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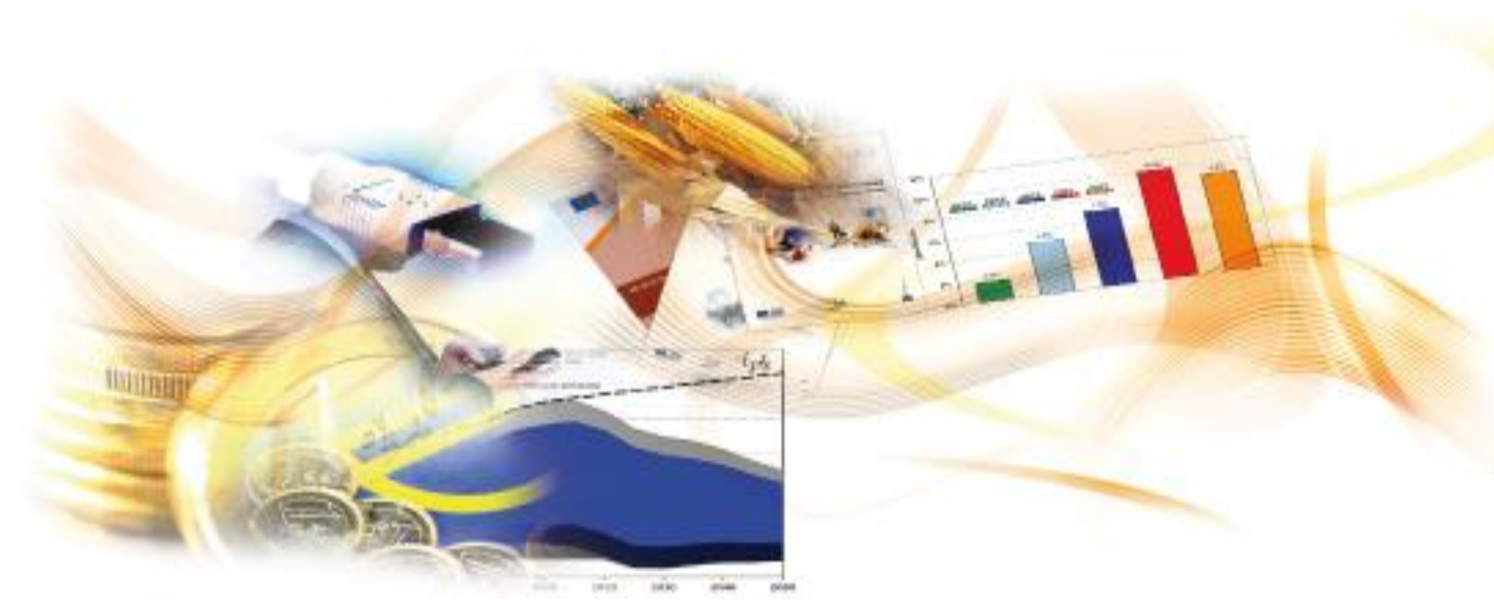

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ICT and Productivity: A Review of the Literature

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Abstract

In this report we review the literature on the relationship between ICT and productivity. In Section 1 we discuss in broad terms the theoretical relationship between ICT and productivity, while in Section 2 we present the growth accounting methodology, which tries to measure the contributions to growth from difference sources (ICT and non ICT capital, human capital, total factor productivity). Within the growth-accounting methodology, in Section 3, we discuss the U.S./E.U. productivity gap and the role of ICTs, and we show that the latter are responsible for the U.S. acceleration in productivity growth observed in the period 1996-2006 and for the widening of the U.S./E.U. productivity gap in the same period. Then, in Section 4, we move to regression-based studies, and we review the literature that uses macro, meso (sectoral) and firm/plant level data. While the overall message on the importance of ICT for growth coming from this literature is consistent with the findings of the studies based on growth accounting, the econometric approach allows researchers to investigate a wider set of questions. In particular, we focus on the role of ICT as a General Purpose Technology. We review the literature studying the role of ICT and complementary assets in firms' productivity. We then review the literature exploring the positive externalities related to ICT capital and the impact of ICT usage on the innovative capability of firms. Finally, we review the literature on the relationship between ICT infrastructures and GDP growth.

JEL codes: D22, D24, E01, O30, O47

Keywords: ICT, labour productivity, total factor productivity, innovation.

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Executive Summary

This paper contains a review of the relevant economic research literature regarding the impact of ICT or digital technology on economic growth and productivity growth. This review focuses on two relevant questions for policy makers:

- How much impact does ICT have on the economy?
- Are there any obstacles to realizing the full potential economic benefits of ICT and is there any need for policy measures to correct these?

1. How much impact?

A research interest in this question started in the 1980s, and was sparked by Robert Solow's famous quip "*You can see the computer age everywhere but in the productivity statistics*". This led to an intense effort in the 80s and 90s to measure the impact of ICTs on the economy. The standard methodology used for that purpose is growth accounting, a dynamic approach that tries to capture the contributions of different types of assets (essentially ICT and non-ICT capital, besides human capital) to economic growth[1]. Growth is usually measured in terms of labour productivity, either at aggregate macro-economic level or at sector level. The main findings of this early growth accounting literature can be summarised as follows:

1.1. A majority of researchers agreed on the importance of ICT for the US growth resurgence observed from 1995 to 2006. Jorgenson et al (2008) estimate that the share attributable to ICT in US growth performance went from 43% for the period 1971-1995 to 59% for the period 1995-2000. The contribution from increased investment in ICT capital almost doubled (ICT capital deepening) and there was a more than twofold increase in Total Factor Productivity (both inside and outside the ICT producing sector). For the post-2000 period, Jorgenson et al. (2008) find that the contribution of investment in ICT capital to growth fell and that TFP growth in the ICT producing sector went down (from 0.58 for the 1995-2000 period to 0.38 for the 2000-2006 period). On the other hand, the role of TFP outside the ICT producing sector (and hence in ICT-using sectors) increased. Overall, in the period 2000-2006, it is estimated that ICTs accounted for about 38% of the US output growth. Some researchers, observing the slowdown in productivity and economic growth in the last decade, and the decline in the their contribution to growth observed in the US, claim that ICTs are not able to generate the same long-term and sustainable innovation drive achieved by GPTs in the past. Unfortunately, data from the EUKLEMS project, which is at the root of

[1] What is left unaccounted for is Total Factor Productivity –TFP- also known as Solow's residual in the context of growth accounting.

most of the EU-centred growth accounting studies, are not available after 2007 (and not available after 2005 for the version of EUKLEMS that provides data on human capital).

1.2. In the period 1996-2006, the EU experienced an average annual hourly labour productivity growth rate of about 1.5. This is significantly lower than the average growth rate observed in the EU in the period 1973-2005 (2.4) and it implies the end of the process of convergence in GDP per hour towards the US levels that had been observed in the period 1973-1995. In fact, after 1995, the labour productivity gap between the EU and the US (in terms of GDP per hour worked) began to increase once again (with some notable exceptions like, Finland, Sweden, Ireland, Belgium and Austria), leading to a GDP per capita gap in favour of the US. After 2006, we also notice a slowdown in US labour productivity growth, which translates into a reduction of the EU-US productivity gap.

The rise in the EU-US labour productivity gap is mainly due to three factors, all of which are (directly or indirectly) ICT related. First, the US have experienced a higher productivity growth rate in the ICT producing sector, largely due to the impressive technological improvement characterizing this sector (twice as high in the US as it has been in the EU) and to its size, which is relatively larger in the US (significant exceptions are Finland and Sweden). Second, investment in ICT capital (i.e. ICT capital deepening) has been higher in the US than in the EU. Third, Total Factor Productivity (TFP) in the service sector, and especially in wholesale and retail trade and finance, which are heavy ICT users, has been rising much faster in the US than in the EU (with some exceptions, like the Netherlands and the UK). When looking at the contribution of ICTs to labour productivity growth in the EU and the US, van Ark et al (2008) find that in the EU it went from 1.3 percentage points[2] for 1980-1995 to 0.9 for 1995-2004,[3] while in the US, it went from 1 in the former period to 2.2 in the latter, the largest increase arising from TFP growth. This clearly points to the fact that ICTs were becoming less of a growth-driver in the EU during a period in which the US-EU labour productivity gap was increasing.

1.3. In spite of its merits, the growth-accounting technique raises some major methodological problems. First, it cannot say much on the causation mechanism between labour productivity and its determinants and this reduces its usefulness for drawing policy conclusions. This problems arises because the growth accounting methodology does not try to explain the causal relationships between variables (this would require a fully-specified model), where we could identify exogenous (among which we have policies) and endogenous variables (such a labour productivity), but simply

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2 The annual average growth rate for the overall EU economy (measured in percentage points) in the same period is equal to 1.8.

3 In the interval 1995-2004 the average annual rate of growth for the market economy in the EU is 2.2.

breaks aggregate productivity growth down into its components, under the assumption that the aggregate production function can be represented by a simple functional form.

Second, this framework has a hard time capturing quality-adjusted ICT prices. The information processing capacity of ICT has been growing at an exponential rate. As a result, 1000 euros worth of computing capacity today can do much more than the same amount spent on computers 10 years ago. If ICT investment statistics do not fully capture this quality improvement in the price index, it results in a biased measurement of productivity growth. Underestimation of these quality improvements in price indexes would result in an overestimation of the productivity effect.

Third, growth accounting is normally based on the assumption of constant economies of scale and absence of externalities. Since ICT technology is notorious for its high fixed cost and low marginal cost effects, excluding from the start the possibility of returns to scale does not appear an entirely appropriate choice, as economies of scale in ICT could explain a considerable part of the productivity effect. The growth accounting model also assumes that all impacts remain localised in the ICT acquiring firm and there are no spillovers to other firms and sectors. If there are strong externalities, then the growth accounting framework under-estimates the productivity impact of ICT.

Fourth, while growth accounting may capture some of the direct effects of ICT (those related to ICT capital deepening and to TFP in ICT producing sector), it cannot account for the indirect effects of ICT, which are driven by the consequences of investment and diffusion of ICT on the productivity of ICT using sectors.

Fifth, the macro-economic growth accounting model assumes that all ICT-related productivity improvements are acquired through investment in ICT. In a world with rapidly growing outsourcing and a shift from investments to services delivery, the investment-only model has lost some of its relevance. For example, cloud computing services are increasingly replacing companies' investment in hardware and software. As a result, intermediate ICT inputs become more important.

Last but not least, the growth-accounting model looks at the supply or production side of the economy only. It does not investigate the impact of ICT on consumer behaviour and welfare (productivity effects that take place in the household production and consumption process).

1.4. Attempts have been made to overcome these disadvantages and restrictions. These attempts revolve around several issues:

- Methodology: from macro-economic growth accounting to micro-level firm data econometrics
- Spillover effects of ICT, according to the General Purpose Technology (GPT) hypothesis
- Role of complementary assets, such as human capital and organisational (managerial) capital

- The role of ICT usage

We discuss these below:

a. From macro-economic to firm level data

To circumvent some of these disadvantages, some scholars have explored an econometric approach, with studies conducted at the country, sector or firm/plant level. The main advantage of econometric analysis is that it does not rely on the very strict assumptions imposed by growth accounting and that it can differentiate between the short and the long-term effects of ICT investment and diffusion. One of the results of the analyses using micro-data (Brynjolfsson and Hitt, 1995 and van Reenen et al., 2010) is that ICT capital tends to exhibit excess return (i.e. a return significantly higher than the share of ICT capital in the economy, something that cannot be explained by growth accounting). This can be due either to true spillover effects (more on this in point b) or to errors in measuring inputs correlated with ICT[4] (see point c). However, whatever the interpretation of this empirical regularity, the econometric regression approach basically reaches the same conclusions as the growth accounting approach: ICTs are an important determinant of long-term GDP growth, and more so for the US than for the EU.

b. Spill-over effects:

In order to analyse more precisely the indirect effects of ICT and its GPT nature, more granular data are needed. Some scholars have tried to assess these aspects by using sector-level data and the results are not clear cut. While most studies do not find any evidence of positive externalities and spillovers of ICT investment on the performance (i.e. TFP growth) of ICT-using sectors, some (mostly US based) show that such positive effects appear but only with some time lag.

However, especially with firm and plant level data, it is possible to properly evaluate the indirect effects of ICT investment (those that appear in ICT-using sectors and are related to the GPT nature of ICTs) that make ICTs enablers of product, process and organizational innovations. In fact, it is only with firm and plan level data that we have some hope of capturing the aspects that the literature identifies as the benefits from computerization (using Brynjolfsson and Hitt, 2000, words) "*a significant component of the value of information technology is its ability to enable complementary organizational investments such as business processes and work practices;…these investments, in turn, lead to productivity increases by reducing costs and, more importantly, by*

[4] If organizational capital is complementary to ICT capital and if we do not control for organizational capital in the productivity regression, the coefficient estimated on ICT will also be capturing the role of organizational capital.

enabling firms to increase output quality in the forms of new products or in improvements in intangible aspects of existing products like convenience, timeliness, quality, and variety".

There is clear evidence from firm and plant level data that ICT investment by individual agents (firms/plants in this case) tends to produce positive effects on external users (i.e. positive externalities), both within and across sectors. This evidence is clearer in the long-term and is stronger for the US, though it can also be found for the EU.

The fact that evidence in favour of the spillover hypothesis is found more consistently at the lower level of aggregation is to some extent expected, as external factors tend to be more numerous and more important as we move from the aggregate to the micro level (similar results are found in the literature looking for R&D spillovers). These results are considered as evidence in favour of the GPT hypothesis of ICT.

c. Complementary factors

There is overall convincing evidence that ICT, to be truly productive, require investment in complementary assets,[5] such as human, organizational and managerial capital (but the size of the complementarity effects tends to vary among countries and datasets and tends to be higher for the US and the UK). The empirical results confirming the complementarity hypothesis can also explain the excess return on ICT capital previously mentioned.

Some attempts have also been made to assess the role of institutional factors in accounting for these differential impacts. The main message coming from these studies is that indexes which capture the regulatory burden (both in product and labour markets) tend to reduce the incentives to invest in ICT and in its complementary assets[6] (such as organizational and managerial capital). This could explain why the impact of ICTs in ICT-using industries has been lower in the EU than in the US (product and labour market regulation in services is greater in the EU than in the US). However, the

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[5] The complementarity hypothesis (which goes back to Milgrom and Roberts, 1990) is based on the following intuitions: 1) ICT investment, per se, might have a very low positive impact on productivity (in fact the impact could even be negative); 2) the impact of ICT investment becomes largely positive once it is coupled with organizational change (which, per se, might have a small positive impact); 3) due to the complementarity between ICT investment and organizational change, we should expect some lag between the time we record the investment in ICT and the time we observe the positive impact on productivity and this time-lag is entirely due to the organizational change that the firm has to go through if it wants to reap the full benefit of ICT investment; 4) the distribution of skills among the workforce and the level of human capital are important in determining the impact of ICT investment and organizational change; 5) not all firms could benefit in the same way from ICT investment since not all firms (and not all sectors) are able to implement successful organizational change.

[6] The evidence is stronger for indexes of labour market regulation.

estimates for the regulatory indexes are generally are not robust when firm-specific fixed effects are introduced. This makes it difficult to derive evidence-based policy implications.

d. From ICT investment to usage of ICT

Starting from the intuition that ICT capital and ICT use capture different factors, research on the impact of ICT usage on the performance of firms has recently emerged. While ICT capital - the ICT variable used in growth accounting and in most econometric estimates- captures the overall value of capital invested in ICT, ICT usage variables (use of mobile connections, broadband penetration, use of ICT for Enterprise Resource Planning - ERP, Supply Chain Management - SCM, or Customer Relationship Management - CRM) allow a better understanding of the strategic ICT usage by firms in their organizational structure. Particularly interesting are the recent attempts (Polder et al. 2010) to merge the literature on productivity and innovation on the one hand with the literature on ICT and productivity (through complementary assets) on the other. This has been done by adding organizational innovation to the innovation output variables and ICT to the innovation inputs (together with R&D), based on the recognition of the GPT feature of ICT.[7] While this literature is still in its infancy, we think that it can provide very interesting insights into the relationship between the use of ICT and the innovative performance of firms.

1.5. We have also reviewed the literature that has looked at the economic impact of broadband infrastructures. There are various theoretical motives why broadband infrastructures could have an impact on productivity (levels and growth). First, high-speed Internet, via broadband infrastructures, generates cheaper and more rapid exchange of information between economic agents (both within and across organizations). This can give rise to the development of new products and processes and to new business models (so that broadband infrastructure can be interpreted as an investment fostering the GPT features of ICT). More generally, high speed connections can increase competition also through higher transparency among consumers[8] (i.e. through a demand-side effect).

While the positive association between GDP per-capita growth and indexes of broadband penetration is commonly found in many studies, the main problem concerning this relationship as regards deriving policy implications is the causality chain. If the policy question is related to the issue of public (or private) investment in broadband infrastructures, we would like to be sure that the positive association between the two variables is not simply capturing the fact that richer

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[7] The underlying hypothesis is that ICT usage induces organizational innovation that, in turn, induces higher productivity growth.

[8] Broadband networks provide the framework for the delivery of different services ranging from telephony and its variants to high-speed internet access and very diverse multimedia services (video streaming, online games, tele-working, etc.).

countries, on average, are characterized by higher broadband penetration since richer individuals are ready to pay more for broadband services (which is a purely demand-side effect).

From the two studies reviewed here - Czernich et al. (2009) and Koutroumpis (2009), both of which try to capture separately the supply- and demand-side effects, it appears safe to conclude that broadband infrastructures have a positive effect on GDP growth. The main result that emerges is that a 10% increase in broadband penetration –on average- increases GDP by 0.25 percentage points. This also implies that almost one-tenth of the observed growth of the 22 OECD countries analyzed in Koutroumpis (2009) can be traced to broadband infrastructures. When trying to verify whether investment in broadband infrastructures might have a different impact on GDP depending on the initial level of broadband penetration, Koutroumpis (2009) finds that a much larger effect is reached for countries that have a penetration rate starting value higher than 30%. The higher return on broadband capital in countries that already have high levels of broadband capital is related to the existence of network externalities and points to the fact that a critical mass for broadband penetration has to be reached before the full benefits of broadband infrastructures can be reaped.

2. What are the policy implications?

The first question for policy makers is whether policy interventions are needed to realize the maximum potential impact of ICT on the economy. In principle, policy interventions would be required only if the case can be made for market failures. So the question can be rephrased as follows: do market prices reflect the true social costs and benefits of ICT? Alternatively, are there any positive or negative externalities that need to be taken into account to derive a more adequate picture of the economic implications of ICT? The evidence from firm and plant-level data points consistently to the presence of spillover and external effects generated by ICT capital (at the industry or aggregate level). This implies that there may be a need for public polices to support investment in ICT. The case may even be stronger for policies supporting R&D in the ICT sector since there are two types of externalities here, one related to ICT capital and the other to R&D capital.

Apart from market failures, van Reenen et al (2010) find that ICT investments respond faster to demand shocks than other forms of capital. This implies that programmes stimulating ICT investment may be beneficial for counter-cyclical policies, and this could turn out to be especially important in times of economic crisis.

Second, if there is a case for public policy intervention, this can take essentially three forms: direct public investment in ICT, subsidies that affect the private price of ICT investment and usage[9] and bring it more in line with the socially optimal price, and finally regulatory interventions to re-allocate the costs and benefits between economic agents and bring prices more in line with true costs and benefits.[10] Though this report does not explicitly cover the research literature that deals with finding the most appropriate type of policy interventions (and the policy mix), a number of indications can be drawn from the empirical research literature surveyed here.

For example we report clear indications that broadband infrastructure has a strong impact on productivity growth. Moreover, there is some evidence that a critical mass in terms of broadband penetration (between 50 and 75% of the population) exists. Past these levels, the impact on GDP is still dependent on the path of broadband penetration. Hence policies that target the development of broadband penetration may be desirable. This can be achieved by various means: direct government investment (subsidies) for broadband, price interventions that increase the private rate of return on broadband investments to a socially-optimal level and regulatory interventions that re-allocate revenue from users of broadband services (consumers, content and services providers) to investors in broadband (telecoms, cable companies, etc.).

Another example of regulatory intervention concerns regulatory barriers to product and factor markets. For example, given the evidence of strong complementarities between ICT, organizational capital and human capital, barriers to the accumulation of these complementary factors should be removed, in particular, those affecting people management and decentralisation. In particular, van Reenen et al. (2010) stress the need for more competition in the product market and, especially, of less stringent labour market regulations.

Government intervention should not necessarily be limited to the ICT sector itself. For example, there may be a potential market failure in the financing of innovation and ICT investment. To the extent that investment in organizational restructuring entails some sunk costs, (small) firm size and market segmentation tend to reduce the scope for managerial restructuring. Since the vast majority of firms in the EU are SMEs and given that access to capital for them is generally more costly, we are not very surprised to find that EU firms are less ready to invest in ICT and implement the necessary organization changes. The existence of market failures in the access to funding might justify some public intervention specifically directed at supporting ICT investment by SMEs. Also, it

[9] Subsidies can take various forms, for instance public support for private investment in ICT infrastructure, ICT investment tax breaks, subsidies for ICT research, etc.

[10] Most public authorities are active in the regulatory domain that affects the private return to ICT and brings it more in line with the social return (pricing and regulation of access to infrastructures, net neutrality, privacy, etc.).

may be worth raising awareness, especially among SMEs, of the potential benefits arising from the combination of ICT, people management and decentralization.

1 Introduction

Information and communication technologies (ICT) have drastically changed society in the last quarter of the century inducing unexpected qualitative and quantitative changes. During the mid 80s and early 90s, an intense effort was made to try to measure the impact of information and communication technologies (ICT) on growth. The discussion was stimulated by the famous sentence of Robert Solow (1987): "*You can see the computer age everywhere but in the productivity statistics*" (the so called Solow paradox or productivity paradox[11]). Most of this literature was based on macro data and the main analytical framework was growth-accounting. While until the early and mid-1990's the Jury on the role of ICT for productivity and growth was still out, as the effects of the ICT revolution on growth were not yet fully visible or measurable, by the end of the nineties, the academic literature[12] –in its majority- agreed on the importance of ICT for the U.S. growth resurgence observed from 1995 to 2000 (in particular according to authors such as Jorgenson, Stiroh and Ho, Oliner and Sichel, van Ark, Timmer and O' Mahony).

