ICT and productivity: a roadmap for empirical research

The **department for "Industrial Organisation and New Technologies" at the Ifo Institute**, headed by **Prof. Tobias Kretschmer**, focuses its research on strategic issues in ICT markets. Along with studies of the contribution of ICT to productivity at company, sector and country level, the department is especially concerned with the complex interactions between different information technologies, and also with complementarities between ICT use and organization structures. Other lines of research are the dynamics of consumer electronics markets and the diffusion of new communications technologies.

The underlying studies can be accessed on the website of the ifo department of **Industrial Organisation and New Technologies:** http://www.cesifo-group.de/int

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ICT and productivity: a roadmap for empirical research

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The European growth model enjoyed decades of success and brought prosperity to several million people in Europe. Now the European debt crisis has made it clear that this growth model has reached its limits: structural problems followed by a halt in productivity growth are seen as the main causes of the difficult economic conditions in some parts of Europe. A comparison with the USA shows that Europe as a whole has some catching up to do – since the mid-1990s, productivity growth in the USA has been ahead of that in Europe. The big advances in productivity in the USA have been mainly achieved by the extensive use of information and communications technologies.

Management summary

– Although the positive contribution of information and communications technology (ICT) to productivity and economic growth is beyond dispute, the academic and policy-related literature is marked by widely varying findings and approaches to measuring the contribution of ICT.

– Most approaches are based on a production function, in which inputs (production factors) are transformed into outputs (goods produced). ICT is included as an additional production factor. Growth accounting compares the documented investment in ICT with the goods produced. These studies are mostly at the sectoral level. Econometric estimates are designed to quantify the additional output generated by increased investment in ICT. This methodology is especially applied at the firm level.

– Growth accounting studies distinguish between the ICT contribution in a narrow sense (i.e., attributable to ICT investment alone) and the contribution of the knowledge economy (which also includes the indirect effects of ICT on other sectors and production processes). Up to 80% of the growth in productivity over the last few decades is attributed to the knowledge economy.

– The vast majority of econometric estimates finds that ICT has a positive effect on growth. On average, the studies consulted show that a 10% increase in ICT investment results in a growth in output of 0.5–0.6%. In the last few years, this growth effect has actually been higher.

– This rising growth effect is consistent with the increased ability of organizations to make optimum use of information and communications technology. It is therefore particularly interesting to know which complementary investments and capabilities contribute to the optimum use of ICT.

In the academic and policy-related literature, widely different figures are put forward for the relationship between information and communications technology (ICT) and productivity. The aim of this report is to produce a roadmap for empirical research, giving a brief account of the key methods of measuring productivity followed by an overview of the spread of existing estimates of the effect of ICT on productivity.

1. Productivity as a driver for prosperity

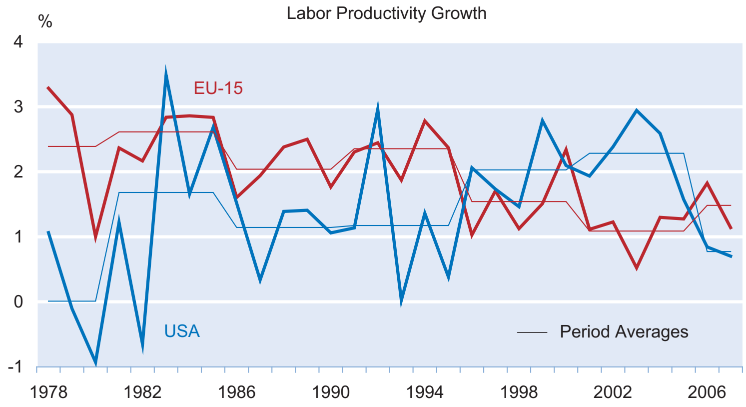
Productivity in its most general sense describes the relationship between the output produced and the inputs used to do so. Where there is information on the individual values, the relationship can be established and measured both at the macroeconomic level for a national economy and at company and industry level.

Productivity measurement serves not only to assess the efficiency with which input factors are transformed into output but also to provide essential clues to prosperity and standard of living within a national economy. Because, as productivity increases, wages and salaries can rise too. Studies of productivity and its growth are therefore of interest not only to economists; they also provide important pointers for the development and sustainability of social progress.

