn, I., 2010. Patents and the survival of internet-related IPOs. Res. Pol. 39, 214–228.
Want, R., Schilit, B., Jenson, S., 2015. Enabling the Internet of Things. Google IEEE Computer Society.