The delay in recognizing the importance of ICT in accounting for labour productivity growth can be explained by various factors. First, there existed (and, in part, still exists) a lack of accurate quantitative measures for the output and value created by ICT. Measuring the value of ICT capital is a very difficult task, which depends dramatically on the depreciation rates used. Second, measuring productivity in the service sector –which is a heavy user of ICT- is also very difficult.[13] This problem is exacerbated by the fact that firms or organizations often invest in ICT with the intent of improving the <u>quality</u> of processes or products, aspects which are typically poorly captured by existing statistics.[14] Finally, the overall effect of ICT diffusion and use on GDP growth is likely to be proportional to the ICT capital stock existing in an economy. So, even fast technological progress in the ICT-producing sector cannot have a major effect on the overall economic performance if the value of ICT capital in ICT-using sectors is low relative to other types of capital.

To overcome these issues sector or –even better- firm and plant-level data are needed, since only at a much disaggregated level it is possible to capture evidence of the multifaceted improvements that ITs can provide. This is why, starting from the early 90s, the macro and meso-based literature was enriched by a more micro-based literature, which was trying to provide and answer to the Solow's paradox. To use Brynjolfsson and Yang words (see Brynjolfsson and Yang, 1996): "*it is*

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[11] This quote was actually expressing concern that, while investment in ICT during the eighties and early nineties was growing exponentially in the U.S. and quality-indexed prices for computer were rapidly (and exponentially) falling, productivity in the service sector, in which about 80% of IT investment is made, was actually stagnating. On the productivity paradox, see for example Lee and Barua (1999), Morrison and Berndt (1990), Roach (1989) and Panko (1991).

[12] It is also worth mentioning that at that stage almost all the literature was based on U.S. evidence, due to the U.S. lead in the IT revolution.

[13] For an attempt to measure productivity in the service sectors in the U.S., with special attention to the role of ICT investment in ICT-using service industries see Triplett and Bosworth (2003) and Bosworth and Triplett (2007). The main result from their analysis is that ICT has had an important impact on labour productivity growth in the service sectors in the period 1990-2000 but not in the acceleration of productivity growth observed after 1995, which was mostly attributable to increased MFP within the service industries. This result is consistent with the hypothesis that it takes time to reap the benefits of ICT investment (for instance because investment in complementary assets is necessary).

[14] If ICT creates value that is not easily measured we incur the risk of apportioning to TFP effects that should be attributed to ICT and its complementary inputs. This problem is exacerbated when macro data are used.

possible that the benefits of IT investment are quite large, but that a proper index of its true impact has yet to be identified. Traditional measures of the relationship between inputs and outputs fail to account for non-traditional sources of value". Such a problem is particularly evident for most recent applications of ICT (such as cloud computing). Again, quoting Brynjolfsson and Yang, "*the sort of benefits that managers ascribe to information technology- increased quality, variety, customer service, speed and responsiveness- are precisely the aspects of output measurement that are poorly accounted for in productivity statistics as well as in most firms' accounting numbers…The measurement problems are particularly acute for IT use in the service sector and among white collar workers*".

Notice that similar problems occur with respect to ICT-enabled product innovation: it is very difficult to express a value for variety. These aspects lead Brynjolfsson and Yang to conclude that "*Increased variety, improved timeliness of delivery and personalized customer service are other services that are poorly represented in productivity characteristics. These are all qualities that are particularly likely to be enhanced by information technology. Because information is intangible, increases in the implicit information content of products and services are likely to be under-measured compared to increases in material contents*".

This literature review will proceed as follows. First we discuss, from a theoretical perspective, how ICT could affect productivity (Sect. 2). Then we present the growth accounting approach (Sect. 3), as this has been the most widely used analytical tool when assessing the impact of ICT on growth at the macro level. Then (Sect. 4) we move to the empirical estimates of the impact of ICT on productivity, starting with the review of the literature based on growth accounting (Sect. 4.1). This literature, by construction, is more able to capture the direct effects of ICT, (arising from technological progress in the ICT-producing sector and from ICT capital deepening) and hence can at best provide a lower bound for the overall impact. Then we will consider the regression-based literature which goes beyond the growth-accounting methodology and tries to capture both the direct and indirect effects of ICT adoption on productivity and growth (Sect. 4.2). In the context of these more micro-oriented studies we also discuss the ICT complementarity issue, according to which the higher returns on ICT capital observed with micro-meso data can be accounted for by the fact that ICT investment is accompanied by changes in organizational and managerial practices that increase the productivity effect of the former. Finally, we will consider also the specific impact of broadband infrastructures on GDP (Sect. 4.3). We conclude our work with some reflections on the policy implications of our study and with some directions for future research (Sect. 5).

2 Theories on the impact of ICT on productivity and growth

ICTs affect growth and productivity both directly and indirectly. First, ICT are part of currently produced goods or services (think of computers and Internet) and technological improvement and productivity growth in ICT-producing sectors have a direct effect on aggregate productivity that is proportional to the size of the ICT sector (see Jorgenson, Ho and Stiroh, 2002 and 2008, Gordon, 2000 and 2012 and van Ark, O'Mahony and Timmer, 2008). But, as they play a substantive role in the generation, storage and transmission of information and in the reduction of market failures related to information asymmetries, ICT are also affecting productivity in sectors that use them.[15] In particular, ICT are enablers of product, process and organizational innovation in ICT-using sectors, and this, according to Bresnahan and Trajtenberg (1995), qualifies them as General Purpose Technologies (GPT):[16] technologies that are pervasive –i.e. can be applied to several production processes - allow continuous improvements and experimentation and facilitates innovation in using sectors (through co-inventions).[17] The effects of the development of a GPT on growth and productivity are not likely to be observed immediately after its invention, as adjustments and network effects are at place. In fact, David and Wright (1999), analysing the impact of the main GPTs from an historical point of view, have identified three main stages that follow the development of a GPT (some of these stages may overlap): 1) at the beginning, an increase of productivity growth in the GPT sector is observed; 2) afterwards a significant increase in capital is noticed, due to fast capital investment, stimulated by a the price reduction of the goods embedding GPT; 3) finally, a reorganization of the production in those sectors that use the GPT takes place.

ICT appear to have all of these characteristics, as, in many contexts, the productivity-enhancing effects of ICT are not direct but they are mediated by the development of other technologies that are specific to the ICT-user sector.[18] Thus, ICT are potentially able to generate increases in the productivity in the whole economy, mainly due to the spillover effects associated with them: 1) vertical spillovers between the ICT producing sector and a particular productive sector in which the ICT are applied, 2) horizontal spillovers between different sectors where ICT are applied. The fact that it takes time to generate and observe such spillovers, which, by itself, tends to slow down the process of ICT diffusion, has been interpreted as an explanation for the weak link between investment in ICT and productivity growth during the eighties and early nineties, well expressed by the Solow Paradox.

What is important about ICT as a GPT is that, as co-inventions and co-innovations increase in number and importance, the benefits from additional progress and innovation in the GPT increase as well (due to networks effects, which can be interpreted as a special case of spillovers), hence generating a virtuous circle that can break the law of diminishing marginal returns predicted by standard neoclassical theory.

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[15] This line of argument is based on the idea that it is possible to separate ICT-producing sectors (those in which the direct effects become manifest) from ICT-using sectors (in which the indirect are mostly observable) and the OECD and other international organizations (such as the United Nations) have devoted a considerable amount of time and effort to the identification of ICT products and services and ICT-producing and using sectors. See Appendix 1 and OECD (2002, 2006a, 2006b, 2008, 2011, 2012).

[16] David and Wright (1999), analysing the impact of the main GPTs from an historical point of view, have identified three main stages that follow the development of a GPT (some of these stages may overlap): 1) at the beginning, we observe an increase of productivity growth in the GPT sector; 2) afterwards, we note a significant increase in capital, due to fast capital investment, stimulated by a the price reduction of the goods embedding GPT; 3) finally, we observe, a reorganization of the production in those sectors that use the GPT.

[17] Examples of GPTs are the invention of the railway or of the electricity, the steam engine and internal combustion engine.

[18] When a radical innovation comes to life, other applications, in the form of incremental innovations can be easily implemented, like in the case of Internet, e-commerce and other ICT applications (see Varian et al., 2004). It has been stressed that co-inventions concerning ICT generate high adoption costs that often overcome the direct cost of the ICT adoption and this can be the reason why we do not observe an immediate increase in firms' productivity after the adoption of ICT. See the interesting debate between Bessen and Comin on the theme: Bessen (2002), Comin (2002) and Bessen (2003).

Bresnahan and Trajtenberg (1995) also show that the market equilibrium prevailing in the presence of a GPT (the Nash equilibrium) tends to be suboptimal, leading to "*too little, too late in both the GPT and the application sectors*", as the vertical and horizontal spillovers that characterize the presence of the GPT are not internalized. There are several policy implications from such sub-optimality. First, technological progress within the GPT (i.e. innovation in the ICT producing sector) should be supported by appropriate policies, given that the private return to R&D (considered as the typical innovation input) is –even more that usually- lower than its social return.[19] Second, investment in ICT capital, ICT goods and ICT services should be supported, as this will increase the diffusion of ICT within the economy (the "pervasiveness"). Third, innovation in GPT-using (i.e. ICT-using) sectors should be supported as well, as this would increase the benefits obtainable from the existing GPT technology but would also increase the benefits from technological progress within the GPT[20] (exploiting the vertical spillovers and the feedback mechanisms). Fourth, knowledge flows and coordination between GPT-using sectors should be supported, since this would increase the ability of the economy to benefit from horizontal externalities.[21]

Jovanovic and Rousseau (2005) compare Electricity and ICT in terms of their ability to generate economic growth and they conclude that, while Electricity is more pervasive, ICT is more able to generate improvements and to spawn innovation in the rest of the economy and within the ICT

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[19] The incentives to innovate in the GPT industry depend upon market structure and appropriability of the value generated in such industry, which, in turn, depend heavily on both the level of technological advancement and on the demand for the GPT goods arising from the GPT using sectors. In Bresnahan and Trajtenberg (1995) the GPT coincides with the semiconductors industry. While policies such as limits on foreign competition or the relaxation of antitrust standards would certainly help the semiconductor industry and increase the private return to innovation within such industry, they would also increase the costs for the downstream using industries (as semiconductors prices would be higher), hence reducing their incentives to innovate. Increased intellectual property protection could have both positive and negative effects on the overall incentives to innovate. The negative effects on the semiconductors using sectors would be avoided if the public sector were to provide some form of financial support to the semiconductor sectors. However, in this case, society would face the consequences of higher taxes.

[20] This also raises the question on the need for countries to be engaging in research in the GPT as a precondition for growth. In our context this means answering the question whether engaging in R&D in the ICT sector is a necessary step to reap the full benefits offered by such technology. We will see that growth accounting exercises tend to answer negatively to such question but we think that this is really not the appropriate methodology to follow when one wants to evaluate policies that involve complex causal relationships (including feedback loops).

[21] Notice that the GPT hypothesis put forward by Bresnahan and Trajtenberg (1995) can be considered as a first attempt to bridge the gap between the New Growth theory à la Romer and industrial organization (for a general equilibrium approach see Helpman and Trajtenberg, 1998). In fact, while in the New Growth Theory, the R&D activity and innovation are typically assumed to take place in a unique sector (the R&D sector), in reality we know that R&D and innovation are pervasive and diffused in many sectors. In the presence of a GPT, that is of a technology that stimulates innovation in sectors adopting the GPT (i.e. in the presence of "innovation complementarities", in the language of Bresnahan and Trajtenberg), there is a serious issue of cross-sector coordination. The market-failure in this case arises because each GPT-using industry benefits from increase demand for the GPT from other GPT-using industries, since the level of technology in the GPT producing sector (which benefits all the users) depends upon i) the number of GPT-using industries; ii) the quantity of GPT purchased by each GPT-using industry and iii) the price paid by the GPT-using industry. Notice that the level of technology of the GPT is analogous to a public good. The presence of a strong and stable demand from the public sector through procurement can help in solving such market failure and hence can end up favouring the other GPT-using industries. In fact, many believe that NASA and the Department of Defence in the US have played a decisive role in generating an innovation virtuous cycle. Regulation could also play a decisive role here, in terms of both vertical and horizontal externalities, as it could reduce coordination problems.

producing sector, and this, together with the declines in ICT prices that will further increase its pervasiveness, makes the authors optimistic about the growth prospects of ICT.

A confirmation of the fundamental role of ICT as a GPT can be found in the work of Lipsey and co-authors (Lipsey and Carlaw, 1998; Carlaw and Lipsey, 2002; Lipsey et al, 1998) in the context of what they call the structuralist-evolutionary approach to technology. The starting point of this approach is that neoclassical economics, as such, it is incapable of capturing the most relevant aspects of technological change, as the latter is mostly expressed by TFP, which is, in fact, a measure of our ignorance. Even the departure from perfectly competitive markets, according to Lipsey's interpretation, cannot account for the richness and complexity of the technological relationship we observe in reality, since it restricts attention to market failures (and the corresponding policy corrections), due to the externalities arising from aggregate technological knowledge.

According to the structuralist view, technological progress within an economy is the outcome of various effects, the main one being spillovers and technological complementarities. In general, a given technology becomes available as a fairly crude object, with limited number of uses, and only later evolves in complexity, range of use, variety of outputs it helps to produce and in the range of product and processes it enables. In other words, each technology generates a spillover, where such term should be interpreted as an effect produced in a sphere that is not the one of the inventor of the technology. Such spillover is not necessarily an externality, given that the inventor of the technology might get the full return for its innovation.[22] The main point is that each spillover is potentially capable of generating a response from individuals and organizations affected by it, which could give rise to an additional spillover. Spillovers across different technologies tend to produce technological complementarities, which are very important source of growth. General Purpose Technologies are an extreme example of technological complementarities, as they are pervasive through the economy. In fact, GPTs form a complex web of spillovers, with non-linear relationship among them. As they diffuse through the economy other sectors learn how to use them and how to improve their performance in connection with other existing technologies. According to this approach, GPT and technological complementarities provide very useful opportunities for growth[23] oriented policies, even in the absence of externalities,[24] because they "*expand the space of possible inventions and innovations, creating myriad new opportunities for profitable capital investment, which in turn create other new opportunities, and so on in a chain reaction that stretches over decades, even centuries*" (Carlaw and Lipsey, 2002). Notice that, according to this theory, the spillover effects and the technological complementarities cannot be captured by TFP (unless they give rise to proper externalities), which makes the latter a very poor measure of technological progress (Carlaw and Lipsey, 2003). Moreover, given that, according to the structuralist hypothesis, there is no unique optimal allocation of resources, as technology is

22 According to this theory, spillovers are a more general concept than externalities, since the latter involve some form of gain in consumer/producer surplus for third parties, while spillovers simply require usefulness for third parties.

23 Economic growth is viewed as a succession of GPT, which could overlap in time or remain separated.

24 Compare this with Bresnahan and Trajtenberg (1995) where GPTs inevitably give rise to a suboptimal market allocation due to externalities and network effects.

changing endogenously, it is impossible to derive the type of first best policies that neoclassical economics normally focuses on.[25]

As for ICT, Lipsey and co-authors clearly interpret it a GPT, in fact as the GPT of our times (Lipsey et al, 1998), with a strong potential ahead (Lipsey et al. 2007), and point to the fact that productivity might be a poor measure for the relevance of a GPT, as small (large) changes in technologies might have large (small) impacts on productivity.[26] Moreover, given that TFP is not considered as the appropriate index of technological progress, regression of TFP in ICT using sectors on indexes of ICT capital and ICT diffusion are considered to be irrelevant with respect to the qualification of ICT as a GPT, with the additional implication that policies supporting ICT and its links with other technologies are useful even when there is no evidence of externalities in production (captured by TFP).

Gordon (2000, 2002), while recognizing the important role of ICT in the U.S. resurgence of the 1990's, is sceptical about the possibility of considering ICT as a true GPT, and this scepticism is confirmed in a recent paper (Gordon 2012) where the author argues that, while the previous industrial revolutions created long-lasting consequences, the consequences of the IT revolution are much shorter and, in his opinion, already exhausted. The first industrial revolution (1750-1830) was spun by the first GPT, the steam engine, which was at the basis of the development of the cotton spinning, railroads and intense maritime transportation. The second industrial revolution (1870-1900) is originated by the development of two GPT (electricity and the internal combustion engine) and the development of running water with indoor plumbing. Gordon argues that the benefits from these revolutions have been spanning for many years, and that the high growth rates observed in the U.S. in the period 1950-1970 are partially to be traced to the second industrial revolution, as many new products and processes deriving from electricity and from the internal combustion engine where introduced in this period (such as air conditioning, home appliances and the interstate highway system). However, when it comes to the third industrial revolution, the one spurred by development and diffusion of ICT, Gordon thinks that it will not live up to the previous ones. According to Gordon, the main productivity gains from ICT investment and diffusion have already been captured, in terms of substitution of older capital for new ICT capital or unskilled workers for skilled ones. Innovation in ICT since 2000 is mostly in improving the performance of entertainment and communication devices and, according to Gordon, this is not likely to "*fundamentally change labour productivity or the standard of living in the way that electric light, motor cars, or indoor plumbing changed it*". In fact, Gordon concludes that, while the effects of the second industrial revolution lasted 81 years (from 1891 to 1972), those of the IT revolution lasted only 8 years (from 1996 to 2004), given that, according to Gordon, "*the productivity effects of the third industrial*

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[25] The strengthening of the patent system, subsidies to private R&D and direct engagement in R&D by the public sector are the typical policy measures suggested to overcome market failures that arise from indivisibilities, partial appropriability and uncertainty (Arrow 1962a).

[26] Consequences of ICT –which are partly related to its interpretation as a GPT- are changes in management structures, favouring more flexible and horizontal relationships and reduction in minimum efficient scale of production in many sectors using ICT (due to technological progress in the ICT producing industry), hence making economies of scope more important than economies of scale (which are at the root of Fordism) and has also accentuated the trend toward servicisation (a range of activities that used to be conducted in-house by manufacturing firms are now contracted out to firms providing service activities such as product design, marketing, accounting etc.) and globalization (ICT allow the disintegration of production into a series of independent operation that can be delocalized based on cost efficiency and later coordinated thanks to ICT), besides leading to a reduction in the relative demand for unskilled labour (which can have effects of both wages and employment).

revolution had faded away by 2004", due to the fact that, again according to Gordon, labour-saving (and productivity enhancing) innovation spurred by ICT had stopped, replaced by improvements in entertainment and communication devices that are not likely to radically change productivity, as they mainly substitute or perfection devices that were already existing.

In conclusion, with some relevant exceptions (Gordon 2012, Rutten 2008), most of the literature tends to interpret ICT as a GPT (OECD 2012), that is a technology able to induce radical and long term consequences on the growth path of the economy, similarly to other GPT in the past, because it endogenously leads to product, process and organization innovations in sectors/firms investing in ICT and this reinforces the benefits from technological progress in the ICT producing sector.[27]

Related to the interpretation of ICT as a GPT is the complementarity between ICT and other assets (such as human capital and organizational capital). In fact, an important stream of research, led by scholars such as Bresnahan, Brynjolfsson and Hitt,[28] has looked at the conditions –in terms of organizational adaptations- necessary for ICT investment to become productive within the firm. These scholars question the traditional interpretation of the link between productivity and growth, which rests upon the effects of ICT on productivity mainly driven by the decline in ICT prices and by the deepening of the capital/labour ratio employed at firm level.[29] In particular, Bresnahan et al (2001) argue that, in the short run, the introduction of ICT can imply employee lay-off and few or even negative gains in productivity, while in the medium-long, the successful adoption of ICT requires a re-shaping of internal workplace organisation and high skills to generate product innovations. According to Bresnahan et al (2001), this combination of innovations following the introduction of ICT is the bulk of the impact of ICT on firm's productivity.[30] However, given that it takes time to implement all the complementary changes, the effects from ICT investment are more likely to be seen with some lag, as only with learning and time workers and the organization become more efficient and effective in the use of the technology.[31]

Notice that the distinction between the direct and indirect effects of ICT on labour productivity should be considered alongside the academic debate between neoclassical and new growth theory. The neoclassical approach to growth stresses the leading role of prices in determining the equilibrium allocation and consumers' welfare and is hence particularly interested in capital

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[27] The fact that the US productivity acceleration of the 1990's has been largely driven by the IT revolutions, by itself, is not sufficient to conclude that ICT is a GPT, because this requires an analysis of the impact of ICT adoption and investment in ICT using sectors and an analysis of the feedback from this to the ICT producing sector. Moreover, technological revolutions spun by GPTs tend to have a large horizon, and this increases the difficulty of making conclusive statements on the GPT properties of ICT if we only have a short run perspective.

[28] See also for example, Brynjolfsson and Hitt (2000, 2003), Brynjolfsson Hitt and Yang (2002), Greenwood and Yorokoglu (1997), Hornstein and Krussell (1996), Hall (2001), Bresnahan and Trajtenberg (1995), Caselli (1999) and Black and Lynch (2001).

[29] Indeed, in order to have substantive productivity improvements, it is not sufficient to use new technologies as substitutes for the old ones (for instance sending an e-mail as opposed to postal mail), but it is necessary to change the organization of the whole productive process, taking advantage of the opportunities created by the new technologies.

[30] They also remark that ICT-skilled labour complementarity is the main determinant of skill-biased technological change: while ICT and unskilled labour are substitute, ICT and skilled labour are complements, as ICT also requires more skilled workers able to run non-routine and complex tasks (see Autor et. al., 1998).

[31] Learning is both a personal and joint activity that requires time in order to become effective (David, 1999).

accumulation as a driver of growth: physical capital (ICT and non ICT), human capital, intangible capital –including research and development- are all assets that increase the ability to produce more and more efficiently. However, due to the neoclassical assumption that markets are perfectly competitive and that there are diminishing marginal returns to each of these accumulable factors, neoclassical models (Solow 1956; Swan, 1956), even when amended with human capital (such as in Mankiw et al. 1992), cannot generate long-run growth in the absence of exogenous technological change (i.e. positive TFP growth rates). The new growth theory, on the contrary, abandons the assumption of decreasing returns to accumulable factors and opens the way to equilibrium with constant or increasing returns, based on the ideas that *a*) physical and/or human capital accumulation generate spillovers (i.e. positive non pecuniary effects) on agents different from those making the investment choices[32] and *b*) markets where ideas are created and sold are not competitive. The result of this line of research is that it is possible to generate long-run growth even in the absence of TFP growth and the focus on the analysis is shifted towards the market failures able to generate growth (knowledge spillovers).[33]

Studies based on growth-accounting methodology - which is deeply rooted in the neoclassical tradition- are mostly interested in assessing the role of TFP growth in ICT producing sectors (which, however, they cannot explain) and the role of capital deepening in ICT-using sectors (both are direct effects), but cannot capture the indirect effects (including the non-pecuniary spillovers[34]) that are produced in the ICT-using sectors as a result of investment in ICT, possibly in conjunction with investment in complementary assets.