The drivers for productivity growth are continuous improvement in the quality of the input factors, such as the level of training and technological knowledge, and also the advance of product and process innovation. The more productively input factors can be deployed, the greater the return on investment in physical and human capital and the higher the standard of living in a country. Social progress is therefore closely linked to productivity growth and reflects not only the efficient provision of output values but also the accumulation of intangible assets such as human capital, knowledge and access to knowledge networks.

International comparisons offer interesting insights into the performance of national economies. If we compare the trend in productivity growth between the economies of the USA and Europe over the period from 1978 to 2007, some clear differences can be discerned (see Figure 1). Whereas productivity growth in Europe ran ahead of the trend in the USA up to the early 1990s, the reverse has been true since the mid-1990s. Instead of a progressive convergence between the two economic blocs, there was a divergence in productivity growth. The USA has twice experienced accelerating growth in productivity, in the periods after 1995 and after 2000. Europe, on the other hand, suffered a significant slowdown in growth in the same period. It is only since 2006 that the figures show a converg-

Figure 1
Productivity Growth in the USA and Europe (EU-15), 1978–2007



Source: EU KLEMS (2009).

ing trend between the two regions. If we take the initially favorable productivity developments in Germany and France in 2005/2006 as representative of the EU-15 countries, these saw a massive collapse in the course of the financial crisis in 2008/2009. In contrast, development in the USA was much more positive, and we can once more see a divergent trend in growth rates between the two regions (Conference Board, 2011).

To explain the weak growth in Europe, we can identify not only the contributions from the number of hours worked and improved quality in the input factors, but also other factors such as research and development spending and the increased use and diffusion of information and communications technology (ICT). The ICT element of total capital expenditure itself differs markedly between the regions (see Figure 2). Since the early 1980s, the proportion of ICT capital invested in Europe and the USA has diverged sharply. This tendency intensified more and more in the mid-1990s and only stabilized when the dot.com bubble burst in the period after 2000.

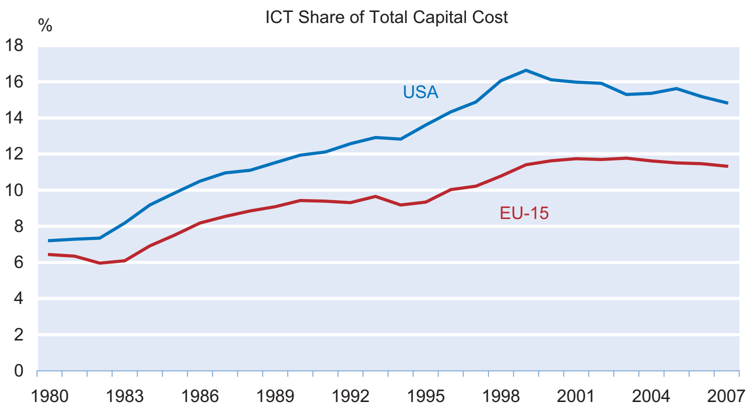
When deriving productivity measures, different concepts need to be applied according to the question asked and the availability of the necessary data. As an output measure, we generally use the production value, or the production value adjusted for intermediate inputs, i.e., what is known as gross value added. Along with various output measures, different input measures may also be considered, with a distinction between univariate and multivariate productivity measures, according to whether we are investigating the relationship between one or more inputs and the output produced.

The transformation of input factors into outputs can be empirically measured and presented in various ways. If we measure output as gross value added and apply the most common version of a Cobb-Douglas production function, we obtain the following relationship:

$Y = AK^{\alpha} L^{\beta}$
Equation 1: Cobb-Douglas production function

Equation 1 assumes a multiplicative relationship between the output produced Y and the input X needed to generate it. K then represents the capital invested in the production process, and L is the labor needed, while α and β stand for the respective factor elasticities in the input factors. The factor elasticities show the percentage by which output rises given a 1% increase in the input. Finally, the value A measures the total factor productivity (TFP), which is often taken as a measure of technological progress.

Figure 2
ICT Intensity in the USA and Europe (EU-15), 1980–2007



Source: EU KLEMS (2009).

The TFP assumes particular importance in connection with the influence of ICT as a measure for a general purpose technology (GPT; Bresnahan and Trajtenberg, 1995) or as a basis for the ‘spill-over’ theory of ICT. The first suggests that ICT constitutes a special kind of technology, which can be deployed to enhance efficiency in many production processes. It is not only the direct use of ICT but also the development of new complementary technologies that leads to productivity increases. The spill-over theory assumes that initial productivity increases in ICT-producing industries reach other industries, particularly those that make intensive use of ICT, after a certain time delay.

Output and productivity quantities (Schreyer and Pilat, 2001)

In contrast to the pure production value (gross output), gross value added has the advantage of avoiding double-counting by cleansing the figures of intermediate inputs. Measurement on the principle of gross value added also offers a direct link to income per capita or per hour, which are widely used indicators to measure the standard of living.

In the case of univariate productivity measurements, the output is related to one input factor, usually in the form of labor productivity (output to labor). It is also possible to relate it to the factor of capital (capital productivity). With multivariate productivity measures, we look at output in relation to all factor inputs. The resulting indicators are then called total factor productivity (TFP) or less commonly multi-factor productivity (MFP).

2. How the contribution of ICT to productivity is measured: growth accounting and econometric estimates

2.1. Growth accounting: causes of productivity growth

Growth accounting breaks down productivity growth into its input elements. Here, both output and input values are generally related to the labor factor (Jorgenson et al., 2005, 2007; Aghion and Howitt, 2007) and formulated as a dynamic equation, i.e., the growth rate for labor productivity ($\Delta \ln y$) is explained by the growth rates for the input factors. In this approach, a distinction is made between the capital intensity of ICT ($\Delta \ln k_{ICT}$) and non-ICT goods ($\Delta \ln k_{NICT}$), and labor quality ($\Delta \ln L_Q$) is taken as an explanatory factor for labor productivity. The growth contribution of ICT can be further isolated by looking separately at the growth in total factor productivity in ICT-intensive ($\Delta \ln A_{ICT}$) and non-ICT-intensive industries ($\Delta \ln A_{NICT}$) (see equation 2).

$$\Delta \ln y = \overline{\upsilon}_{ICT}\,\Delta \ln k_{ICT} + \overline{\upsilon}_{NICT}\,\Delta \ln k_{NICT} + \overline{\upsilon}_{L}\,\Delta \ln L_{Q}$$
$$+ \overline{\varpi}_{ICT}\,\Delta \ln A_{ICT} + \overline{\varpi}_{NICT}\,\Delta \ln A_{NICT}$$

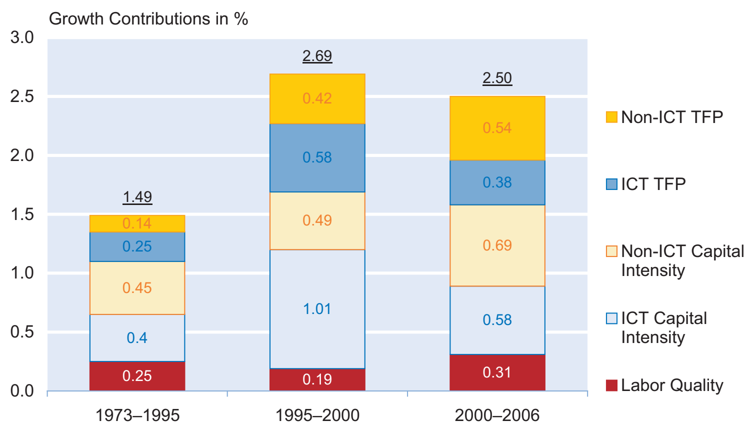
Equation 2:
Input contributions in growth accounting

In order then to calculate the contributions to productivity growth, the growth rates for the individual factor inputs are weighted with their nominal factor income percentages. These describe the quantitative contribution of the two input factors, capital ($\overline{\upsilon}_{ICT}$ and $\overline{\upsilon}_{NICT}$) and labor ($\overline{\upsilon}_{L}$), to the output produced. In order to weight the two TFP values, we use the nominal gross value added percentages for the industries ($\overline{\omega}_{ICT}$ und $\overline{\omega}_{NICT}$). The two figures below show a breakdown of the aggregated growth in labor productivity into its individual contributions for the USA, as derived from equation 2. Instead of reported annual contributions, averages over three periods are shown.

It can be seen from Figure 3 that the growth in labor productivity in the USA during the New Economy period (1995–2000) in particular was driven by increased ICT capital intensity. Where the greater contribution to growth between 1973 and 1995 came from non-ICT factors, after 1995 there was an increased substitution of ICT for non-ICT goods. The 0.58% TFP growth of ICT-intensive sectors also made a major contribution to productivity growth. Although the ICT contribution in the USA has remained high since 2000, it is clear that the productivity effects associated with ICT are waning.