Overall, while there seem to be no doubt about the fact that ICT have contributed highly to the growth performance of the U.S. and, to a lesser extent, to that of Europe, both directly and indirectly (i.e. acting as GPT), there is still no conclusive evidence on the measurement and interpretation of such effects. In other words, it is not clear to which extent there are spillovers and/or externalities (to be intended a la Lipsey) arising from ICT investment or capital, keeping in mind that positive externalities from the latter would induce a positive correlation between measures of ICT capital at the meso-aggregate level and TFP growth in ICT-using sectors (which is what distinguishes neoclassical from the new-growth theory). This issue is also very important from a policy perspective as the existence (and the size) of such spillovers and externalities provide evidence in favour of public support of investment in ICT (and, more generally, support of the ICT-producing sector).

Notice also that the literature comparing the impact of ICT on growth across the Atlantic points to a lower indirect role of ICT investment and diffusion in the service sector in the E.U. relative to the U.S. (especially in finance, wholesale and retail trade), which is an indication that ICT has turned out to be less of a GPT on this side of the Atlantic. Again, understanding the sources of this differential impact of ICT as a GPT is important from a policy perspective: if it turns out that the E.U. is lagging

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[32] Externalities might arise due to human capital accumulation (Lucas 1988), learning by doing (Arrow 1962b), R&D stock (Romer 1986), physical capital (Romer 1990) and R&D stock of international trading partners (Coe and Helpman, 1995).

[33] In fact, if we were to interpret a new growth model from the standpoint of a neoclassical economist, we would end up assigning to TFP growth all the external effects and spillovers that are the juice of the new growth theory.

[34] The only spillover that the growth accounting methodology can capture is the one related to the decrease in prices of ICT inputs and outputs, but these are of the pecuniary type.

behind in ICT investment – for instance due to a fragmented market which makes investment in ICT less profitable (van Ark and Inklaar, 2005) - the appropriate policy is to stimulate investment in ICT. However, if the source of the problem is in the fact that in the E.U. the conditions to make ICT a true GPT are missing (for instance because there are institutional and economic factors hindering innovation in ICT-using sectors) policies should be directed primarily in addressing these factors.

3 ICT and productivity: the growth accounting approach

The two more commonly used measures of productivity are labour productivity (LP) and total factor (or multifactor) productivity (TFP or MFP[35]). Labour productivity, measured in term of either gross output or value added,[36] is a measure of the total gross output (or value added) produced by each worker. Hour labour productivity is obtained dividing gross output or value added by the number of hours worked.

Total factor productivity, which is basically a ratio between an index for output and an index for inputs, can be taken as an indicator of the ability of a given economic unit (or of an economy, if we are considering macro data) in transforming inputs into outputs. However, the precise economic interpretation of TFP rests upon additional assumptions. For instance, if the production function satisfies certain separability properties and in the absence of measurement error, TFP can be interpreted as a measure of the rate of disembodied technological change, as long as the firm is on its production frontier, there are constant returns to scale and markets are competitive (see Domar 1961, and Hulten 2001). More generally, TFP is a combination of effects arising from scale of operations and increasing returns to scale, technical efficiency, technological change, plus measurement error (Coelli et al., 2005, Diewert and Nakamura 2007, Carlaw and Lipsey 2003). Only if we can measure the size of each of these factors we can derive the technological change component of TFP: otherwise[37] TFP becomes mostly a measure of our ignorance.

The relevance of TFP in our discussion of the contribution of ICT to productivity and growth can be better understood by using the typical building blocks of production theory.

If our (real) output variable in country *i* at time *t* is indexed as Y_{it} and we assume that such output is produced with the use of labour (L_{it}) and capital (K_{it}), we can write the production function as

$$Y_{it} = f(A_{it,}L_{it}, K_{it}) \qquad (1)$$

[35] We will use the two terms as synonymous. However, Jorgenson uses MFP for the residual in growth accounting exercises that use sector-level data and TFP for the residual in studies that use national account data.

[36] The choice between gross output and value added is irrelevant when looking at aggregate country data (in this case the two coincide), but it becomes very important when one uses sectoral data, since the type of information that we can get from the two variables is different (we will come back to this when discussing the sectoral approach).

[37] For instance because we have increasing returns to scale that are not accounted for or because we are not fully capturing some of the inputs used in production or some of the outputs produced.

where A_{it} represents the position of the production frontier given the levels of capital and labour (i.e. the level of technology). If we make the assumption that the production function is separable in A_{it} we can rewrite the previous expressions as

$$Y_{it} = A_{it,}g(L_{it}, K_{it}) \qquad (2)$$

so that, by taking the ratio of Y_{it} and *g*( ), we would get a measure of A_{it} (the level of technology). This relationship is at the basis of the growth-accounting approach to the study of the impact of ICT on productivity, where the latter is a mechanical exercise that allows researchers to assign to both observables and unobservables[38] their contribution to economic growth.[39]

The typical growth-accounting exercise assumes that there exists a production function where output can be expressed as a function of *N-1* factors, of which at least one is unknown. By observing the growth rates of output and of the *N-2* observables factors, and given the linear relationship relating output to inputs, it is possible to uniquely determine the value for the unknown input (TFP). The contribution of TFP to growth, defined as the Solow residual, is the part of growth that cannot be accounted for by changes in observable factors of production.[40]

In practice, growth-accounting exercises typically focus on a given time-period and try to verify how much of the rate of change in output can be accounted for by the rate of change in observable inputs[41] (Capital and Labour), while the residual is interpreted as a measure of the rate of change of unobservable technology (i.e. technological progress). A typical growth-accounting exercise that looks at the problem from a supply-side perspective would tell us how much of the observed rate of change in per-capita output is due to capital deepening (assuming no technological change) and how much by the exogenous rate of technological change[42] (assuming no capital deepening).

Most growth-accounting exercises assume the existence of an aggregate production function of the Cobb-Douglas type, with constant returns to scale. This implies that we can write:

$$Y_{it} = A_{it}(L_{it}^{\alpha} K_{it}^{1-\alpha}) \qquad (3)$$

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[38] Given that by assumption there are observables and unobservable variables, one would like to have data on as many observables as possible, such that the number of unobservables is reduced as much as possible. Ideally, if the total number of relevant variables is N, one would like to have data on N-1 observables, so that the value for the unobservable variable becomes known as well and our ignorance disappears.

[39] This might explain the worldwide success of the basic Solow model, which has easily understandable implications for growth accounting.

[40] Growth accounting can also help in identifying the sources of growth coming from the demand side (investments, private and collective consumption, exports, imports, etc.).

[41] Notice that this exercise makes sense out of the steady state, since, by definition, in the steady-state of the Solow model, per capita variables grow at the exogenous rate of growth of TFP, which is hence the unique steady state driver. Out of the steady-state (and assuming that the steady-state capital-labour ratio grows at the instantaneous TFP growth rate) we would observe changes in per-capita variables. Specifically, if we approached the steady state from below, we would observe capital deepening (i.e. a rise in the capital-labour ratio) at a rate greater than the TFP growth rate but decreasing with time.

[42] The first thing to notice is that growth-accounting is about accounting for changes in variables, not for difference in levels. This is a very important but often neglected issue, see Caselli (2005), and Inklaar and Timmer (2007, 2008)

Then we take (natural) logs of eq. (3) and we take the time derivative of it. This gives us a function where rates of change in (real) output are expressed in terms of rates of change in capital, labour and technological progress

$$\Delta lnY_{it} = \Delta lnA_{it} + \alpha\Delta lnL_{it} + (1-\alpha)\Delta K_{it} \qquad (4)$$

Given observations on changes in Y_{it}, L_{it} and K_{it}, we can obtain our desired measure of technological change as

$$\Delta lnA_{it} = \Delta lnY_{it} - \alpha\Delta lnL_{it} - (1-\alpha)\Delta K_{it} \qquad (5)$$

As already mentioned, this works provided that the production function is correctly specified (including the Constant Returns to Scale assumption), there are no inefficiencies and no measurement errors (the latter end up in the measured rate of TFP change).

Finally, the previous model gives a nice prediction for the relationship between labour productivity growth and TFP growth. Exploiting the properties of the production function, we can rewrite eq. (5) as

$$\Delta lny_{it} = \Delta lnA_{it} + (1-\alpha)\Delta lnk_{it} \qquad (6)$$

where $y_{it} = \frac{Y_{it}}{L_{it}}$ and $k_{it} = \frac{K_{it}}{L_{it}}$ represent, respectively, output and capital per-worker. According to this very simple model, growth in labour productivity can be obtained either by capital deepening (increasing the amount of capital per worker: Δlnk_{it}) or by improvement in technology (TFP growth: ΔlnA_{it}).

For equation (5) and (6) to be fully implementable we need to have the value of α and this is where the assumption of perfectly competitive markets plays a decisive role, since the corollary of this assumption is that factors are paid a return equal to their marginal productivity, so that we can go from the shares of capital and labour in national accounts to the value of.

These assumptions lead to the following equation for output (or value added) growth:

$$\Delta lnY_{it} = \Delta lnA_{it} + v_{Lit}\Delta lnL_{it} + v_{Kit}\Delta lnK_{it} \qquad (7)$$

where v_{Kt} and v_{Lt} are, respectively the shares of capital and labour in total value added. If we prefer to present the results in terms of per-capita variables we can write:

$$\Delta lny_{it} = \Delta lnA_{it} + v_{Kit}\Delta lnk_{it} \qquad (8)$$

The interpretation of the capital deepening variable and its relationship with technological progress deserves some attention. Suppose that a firm purchases a new and better machine that halves production time, increasing firm's productivity. Such an effect is entirely due to technological change, but of a type that would not be captured by TFP changes for the purchaser, as the technological advancement is embodied in the acquired capital goods (captured by capital deepening). This immediately clarifies that –even in the best scenario- TFP is not the only measure of technological progress.[43] In fact, things are even more complex: suppose for a second that for such a new capital good the firm pays a low price, equal to half of the gains in marginal productivity that the new machine allows. In this case, the part of the gains in productivity (due to technological progress embedded in the new capital good) for which the firm does not pay show up as TFP. From these examples it should be clear that TFP is really a measure of the rate of technological progress for which the firm does not pay a price[44] (it is a measure for the external effects of any investment). This also explains why this discussion is very important in the context of the analysis of the impact of ICT on productivity, since ICT are –at least potentially- credited of producing positive externalities for which firms and individuals do not actually pay for.

Finally, notice that even in the case in which TFP growth measured disembodied technological change, growth-accounting would not likely capture the full impact of TFP growth on output (or value added) growth. This happens because the growth-accounting methodology is inherently static (despite being based on a growth concept). The point can be better understood with an example (adapted from Hulten 2001). Suppose that in year 1 we have a jump in technology, which allows us to be more productive, so that, in the initial year, technological change (as measured by TFP growth) is fully responsible for the change in output. Suppose also that in all the subsequent years there is no change in technology. However, this does not mean that the impact of the initial change did not produce effects after year 1. In fact, as a response to increase productivity in year 1, we are likely to observe an increase in investment (since capital is now more productive) and this capital deepening will increase labour productivity in year 2, even in the absence of a technological improvement in year 2. With a growth-accounting methodology, we will trace all the change in labour productivity occurring in year 2 to capital deepening, while the ultimate cause (the one that matters for interpreting the phenomenon) lies in the initial change in technology.[45] But this means that, at bests, the growth-accounting methodology, while offering some (incomplete) measurement of the relationship between ICT and productivity, cannot inform us on the causal relationship between the relevant variables (it can only explain part of the “what” question but cannot say much on the “why”).

So far we have assumed that there is only one type of labour and one type of capital. In reality we know that there exist different skills, different educational curricula and different abilities. A first step towards a better understanding the role of changes in labour composition is hence to control for human capital, expressed as the additional input, over and above the labour input provided by raw (i.e. unskilled) labour. The second major change is the distinction between ICT and non-ICT capital.[46] This is a necessary step if 1) we want to take into account the different depreciation rate that apply to ICT capital and 2) if we want to be able to identify some specific role for ICT capital (for example in the productivity of ICT-using sectors).

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[43] On the disembodied vs. embodied interpretation of technological change see Nadiri (1970) and Hercowitz (1998).

[44] Notice also that we might have a measurement issue here: if capital is not properly measured, the measurement errors end up affecting our measure of TFP.

[45] Note that, in order to have across-year comparable values, it is important to transform nominal values into real values, and this applies both to outputs and inputs (in the case of ICT capital this raises the very important issue of the choice of price deflators, i.e. price indexes that allows us to go from nominal to real values: see Ahmad et al, 2004; Pilat et al. 2004; Triplett 2004)).

[46] The creation of an across-country comparable datasets taking into account those aspects is one of the major achievement of the Groningen Development and Growth Research Centre data collection program (some datasets later migrated to the Conference Board), financed, in part, by the E.U. Commission.

Once we allow for both human capital and ICT capital into the picture, our basic growth accounting equation becomes the following:

$$\Delta lny_{it} = \Delta lnA_{it} + v_{Lit}\Delta lnq_{it} + v_{ICTKit}\Delta lnk_{ICTit} + v_{Kit}\Delta lnk_{it} \qquad (9)$$

Where $\Delta lnq_{it} = \Delta lnHC_{it} - \Delta lnL_{it}$ represents the difference between the rates of growth of labour services (which take into account the quality of the input, and hence education of the labour force) and raw labour (as measured by the number of workers[47]). This equation simply states that the growth rate of per-hour labour productivity (LP) is a function of TFP, the rate of improvements of labour quality (typically accounted for by changes in the education composition) weighted by the share of labour in total GDP (i.e. total value added), the rate of change in ICT capital, weighted by the share of payments to ICT capital over total GDP and, finally, to the rate of change of non-ICT capital, weighted by the share of such payments over total GDP.

We can immediately see how crucial is to measure correctly all the inputs: any error in measuring the changes in the quality of the workforce or in the stock of ICT capital (and its costs) will immediately affect the measured TFP index (i.e. the rate of change in TFP).

Notice that so far we have been presenting the problem as if we only had access to aggregate data, while, in fact, sectoral data are available as well (such as those of the EUKLEMS project). In this case, we can express each aggregate level variable in eq. (9) as an index of its corresponding sector-level variable[48] (each sector is weighted by its contribution to aggregate GDP).

Such a sectoral approach allows us to provide an answer to questions that concern the direct role of the ICT sector in the growth performance of a given country, such as “What has been the contribution of the ICT sector to the overall performance of the E.U. economy?” Moreover, only with sectoral data we can try to answer the question concerning the indirect role of ICT: i.e. test if sectors that have invested more in ICT tend to have a better TFP performance. This can be done by computing the residual (TFP change) from a sector-level growth accounting equation (among whose inputs we have ICT and non-ICT capital and human capital) and then regress such residual on the variable capturing the intensity of ICT investment[49] (since in the first stage we are controlling for ICT capital, the second stage regression captures only the potential external effects from ICT investments).

One issue that arises when working with sectoral level data is the choice concerning the dependent variable: we can either use gross output[50] or value added. If we use value added we know that, by summing value added across all sectors, we obtain total value added, which equals GDP, so that a nice linear relationship appears for our “dependent” variable, which also means that it is quite easy to evaluate the contribution of individual sectors to aggregate productivity growth. An additional

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[47] Often the total number of hours is used as a measure of raw labour. This is preferable when there are large variations in number of hours worked across time, countries, gender etc..

[48] However, we have to be careful at this stage since not everything is nicely linear (more on this later).

[49] In general, the relationship between ICT intensity and TFP can be estimated at the aggregate level as well, but in this case we have much less variation and hence it is going to be more difficult to estimate the potential impacts.

[50] Notice that, in order to estimate TFP from a gross output equation we have to take into account the role of intermediate inputs (i.e. gross output is a function of both human capital, ICT and non ICT capital, and intermediate inputs, including energy).

plus of this choice is that our labour productivity variable would be less dependent on outsourcing.[51] However, we have to remember that if we chose value added as our relevant measure we would be getting a value added measure of TFP. While such a measure has the nice property that by simply summing VA-based sectoral TFP changes (weighting each sector by its share in nominal value added) we obtain aggregate TFP change, the negative side of this is that the VA-based TFP change measure depends on the ratio of each sector VA over total VA, hence on the time path of inputs, outputs, prices, besides technology. The interpretation of TFP in this case is quite far from the one of technological change since it would really measure the ability of a given industry to translate technological progress into income (from a policy perspective this might be a very interesting question).

Some (such as Triplett, Bosworth and Jorgenson) argue that a gross-output measure of TFP is preferable when using sectoral data because it is more easily interpretable in terms of technological change, (conditional on all the usual assumptions being satisfied) and because only a gross output based measure of TFP allows us to trace the sources of productivity growth to the right sectors (because it is the only TFP measure that allows us to say if the same inputs are able to produce more output). An example might useful to fully understand the point. Suppose that we focus on two sectors: the one that produces semiconductors and the one that produces computers using semiconductors. Suppose also that the only source of technological progress is in the semiconductor sector, which delivers more powerful inputs at a decreasing price to the PC producing sectors. If we used a Value Added measure of TFP change, most of the gains in productivity would be attributed to the PC producing sectors, since this sector uses more powerful and cheaper inputs to produce better PC. If the prices of PC decline less than the prices of semiconductors (so that the PC sector is able to appropriate a large part of the gains arising from the semiconductor sector technological progress), in the PC producing sector we would observe an increase in the portion of value added that cannot be accounted for by the increase in inputs, hence leading to a positive TFP growth rate. In such a situation we would be driven to conclude that technological progress occurred in the semiconductor using sector, while in fact it only occurred in the semiconductor producing sector (value added TFP growth will likely improve in such sector as well). The only way to assign TFP growth to the appropriate sector (the semiconductor producing sector in our example) is to use a gross-output based measure of TFP growth.[52]

Notice that this also means that labour productivity and total factor productivity are not alternative measures of productivity but should be used in a complementary way. For instance a value added based measure of labour productivity could inform us about the ability of a given industry to generate additional value added per worker and hence about its contribution to aggregate GDP growth. However, if we want to look at the technological sources of the gains we would have to use an output based measure of TFP (with all the caveats of the interpretation of such measure as a proxy for technological change).

Summarizing the main implications of growth accounting methodology:

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51 If a firms outsources part of its production we have both a decrease in Value Added –the numerator- and in labour units –the denominator; the first part would not hold if we used a gross-output measure of labour productivity.

52 Notice that an interesting result from Domar (1961) allows us to go from an output based measure of TFP change to a value added measure of TFP change and vice versa, so that, in general, we are always able to choose the most appropriate measure depending on our research question.

1. Technological progress in the ICT sector has a positive impact on aggregate TFP, whose size depends crucially on the relative size of the ICT industry.
2. Technological progress in the ICT sector has a positive impact on capital deepening, since an improvement in the ICT-producing sector generates more demand for ICT capital in ICT-using sectors (due to lower quality-adjusted prices). In this occurrence, TFP in ICT-using sectors does not increase but ALP increases as a consequence of ICT capital deepening in such sectors.
3. When there are strong complementarities among different types of capitals (ICT may favour a better labour quality, for example, promoting learning processes or working organization) and spillovers/externalities among firms of the same sector or of different sectors, we have an additional increase in productivity due to TFP growth in the ICT-using sectors. However, such effect cannot be properly captured by growth-accounting.

4 ICT and productivity: results from empirical analyses

One of the research questions that have been at the forefront of economics in the last 20 years is the contribution of ICT (not just the ICT sector) to growth. In particular, this issue has been raised initially[53] with reference to the U.S. in the early 1990's when the U.S. started to see the initial effect of the IT revolutions, which became more evident with the strong LP acceleration observed in the U.S. after 1995. Given that the stellar performance of the U.S. was not followed by a similar E.U. performance, interest emerged in trying to understand if the U.S. –E.U. productivity gap was in any way attributable to ICTs. This line of research was taken up by scholars such as van Ark, Inklaar, O'Mahony and Timmer, part of the Groningen Growth and Development Centre, and by Daveri and Oulten, among others.

In terms of methodologies, two approaches have been followed by the literature.

On the one hand, we have the growth-accounting methodology –whose theoretical structure has been presented in the previous paragraph- which imposes a set of strictly neoclassical assumptions that buy the possibility of having a clear interpretation of the relationship between labour productivity growth and capital (including ICT capital), labour and total factor productivity, but does not allow us to measure the indirect effects of ICT investment. On the other one, we have regression based models, in which the starting point is the definition of a set of equilibrium conditions that allow for more flexible functional forms, compatible with non-neoclassical assumptions concerning the relationship between labour productivity and its determinants,[54] and, hence, allow us to capture both the direct and indirect effects of ICT investment and diffusion.

While growth accounting is generally applied only to sector/macro level dataset (simply because it has the purpose of answering to questions like "*What is the role of the ICT sector in the growth performance of the E.U./U.S. economy in the period 2000-2005?*"), the regression based approach has a wider scope, and it can be applied to any type of data, from macro to micro.

[53] See the work by Jorgenson, Oliner, Sichel, Gordon,Triplett, Bosworth, Ho, Stiroh, Nordhaus, Basu and Ferland, to name just a few.

[54] In other words, the regression based approach does not necessarily imposes that all the relevant effects pass through prices and it leaves room for the existence of non-pecuniary externalities (and is hence compatible with the new growth theory).

Here we can briefly compare the two approaches using the same analytical framework. Focussing on the simplest growth-accounting formulation in per-capita term, we know that we can write

$$\Delta lny_{it} = \Delta lnA_{it} + v_{Lit}\Delta lnq_{it} + v_{ICTKit}\Delta lnk_{ICTit} + v_{Kit}\Delta lnk_{it} \quad [10]$$

where v_{Lit}, v_{ICTit} and v_{Kit} are, respectively, the shares of labour, ICT capital and non-ICT capital in value added. From this specification it is obvious that the rate of change of Total Factor Productivity can be obtained as a residual:

$$\Delta \mathrm{TFP}_{it} = lnA_{it} = \Delta lny_{it} - v_{Lit}\Delta lnq_{it} - v_{ICTKit}\Delta lnk_{ICTit} - v_{Kit}\Delta lnk_{it} \quad [11]$$

As an alternative, we could use a regression based approach and estimate the following equation:

$$\Delta lny_{it} = \beta_1\Delta lnq_{it} + \beta_2\Delta lnk_{ICTit} + \beta_3\Delta lnk_{it} + \varepsilon_{it} \quad [12]$$

which produces estimates for β_1, β_2 and β_3, besides providing values for $\hat{\varepsilon}_{it}$, which can then be interpreted as estimates for TFP growth, given that

$$\hat{\varepsilon}_{it} = \Delta lny_{it} - \hat{\beta}_1\Delta lnq_{it} - \hat{\beta}_2\Delta lnk_{ICTit} - \hat{\beta}_3\Delta lnk_{it} \quad [13]$$

The regression based approach has the additional advantage that it can be used when returns to scale are not constant (simply need to introduce an additional term capturing the size of returns to scale) and it can accommodate for the presence of externalities and spillovers (which can be included among the regressors). Notice that, by including measures of returns to scale or measures for external and spillover effects (for instance those related to R&D or to aggregate ICT capital) we tend to reduce the size of the estimated residual (and hence the role of TFP). This will turn out to be important when discussing the literature addressing the GPT role of ICT.

In Sect. 4.1 we present the results from growth accounting. In particular, we provide a brief recap of the main findings on the role of ICT in the U.S. growth performance according to Jorgenson, Ho and Stiroh (2008) and then we move to the discussion of the ICT sector in accounting for the E.U.-U.S. labour productivity growth differential.

In Sect. 4.2 we review studies that have used a regression based approach, using both sector and firm and plant-level data, which allow for a more in depth view of the relationship between ICT and productivity growth (in some cases at the cost of losing the capacity of making general statements about the impact of ICT in accounting for growth differentials between countries).

4.1 Results from growth accounting

4.1.1 The role of ICT in the 1995-2005 U.S. productivity acceleration

After two decades of productivity slowdown, in the mid to late 1990's the U.S. experienced a period of rapid economic expansion. Many observers (Jorgenson, 2001, Jorgenson et al. 2002, Gordon, 1999) have assessed a positive relationship between ICT and the resurgence of the American economy during the late 90s.

Oliner and Sichel (1994) are among the first to document the impact of ICT capital on labour productivity. However, because they use aggregate data (as opposed to sector data) they cannot go beyond the relationship between labour productivity growth and ICT capital deepening (i.e. they cannot study the impact of technical progress in the ICT-producing sector on the productivity of ICT-using sectors). The main result of Oliner and Sichel (1994) is that the contribution of ICT capital to labour productivity growth in the period 1970-1992 is minor, mainly due to the small size of ICT capital.[55] However, this finding is challenged by Jorgenson and Stiroh (1995, 1999), who find a faster (than previously computed) decline in the price of constant-quality services provided by ICTs , which gets reflected in a higher (but still not major) contribution of ICTs to the U.S. productivity performance.

Things change after 1995, a period in which U.S. productivity growth accelerate. First, ICT capital and ICT services are now sizeable in the U.S. and, second, industry level data become available. In fact, Oliner and Sichel (2000) find that the mix of factors leading to labour productivity growth has changed since their 1994 study: in comparison to the early 90s, the increase in productivity growth since 1995 seems to be down to capital deepening (mainly in ICT equipment), and to efficiency gains in the production of ICT goods. They conclude that "*the use of information technology and the production of computers accounted for about two thirds of the 1 percentage point step-up in productivity growth between the first and second halves of the decade*".

The relevance of ICT for the U.S. growth acceleration from 1995 to 2000 is confirmed by Jorgenson, Ho and Stiroh (2002), Oliner and Sichel (2002) and Daveri (2003). While the former study documents that ICT capital deepening and TFP in ICT-producing sectors together explain three quarters of the post 1995 increase in labour productivity, in the latter it is estimated that ICT accounts for almost 100% of the acceleration.

The changing role of ICT in the U.S. can be assessed by looking at Table 1 (corresponding to Table 1 from Jorgenson, Ho and Stiroh, 2008). In the period 1973-1995 the average annual growth rate of labour productivity is 1.49, which becomes 2.7 for the period 1995-2000 (the acceleration period) and 2.50 in the period 2000-2006. Overall, the share attributable to ICT goes from 43% for the period 1971-1995 to 59% for the period 1995-2000, with an almost doubling of the contribution from capital deepening and a more than twofold increase from total factor productivity (both inside and outside the ICT producing sector).

When looking at the post-2000 experience - a period in which labour productivity growth in the U.S. has remained high (2.5 average annual growth rate) at the expenses of hours worked- Jorgenson et al. (2008) find that ICT capital deepening has reduced its role (from 1.01 to 0.58) and that TFP growth in ICT producing sector has gone down (from 0.58 for the 1995-2000 period to 0.38 for the 2000-2006 period), while it has increased the role of TFP outside the ICT producing sector (and hence also in ICT-using sectors).

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[55] Notice that they only focused on ICT hardware, as software was reclassified as an investment good (as opposed to an intermediate good), and hence part of GDP, only in 1999.

Table 1: Sources of U.S. Output and Productivity Growth 1959 – 2006 (average annual growth rates) by Jorgenson et al (2008).

	1959–2006	*1959–1973*	*1973–1995*	*1995–2000*	*2000–2006*
Private output	**3.58**	**4.18**	**3.08**	**4.77**	**3.01**
Hours worked	1.44	1.36	1.59	2.07	0.51
Average labor productivity	2.14	2.82	1.49	2.70	2.50
Contribution of capital deepening	**1.14**	**1.40**	**0.85**	**1.51**	**1.26**
Information technology	0.43	0.21	0.40	1.01	0.58
Non–information technology	0.70	1.19	0.45	0.49	0.69
Contribution of labor quality	**0.26**	**0.28**	**0.25**	**0.19**	**0.31**
Total factor productivity	**0.75**	**1.14**	**0.39**	**1.00**	**0.92**
Information technology	0.25	0.09	0.25	0.58	0.38
Non–information technology	0.49	1.05	0.14	0.42	0.54
Share attributed to information technology	**0.32**	**0.11**	**0.43**	**0.59**	**0.38**

Notes: Data are for the U.S. private economy. All figures are average annual growth rates. A contribution of an input reflects the share-weighted growth rate. Capital is broadly defined to include business capital and consumer durables. Information technology includes computer hardware, software, and communications equipment. "Share attributed to information technology" is the average contribution of information-technology capital deepening plus the average contribution of information-technology total factor productivity divided by average labor productivity for each period.

These results seem to indicate that in the U.S., after 2000, ICT capital deepening and technological progress within the ICT-producing sector are reducing their effect on growth and that, symmetrically, the contributions from TFP and capital deepening in non ICT-producing sectors are becoming more relevant[56] (in line with the results of Basu et al. 2003, and Basu and Fernald, 2007, and with the literature that have addressed the issue using firm level data). They are also partially in line with those of Triplett and Bosworth (2004) and Bosworth and Triplett (2007) who anticipate to the period 1995-2000 the relevance of TFP growth in ICT-using services. In fact, in their analysis of the sources of the post-1995 U.S. performance, Bosworth and Triplett find that the service-producing industries – which accounted for about 80% of the increase in ICT capital- are responsible for the acceleration in aggregate TFP. Within services, the largest gain are from wholesale, retail, finance, real estate and health, while for manufacturing, the positive contributions coming from the ICT sector are counterbalanced by negative contributions coming from other sectors.

Notice, however, that Triplett and Bosworth's interpretation of the role of the ICT sector for the U.S. productivity resurgence is slightly different from the one of Oliner and Sichel. While the latter stressed the importance of ICT capital deepening in ICT using industries and of TFP growth in the ICT producing industries[57] –<u>both are direct effects</u>-, Triplett and Bosworth, in their search for a cure

[56] Notice that the direct role of ICT in post-2000 U.S. growth performance is still sizeable, as it accounts for about 38% of the labour productivity growth observed in the period 2000-2006 (see Jorgenson, Ho, Stiroh, 2008).

[57] In fact they argue that these are the only industries experiencing TFP growth.

of Baumol's disease for the service sector[58] in the U.S., find that TFP growth is high especially in those service industries that use ICT intensively[59] (hence pointing to a potential indirect effects of ICT). The role of TFP in the services sector is confirmed by Jorgenson, Ho and Stiroh (2005) and by Corrado et al. (2007). These results are also in line with Colecchia and Schreyer (2002a), who pointed to the role of ICT diffusion in explaining the growth performance of OECD countries as they find that "*in relative terms, ICT capital accounted for between one-third and close to 100 percent of the overall contribution of capital services to output growth (…) Effects have clearly been largest in the United States, followed by Australia, Finland and Canada*"). They also provide some preliminary evidence that the existence of a large ICT producing industry is "*neither a necessary nor a sufficient condition to successfully experience the growth effects of ICT*", since a large part of capital deepening and growth in TFP seem to have happened in ICT-using sectors[60] (mostly in services and mostly after 1995).

The pioneering work by Jorgenson and co-authors is very much based on the intuition that a sectoral approach is necessary because only with sector data it is possible to trace the source of the TFP gain. In fact, Jorgenson and co-authors tell a story that is very much based on the large technological progress occurring in the semiconductor sector, which has then been transferred to the computer-producing sector and finally to computer-using sectors.[61] Hence, the interpretation by Jorgenson and co-authors is very much "neoclassical" as it is a story stressing the direct role of the ICT sector, a role that we have some hope to capture with growth-accounting.[62] A simple growth-accounting methodology, however, cannot capture and explain the indirect effect of technological progress occurring in ICT-using sectors, such as those at which Triplett and Bosworth point at. To capture these indirect effects, which originate from production spillovers or network effects (i.e. by non-pecuniary externalities), a regression-based approach that uses sector (or firm) level data is necessary[63] (more on this is Sect. 4.2).

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[58] Baumol (1967) argued that productivity in the service sector increases less than in manufacturing because in the service sector labour is a predominant factor, hence reducing the impact arising from improvements in capital goods.

[59] Symmetrically, they reduce the role of ICT capital deepening in explaining the acceleration in labour productivity growth (as they argue that ICT investment was already high prior to 1995).

[60] Colecchia and Schreyer (2002a) also document that in many European countries the ratio of ICT capital to total capital has been rising, particularly from 1995, and this explains why the contribution of ICT equipment and software to output growth has been rising from a 0.2-0.5 interval before 1995 to a 0.3-0.9 interval after 1995. The conclusion that the presence of a strong ICT producing sector is not a necessary condition for above-average productivity growth can be found also in Pilat and Lee (2001) and Oulton (2010). A different perspective can be found in Roeger (2001), which stresses the role of technological progress in the ICT producing sector in accounting for the US-E.U. productivity gap.

[61] Notice that semiconductors appear in the "Electronic and electric equipment sector" while personal computers appear in the "Industrial Machinery and Equipment sector". Both are part of the ICT sector but while the former is basically a sector supplying only intermediate goods, the latter includes both intermediate and final goods. Only with sectoral data it is possible to pin down the exact source of technological progress.

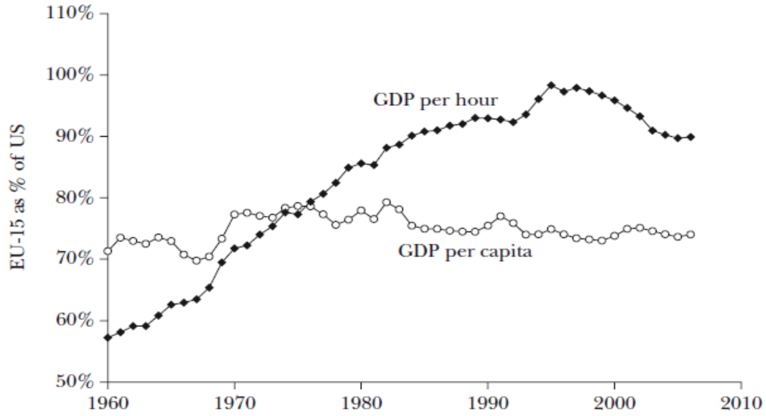
[62] Suppose that ICT-using sectors buy better quality ICT products for lower real prices (a pecuniary externality) and this leads to increased ICT-capital deepening (increase in real services provided by the ICT sector). To the extent that the existing data use the appropriate quality-adjusted depreciation rates, such an effect can be captured by the growth-accounting methodology.

[63] In order to test the presence of positive spillover effects with sector-level data (as opposed to firm level data) one needs to regress TFP growth rates in ICT-using sectors against a measure of ICT capital deepening. While lacking any theoretical foundation (the issue of complementarity cannot be fully

4.1.2 *The role of ICT in accounting for the U.S.-E.U. productivity gap*

When looking at the productivity gap between the E.U. and the U.S. and at the role of the ICT sector, it appears evident that the post-1995 acceleration has not affected the E.U. (see Fig.1, corresponding to Fig.1 in van Ark et al 2008).

Figure 1: Total Economy GDP per hour worked and GDP per capita in the EU-15, 1960 – 2006 (relative to the United States)



Source: The Conference Board and Groningen Growth and Development Centre, Total Economy Database, January 2007, at ⟨http://www.ggdc.net/dseries/totecon.shtml⟩.
Notes: EU-15 refers to the 15 countries constituting the European Union before 2004 and include Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom. The EU has expanded to include ten new member states mainly in Central and Eastern Europe in 2004 and another two in 2007; the new members are not included here. Relative levels are based on purchasing power parities for GDP for 2002 from the OECD.

Considering the 1973-2006 period and using data from the Conference Board and from the Groningen Growth and Development Centre, van Ark, O'Mahony and Timmer (2008), document that, in the interval 1973-1995, hourly labour productivity (i.e. GDP per hour) in the E.U. has been rising at an average annual growth rate of 2.4%, which is twice as high as the rate of 1.2% estimated for the U.S. for the same period[64] (see Table 2, corresponding to Table 1 in van Ark et al 2008). This implies that in the 1973-1995 period, the hourly labour productivity gap between the U.S. and the E.U. has been shrinking (from the 25 percentage points observed in 1973 to approximately two percentage points observed in 1995). However, when looking at the period 1996-2006, van Ark et al. (2008) find a reversal of the positions: the U.S. experienced an average annual hourly labour productivity growth rate of about 2.3% while the value for the E.U. for the corresponding period is only 1.5%. This implies that after 1995 the labour productivity gap (in terms of GDP per hour worked) has begun to increase once again.

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addressed with sector-level data) we can still have a clear indication of the existence of some relationship between ICT utilization and TFP growth.

64 Notice that the estimates for the U.S. from van Ark et al (2008) for the period 1973-1995 are lower than the one by Jorgenson et al (2008) for the same period. The two sets of estimates are based on different data.

Table 2: Average Annual Growth Rates of GDP, GDP per Capita, and GDP per hour worked, EU-15 and United States, 1950 – 2006 (*in percent*)

	Growth in		
	GDP	*GDP per capita*	*GDP per hour worked*
1950–1973			
EU-15	**5.5**	**4.7**	**5.3**
US	3.9	2.4	2.5
1973–1995			
EU-15	**2.0**	**1.7**	**2.4**
US	2.8	1.8	1.2
1995–2006			
EU-15	**2.3**	**2.1**	**1.5**
US	3.2	2.2	2.3

Source: Calculations based on the Conference Board and Groningen Growth and Development Centre, Total Economy Database, January 2007, at ⟨http://www.ggdc.net/dseries/totecon.shtml⟩.
Notes: See Figure 1.

From Table 2 we also get another interesting result when we compare the evolution of GPD per capita to that of GDP per hour. The divergence between the evolution of the hourly labour productivity gap- which was shrinking, at least up to 1995- and the GDP per-capita gap (which remained roughly constant) is due to the fact that in the E.U., relative to the U.S., labour hours have been declining from 1950 to 1995. In other words, there is ample evidence that the labour market in the E.U. and in the U.S. have been functioning very differently in the period 1950-1995, and this might also explain why in this period the levels of investment in capital in the E.U. have been higher than in the U.S.[65]

Notice also that, after 1995, there has been a reversal in term of hours worked[66] and capital intensity[67] (see Table 3, corresponding to Table 2 in van Ark et al, 2008). In fact, while up to 1995 capital services per hour had been larger for the E.U. than for the U.S. (due to the relatively higher costs of labour in Europe), after 1995 the reverse is true.[68]

[65] The hypothesis of van Ark et al. (2008) is that labour market rigidities are at the root of the labour productivity miracle of the E.U. in the period 1973-1995.

[66] The U.S.-E.U. gap goes from about 24 to about 18 percentage points from 1995 to 2004.

[67] The U.S.-E.U. gap goes from about 3 to about 10 percentage points, from 1995 to 2004.

[68] The role of the labour market in explaining the post-1995 E.U. productivity slowdown have been extensively investigated (see the work by Gordon and Blanchard) and we feel quite safe in concluding that labour markets do not appear to be at the root of the slowdown.

Table 3: Levels of EU-15 relative to the United States

	1950	*1973*	*1995*	*2004*
GDP per capita	45.5	76.8	74.9	74.1
Hours worked per capita	115.2	101.9	76.2	82.1
GDP per hour worked	39.5	75.4	98.3	90.3
Capital input per hour worked*		82.3	97.0	90.0

Source: Calculations based on the Groningen Growth and Development Center Total Economy Growth Accounting Database (June 2005) as described in Timmer and van Ark (2005). Output and capital levels are converted by GDP purchasing power parities for 2002.
* Measured as capital services per hour worked. Entry for 1973 refers to 1980.

One of the possible interpretations of the increasing post-1995 U.S.-E.U. productivity growth gap resides in the role of ICTs. This hypothesis, which is based on the work of Jorgenson and co-authors for the U.S., posits that the E.U. has not benefited from the higher rates of aggregate TFP growth and ICT capital deepening that have been observed in the U.S.[69] While the first argument is very much based on the structural composition of the economy (the size –and innovativeness- of the ICT sector), the second one is more of a puzzle, in the sense that it is not immediately obvious *i*) why E.U. companies would be less interested in investing in a promising and "cheap" technology and *ii*) when they invest, why would they get a lower return.[70]

By 2005 we can observe a wide consensus on the need to use more granular data to investigate the impact of ICT on growth: the link between ICT investment and TFP growth in services (among which we have many ICT-using industries) appeared as a very interesting research questions, which could be pursued only using sectoral or firm level data. In fact, the underlying hypothesis that ICT where the drivers of the post-1995 U.S. LP acceleration because they improved efficiency in ICT-using sectors (mostly services) posed the question on how to measure ICT investment and use in such sectors.

The role of ICT in the ICT-using sectors and, particularly, in the service industries is also very much at the root of the interpretation by van Ark and co-authors in their analysis of the E.U.-U.S. productivity gap conducted using the EUKLEMS data for the period 1980-2004 (the latest version of the dataset is up to year 2007) for 10 E.U. countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Spain, UK).

[69] Daveri (2002) uses data from WITSA/IDC on ICT expenditures, from which data on ICT investment are derived, and finds that a large part of the productivity gap originates from a lower (average) investment in ICT in the E.U.. However he also finds that there are important differences among E.U. countries: while in Italy, Spain, Greece and Portugal the investment rate in ICT is much lower than the one observed in the US, in the U.K., Netherlands and Sweden the rates are substantially not different from those found for the US. Germany and France are in between these two groups. The within-E.U. across-country variability is confirmed when looking at the contributions of ICT to growth (using a standard growth accounting method). The highest contributions are recorded for U.K., Netherlands, Ireland and Sweden, while the lowest are registered for Italy, Spain and Greece.

[70] A partial explanation for lower capital deepening in the E.U. might come from the structural composition of the economy: for instance, the wholesale and financial sectors, which are heavy users of ICT, tend to be relatively larger in the U.S. than in the E.U.

Table 4: Contributions to growth of real output in the market economy, the European Union and the United States

		European Union		United States	
		1980–1995	1995–2004	1980–1995	1995–2004
1	Market economy output (2) + (3)	1.8	2.2	3.0	3.7
2	Hours worked	−0.6	0.7	1.4	0.6
3	Labor productivity (4) + (5) + (8)	2.4	1.5	1.5	3.0
	Contributions from				
4	Labor composition	0.3	0.2	0.2	0.3
5	Capital services per hour (6) + (7)	1.2	1.0	0.8	1.3
6	ICT capital per hour	0.4	0.5	0.5	0.8
7	Non-ICT capital per hour	0.8	0.5	0.2	0.4
8	Multifactor productivity	0.9	0.3	0.5	1.4
	Contribution of the knowledge economy to labor productivity (4) + (6) + (8)	**1.6**	**1.1**	**1.3**	**2.6**

Source: EU KLEMS database, see Timmer, O'Mahony, and van Ark (2007).
Notes: Data for European Union refers to ten countries: Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Spain, and the United Kingdom. "ICT" is information and communications technology.

Their work starts with an analysis of the E.U.-U.S. aggregate labour productivity gap, where the aggregate data are obtained from the underlying sectoral data. While the values of the E.U. and U.S. average annual growth rates in LP obtained from this dataset differ from those of the aggregated dataset described in Table 4 (corresponding to Table 3 in van Ark et al, 2008), the values for the gap in LP are largely consistent: in the period 1980-1995 the E.U. was experiencing a positive gap in average annual LP growth of about 0.9, which became a value of -1.5 for the period 1995-2004. When looking at measuring the contributions to the LP performance of the E.U., the evidence points to a minor but steady role of improvement in the skill content of the labour force (arising mainly from newer more educated cohorts), while the contribution of ICT capital (ICT capital deepening) in the E.U. has been lower than in the U.S. and also increasing at a lower rate (0.4 against 0.5 in the period 1980-1995 and 0.5 against 0.8 in the period 1995-2004), partly due to the post-1995 increase in hours worked observed in the E.U.. The largest difference between the E.U. and the U.S. is in the contribution of TFP growth: while in the U.S. it went from 0.5 from 1980 -1995 to 1.4 for 1995-2004, in the E.U. it declined from 0.9 for 1980-1995 to 0.3 for 1995-2004.