Similar findings emerge when aggregating individual growth contributions to a shared contribution from ICT capital intensity and TFP for the ICT-intensive industries, and the same contributions taking account of labor quality and the TFP contributions of non-ICT producing industries (the knowledge economy), are aggregated (see Figure 4). The first form of aggregation is equivalent to the ICT contribution in a narrow sense, without any spill-over effects. The "knowledge economy", on the other hand, measures a wide range of effects associated with the use of ICT. Hence, it also includes the effect of an altered composition of the workforce, with more highly-qualified workers (complementarities between better qualified workers and ICT) and the macroeconomic TFP contribution, i.e., the contribution of all industries. The cross-industry TFP contribution in particular is a major feature of the technological progress and

Figure 3
Sources of Productivity Growth in the USA



Source: Jorgenson et al. (2008).

Total factor productivity (TFP)

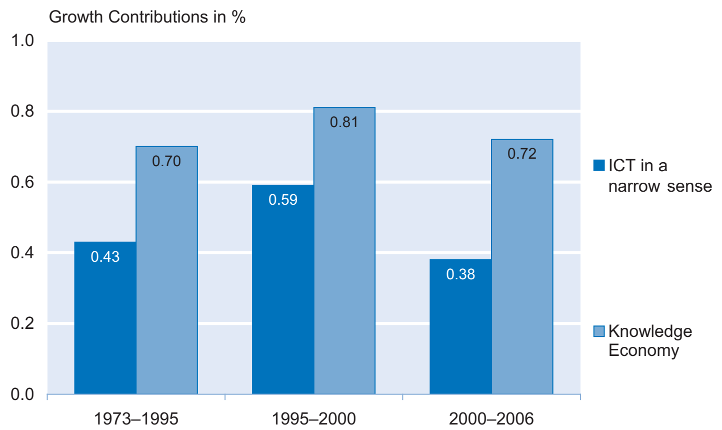
The total factor productivity (TFP) derived as part of the production function is calculated as the residual value of output, capital and labor. It measures how productively the individual input factors are combined with each other to generate the output. Under some assumptions, TFP can then be interpreted as technological progress. Where there are variances from the assumptions of constant economies of scale, efficient production and competitive factor markets, TFP measures not only non-constant economies of scale and changes in production efficiency but also changes in capital utilization and cyclical effects. If we look at different groups of goods and products, with each group weighted with appropriate quality-adjusted prices, any form of measurable technological progress will already be contained in the (priced) input values. We then speak of *embodied* technological progress. On this basis, the residual TFP is then interpreted as *disembodied* technological progress.

innovative activity of a knowledge-based society, as was triggered by ICT in the New Economy period. Here again, we see the impact of an increased focus on technology on productivity growth in the USA, especially in the period 1995–2000.

Growth accounting captures the influencing factors documented in official statistics, which contribute to the growth in labor productivity. Growth accounting allows the growth effects to be related to ICT intensity in a narrow sense and to the knowledge economy in the broader sense. The latter then also reflects the indirect growth effects of increase ICT use.

Figure 4

Productivity Growth Contribution of ICT and Knowledge Economy in the USA



Source: Jorgenson et al. (2008).

2.2. Econometric estimation of a production function

As with growth accounting, the Cobb-Douglas function is again the basis for econometric estimation, for which it takes the following form (Brynjolfsson and Hitt, 1995, 2003):

$$\ln Q_{it} = \beta_1 \ln C_{it} + \beta_2 \ln K_{it} + \beta_3 \ln L_{it} + controls + \varepsilon_{it}$$

Equation 3: Logarithmic Cobb-Douglas production function

Here, the output Q (in company and industry studies, usually taken as gross value added; in country studies, generally GDP) is related to the ICT capital C, the capital stock of non-ICT goods K and labor L. The indices i and t represent the unit of analysis (i.e., company, industry or country) and the time respectively. The existing ICT capital is sometimes approximated by penetration rates; in some studies, for example, telecommunications capital is derived from the number of telephone lines per inhabitant, and IT capital at firm level is taken as the number of computers per employee. Common control variables are time and dummy variables for the unit of analysis concerned (fixed-effect models), the latter capturing constant idiosyncratic productivity effects – for example, some companies are constantly more productive, e.g., because of good management or an advantageous market position.

Unlike growth accounting, econometric estimation estimates the relative contributions to growth of the individual inputs as parameters rather than calculating them from income statistics. In contrast to growth accounting, econometric estimates can be used to identify statistically significant and causal relationships. That means, for example, that conclusions can be drawn as to the scale of the growth contribution based on a number of observations of individual companies.

A particular challenge is how to interpret any causal relationships. For example, investment in ICT may be both a cause and an effect of economic growth. This is referred to as the endogenity problem, as the direction of causality cannot be established beyond doubt. In order to circumvent the problem of reverse causality, some empirical studies use different econometric methods, in which the ICT variables are replaced by specified time-delayed variables (e.g., Bloom et al., 2010, Brynjolfsson and Hitt, 1995, Hempell, 2005b, Tambe, 2011). As current growth cannot have any influence on past investment, we can rule out reverse causality in this case. Alternatively, structural models can be estimated, in which the different influences are modeled in multiple equations

Factor elasticity and marginal product

By estimating the Cobb-Douglas production function, we can use the estimated parameter β_1 in equation 3 to obtain the elasticity of the factor input ICT capital directly. This indicates the percentage by which output changes given a one-percent increase in ICT capital. To measure the amount in euros by which output changes given a one percent increase in ICT capital, we need the marginal product of ICT capital (GP_{ICT}), which can be calculated by reformulating the elasticity using *Q* (output) and *C* (ICT capital) as follows:

$$GP_{IKT} = \beta_1 \frac{Q}{C}$$

The marginal product indicates the effect of the last euro of ICT capital spent.

(Koutroumpis, 2009, Röller and Waverman, 2001). Another approach is to start by estimating broadband penetration using a diffusion equation which is unaffected by current economic growth (Czernich et al., 2011).

A further econometric approach involves estimating TFP regressions (Basu et al., 2003, Inklaar, 2008, Stiroh, 2002a). In this case, TFP, which may sometimes be interpreted as an efficiency gain from the use of all input factors (see box on TFP), forms the dependent variable explained by ICT. This approach thus offers a test of whether ICT use produces spill-over effects that are not captured by (ICT) capital intensity. As spill-over effects mainly manifest themselves in second-round effects, this approach looks mainly at the statistical significance of the delayed impact of ICT. Of particular interest here are the delay with which the spill-over effects occur and the existence of complementary investments (e.g., management quality). Both factors are often difficult to capture empirically.

Apart from the approaches mentioned above, there are other ways of quantifying the economic value of technology. One thread looks at the effects of ICT investment on profitability and so attempts to evaluate the role of ICT in creating strategic competitive advantage (e.g., Im et al., 2001, Tam, 1998). Consumption theory is also the origin of the approach of calculating the consumer return, which quantifies in euros the amount by which consumers benefit from new technologies (Hausman et al., 1997, Greenstein and McDevitt, 2009).

Estimating production functions is a more flexible alternative to growth accounting. It can be used to draw concrete, causal conclusions about the contribution of an increase in ICT capital to productivity growth. However, reliable results can only be expected from studies that address the problem of the possible effect of productivity growth on ICT investment.

3. Overview of the empirical evidence for the contribution of ICT to productivity

3.1. Initial summary

The abundance of studies on ICT and productivity need to be differentiated not only according to the methodological approach taken but also according to other criteria. A major aspect is the ICT product being examined. Various studies focus exclusively on communications technology, and these can in turn be broken down into studies of data communication (mainly broadband), and voice telephony (both fixed and mobile networks). Another category is made up of studies of information technology (computer hardware and peripherals). It is only since the price deflators have been enhanced and software included as investment in the national statistics that software has increasingly been considered also. Another important differentiating feature is the level of aggregation of the units of analysis – companies, industries or countries.

Table 1 provides an overview of these differentiating features and names the two most-cited papers in their respective fields (measured by the Google citation index). As can be seen from the Google citation index, the focus of the existing research is mainly on examining the deployment of information technology in companies and, at the country level, of ICT in general. The field of communications technology is dominated by econometric studies, while growth accounting studies are favored for IT and ICT measurements. The latest field is concerned with the productivity effect of broadband, but there are as yet no studies of the use of voice telephony at the firm level or data communication at the industry level.

The existing literature on the growth contribution of ICT encompasses different levels of aggregation and individual technologies. Growth accounting is used especially at the macro level, and production functions at the micro level.