When looking at the contribution of ICTs to LP growth in the E.U. and the U.S., van Ark et al. (2008) find that it went from 1.3 for 1980-1995 to 0.8 for 1995-2004 for the E.U., while for the U.S. it went from 1 in the former period to 2.2 in the latter, the largest increase arising from TFP growth. The analysis by van Ark and co-authors also points to large across E.U. countries variation (see Table 5, corresponding to Table 4 in van Ark et al., 2008).

Table 5: Contributions to growth of real output in the market economy, the EU economies and the United States, 1995 – 2004 (annual average growth rates, in percentage points

		Output contribution from		*Labor productivity contributions from*				
	Growth rate of output	*Hours worked*	*Labor productivity*	*Labor composition*	*ICT capital per hour*	*Non-ICT capital per hour*	*MFP*	*Labor productivity contribution from knowledge economy*
	1 = 2 + 3	*2*	*3 = 4 + 5 + 6 + 7*	*4*	*5*	*6*	*7*	*4 + 5 + 7*
Austria	2.6	0.4	2.2	0.2	0.6	0.1	1.2	2.1
Belgium	2.4	0.6	1.8	0.2	0.7	0.4	0.4	1.4
Denmark	2.3	0.9	1.4	0.3	1.2	0.3	−0.4	1.1
Finland	4.4	1.1	3.3	0.1	0.5	−0.1	2.8	3.4
France	2.5	0.4	2.0	0.4	0.5	0.4	0.8	1.6
Germany	1.0	−0.6	1.6	0.1	0.5	0.6	0.3	1.0
Italy	1.4	1.0	0.5	0.1	0.2	0.6	−0.4	−0.1
Netherlands	2.8	0.8	2.0	0.2	0.6	0.1	1.0	1.9
Spain	3.6	3.3	0.2	0.4	0.3	0.4	−0.9	−0.2
United Kingdom	3.3	0.7	2.7	0.5	1.0	0.4	0.7	2.2
European Union	2.2	0.7	1.5	0.2	0.5	0.5	0.3	1.1
United States	3.7	0.6	3.0	0.3	0.8	0.4	1.4	2.6
Standard deviation**	1.0	0.9	1.0	0.1	0.3	0.2	1.0	1.1

Source: Calculations based on EU KLEMS database, see Timmer, O'Mahony, and van Ark (2007).
Notes: "ICT" is information and communications technology. "MFP" is multifactor productivity. Data for Italy excludes agriculture and private households. Data for the European Union refers to the ten countries in the table. Numbers may not sum exactly due to rounding.
** Standard deviation for EU countries and the United States.

In the 1995-2004 period, we have countries like Finland and the UK with, respectively, LP growth rates of 3.3 and 2.7, performing very closely to the U.S., and countries like Italy or Spain, with LP rates of, respectively, 0.5 and 0.2. When looking at the factors that account for such variation in LP performance,[71] what emerges clearly is that differences in TFP drive the within-E.U. across-country divergences in labour productivity (as they do when comparing E.U. with the U.S.).

Then van Ark at al. (2008) move to the sectorial analysis and here it clearly emerges that the E.U. has been shifting employment from manufacturing to the service industry: in the period 1980-2004 it is estimated that E.U. manufacturing has lost about one third of its labour input (large difference exists within E.U. countries). Still, in relative terms, in the E.U. the service industry accounts for a lower share of total employment, when compared to the U.S. This element, per se, is part of the reason why the E.U. has benefited less than the U.S. from investment in ICT within ICT-using sectors.

[71] The contribution of a given input to output growth is given by the rate of growth of the input weighted (i.e. multiplied) by the input's income share.

Table 6: Major Sector Contribution to average annual labour productivity growth in the market economy, 1995 – 2004 (annual average growth rates, in percentage points)

	Market economy	*ICT production*	*Goods production*	*Market services*	*Reallocation*
	1 = 2 + 3 + 4 + 5	*2*	*3*	*4*	*5*
Austria	2.2	0.3	1.7	0.3	−0.1
Belgium	1.8	0.3	1.0	0.5	−0.1
Denmark	1.4	0.3	0.8	0.3	0.0
Finland	3.3	1.6	1.3	0.4	0.0
France	2.0	0.5	1.0	0.6	0.0
Germany	1.6	0.5	0.9	0.2	0.0
Italy	0.5	0.3	0.3	−0.1	0.0
Netherlands	2.0	0.4	0.6	1.1	−0.1
Spain	0.2	0.1	0.1	0.1	−0.1
United Kingdom	2.7	0.5	0.7	1.6	−0.2
European Union	1.5	0.5	0.8	0.5	−0.2
United States	3.0	0.9	0.7	1.8	−0.3

Source: Calculations based on EU KLEMS database, see Timmer, O'Mahony, and van Ark (2007).
Notes: The reallocation effect in the last column refers to labor productivity effects of reallocations of labor between sectors. The European Union aggregate refers to ten countries in the table. Information and communications technology production includes manufacturing of electrical machinery and post and telecommunications services. Goods production includes agriculture, mining, manufacturing (excluding electrical machinery), construction, and utilities. Market services include distribution services; financial and business services, excluding real estate; and personal services. Numbers may not sum exactly due to rounding.

Table 6 (corresponding to Table 5 in van Ark et al., 2008) summarizes the contributions to aggregate labour productivity growth by three different subsectors: ICT producing (goods and services), goods producing (other than ICT) and market services (other than ICT) in the period 1995-2004. The first thing we notice is that, in the E.U., services and ICT production contributed equally to labour productivity growth, with a value (0.5) that is lower than the one observed for the goods production. When comparing the average E.U. performance with the one of the U.S., these data show that the E.U. has been performing slightly better in goods manufacturing (0.8 for E.U. against 0.7 for U.S.), but worse in ICT production (0.5 for the E.U. and 0.9 for the U.S.) and much worse in the service industry (0.5 for the E.U. against 1.8 for the U.S.). Once again, this points to the crucial role of the service industry (see also Denis, McMorrow and Roger, 2004). When looking within the E.U., a wide across-country variation in contributions to LP average annual growth rates emerges in all the three sectors considered (Netherland and the UK are the countries exhibiting higher productivity growth in market services, while Italy, Spain[72] and Germany are the countries exhibiting the lower contribution from this sector). Additional analysis by van Ark et al (2008) shows that – within the service industries- those who are mostly responsible for the E.U.-U.S. LP gap are distributive trade (retail, wholesale trade and transport services) and financial and business sector (personal services also contributed to the gap). In particular, trade contributed 0.6 percentage points

[72] Italy and Spain also register minor contributions from manufacturing sector, which –at least for Italy- used to be a success story but which has been challenged by emerging economies from the mid 90s.

to average annual LP growth in the E.U. but 1.6 percentage points in the U.S., while for finance and business sector the contribution was 0.1 in the E.U. and 1.2 in the U.S.. Moreover, such gaps are explained by within-sector differences in TFP much more than by within-sector differences in capital (ICT or non ICT) intensity, hence confirming the results by Jorgenson et al (2008) and by Bosworth and Triplett (2007).[73] It is important to note that the results of van Ark et al. (2008) are based on a distinction between ICT producing (goods and services), goods producing (other than ICT) and market services (other than ICT) and not on ICT producing, ICT using and neither ICT producing or using (the ICT irrelevant) sectors. In fact, the identification of ICT-using sectors is problematic, as ICT are used in most sectors and changes in the classification of some key sectors (among which retail or transport equipment) might have dramatic results on the results of the growth accounting exercises and hence on the policy implications.[74]

Trying to summarize the results obtained from the literature that has looked at the impact of ICT on labour productivity comparatively and using a growth accounting methodology, we can conclude the following:

a) GDP per capita growth has been stronger in the U.S. than in Europe in the period 1996-2004, and the major explanation for the diverging pattern comes from the fact that the

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[73] For a discussion on the comparability of productivity measures in services across the U.S. and the E.U. see Hartwig (2008).

[74] A different interpretation of the E.U.-US productivity gap is offered by Daveri (2004), which uses the same data used by van Ark et al (2003)[74] but proposes a different sectoral aggregation. The main contribution of Daveri (2004) resides in the attempt to test the robustness of the studies that try to answer the two following questions: how much of the US productivity acceleration and how much of the E.U.-US productivity gap can be accounted for by ICT, either in terms of ICT producing or ICT using sectors?
As for the ICT-producing sector (as an aggregate), Daveri finds that it is responsible for about 20% of the US labour productivity acceleration, while it is not able to explain any of the E.U.-US gap, since productivity in ICT producing sectors has been growing at similar rates in the E.U. and in the US[74] (in the E.U. the growth is mostly in services while in the US is mostly in manufacturing), leading to the conclusion that acceleration of labour productivity in ICT producing sectors was not a phenomenon limited to the US.
When looking at the contribution of ICT-using sectors both to the US acceleration and to the E.U.-US gap, Daveri (2004) finds a very different answer from the one proposed by van Ark and co-authors. The main issue is how to define a sector as ICT user. According to van Ark et al. (2003), which follow Stiroh (2002a), to be included among the ICT-using sectors, an industry needs to be among the top 50% (above median) in terms of ICT capital service share in value added in the period 1979-1995 and 1995-2000 in the US (application of this methodology using data from France, Germany, U.K. and Netherlands provides a very close classification). Daveri proposes to define as "ICT users" the sectors that exhibit above-mean values for the ICT capital service share in value added for the same period and for the same years. Under the classification proposed by van Ark et al. et al (2003), the ICT-using sectors are responsible for about 87% of the US productivity acceleration and about 60% of the E.U.-US productivity gap. However, when the different classification proposed by Daveri is applied, the contribution of ICT-using sectors to the US acceleration is reduced to 56% and their contribution to the E.U.-US gap is reduced to 38%. Notice that in this case retail would no longer appear among the ICT-using sectors.
While any classification as such is arbitrary, the merit of Daveri (2004) is to show how risky it is to draw policy conclusions from non-robust evidence. In fact, if the Jorgenson-Stiroh-Van Ark and co-authors story is correct, the greatest acceleration in the US productivity is observed in ICT-using sectors and this is also the main explanation for the E.U.-US productivity gap (i.e. lower diffusion of ICT and lower return to ICT in the E.U. relative to the US). However, if, on the contrary, the acceleration of US productivity can be traced either to the ICT-producing sector (particularly to the manufacturing sector producing ICT durable goods, which, according to Gordon, is responsible for about 66% of the acceleration of US productivity) or to sectors that are neither producers nor users of ICT, it is difficult to maintain the policy prescription that ICT diffusion should be the main focus in the E.U.

labour productivity gap between the U.S. and the E.U. has been rising (with some notable exceptions like, Finland, Sweden, Ireland, Belgium and Austria).

b) The rise in the gap is due to two main reasons. First, the U.S. have experienced a higher productivity growth rate in ICT goods producing sectors, largely due to the impressive technological improvement characterizing this sector, which is also relatively larger in the U.S.. Second, TFP in the service sector, and especially in those sectors that use ICT extensively such as wholesale and retail trade and finance, has been rising much faster in the U.S. than in the E.U. (with some exceptions, like the Netherland and the UK). This points to the role of ICT in explaining productivity growth in ICT using sectors, a question that cannot be answered in the context of growth accounting.

c) After 2005 we also notice a slowdown in U.S. labour productivity growth, which translates into a reduction of the E.U.-U.S. productivity gap.

4.2 Results from regression-based studies

The growth-accounting technique raises some major methodological problems. First, it cannot say much on the causation mechanism between LP and its determinants and this reduces the possibility of drawing policy implications. Second, the role of prices in a growth-accounting framework is crucial when trying to capture the direct role of ICT, since all the effects of quality improvement that are not fully captured by market transactions appear in TFP. Third, growth accounting is normally based on the assumption of constant economies of scale and absence of externalities, so that the impact of ICT on productivity estimated by growth accounting is over-weighted if in reality we have economies of scale and under-weighted if ICT investment generates positive external effects.

For all these reasons (besides those discussed in Section 3) the results of growth-accounting exercises must be taken with extreme care.[75] Scholars have hence explored the econometric approach, with studies conducted mostly (but not only) at the firm level.[76] This type of literature can better evaluate the indirect effects of ICT investment (those that appear in ICT-using sectors) and for this it looks at the role of complementary assets (see Sect. 2). The basic intuition of this literature is that capital goods that embed digital technology are often substituted for unskilled labour in routine jobs,[77] and complementary to more complex and cognitively demanding jobs (mostly managerial). This effect –which Bresnahan, Brynjolfsson and Hitt (2001) call the *limited substitution effect*– is likely to be observed directly in standard statistics and be captured by growth accounting methodology (in fact, it is the only effects that can be captured by such methodology in ICT-using sectors). However, ICT are a general purpose technology and hence they operate as enablers of product, process and organizational innovations. When managers are asked to name

[75] Following Caselli (2005), growth accounting for LP works a bit like the thermometer for fever: it detects its presence but it cannot help us much to understand its origin, nor does it provide clues as to a cure. However, nobody would dispute that thermometers are useful.

[76] An example of a regression based model using sectoral data (EUKLEMS) is Spiezia (2001), where a Cobb-Douglas production function is estimated for different countries (and sectors). The results of this study show that the input elasticities are not too distant from those assumed in growth accounting, but for ICT capital, for which the estimated elasticity is higher than the share of ICT capital over total capital (the one used in growth accounting) hence indicating the existence of potential spillover effects from ICT investment.

[77] Since computer business systems are most effective in automating routines and well defined work tasks, we expect computers to substitute for labour in clerical work.

and possibly rank the benefits coming from computerization they indicate the following: increases product differentiation, better supply chain management, improved product quality, better producer-customer relationship. These factors are very likely to go unmeasured by standard price deflators but they are a clear representation of the effects of ICT as a GPT. It is exactly the role and the relevance of such complementary innovation that lead Brynjolfsson and Hitt (2000) to conclude that "*a significant component of the value of information technology is its ability to enable complementary organizational investments such as business processes and work practices;…these investments, in turn, lead to productivity increases by reducing costs and, more importantly, by enabling firms to increase output quality in the forms of new products or in improvements in intangible aspects of existing products like convenience, timeliness, quality, and variety*".

4.2.1 Analysis based on aggregate and sector-level data

Only few studies have investigated the relationship between ICT investment and growth in a regression framework using aggregate country-level data, and some of them have also looked at the interplay between institutions and investment in new technology (which is not possible in a growth accounting framework).

O'Mahony and Vecchi M. (2005) look at the long-run relationship between ICT capital and output growth, using panel co-integration techniques. Using U.S. and UK data for the period 1976-2000 for 55 separate sectors, the authors find that, when using standard panel data techniques, the coefficient on ICT capital enters with a negative and significant coefficient, both when levels of logarithmic output and differences in logarithmic output (i.e. growth rates for output) are used, in sharp contrast with the growth accounting results that point to a positive contribution from ICT capital deepening.[78] However, these results are interpreted as being driven by the incorrect choice of the econometric specification (which does not allow for the variation in ICT diffusion across sectors and time). In fact, under the preferred estimation technique (Pooled Mean Group estimator), which allow for heterogeneous dynamic adjustments towards a common lung-run equilibrium, the authors find that ICT capital positively affects output growth, with a return to ICT capital higher than the one on non-ICT capital, especially in the U.S.. This result is consistent with those from growth accounting (for the two countries here considered).

Another study that looks at the long-run effects of ICT on growth is Venturini (2009), who uses cointegration techniques in order to capture a common long-run relationship between ICT and output growth, while contemporaneously allowing for heterogeneity in short-run dynamics. He uses the Groningen Growth and Development Centre (GGDC) Total Economy Growth Accounting Database, which includes 15 E.U. Member States and the United States, for the period 1980-2004. The preferred specification is the one using the Dynamic Seemingly Unrelated Estimation (DSUR); which increases efficiency of the estimates by allowing for a common across-equation co-integrating vector. The 16 countries are divided into three groups: Big countries (U.S.; Germany, France, UK and Italy), Medium Countries (Spain, Netherlands, Belgium, Sweden and Austria) and Small Countries (Greece, Portugal, Denmark, Finland, Ireland and Luxembourg). The results clearly indicate that ICT capital is an important source of long-run growth only for the U.S. and for the group of Small Countries, while there is no evidence of a significant effect for the E.U. Big Countries,

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[78] Positive relationships are found when regressing ICT capital and other measures of ICT diffusion against TFP growth rates (see also O'Mahony and Vecchi, 2003)

hence someway confirming the results from the growth accounting studies of van Ark and co-authors. Moreover, there is clear indication that, for the groups of countries for which ICT capital appears as an important source of growth, the long-run effect is much higher than the short-run one,[79] which leads the author to conclude that this evidence is in line with the GPT hypothesis, according to which it takes time to observe the effects of the ICT revolution.

Becchetti and Adriani (2005) study the impact of ICT on the level and growth rate of per capita income, using data from various sources and for various time intervals (from 47 to 95 countries and for the following two periods: 1991-1997 and 1983-1997). Their main intuition is that ICT affects the growth rate of the labour augmenting technological progress in a Mankiw-Romer-Weil (1992) type-model along two lines. On the one hand, technological progress in ICTs is a major driver of technological progress in the overall economy, acting like a semi-public good (it is non rivalrous and hardly excludable). However, the extent to which technological progress in such sector can be appropriated by the different countries depends upon the existence of bottlenecks, such as the capacity of networks to transfer information and data, the access of individuals to such networks and the power of the instruments used to access the networks. This means that, while technological progress in ICTs can potentially improve per-capita income, both in level and growth terms, the extent to which this happens depends upon the country-specific factors affecting the possibility of accessing such progress. This approach leads to two important variables added to the standard Mankiw-Romer-Weil (1992) model: first we have the level of ICT technology in each country in the initial year (which is a proxy for the availability of technology at the beginning of the period and hence acts as a country-specific intercept in the growth equation) and then we have the growth rate of the available technology for all the subsequent years. Both variables[80] are relevant in the levels and in the growth equations. The results obtained for the level equation (using fixed effects and instrumental variables) confirm the relevance of the various variables used to proxy available ICT technology:[81] the coefficients are positive and significant (the largest coefficients are reported for main telephone lines per 1,000 inhabitants and for mobile phones per 1,000 people). When looking at the impact of ICT on per-capita GDP growth rates (as opposed to levels), the start-of-period values for the ICT variables enter with a positive and significant coefficient (especially for main telephone lines per 1,000 inhabitants and for mobile phones per 1,000 people), while the only growth rates for the variables capturing available ICT technology that enter with a positive and significant coefficient are the number of mobile phones per 1,000 people and the number of personal computers per 1,000 people (the composite index has a positive and significant coefficient as well).

Similar results are obtained by Biagi (2005), who estimates the impact of ICT diffusion on GDP per capita growth with a balanced panel of 14 European Countries plus the U.S. for the period 1980-

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[79] In the short run the coefficient on ICT capital is significant only for the Small and Medium Countries but the coefficient is about two thirds of the one observed for the same group in the long run.

[80] The variables used to capture the levels and the growth rates for the available ICT technology are: 1) the number of main telephone lines per 1,000 inhabitants, 2) Internet hosts per 10,000 people or the number of computers with active Internet Protocol (IP) addresses connected to the Internet per 10,000 people; 3) mobile phones per 1,000 people, 4) personal computers per 1,000 people. The authors also consider a composite indicator of the previous four (notice that not all the ICT variables are observables for the same number of years).

[81] In this case, because of the use of fixed effects, the authors cannot control separately for the initial level of ICT and for its growth rate and they simply use the level of ICT available technology at each year (under the various definitions for the ICT variable).

2000, using the ratio of ICT capital over total capital as a measure of ICT diffusion. Under the preferred estimation (GMM estimation), both the level of ICT diffusion and its rate of change affect positively per-capita growth. Moreover, the results indicate that countries spend most of their time close to their steady state, which itself depends upon the level of technology and its progress, hence indicating that investments in ICT can be an important source of growth.

The first to look at the relationship between institutions, investment in ICT and productivity are Gust and Marquez (2004), who focus on the E.U.-U.S. productivity gap and its relationship with investment in ICT and analyse whether the lower investment in ICT and the lower productivity impact of ICT in the E.U. can be related to the regulatory framework in the E.U. relative to the one of the U.S.. In particular, their main interests reside in labour and product market regulations. Their working hypothesis is that excess product regulation –creating barriers to entry and exit and hence reducing market dynamism- reduces the incentives to invest and adopt new technologies. Similarly, rigidities in the labour market tend to reduce the ability of firms to adjust flexibly their workforce (as suggested by the ICT-Organizational change- Human capital complementarity hypothesis) and hence discourage ICT adoption and reduce the impact of ICT on productivity.[82] The authors regress labour productivity growth rates on the share of ICT production over total GDP (to capture the size of the ICT-producing sector) and the share of expenditures in ICT over GDP (to measure diffusion of ICT within the economy), while controlling for changes in the labour force participation rate. They find that both ICT-related variables are positively and significantly correlated with productivity growth (the coefficient on the share of ICT production over GDP tends to be more robust to the introduction of additional controls[83]). When exploring the determinants of ICT expenditures, Gust and Marquez add, as additional controls, human capital (proxied by the years of schooling in a given country), the share of the service sector (to control for differences in industrial composition), an index of overall regulatory burden, an index capturing the regulatory burden to start-ups (Word Competitiveness Report 1993 and Global Competitiveness report 1998) and an employment protection legislation index (ELP developed by the OECD). They also control for an index of the availability of Venture Capital and an index of trade openness. While they find clear indications that years of schooling and the share of the service sector are positively and significantly associated with greater ICT expenditures, the evidence on the variables capturing the regulatory burden and employment protection is less clear. On the one hand, the general and the start-up specific regulatory burden indexes enter with a negative and significant coefficient, when no additional controls are included. On the other one, the significance of such coefficients is not robust to the introduction of additional variables (probably capturing some form of multi-collinerarity). The ELP variable – when considered alone- enters with a negative and significant sign. However, when the variable capturing ELP protection is considered together with the other two variables capturing the intensity of regulatory burden in the product market, the coefficients on the regulatory variables are no longer individually significant, while they still remain jointly significant. Overall, these results tend to indicate that increased regulatory burdens, either related to general business or to starting a business or specific to the labour market, tend to be associated to lower ICT expenditures, and hence, indirectly, to lower productivity growth.

[82] The hypothesis that rigidities in the labour market can have a negative effect on technological progress can be found in Saint-Paul (2002). For a pioneering analysis of the relationship between investment and labour market rigidities see Bertola (1994).

[83] The results for both ICT related variables are quite robust to the introduction of country fixed effects.

More recently, Conway et al. (2006) have looked at the impact of ICT diffusion on the relationship between product market regulation and productivity growth. Their intuition is that a given level of product market regulation might have a stronger negative impact on productivity growth for countries and sectors that tend to produce or use ICT more extensively, because it is exactly in these cases that a stronger regulatory burden raises barriers to technological improvement and reduces incentives to innovate.[84] This implies that countries/sectors that use ICT more extensively have an additional advantage in lowering product market regulation because, by doing do, they are able to reap the full benefits of ICT investment. Conway et al. (2006) construct a country and sector-specific regulatory index[85] (regulation impact indicator). The analysis is conducted using both aggregate business sector data[86] and sectoral data.[87] In both cases, Conway et al. (2006) regress productivity growth in a given country/sector on productivity growth in the leader country/sector (to control for changes in the technological frontier), for the productivity gap with respect to the latter (to control for the speed of the technological catch-up process), on country/industry and time dummies, on the regulation impact indicator and on the interaction between the latter and the productivity gap (the hypothesis is that the higher is the technological gap the more regulation hinders productivity growth). The author finds that productivity growth in the leader country/sector is positively related to other countries/sector productivity growth in all specifications. They also find that productivity growth in a given country/sector is negatively related to the variable capturing the productivity gap, indicating that countries/sectors that are further away from the technological frontier (captured by the productivity level of the leader country/sector) tend to growth faster (possibly due to technological catch up). The speed of technological catch up, however, is slowed down by the degree of product market regulation. Interestingly, and contrary to their expectation, the authors do not find evidence of a direct effect of product market regulation on productivity growth, neither with aggregate or sectoral data (the coefficient on the regulation index is not significant). However, when using sectoral data and running the regressions separately for ICT intensive and non-ICT intensive sectors, Conway et al. (2006) find that the regulation index has a negative effect on productivity growth in the ICT intensive sector only. They interpret this result as a confirmation of the hypothesis that a higher level of regulation tends to depress productivity growth especially in more technologically advanced sectors. The authors also test whether the regulatory index has any relationship with the share of ICT investment over total investment (taken as a proxy for ICT diffusion), under the assumption that lower barriers to entry tend to increase the benefits from investment in ICT and lower the price of ICT products and services. Their results indicate that this is indeed the case: a higher level of regulation tends to be negatively correlated with the share

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84 The authors need to reconcile two apparently contrasting phenomena: a general process of cross-country reduction in product market regulation starting from 1990 (i.e. convergence in regulation towards the more liberal models) and increased across-country divergence in productivity growth.

85 Conway et al. (2006) start from an aggregate indicator of product market regulatory conditions in seven non-manufacturing sectors, which is then transformed in a country and sector-specific regulatory index for all the sectors by multiplying the former by weights measuring the extent to which intermediate inputs from these non-manufacturing sectors are purchases and used by all the other sectors of the economy. The hypothesis is that regulation in non–manufacturing sectors affects not only the market conditions in the latters but also the cost structure in the sectors that use their product as intermediate inputs.

86 For the aggregate business sector model, Conway et al. (2006) use data for 21 OECD countries from 1978 to 2003.

87 For the sectoral model, Conway et al. (2006) use data for 20 OECD countries and 20 sectors from 1981 to 2003.

of ICT investment over total investment and product market regulation is estimated to explain about 12% of the cross-country variation in ICT (relative) investment.

Various studies have used sectoral data and investigated the GPT nature of ICT by looking at the relationship between ICT investment and diffusion (however measured) and TFP growth in ICT-using sectors.[88] The results obtained by these studies are mixed. Using U.S. data, Stiroh (2002a) and Basu and Fernald (2007), find a positive correlation using industry level data, while Berndt and Morrison (1995) and Stiroh (2002b) do not.[89] Similar negative evidence is found using EUKLEMS data by Inklaar et al. (2008) and by Van Ark and Inklaar (2005), while McMorrow et al (2010) find only very mild and not very robust evidence of a positive relationship. In the following pages we will review the studies that, in our opinion, are more informative.

Stiroh (2002a) considers 61 U.S. industries in the period 1987-1999 and it relates the post-1995 TFP growth performance to the intensity of ICT investment in 1995 (i.e. lagged values). The positive relationship between TFP growth and lagged values of ICT investment is compatible with the GPT interpretation of ICT. These results are also in line with those obtained by Basu and Fernald (2007), who regress industry-specific measures of TFP on contemporaneous and lagged values of ICT capital growth and find that, while lagged values are positively correlated with TFP, current ICT investment is not (in fact it is negatively correlated). This is interpreted as evidence in favour of the GPT hypothesis, according to which it takes complementary investments and time to make ICT productive.[90] However, Basu and Fernald (2007) also argue that this evidence cannot be interpreted

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88 In Sect. 4.1.2 we have already discussed the important consequences arising from the classification of sectors into ICT-using versus non ICT using.

89 The results obtained by Stiroh in the two papers might appear contradictory, but in fact they are not In Stiroh (2002b) the author looks at the relationship between contemporaneous investment intensity in ICT and TFP growth within the manufacturing sector, while in Stiroh (2002a) the analysis is conducted on all the sectors and it relates the post-1995 TFP growth performance to the intensity of ICT investment in 1995. The opposite results found in the two papers can hence be reconciled realizing that Stiroh (2002b) only considers the manufacturing sector and relates TFP growth to contemporaneous ICT investment, while in Stiroh (2002a) the analysis is extended to all the sectors and the focus is on the relationship between post-1995 TFP growth and 1995 values of ICT investment (i.e. lagged values). The positive relationship between TFP growth and lagged values of ICT investment is hence perfectly compatible with the GPT interpretation of ICT.

90 Indirect evidence on the GPT nature of ICT is contained in Stiroh (2010), where he looks at U.S. industry data for the period 1987-2000 and finds that the coefficient for the gross output elasticity on ICT capital varies considerably depending on the specification used. In particular, when only year-dummies are included, the point estimate is 0.047 but this value is reduced to 0.012 when industry fixed effects are introduced. While the first number implies excess return to ICT capital (and hence potential spillovers from ICT), the second one does not. Stiroh (2010) contains also a meta-analysis that looks at the results of 20 different studies on ICT and productivity conducted at different levels of aggregation, for different sample periods and using different econometric specifications. The mean elasticity of ICT capital across these studies is about 0.05, but the standard deviation is also quite high (0.05). The results of the meta-analysis indicate that firm-level studies tend to produce lower elasticities, compared to studies using more aggregate data. Moreover, studies using more recent data tend to show higher elasticity (in part because the diffusion on ICT has increased with time), while studies using gross output tend to obtain lower coefficients than those using value added. A reduction in the coefficient is also found when fixed effects are introduced. Finally, about 35% of the variation in the estimated elasticities is predictable, i.e. can be explained by the characteristics of the data and by the methodological approach. This reinforces the confidence that, indeed, ICT have an impact on growth. However, this result also confirms that there exists a large variation in estimates that cannot be accounted for by observable characteristics, so that it is very difficult to select a unique value for the elasticity of labour productivity to ICT as the preferred one. This

as confirmation of the new-growth theory interpretation of the role of ICT, as a purely neoclassical one would be possible if investment in complementary assets goes unmeasured (i.e. if we were able to measure all the investment in complementary assets, which are typically intangibles, the correlation between TFP and lagged ICT investment would disappear, since TFP is in fact measuring such complementary assets). Motivated by this research question, Acharya and Basu (2010) try to understand whether the use of ICT (however proxied) generates true spillover effects -which would justify a positive relationship between ICT use/investment/diffusion and TFP growth in ICT-using sectors- or whether ICT use/investment/diffusion goes hand-in-hand with complementary investments which, when not properly accounted for in the growth-accounting exercise, show up as TFP[91] (since they are by definition complementary to ICT we find a positive correlation between ICT and TFP growth). This is an important question, as the policy implications are quite different in the two cases: if ICT generates positive externalities there is room for a policy supporting investment in ICT investment. However no support for a similar policy would be justifiable if we simply have a mis-measurement problem. Using data for 24 industries for 16 major OECD countries in the interval 1973-2004, the authors reject the "ICT externality hypothesis"[92] and in favour of the "mis-measurement of complementary assets[93]" one. However, such results are not clear cut.

Similarly, Inklaar et al. (2008), who, use the EUKLEMS dataset and control for distance-to-frontier[94], find no evidence in favour of the hypothesis that ICT adoption positively affects TFP in ICT-using sectors, hence concluding against the GPT nature of ICT (and confirming the appropriateness of the neoclassical model). Analogous results are obtained by McMorrow et al (2010) who analyse the determinants of TFP growth in the context of the E.U.-U.S. productivity gap, using data from the EUKLEMS for 9 E.U. countries and the U.S. in the period 1980-2004. Their main research hypothesis, which is in line with the new-Schumpeterian approach to economic growth, posits that, for each sector and country, the rate of growth of TFP is a function of: *i*) the rate of TFP growth in the same sector in the frontier country (which captures the public good aspects of technological progress); *ii*) a sector-country specific technological gap, expressed by the logarithm of the ratio between TFP in each country-sector and TFP in the same sector in the leading country (to capture the idea that countries far away from the technological frontier might benefit from imitation); *iii*) human capital (captured by the share of skilled labour compensation); *iv*) share of ICT capital (captured by the ratio of ICT capital over non ICT capital) and *v*) the share of R&D expenses over total expenses. The results indicate that the coefficient on the share of ICT capital is significant only when industry effects are not controlled for, indicating that investment in ICT does not have an additional effect on TFP growth once sectoral differences are properly controlled for.

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also implies that it is hard to provide a unique reliable number for ex-ante assessments of the impact of ICT on growth.

91 In general, if we mismeasure output, the contribution of TFP is underestimated when unmeasured output is growing. Symmetrically, if we do not measure inputs correctly, we are going to have a overestimation of TFP when unmeasured inputs are growing.

92 As a proxy for the positive externality from investment in ICT they use the aggregate value for ICT capital at the country level.

93 As a proxy for complementarity between ICT and other asses the authors use contemporaneous and lagged values for the product between the within-industry share of ICT capital in gross output and the growth rate of ICT capital in any given industry. They expect a negative coefficient on contemporaneous values and a positive one for the lagged value, given that current investment in ICT distracts resources from output production, resources that become productive only with a time lag.

94 Distance to frontier is approximated by the ratio of country and sector-specific TFP level to the same sector TFP levels observed in the U.S.

It seem safe to conclude that, aggregate data provide convincing evidence that ICTs are an important determinant of long-run GDP growth, and more so for the U.S. than for the E.U.. However, when looking at the GPT hypothesis, sector data do not provide conclusive evidence either in favour or against it. The use of more granular data might turn out to be very useful.

4.2.2 Analysis from firm or plant-level data

A better understanding of the relationship between ICT and productivity –including the GPT hypothesis- can be obtained using firm or plant level data, possibly in longitudinal form, especially if one is interested in the role of complementary assets.[95]

Brynjolfsson and Hitt (2003), who study a panel of 527 U.S. firms in the period 1987-1994, provide indirect evidence in favour of the GPT hypothesis, as they find that computer spending affects positively measured total factor productivity, and it does so more in the long-run (five years or more) than in the short-run (one year). These results are also consistent with Brynjolfsson and Hitt (1995), who find that the long-run elasticity of output to ICT capital tends to exceed ICT capital costs and they both indicate that ICT, through investment in complementary assets, can generate additional increases in productivity. However, given that there is no direct control for spillover effects, such evidence is only indirectly consistent with the GPT hypothesis, as it can simply be due to lack of appropriate controls for the investment in the complementary assets.

The first formal test of the size of spillovers from ICT can be found in van Leeuwen and van der Wiel (2003), who use Dutch market services firm-level data for the period 1994-1998 to investigate whether the high rate of return to ICT capital could, in fact, hide the presence of some relevant positive externalities related to aggregate ICT diffusion. In particular, they assume that such spillovers could be well captured by the ICT capital stock at the industry level[96] (from which the firm's own ICT capital stock is subtracted). Their system-GMM estimates indicate that ICT spillovers are significant and sizable. Moreover, when comparing the estimates obtained when controlling for ICT spillovers with those obtained when excluding them, the authors find that the coefficient on own ICT capital in the latter case is about twice as high as the coefficient in the former, indicating that the excess return on own ICT capital – at least for the sample used in this study- is really the outcome of ICT spillovers which are correlated with own ICT capital (the other possible explanation that relies on the correlation between ICT capital and unmeasured complementary assets cannot be tested here since the authors do not have data on such assets). Notice that, by explicitly controlling for ICT spillovers, the importance of ICT capital deepening is reduced and the results are in line with those of the growth-accounting literature.

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[95] Besides those considered here, other studies have looked at the relationship between ICT and productivity at the firm level. Broersma et al. (2003) find that computers contributed positively to productivity, even when firm-specific effects such as labour quality are accounted for. In retail trade, computers yielded returns above their relatively high rental price. Doms et al. (2004) find evidence of a significant relationship between ICT investment intensity and productivity growth for large firms. Large firms also account for most retail ICT investment, employment and establishment growth. Mendelson and Pillai (1997) use survey data on computer and electronic industry and find a positive relation between the measure of "digitalization" and business success (profitability and growth). For a discussion of the econometric issues related to the estimation of the productivity effect of ICT using firm-level data see Hempell (2002).

[96] The effects of the ICT spillover in a growth accounting exercise would be attributed to TFP.

Using company data for the U.S. and four European countries (UK, Germany, France and the Netherlands) for the period 1991-2001, Rincon and Vecchi (2010) directly investigate the GPT nature of ICT. The authors regress output growth on the growth of capital, labour and R&D capital, capturing ICT spillovers with three different variables. First, they introduce the value of ICT capital at each industry level, which accounts for spillovers within the industry (intra-industry spillover). Then they control for cross-industries spillovers by combining industry ICT according to the taxonomy developed by van Ark et al. (2002), which distinguishes industries based on whether they use ICT more or less intensively (industries that fall into the same category share the same spillovers). Finally, they also control for the size of ICT investment in the U.S., taken as the frontier country in ICT investment (this variable is relevant only for the E.U. countries). The results for the U.S. indicate that both the within and the cross-industry spillovers affect positively short-run productivity, with the effect of the former effects dominating in size.[97] Surprisingly, the same does not hold for the European countries, as both inter-industry and intra-industry effects are not significant (the coefficient on the level of ICT investment in the U.S. is not significant either). However, when they consider the long-run by means of estimating a co-integration relationship, they confirm the relevance of both types of spillovers for the U.S. (the effects are stronger for manufacturing and for the intra-industry variable). As for Europe, they find evidence that there exist positive and significant effects from both intra and inter-industry spillovers (with stronger effects for the latter and for the manufacturing sector).

A recent study by Van Reenen et al. (2010) studies the impact of ICT capital on labour productivity using a firm-level dataset of 13 European countries for the period 1998-2008 (AMATECH). Their results indicate that a 10% increase in ICT capital is associated to an increase in output between 0.9% and 0.23% (the latter is the preferred estimate) and hence confirm the importance of ICT for growth (these results are in line with those by Brynjolfsson and Hitt, 2003, estimated for the U.S. in the period 1987-1994). Notice that these values also imply “above normal” returns to ICT investment,[98] which, however, cannot be taken as evidence of spillover effects from ICT as they can

[97] Rincon et al. (2012) focuses only on the US and, while confirming the choice of industry ICT capital as the proxy for the intra-industry spillovers, as a measure for the cross-industry (i.e. inter-industry) spillovers uses a weighted ICT industry variable, where the weights are given by input-output coefficients (this captures potential benefits that each industry might get from investments in ICT by upstream and downstream industries). The results show that intra industry-spillovers have a contemporaneous negative effects (it takes about five years to have a positive effect of such spillovers), while inter-industry spillovers affect positively productivity, both in the short-run and in the long-run (more so in the long run).

[98] Brynjolfsson and Hitt (2003), studying a panel of U.S. firms for the period 1987-1994 find that the coefficient on ICT capital is the range 0.020-0.035, which is consistent with a return higher than the share of ICT capital in the production function. When Van Reenen et al. (2010) perform a similar analysis using both U.S. and E.U. data for the period 1996-2008 they find similar coefficients on ICT for the E.U. and the U.S.. Moreover, they also document that there are large within-E.U. across-country variation in estimates for the elasticity of output to ICT capital, with the highest values registered for the U.K. However, most of this large across-country variation disappears when firm-specific fixed effects are introduced, pointing to the fact that –within the E.U.- firms-specific unobservable characteristics are driving the results. The importance of unobservable characteristics is confirmed when they introduce time-varying country specific proxies for labour and product market regulation –which could explain the observed cross-country variation in estimated coefficients. Van Reenen at el. (2010) find that such variables are negatively and significantly interacting with ICT investment (i.e. the same level of ICT investment has lower effects on output the more the labour market and the product market are regulated), but the significancy of this coefficient disappears as firm-specific fixed effects are introduced. Notice that, when significant, the effects are five times larger for the proxy of labour market regulation. It is also worth mentioning that Van Reenen et al. (2010) find evidence supporting the theory that the labour productivity effects of ICT

simply be traced back to the effects of (unmeasured) assets that complement ICT capital.[99] This is one of the main reasons why scholars have moved to the analysis of complementarity between ICT and other assets -mainly organizational and human capital.[100]

The literature that, in the last 15 years, has studied the relationship between ICT capital and organizational and human capital is, in fact, the result of the intersection between different strands. On the one hand we have the literature on the effect of work-practices on productivity and wage inequality, while, on the other one, we have the literature that studies the impact of ICT induced changes on firms' organizational structure and productivity. These two strands have been brilliantly joined by Brynjolfsson and co-authors.

As Brynjolfsson writes, there are "two central questions which comprise the productivity paradox: 1) Why would companies invest so heavily in information technology if it didn't add to productivity; 2) If information technology is contributing to productivity, why is it so difficult to measure it?"

The answers to these questions clearly depend on the ability to properly measure all the relevant factors. However, many of the benefits from computerization are often indirect and hard to measure effects[101] and ICT become productive only when coupled with investment in complementary assets, such as organizational and human capital, which need to be measured as well.

The implications of the complementarity hypothesis (which goes back to Milgrom and Roberts, 1990) are that: 1) ICT investment, per se, might have a very low positive impact on productivity (in fact the impact could even be negative); 2) the impact of ICT investment becomes largely positive once it is coupled with organizational change (which, per se, might have a small positive impact); 3) due to the complementarity between ICT investment and organizational change, we should expect some lag between the time we record the investment in ICT and the time we observe the positive impact on productivity and this time-lag is entirely due to the organizational change that the firm has to go through if it wants to reap the full benefit of ICT investment; 4) the distribution of skills among the workforce and the level of human capital are important in determining the impact of ICT investment and organizational change; 5) not all firms could benefit in the same way from ICT investment since not all firms (and not all sectors) are able to implement successful organizational change.

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investment are particularly high in sectors that are ICT intensive. However they do not find evidence supporting the hypothesis that the impact of ICT on labour productivity changes with firm's size of firm's age.

[99] The coefficient on ICT capital estimated in the productivity equation would be capturing both the effect of ICT capital and the effects of the assets that are complementary to it (including the interaction between them). But this also implies that the excess return to ICT would disappear once the complementary effects have been controlled for.

[100] Being a general purpose technology, ICT is embedded in many manufacturing products and it gives rise to a process of co-invention. New process and product innovations are the result of the investment in ICT, especially by the service sector. Moreover, ICT is an enabler of organizational change: it leads to a redefinition of strategies, of processes and of the practices with clear results on the operational and innovation capabilities of firms.

[101] Brynjolfsson and co-authors conclude that the real benefits from computerization could be of an order of magnitude (i.e. 10 times larger) than those that are normally recorded by growth accounting exercises with macro data.

The complementarity hypothesis[102] and the derived corollaries are important because they provide: a) an explanation for the Solow's paradox (it takes time to observe the benefits from computerization); b) an explanation for the large increase in productivity observed in the U.S. in the second half of the nineties (especially in ICT-using sectors); c) an interesting interpretation for inter-firm and inter-sector variability in the impact of ICT on productivity (which the data show).

The types of organizational changes that are particularly relevant when thinking about ICT are related to organizational practices that influence the costs of information gathering and processing. As Malone (1987) and Radner (1993) noticed, hierarchical organizational structures (i.e. vertically integrated ones) typically emerge when communication costs are high: a hierarchical structure reduces the number of communication nodes between the different actors and hence reduces costs.[103] However, since the ICT revolution has clearly reduced the costs of gathering and transferring information, we expect that the new technology permits and complements better with more horizontal structures. Analogously, the standardization of products if mostly appropriate in situations in which the production function is at the same time inflexible and subject to economies of scale. Flexibility and the extent of economies of scale are variables that are heavily touched by the ICT revolution[104] (see Appendix 2).

The management literature is full of case studies that show the potential and actual benefits arising from digitalization and workplace restructuring, but if one wants to obtain an estimate of their overall impact it is necessary to rely on large-sample empirical studies.[105] Among the first studies we have Brynjolfsson and Hitt (1995, 1996) and Lichtenberg (1995) where a production function is estimated including ICT capital and ICT labour among the regressors. Results from these studies show a clear positive relationship between productivity and ICT investment. These studies also show that the contribution of ICT capital to output (i.e. the output elasticity of ICT capital) is generally higher than the measured input share of ICT. A possible interpretation of this mismatch is the fact that the input share is under-measured, because the traditional measure do not take into account the role of (unmeasured) complementary investment (i.e. there are large but unmeasured inputs that are correlated with measured ICT). Evidence in favour of this hypothesis comes from studies that have looked at the long-run impact of ICT investment on productivity. For instance, Brynjolfsson and Hitt (2000) find that the returns to ICT investment are higher when a longer period is considered (up to 7 years after the investment): the lag between the time the investment is made and the time in which it becomes mostly productive are interpreted as the expression of time needed (and the associated costs) for the re-organization that firms have to go through when they invest in ICT. The effects of ICT capital are up to five times higher in the long-run when compared to the short-run.

[102] A further point is related to the differential impact of ICT on the organisational structure of large and small companies which may constitute a further point of analysis with special emphasis on two different but complementary phenomena: the externalisation and sub–contracting of non–core activities by large companies and the attempt of building networks by small and medium enterprises in order to cope with the technological change and the economic instability connected with the globalisation process.

[103] See also Garicano (2000) and Garicano and Rossi-Hansberg (2006).

[104] Notice that these changes can apply both to manufacturing and services (and hence perhaps explain the increased productivity in services).