3.2. Growth accounting results

Figure 5 compares the growth rates for weighted ICT capital intensity for different growth accounting studies. Despite the use of standardized methods and largely identical data sources, the results differ in detail. Along with different periods covered, the reasons lie in the use of different price deflators and returns on capital, the latter being incorporated into the weightings of the factor income elements. Some studies also relax the restrictive assumptions by considering capacity utilization and non-competitive factor markets (e.g., Oliner et al., 2007).

As the comparison between the USA (blue lines) and the EU (red lines) in Figure 5 shows, the EU invested much less

Table 1
Star paper matrix

ICT product/ aggregation level	**Company level**	**Industry level**	**Country level**
Voice telephony (mobile/fixed network)	–	Greenstein/Spiller (1995, *44*); Correa (2006, *14*)	Röller/Waverman (2001, *441*); Hardy (1980, *184*)
Data (Internet/broadband)	Grimes et al. (2009, *6*)	–	Lehr et al. (2006, *73*); Crandall (2007, *58*)
IT (hardware/software)	Bresnahan (2002, *1609*); Brynjolfsson/Hitt (1996, *1319*)	Baily/Lawrence (2001, *241*); Stiroh (1998, *133*)	Gordon (2000, *1123*); Jorgenson (1999, *298*)
ICT (general)	Bertschke/Kaiser (2004, *118*); Hempell (2005, *92*)	Stiroh (2002b, *608*); Morrison (1997, *251*)	Oliner/Sichel (2000, *1417*); Jorgenson (2001, *991*)

Note: The number of Google Scholar citations is shown after the year of publication.

Source: Google citation index (spring 2011).

in ICT in the late 1990s, which is however less strongly reflected in the contribution of ICT capital intensity because of low labor productivity in the same period. In the 2000s, investment tails off in both regions.

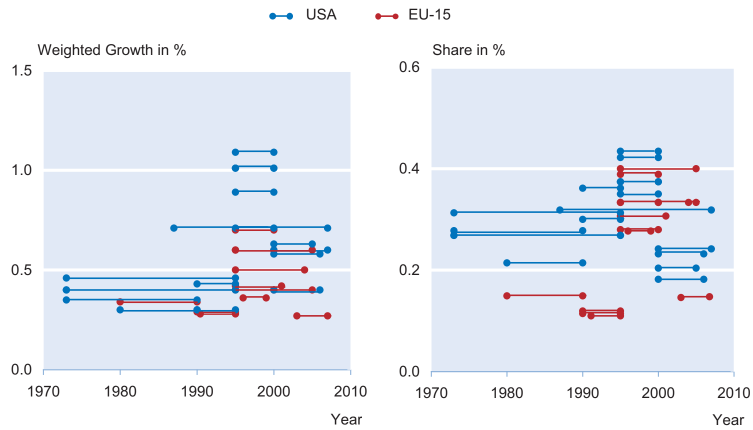
The next two charts (see Figure 6) show the weighted TFP growth rates. As mentioned earlier, TFP is an important indicator as it reflects efficiency gains. Here we can clearly see the much greater significance of the ICT-producing industry in the USA, as all US-based studies find a higher growth contribution from ICT than their European counterparts. For aggregated TFP across all sectors, it can be seen that since 1995, TFP has been much higher in the USA than in Europe. However, the latest figures published by the European Commission again show a trend towards pre-1995 productivity levels.

Further differences between Europe and the USA emerge when we break down the growth in labor productivity by sector (see Figure 7). This shows that the USA has productivity advantages not only in ICT-producing but also in ICT-intensive (i.e., heavy ICT-using) sectors such as the financial industry, research-intensive sectors and corporate services. The EU, on the other hand, has higher growth rates in non-ICT-intensive sectors. Given this successful use of ICT in the USA, we may ask whether any complementary investments, such as hard-to-quantify organizational capital and management quality, have not been captured. In one of the few studies on this, Bloom et al. (2010) highlight management quality to explain differences in ICT productivity between the UK and the USA. Acharya and Basu (2010) use intangible capital, which reduces residual TFP.

If we look at the contribution of the knowledge economy (ICT in the broader sense) to labor productivity from various sources for the USA and Europe (see Table 2), similar contributions can be found for both regions. However, the USA registers a much wider spread of positive growth contributions in the period 1995–2005. In terms of ICT contribution, on the other hand, Europe lags significantly behind the growth contributions in the USA right up to the end of 2000. Only after 2000 do these start to converge, while the ICT contribution in Europe displays a downward trend.