[105] As already mentioned, these studies need be conducted at the firm or plant level, since it is only at this lower level of aggregation that the phenomena of interest are measurable.

In Brynjolfsson et al. (2002), the authors document the fact that firms that invest in computers have an increase in their market evaluation of about 10 dollars for every dollar invested. However, such a high return is observed in firms that accompany the ICT investment with organizational change (specifically with a greater use of teams, broader distribution of decision rights and increased workers training). This is again interpreted in favour of the hypothesis that ICT lower the costs of information acquisition and processing and this leads to preference for organizational structures that are based on delegation and decentralized decision-making.

Bresnahan et al. (2002) study the impact of ICT and organizational change on the skill composition of the demand for labour. The authors find that IT investments and organizational change,[106] coupled with changes in products and services offered by the firm, induce a shift in the demand for labour that favours skilled labour over unskilled on. This result is taken as evidence that IT and organizational change become more productive when they are realized in an environment in which skilled labour is relatively more abundant. This is possible because the organizational redesign that favours more decentralized decision-making and focusses on product and service development works better in environments in which skills are horizontally distributed. As for organizational change, the variables considered by Bresnahan et al (2002) are: increased delegation of authority to individuals and teams, greater level of skill and education in the workforce, greater emphasis on pre-employment screening for education and training.[107]

Particular attention to the issue of organizational capital and organizational change is present in the work by Black and Lynch.[108] After having defined and measured organizational capital, in Black and

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[106] The proxy for organizational change is a linear combination of questions of team working (team use, team building activities, teamwork as a promotion criterion and the use of employee involvement groups or quality circles), and the extent to which workers have authority over their pace and methods of work. Notice that this variable is obtained from a cross-section (conducted in 1995 and 1996), while data on productivity and ICT are obtained from a 1987-1994 longitudinal dataset. Approximately 55% of the observations are from manufacturing, mining or construction and 45% are from services. Notice that the variable used by Bresnahan et al. (2002) can be interpreted as a proxy for organizational capital but hardly for organizational change, even if Bresnahan and coauthors argue the contrary.

[107] It is also interesting to note that the authors find that these practices are correlated among themselves, in other words they constitute a complementary work-system. Similar results have later been confirmed by studies that have looked at sectorial dynamics. Sectorial studies also confirmed that IT tend to be associated with smaller firms and less vertical integration, confirming the theoretical prediction that IT lowers procurement costs.

[108] In Black and Lynch (2005) the two authors provide a taxonomy of organizational capital, which is divided into three broad components: workforce training, employee voice and work design Workforce training is a joint decision undertaken by the worker and the firm to invest in additional skills training after an employment relationship has begun. Training is necessary when new technologies are introduced, but it is also very useful when new organizational structures -such a team work- are put in place. Employee voice is defined as "*organizational structures that give workers, especially non-managerial workers, input into the decision making associated with the design of the production process and greater autonomy and discretion in the structure of their work. Traditional forms of work organization are very task-specific; each production worker has a specific task to complete, and once they learn how to accomplish the task, there is little independent though involved. However, newer forms of organization involve giving employees, specifically lower level production workers, more input into the production process and greater opportunities to improve efficiency. As employees voice increases, firms are better able to tap into the knowledge of non-managerial workers*". Finally, work design includes the use of cross-functional production processes that result in more flexible allocation and re-allocation of labour in the firm(changes in the occupational structure of the workplace, the number of workers per supervisor, the number of levels of management within the firm, the existence and diffusion of job rotation, and job share arrangements,

Lynch (2004) the two authors look at the impact of organizational change and ICT capital (proxied by the share of non-managerial workers that use a PC) on labour productivity. In their work the two authors use two cross-sections (1993 and 1996) from the Educational Quality of the Workforce National Employer Survey,[109] which contains a series of measures for organizational capital and technological change, and estimate productivity equation using both the 1996 cross-section and a longitudinal dataset, obtained from the two cross-sections matched with the Bureau of the Census' Longitudinal Research Database.[110] Their results confirm that high-performance workplace practices (incentive schemes offering profit-sharing or stock options) and employee voice (share of workers involved in the decision making process) are positively and significantly associated with higher productivity. The same holds for the share of non-managers who use computers at work (the proxy for ICT). Black and Lynch also show that establishments with unionized and traditional labour-management relationships (with little or no participation of employees in decision making) have lower productivity, compared to unionized plants that have adopted new workplace practices (they are also more productive than non-unionized plants that have adopted similar high performance workplace practices). These results lead the two authors to conclude that "*establishment practices that encourage workers to think and interact in order to improve the production process are strongly associated with increased firm productivity*". Moreover "*the higher the average educational level of production workers within a plant is, the more likely the plan has performed better than average over the period*".

Black and Lynch also estimate the overall impact of organizational capital on TFP growth in the manufacturing sector. They find that workplace practices contributed 1.4 percentage points per year, so that "*changes in organizational capital may have accounted for approximately 30 percent of output growth in manufacturing over the period 1993-1996, or 89 percent of multifactor productivity*". This is indeed a very large number to be associated to investment in the so-called organizational capital, and the two authors are well aware that many of the components of workplace practices are strongly associated with technological change (such as IT investment). However, given that their specification does not include interaction terms between changes in organizational capital and ICT investment, they are not able to assess the role of the two factors when considered separately from the role they have when they are considered jointly.[111]

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the use of benchmarking). Even if not an organizational practice per se, incentive-based compensation are often associated to an increase in organizational capital. As Black and Lynch say "*while incentive-based pay is not organizational capital per se, it is an important glue that holds the organizational capital together and keeps it within the firm*".

[109] The Survey has been subministered to both manufacturing and non-manufacturing firms, but Black and Lynch only look at manufacturing firms.

[110] This is important because in previous work the two authors estimated the same equation with just one cross-section of the EQW-NES so that they were not able to focus on changes in organizational capital (besides facing the risk of bias in their estimate).

[111] Interesting for the perspective of this study is also Lynch (2007), where the author looks at the determinants of organizational change. She finds that past profits tends to be positively associated with organizational innovations, indicating that only firms that have deeper pockets can afford the costs of investing in organizational capital. She also finds that firms with a more external focus and broader networks (those that export a higher fraction of their output, use benchmarking and are part of a multi-establishment firm) are more likely to learn about best practices and adopt them. Moreover, she finds that firms' investments in human capital, information technology, R&D and -more generally- in physical capital appear to be complementary and precede investments in organizational innovation. The issue of timing is important here because it shows how firms first invest in technology and then they shape their

Additional evidence on the positive impact of innovative HR management systems on productivity can be gathered by the work of Ichiniowski, Shaw and co-authors (well summarized in Ichiniowski and Shaw, 2003). One of the reasons behind the positive impact of workplace re-organization on productivity is that the former interacts with the information diffusion process. If speed, breadth and depth of information diffusion within the firm have an impact on firms' innovative capacity, then we have an additional source of ICT, organizational capital and human capital complementarity: firms can become more productive if they properly use ICT to obtain a more fluid information diffusion process, which works best when the firms' organizational structure and human capital is shaped so as to take advantage of ICT.[112]

Particularly interesting are the studies that have looked at the relationship between ICT, organizational change, human capital and productivity growth for E.U. countries.

The first one is Caroli and Van Reenen (2001), who use French data to test the ICT-Organizational Change (OC)-Human Capital (HC) complementarity hypothesis, according to which recent managerial changes (possibly ICT induced) shifting towards less hierarchical and more flexible organization forms, to be successfully implemented need workers with a high human capital level, since in such organizational forms workers have to deal with increased uncertainty and responsibility.[113] Benefits from decentralization of decision making processes arise first because of the reduction in costs of information transfer and communication: information is processed at the level where it is used. Second, decentralization increases firms' reactivity to market changes. In a hierarchical environment, where tasks are more specialized and defined for each layer, we expect that reaction to market changes involve the coordination of a large number of activities. If the coordination costs are high, the reaction time might be slow. In more horizontal structures workers usually work in teams and, in each team, multiple skills and tasks are present, so that coordination

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organization so as to make the investment fully productive. Finally she finds that organizational innovations are more likely in firms where the management is younger.

112 The empirical literature on this is quite scant, but there is a paper by Aral, Brynjolfsson and Alstyne (2012) that it is worth mentioning. The three authors are able to study the social network of a medium size executive recruiting firm, using 10 months of e-mail data and accounting data detailing project co-work relationship. Over this period they divide the type of information shared in two groups. On the one hand they have messages that fall into the category of "event news" defined as simple declarative, factual information that is likely triggered by external events and is often of general interest to people in the organization. On the other hand they have "discussion topics", which are more specific, complex, procedural and characterized by back-and-forth discussion of interest to limited and specialized groups of people. They find that the diffusion of the two types of information follows different paths. In particular they find that "event news" –which are diffused pervasively through the organization- are influenced by demographic and network factors, but not by functional relationships or strength of ties with co-workers. On the contrary, diffusion of "discussion topics" (which is more shallow and characterized by more back-and-forth communications), is heavily influenced by functional relationships and the strength of ties, as well as demographic and network factors. It is also important to notice that access to information strongly predicts employees' productivity (the impact of the proxy for access to information has a stronger impact on productivity than traditional human capital variables, such as education and experience). These results, which obviously cannot be generalized beyond this case, are anyway interesting because they show that information diffusion –which is generally improved by the adoption of ICT- has a strong impact on productivity.

113 New organizational models are characterized by a shorter chain of command and a substantial portion of decision-making is delegated to lower levels. As long as education helps in increasing the capability of solving problems, we expect these organizational changes to be correlated with higher education levels in the workforce. As a corollary, this also implies that organizational change implemented without the appropriate work-force ends up being unproductive.

costs are reduced and response to market change can be faster. Third, decentralization reduces monitoring costs. Finally decentralization might improve productivity through rising job satisfaction: workers are more involved, they participate at some level at the decision and implementation process and get more satisfaction from their job.

However decentralization does not come for free. Costs of decentralization can be summarized as follows. First, in the absence of centralized decision making there is a risk of replication of information processing. Second, reduced monitoring can lead to increased risk of errors. Decentralization also tends to jeopardize the exploitation of increasing returns to scale (in decentralized structures multitasking prevails, but multitasking reduces the possibility of obtaining returns from specialization, which is one of the elements of increasing returns to scale). Finally, workers might not like the additional risk and stress arising from being part of the decision making process and they might respond to this by reducing their effort and hence their productivity.

In general, higher skills are expected to improve the ability to process information: the benefits of decentralizing information processing are expected to be increasing in the skill composition of the workforce. Skilled workers are also more able to communicate, hence reducing the risk of duplication of information, and are also more apt to multitasking and easier to train. Caroli and Van Reenen argue that "*a higher skill level of the workforce tends to reduce the costs and increase the benefits of decentralization. In other words, skills appear to complement organizational change*". The major implications for empirical analysis are that: 1) organizational change leads to skill upgrading; 2) skill-intensive firms are likely to reap greater productivity growth from organizational change. The interplay between skill composition and organizational change is also affected by technology. More specifically, the introduction of ICT reduces the costs of ex-post monitoring, reduces the risk of mistakes and reduces the communication costs among workers, while at the same time increasing their ability to process information. All these aspects lead Caroli and Van Reenen to predict that high skills, organizational change and ICT diffusion are complementary.

Their results confirm the hypothesis that organizational change and the skill composition are complementary in a productivity equation. As for complementarity between OC and ICT, their results are mixed: on the one hand the interaction term is positive, indicating that positive interactions indeed exist. On the other one, the estimated coefficient is not significant at customary significance levels. The authors read their overall results of a clear indication of Skill-Biased-Organizational-Change, while –for the complementarity hypothesis between OC and ICT- they think that the evidence gathered is indicative of its existence and they justify the poor significance of the coefficients on the ground of likely multi-collinerarity between OC and ICT. In other words, if ICT and OC are always strongly associated (because managers know that ICT investment is productive only when complemented with OC), then it is almost impossible to estimate the impact of each factor individually on the overall firm's performance.[114]

Crespi et al. (2007) look at the issue of complementarity between ICT capital and OC using UK data from the Third Community Innovation Survey (which records info on firms' activity between 1998 and 2000, covering firms in manufacturing and services). The variable used to capture OC are the following: a) implementation of new or significantly changed corporate strategies (e.g. mission

[114] The variable used by Caroli and Van Reenen for organizational change in France captures the presence of the following elements: delayering (i.e. removing one or more managerial levels); use of just-in-time production, existence of quality circles, existence of total-quality-management.

statement, market share); b) implementation of advanced management techniques within the firms (e.g. knowledge management, quality circles); c) implementation of new or significantly changed organizational structures (e.g. investors in people, diversification); d) significant changes in the firm marketing concepts/strategies (e.g. marketing methods). In particular, b) and c) are the aspects closer to the concept of OC discussed in the literature. The authors also consider the existence of process innovation as part of organizational change. As for IT investment, the CIS reports data on the amount of expenditures on acquisitions of machinery and equipment (including computer hardware) in connection with product or process innovation. This variable is then used to create a variable that captures the fraction of total investment that goes to IT. Their results indicate that there are significant returns to IT (30%) when OC is not controlled for. However, the returns to IT are reduced when a measure for OC is introduced among the regressors, indicating that OC and IT tend to be correlated. Finally, in the specification where they also introduce an interaction term between IT and OC (capturing the complementarity effect), they find that: 1) the intensity of IT investment, per se, has a positive but not significant impact on productivity; 2) OC alone has a negative but not significant effect on productivity; 3) the interaction term between OC and IT enters with a large positive and significant estimated coefficient, indicating the existence of strong complementarities among the two variables

These results are then interpreted as evidence in favour of the complementarity hypothesis for the UK. It is also interesting to note that the authors find that U.S.-owned firms are more likely to introduce OC relative to other MNEs and exporters (but among these firms, OC is more likely than in UK non-exporting firms). This result is interesting when put in the context of the E.U. slowdown in productivity characterizing the late 20th century (especially if we think that UK firms were among the good performers): the hypothesis is that the E.U. economy is not growing as much as possible also because it is not fully benefiting from the gains that the ICT revolution, together with new management styles, would allow.

The OC-ICT complementary issue is addressed also by van Reenen et al., (2010), using an ad hoc dataset that measures management practices (see Appendix B of van Reenen et al. 2010). Their results indicate that while there is only a weak direct association between decentralization in the decision-making process and productivity, the interaction between the decentralization variable[115] and ICT shows a positive and significant (both statistically and economically) coefficient, indicating that, indeed, ICT is more productive in more decentralized firms (which is robust to the introduction of firm-specific fixed effects). They also find some evidence in favour of the hypothesis that there exist regional and industry spillovers from ICT investment (i.e. that investments in ICT benefit firms that are close either in space or in terms of technology/trade), but such evidence is not robust, inducing the authors to conclude that for ICT there is no clear evidence of a social return higher than the private return. This is someway expected, as ICT investment is embedded in capital goods whose effects are mostly appropriated by their owners and produce only limited effects on outsiders.[116]

[115] This is the unweighted average of 4 underlying variables, each of which has been normalized in order to insure comparability across variables.

[116] The case of R&D investment is different, as in this case non perfectly appropriable knowledge is created, that can be more easily transferred and used by external parties.

These results are in line with those obtained by Bloom et al. (2012), who start from the fact that, as discussed in Sect. 4.1.2, there appear to be a sizeable U.S.-E.U. gap in labour productivity in ICT-using sectors. There are at least two complementary hypotheses that are able to account for such a gap. The first one points to a locational advantage. Due to institutional, economic and social factors (such as lower taxation and regulation, higher product market competition, larger market size, higher human capital, more access to finance), the U.S. provide a better location for business and for innovative activities in particular: conditions are such that returns to adoption of new technologies (such as ICT) and innovation (in ICT-producing and ICT-using sectors) are higher in the U.S. than in the E.U.. The second one points to the role of management: U.S. managed companies might be able to better exploit ICT because they are better able to implement management practices that complement ICT investment. The results from the study by Boom et al. (2012) show that U.S. multinationals operating in Europe[117] tend to use IT more intensively than non-U.S. multinationals and domestic companies. Moreover, relative to such comparison group, U.S. multinationals seem to be able to get higher returns to ICT use, in terms of productivity growth. In particular, using a dataset which reports information on management practices in different countries (U.S. plus E.U. and Asian countries), Bloom et al (2012) are able to show that management practices, and especially "people management" practices such as those previously described, are able to account for most of the higher ICT-output elasticity of U.S. firms. These results complement those by Brynjolfsson and co-authors in confirming the importance of managerial practices in determining the overall impact of ICT on productivity.[118]

The complementarity issue has been recently explored by various studies that have more carefully looked at the actual use of ICT within the firm.[119] In the context of the ESSnet project on "Linking the micro-data on IT", funded by Eurostat and in which National Statistical Offices from 15 E.U. Countries have actively participated, it has become possible to look more precisely at the actual content of ICT utilization (as opposed to a generic monetary measure of investment in ICT) and, hence, at how the different types of ICT use tend to be complementary to organizational (and other types of) innovation. Such project, for each country, collects and merges data from the Business Register, the Production Survey, the Community Innovation Survey (CIS) and the E-business Survey. It is hence possible to link together firm characteristics, firm economic and innovative performance and actual utilization of ICT (variables measure broadband penetration, use of mobile connections, use of ICT for Enterprise Resource Planning - ERP- Supply Chain Management -SCM- or Customer Relationship Management -CRM). Using such merged meso-data (i.e. data obtained aggregating firm level observations, according to specified characteristics such as sector, size, age etc.) for year 2008, Polder (2012) find that the complementarity between the use of ICT for ERP and organizational innovation is quite high among all the 15 countries considered. However, when a more refined analysis that uses firm-level data is conducted for the Netherlands alone, the results show no significant evidence of complementarity between ERP and organizational innovation.

[117] By construction this allow to exclude (most of) the possible positive effects arising from the location of a U.S. company on U.S. soil and hence captures the additional effect of being a U.S. company on foreign soil (i.e. the U.S. management style).

[118] Biagi and Parisi (2012), looking at a panel of Italian manufacturing firms in the period 1995-2003 find no evidence of OC-ICT complementarity, while human capital and organization capital appear to jointly have a positive effect on productivity. Similar results are found by Giuri et al. (2008).

[119] The focus is not so much on "How much you invest in ICT" but on "What you do with it".

A weak complementarity between organizational innovation and investment in ICT capital –proxied by the number of employees using a PC at work[120]- is found by Polder et al. (2012) in a study on Dutch data, in which variables such as the presence of an IT-based automation system for procurement and sales, access to high-speed internet, the percentage of workers having access to internet, broadband penetration (measured by the product of the two previous variables), the percentage of e-purchases and e-sales[121] are used to predict the probabilities of given innovation profiles, while the latters are then interacted with (the proxy for) investment in ICT capital in order to test the complementarity hypothesis in the productivity equation.

Engelstatter (2013), uses data from a German survey to investigate the impact on productivity of various ICT applications to enterprise systems, such as SCM, ERP and CRM. His results show that each of the variables characterizing the enterprise system affects positively productivity (the size of the estimated coefficient on SCM is higher than the one on ERP, which is higher than the one on CRM). At the same time he also finds evidence of complementary effects between SCM and CRM, especially if the ERP system provides the necessary infrastructures for both. In a companion paper Engelstatter (2009) finds that SCM and ERP also affect positively the probability of firms realizing process innovation, both in the short and in the long-run, while CRM positively affects the probability of observing product innovation, but only in the short-run.

These papers are especially interesting as they show that ICT capital and type of ICT use capture different factors. While the former captures the overall value of investment in ICT, it is only through the ICT usage variables (use of mobile connections, broadband penetration, use of ICT for ERP and/or CRM) that it is possible to have a better and deeper understanding of the strategic choices made by the firm in reference to the actual use of digital technology in the context of its organizational structure.[122]

It also worth noting that, until recently, the line of research on complementarity between ICT and organizational capital in production developed in parallel to the line of research that investigated the relationship between R&D, innovation and productivity.[123] However, recently (Polder et al. 2010) there has been an attempt to merge these two literatures, adding organizational innovation among the innovation output variables and ICT among the innovation inputs (together with R&D), based on the recognition of the GPT feature of ICT. This approach does not directly look at complementarity (which is purely a measure of association), as it focuses on the impact of ICT on various types of

[120] This proxy for ICT investment is very debatable, as it does not take into account the additional investments in hardware and software.

[121] These variables are clearly plagued by problems of endogeneity.

[122] Notice that the complementarity issue has been investigated with sectoral data as well. Corrado et al. (2011), following Corrado et al. (2005, 2009) and in the context of the COINVEST and INNODRIVE E.U. funded projects, try to investigate the role of ICT in affecting the relationship between intangibles and productivity growth. The underlying research hypothesis, based on the OC-ICT complementarity theory, is that intangibles tend to have a higher impact on productivity in sectors that use ICT more intensively. Merging the EUKLEMS dataset with the data on intangibles obtained in the context of COINVEST and INNODRIVE, Corrado et al (2011) find that the complementarity hypothesis is strongly supported by their empirical analysis.

[123] Starting with the seminal work by Griliches (where R&D is introduced as a regressor in a productivity equation to take into account the role of knowledge) such literature has matured and reached a structural interpretation with the fundamental work by Crépon, Duguet and Mairesse (1998) and the development of their CDM model, which tries to better understand the relationship between innovation input (R&D), innovation output (product and process innovation) and productivity, through a semi-structural model.

innovation, which implies a hypothesis on the causation mechanism (ICT investment causes product/process/organizational innovation and not vice versa, due to the set-up of the CDM model). Using micro data from the Netherlands the authors find that, in manufacturing, ICT investment has only a minor and barely significant impact on organizational innovation, while, in the service sector, its effects on all types of innovation are larger and more significant.[124] However, when ICT penetration is measured with the percentage of workers who have access to a broadband, the positive effect of ICT on organizational innovation appears also in the manufacturing sector (but it is still stronger for the service sector).

Evidence in favour of the hypothesis that firms that use ICT more intensively also tend to innovate more can be found in OECD (2010), where, linking firm-level data from the ICT Business Survey to firm-level data from the Innovation Survey for 8 OECD countries, it is shown that firms that use ICT more intensively[125] are more likely to obtain new-to-the-firm (but not new-to-the-market) product innovations, organizational and marketing innovations, both in manufacturing and services. However, only in a small subset of countries ICT intensity is positively correlated with the probability of process innovation. Finally, when looking at the trajectory of innovation, the evidence indicates that ICT intensity does not increase either the probability of developing new-product or new-processes in-house or the probability of innovating through cooperation. This is interpreted as evidence that ICTs enables firms to adopt innovation but they do not increase their inventive capabilities.

Summarizing the firm-plant level based empirical literature on ICT and productivity is not easy, since the research questions addressed are different and so are the databases and the econometric techniques used. Despite these difficulties, we think that we can safely conclude that the GPT hypothesis is confirmed, especially for the U.S. and so is the complementarity hypothesis between ICT, organizational capital and human capital (again with stronger results for the U.S.). Finally, the evidence is also supporting the hypothesis that ICTs act as innovation enablers, but studies differ in terms of the strength of the estimated relationship between ICT and product, process, organizational and marketing innovations.

4.3 Productivity and broadband infrastructures

It is worthwhile reviewing here the literature that has looked at the economic impact of broadband infrastructures, which is different from broadband penetration,[126] as the latter captures both supply (the availability of broadband) and demand aspects (the use of the available broadband) and is

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[124] The main differences between Polder et al. (2010) and Polder et al. (2012) is that in Polder et al. (2010) ICT investment enters –together with the variables on ICT use- as innovation inputs into the innovation equation, while in Polder et al. (2012) the ICT usage variables enters into the innovation equation, while (proxied) ICT investment enters into the productivity equation, together with the predicted probability of the different innovation types.

[125] ICT intensity is measured by the number of web facilities and by the number of automated IT links. Results with the first proxy tend to be more stable.

[126] Broadband penetration is usually measured as the number of broadband subscriptions per 100 inhabitants. Given the number of individuals forming an average household, we can approximate the number of individuals having access to a broadband. For instance, if the penetration rate is 30% and we know that households are- on average- formed by 2.5 individuals, if we assume that broadband subscription is equally likely among households of any size, then we can conclude that 75% of the population has access to broadband.

hence more affected by endogeneity problems.[127] There exists various theoretical motives why broadband infrastructures might have an impact on productivity (levels and growth): high-speed Internet, via broadband infrastructures, generate cheaper and more rapid exchange of information between economic agents (both within and across organizations) and can give rise to the development of new product and processes and to new business models[128] (so that broadband infrastructure can be interpreted as a particular application of ICT as a GPT[129]). More generally, high speed connections can increase competition also through higher transparency among consumers[130] (i.e. through a demand-side effect).

While the positive association between GDP per-capita growth and indexes of broadband penetration is commonly found in many studies (for evidence from the U.S. see Holt and Jamison, 2009), the main problem concerning this relationship when one wants to derive some policy implications is the causality chain. If the policy question is related to the issue of public (or private) investment in broadband infrastructures, we would like to be sure that the positive association between the two variables is not simply capturing the fact that richer countries, on average, are characterized by higher broadband penetration since richer individuals are ready to pay more for broadband services (which is a pure demand-side effects[131]).

A clarifying note on this is important: what happens on the demand side is certainly important from a policy perspective, especially in the context of the Digital Economy, where the demand side is crucial. In fact, the correct approach and the correct selection of data depend crucially on the policy question. If the policy has to do with the reduction of barriers to the creation of a E.U. digital market, the demand-side effects are probably the most important ones (but we should also analyze how firms change their investment and innovation policies in response to changes in the regulatory setup and the size of the market), while, if we are thinking about increased broadband infrastructures, the main interest is on supply-side policies (but the effects of such policies are also going to be affected by the response coming from consumers). In our present discussion, which focuses on broadband infrastructures, it is important to obtain estimates that are purified of the effects arising simply from the dynamics of the demand side (but including the effects of developments on the demand side that are the results of the supply-side initial investment). This is clearly a very difficult task, which resembles the difficulties encountered in counterfactual impact

[127] Having said this, in practice it is very difficult to measure broadband infrastructures so that many studies end up relying on broadband penetration. However the different conceptual interpretation of the two variables should be kept in mind, especially when reading the results from the econometric exercise.

[128] As previously documented, the most recent literature on the impact of ICT on innovation and productivity uses broadband penetration at the firm level as a proxy for ICT intensive use. In general, we expect the effect of broadband penetration on labour productivity at the firm level to depend also on the level of broadband infrastructures in the economy (for instance, the return to investment in broadband for e-procurement and customer services at the firm level depends on broadband penetration among suppliers and customers).

[129] An example of this is the VOIP application. For a discussion of how social networks, cloud computing, machine-to-machine communications and data-driven organizational technology –all considered as example of ICT as a GPT- can impact labour productivity see Grajek (2012). See also Masiello and Slater (2012).

[130] Broadband networks provide the framework for the delivery of different services ranging from telephony and its variants to high-speed internet access and very diverse multimedia services (video streaming, online games, tele-working, etc.).

[131] This would happen if citizens of richer countries are ready to spend higher amounts on broadband connections.

evaluation studies.[132] The problem is especially complex in the case of broadband, since, besides the reversed causality issue, we have also other potential endogeneity problems, given that investments in broadband infrastructures are often contemporaneous to changes in regulations and diffusion of other technology –such as mobile phones and computers- who might have, per se, a positive impact on GDP growth.

The solution to this problem proposed by Czernich et al. (2009), which uses data from 25 OECD countries for the period 1996-2007, is to use Instrumental Variable estimation. Given the intent of purifying the impact of broadband on GDP growth from the effects arising simply from the demand-side autonomous dynamics, Czernich et al. (2009) look for variables that are highly correlated with broadband infrastructures but that are not affected by the demand-side evolution, and they find such variables in the some measures of pre-existing (i.e. 1996 values) infrastructures that are normally used for broadband roll-out (such as fixed-line phones and cable-TV networks[133]).

Their results[134] from Instrument Variable estimation show that a 10 percentage points increase in broadband penetration leads to an annual increase of GDP per capita of 0.9-1.5 percentage points, and this, given the short time-interval considered, is interpreted as a lower bound for the potential long-term effects of broadband infrastructure.

A confirmation of the impact of broadband infrastructures on GDP is provided by Koutroumpis (2009), who investigates this relationship within a structural equation model, which accounts for: 1) an aggregate production function, in which broadband infrastructures –proxied by a measure of broadband penetration- affects GDP (together with other types of capital, including human capital); 2) a demand equation for broadband infrastructures, capturing the fact that the demand for higher levels of broadband capital depends –among other things- on the level of GDP; 3) a dynamic equation for the evolution of broadband infrastructures, which just depends upon investment in broadband; 4) an equation accounting for the fact that broadband investment depends upon broadband price levels, the level of inter-platform competition in the broadband market, and on a measure of regulatory control.

The model is estimated using data from 22 OECD countries for the period 2002-2007. While all the relevant coefficients are estimated in such a structural equation model, here we focus on the relationship between broadband infrastructures and GDP in the aggregate equation: this should be interpreted as the overall effect of broadband capital, once the effects of demand-side and supply-side shifters have been properly controlled for. The main result that emerges from the GMM estimation is that a 10% increase in broadband penetration –on average- increases GDP by 0.25

[132] In fact, the appropriate research methodology is exactly the one of counterfactual impact evaluation: find a treated group (countries/regions/areas affected by the supply side policy change for broadband infrastructures) and compare their performance to that of countries/regions/areas that are identical on every respect (including their development stage) but are not affected by the policy change.

[133] The most commonly used broadband standards very often rely on copper wire of the voice-telephony network or on the coaxial cable of the cable-TV network. The underlying assumption is that pre-existing levels for fixed-line phones and cable-TV networks are affecting only broadband penetration (from the supply side) but not per-capita GDP growth

[134] They regress broadband penetration on a logistic function which includes the penetration rates for the fixed-line phones and cable-TV networks in 1996. Then they use the predicted broadband penetration rates arising from the first-stage regression into the second-stage regression, where –together with other variables- they are regressed against per capita GDP.

percentage points.[135] This also implies that almost one-tenth of the observed growth of the 22 OECD countries can be traced to broadband infrastructures.

When trying to verify whether investment in broadband infrastructures might have a different impact on GDP depending on the initial level of broadband penetration, the author finds that a much larger effect is reached for countries that have a penetration rate starting value higher than 30% (in this case the coefficient on broadband penetration is equal to 0.023%, against 0.014 for the groups with penetration rates between 20 and 30% and 0.008 for the group of countries with penetration rates below 20%). The higher return to broadband capital in countries that already have high level of broadband capital is related to the existence of network externalities and points to the fact that a critical mass for broadband penetration has to be reached before the full benefits of broadband infrastructures can be reaped.[136]

5. Summary of conclusions and (some) policy implications:

From the empirical evidence analyzed in this literature review it seems quite safe to conclude that ICT had a major role in the U.S. productivity acceleration observed in the period 1995-2005, both in terms of TFP growth in ICT-producing sectors and capital-deepening in ICT-using sectors. The evidence for Europe is less clear-cut, as some countries such a Sweden and Finland took full advantage of the opportunities offered by digital technologies, while others, such as Germany, France, Italy and, to a lesser extent, the UK, did not. We can also conclude that ICT is largely responsible for the divergence in productivity paths observed between 1995 and 2005 for the U.S. and the E.U. After 2005 we also notice a slowdown in U.S. labour productivity growth, which reduces the E.U.-U.S. productivity gap and hence the role of ICT (van Ark, 2010).

The lack of a E.U. productivity acceleration between 1995 and 2005 can be partially explained by a lower size of the ICT producing industry in Europe, by lower investment in ICT capital, but, especially, by lower TFP within the ICT-producing sector (two times higher in the U.S.) and by lower TFP in the ICT-using sectors, particularly in the service industry, which is three times higher in the U.S., where productivity has been going up particularly in wholesale, trade, and finance.[137] A possible explanation for this is that E.U. firms in these services industries have not been able to reap to full benefits of computerization, in part because they invested less into it but mostly because they have not used it in the most effective way.

The previous conclusions, which are mostly based on studies grounded in the growth-accounting tradition, are broadly confirmed by the studies that use regression methods with aggregate data. However, to fully understand what determines the impact of ICT investment in ICT-using sectors (i.e. the indirect effects of ICT), granular data are necessary and firm and plant level data show that ICT produces its highest returns when firms prepare themselves properly to the new technology, both in terms of acquiring the necessary skills and adapting the organizational structure as to benefit from

[135] The results are not immediately comparable with those of Czernich et al. (2009), given that in that study the dependent variable is per-capita GDP, while here it is GDP.

[136] Notice that a penetration rate higher of 30% effectively means that more than half of the population has access to broadband. In 2006 only Scandinavian countries satisfied this condition. However, as time passes by, more and more countries will reach the 30% threshold.

[137] Data for the financial sector tend to be affected by the presence of bubbles.

the technological opportunities. This result is taken as evidence in favour of the hypothesis that ICT positively complement organizational and human capital.

We also notice that the studies reviewed here document that, within the E.U., there is large across-country variation in the impact of ICT on productivity (with the UK behaving more similarly to the U.S.). Variables capturing the extent of product and, especially, labour market regulation account for most of such variation, indicating that the impact of ICT on productivity is lower in more regulated markets (the evidence for product market regulation is less strong than the one for labour market regulation), and this could explain why the impact in ICT-using industries has been lower in the E.U. than in the U.S. (product and labour market regulation in services is higher in the E.U. than in the U.S.). However, these effects are generally not robust to the introduction of firm-specific fixed effects (which make it difficult to derive evidence-based policy implications).

One of the most relevant policy issues is whether ICT can be defined as a GPT, which is a technology that stimulates co-inventions and product, process and organizational innovations. While the evidence gathered from industry-level data is not conclusive, the evidence from firm and plant-level data seem to point consistently to the presence of spillover and external effects generated by ICT capital (at the industry or aggregate level). The fact that these spillovers and externalities are found more easily with more granular data is consistent with the intuition that, at a lower level of aggregation, we are more likely to have external factors affecting firms' performance (in the limiting case of country-level data the spillovers can come only from outside the country). This means that there might be room for public polices supporting investment in ICT, and even more for policies supporting R&D in the ICT sector, as in this case we have two types of externalities, one related to ICT capital and the other one related to R&D capital.. Moreover, van Reenen et al. (2010) find that ICT investment respond faster to demand shock than other forms of capital, which implies that programs stimulating ICT investment might be beneficial for counter-cycle policies. Given the evidence of strong complementarities between ICT, organizational capital and human capital, barriers to the accumulation of these complementary factors should be removed, in particular, those affecting people management and decentralisation. In particular, van Reenen et al. (2010) stress the need for more competition in the product market and, especially, of less stringent labour market regulations.[138] In our opinion, the role of rigidities in the labour market might be more complex. On the one hand they are on obstacle to firms' restructuring, but, on the other one, they also might induce workers to invest more on firm-specific human capital, which might have the effect of making managerial innovation more productive.

There is also evidence that organizational change and ICT investment, especially when taken together, constitute a relevant financial and economic burden for firms. To the extent that investment in organizational restructuring entails some sunk costs, (small) firm size and market segmentation tend to reduce the scope for managerial restructuring. Given that the vast majority of firms in the E.U. are SMEs and given that access to capital for them is generally more costly, we are not very surprised to find that E.U. firms are less ready to invest in ICT and implement the necessary organization changes. The existence of market failures in the access to funding might

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[138] Some studies –not reviewed here- show that aggregate productivity depends heavily on reallocation (i.e. on exit by less productive firms and on entry and growth by more productive firms). These results are important from a policy perspective, as they show that reductions in barriers to entry and exit can have a strong impact on aggregate productivity.

justify some public intervention specifically directed at supporting ICT investment by SMEs. Also, it might be worthwhile thinking of raising awareness, especially among SMEs, of the potential benefits arising from the combination of ICT, people management and decentralization.

Broadband infrastructures have a strong impact on productivity and productivity growth. Moreover, there seem to be evidence that a critical mass in terms of broadband penetration (between 50 and 75% of the population) exists. Past these levels, the impact on GDP is still dependent on the path of broadband penetration. Hence policies need to be targeted to the development of broadband penetration in each country.

APPENDIX 1

In 1998, OECD member countries agreed to define the ICT sector as "*a combination of manufacturing and service industries that capture, transmit and display data and information electronically*". This definition, based on an international standard classification of activities (ISIC Rev. 3), was considered to be the first step towards obtaining some initial measurement of ICT sector core indicators. The sector definition was complemented by the ICT goods definition in 2003 and by the ICT services definition in 2006. ICT sectors definitions and ICT goods and services definitions have then be revised following the revision of ISIC (Rev. 4) and of the United Nation's Central Product Classification in 2006

To be included in the ICT sector according until 2008, a manufacturing industry must:

- fulfil the function of information processing and communication, including transmission and display;
- and/or use electronic processing to detect, measure and/or record physical phenomena or control a physical process.

After 2008 only the first condition is maintained, hence effectively narrowing the ICT manufacturing sector (which complicates across-time comparisons).

A services industry is classified in the ICT sector if it carries out the function of information processing and communication by electronic means.

By identifying the key sectors whose main activity is producing or distributing ICT products, this definition constitutes a first order approximation of the 'ICT producing sector'.

The practical distinction between ICT producers and ICT user industries, and between high/low ICT use intensity, is arbitrary, as there are few industries that do not use ICT at all, so that the definition of some cut-off point is necessary. Different authors adopt different classifications.

Error! Reference source not found. reports the detailed industrial classification proposed by van Ark t al (2002). This classification is not necessary the best one, but it has the desirable property of a good degree of robustness when applied to cross-country analysis. In fact, the authors' main concern is to group similar industries together across countries. The group of ICT producing industries (distinguished from the group of intensive ICT using industries) is derived from a classification by the OECD (2002) that includes industries producing ICT hardware, software and ICT services, modifies to different extents the classification proposed by Stiroh (2002a) and uses the International Standard Industrial Classification (ISIC) Rev. 3. In order to distinguish between industries that use ICT more or less intensively, it is chosen to rely on the flow of capital services from ICT in total capital services (though sometimes data availability limits the actual implementation of this procedure).

Table A.1: Grouping of ICT producing, ICT using, and less intensive ICT using industries (Van Ark et al., 2002).

ICT-producing industries
ICT-producing manufacturing
Office, accounting and computing machinery
Insulated wire and cable
Semiconductors and other electronic components
Communication and broadcasting equipment
Radio and TV receivers
Medical and measuring equipment and industrial process control
ICT-producing services
Post and telecommunications
Computer and related services
ICT-using industries
ICT-using manufacturing
Wearing apparel, dressing and dying of fur
Printing and publishing
Machinery and equipment
Electrical machinery and apparatus, excluding insulated wire
Precision and optical instruments, excluding ICT instruments
Building and repairing of ships and boats
Aircraft and spacecraft
Railroad equipment and transport equipment
Miscellaneous manufacturing and recycling
ICT-using services
Wholesale trade
Retail trade
Financial intermediation
Insurance and pension funding
Activities related to financial intermediation
Renting of machinery and equipment
Research and development
Professional business services
Less-intensive ICT-using industries
Other Manufacturing
Food products, beverages and tobacco
Textiles
Leather, leather products and footwear
Wood and products of wood and cork
Pulp, paper and paper products
Coke, refined petroleum products and nuclear fuel
Chemicals and chemical products
Rubber and plastic products
Non-metallic mineral products
Basic metals
Fabricated metal products
Motor vehicles, trailers and semi-trailers
Other Services
Repairs
Hotels and restaurants
Transport and storage
Real estate activities
Other business services (non-professional)
Public administration and defense; compulsory social security
Education
Health and social work
Other community, social and personal services
Private households with employed persons
Extra-territorial organizations and bodies
Other Industries
Agriculture, hunting, forestry and fishing
Mining and quarrying
Electricity, gas and water supply
Construction

APPENDIX 2

The role of organizational innovation in modern firms is very much present in the management literature (for a general discussion and references see Murphy, 2002), which documents how firms respond to stronger competitive challenges trying to make a better use of knowledge, technology and human capital. This is reflected by the increasing role of intangibles, including human capital and the ability to continuously innovate.[139] As Murphy (2002) writes: "*Strategic business thinking has shifted away from products, plants and inventory towards employees, technology and knowledge…Firms are adopting new knowledge management strategies which drive organizational change throughout the enterprise…… Firm-level organizational change takes many forms, but can be classified into three broad streams (see Table A.2):*

- *i) the restructuring of production processes;*
- *ii) management systems and employee involvement schemes;*
- iii) *external re-organization emphasizing customer orientation, outsourcing, and firm networks and other collaborative arrangements.*

Table A.2

Production approaches	**Management Practices**	**External relations**
Total quality management	*Decentralization*	*Outsourcing*
Lean production	*Teamwork*	*Customer relations*
Just-in-time	*Knowledge management*	*Networking*
Business re-engineering	*Flexible work arrangements*	
	Flexible compensation	

Source: Table 3 from Murphy (2002)

Internal re-organization typically affects the organization of production … and work practices while external re-organization is associated with the improvement of relations with customers and other firms. In practice, firms tend to apply an eclectic set of organizational practices, often spanning the three broad streams".

ICT are deeply related to many of these practices. The management practices more intertwined with ICT are:

- Lean production (including just-in-time production) and re-engineering, in which ICT support the ability of the firm to have full, constant and detailed knowledge of the various aspects related to procurement and production. Examples of this are Computer Integrated Manufacturing (CIM) systems, functional to Just-in-Time production, and Enterprise

[139] For a macro perspective on the role of intangibles on productivity see Corrado et al (2009).

Resource Planning (ERP), which requires tracking of all the activities, materials, workers and inventories and which is functional to the practice of business re-engineering. Internet-based procurement systems and other inter-organizational information systems have significantly simplified the relationship with suppliers (such as computer based supply-chain-integration). Such methods reduce direct cost of intermediation but also reduce the need for buffer investment and make deliveries more predictable, hence helping up-stream and down-stream firms to better predict their outputs and inputs. Some (Goldman Sachs, 1999) have estimated that these technological innovations are able to reduce procurement costs between 10 and 40%. These number might be too optimistic but even a reduction in the order of 5-10% would be extremely significant.

- Employee's involvement in production, as ICT works as a facilitator in the exchange of information among workers and between workers and management. Workers' involvement can be of different types: involvement at the suggestion stage (excludes participation to decision making), involvement at the job stage (how to actually perform a given routine) and also at the business/strategic stage (when workers fully participate in the design of the business model). Employee involvement can be coupled with teamwork in production or in strategic decision making.
- Relationships with customers. The management literature has shown that digitalization, mainly through the Internet, can have a large impact on the firm-customer relationship. Direct contact with consumers (during ordering or after-sale services such as technical support) is generally positively evaluated by consumers. Moreover, this direct contact with consumers, coupled with internal organizational change, has allowed firms to switch from build-to-stock to build-to-order models of production, generating consistent costs reductions through methods of just-in-time inventory management.[140] A clear application of this is the use of IT in Customer Relationship Management (CRM), such as the set-up of IT-based call centres for customer care (including post-sale activity), technical centres and marketing.
- Outsourcing and delocalization. ICT allow firms to outsource (and delocalize) many activities, both for the supply of components and services and for CRM. This is more likely for non-core activities but is in no way restricted to them.

[140] For a discussion of the relationship between organizational change and firm performance –and the special role of ICT- see Murphy (2002).

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Abstract
In this report we review the literature on the relationship between ICT and productivity. In Sect. 1 we discuss in broad terms the theoretical relationship between ICT and productivity, while in Sect. 2 we present the growth accounting methodology, which tries to measure the contributions to growth from difference sources (ICT and non ICT capital, human capital, total factor productivity). Within the growth-accounting methodology, in Sect. 3, we discuss the U.S. - E.U. productivity gap and the role of ICTs, and we show that the latter are responsible for the U.S. acceleration in productivity growth observed in the period 1996-2006 and for the widening of the U.S. – E.U. productivity gap in the same period. Then, in Sect. 4, we move to regression based studies, and we review the literature that uses macro, meso (sectoral) and firm/plant level data. While the overall message on the importance of ICT for growth coming from this literature is consistent with the findings of the studies based on growth accounting, the econometric approach allows researchers to investigate a wider set of questions. In particular, we focus on the role of ICT as a General Purpose Technology aspects and we review the literature studying the role of ICT and complementary assets in firms' productivity and the literature exploring the positive externalities related to ICT capital and the impact of ICT usage on the innovative capability of firms. Finally, we also review the literature on the relationship between ICT infrastructures and GDP growth.
JEL codes: D22, D24, E01, O30, O47
Keywords: ICT, labour productivity, total factor productivity, innovation.

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