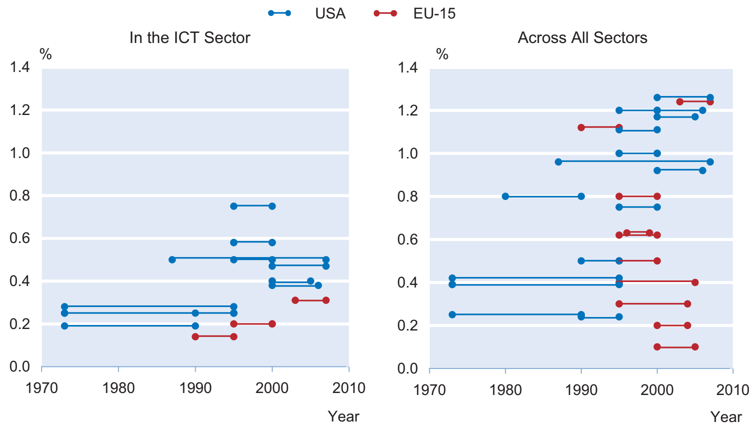
Growth accounting studies in Europe and the USA show a large element of ICT in productivity growth in the last few decades. The growth contribution of ICT in the USA was generally higher than in Europe, but particularly the ICT growth contribution in the broader sense (i.e., via a macroeconomic technology transfer within an advancing knowledge economy) has caught up in Europe in the last few years.

Figure 5
Growth of ICT Capital Intensity and in Percentage of Labor Productivity in the USA and EU, 1970–2008



Sources: USA data: Cette (2009), Gordon (2010), Jorgenson (2001, 2007, 2008), Oliner (2007); EU data: EUKLEMS (2008), EC (2011), O'Mahoney (2009), Timmer (2003), Van Ark (2002, 2008), Vijselaar (2002).

Figure 6
Weighted TFP Growth in the USA and EU, 1970–2008



Sources: USA data: Cette (2009), Gordon (2010), Jorgenson (2001, 2007, 2008), Oliner (2007); EU data: EUKLEMS (2008), EC (2011), O'Mahoney (2009), Timmer (2003), Van Ark (2002, 2008), Vijselaar (2002).

The histogram in Figure 8 shows a clustering of the estimated elasticities around the 0.05 range with a few positive outliers. There are also a few negative elasticities. Also, the right-hand chart shows that the elasticities increase over time with the accompanying increase in the ICT capital stock.

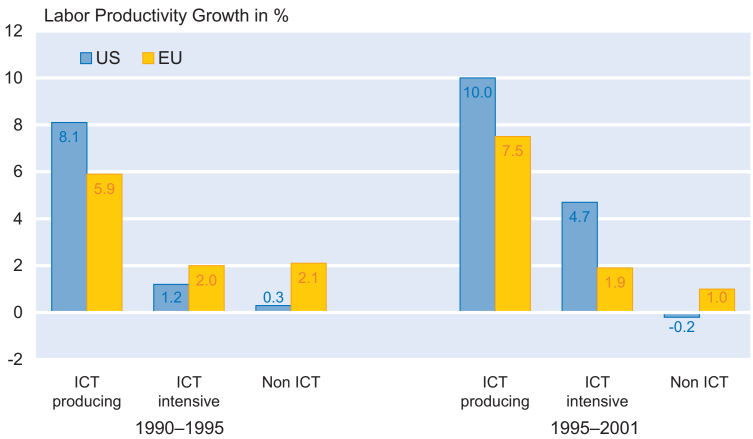
The estimates of elasticity in the ICT product/aggregation level matrix in Table 3 show no systematic differences in elasticities according to aggregation or product level. Interestingly, differentiating by region – unlike in growth accounting studies – produces no significant differences. Overall, the studies of the output effects from the deployment of ICT capital yield a consistent picture, with a mean of 0.05–0.06. That then means that an increase of 10% in ICT investment results in output growth of approx. 0.5–0.6%. It should be stressed that most of the studies examined address the problem of reverse causality.

3.3. Findings on the output elasticity of ICT

The second major thread in the literature on ICT and productivity assesses the impact of increased ICT capital on output (parameter β_1 in equation 3). In the usual modified Cobb-Douglas specification, this effect is measured as a percentage change. This means that β_1 indicates how much output would increase if ICT investment were raised by 1%. In the literature there are a number of variants from this specification, which are not considered below for ease of comparison. As most studies mention several elasticities, the comparison in Figure 5 always takes the estimate produced by the most conservative method (e.g., fixed-effects estimate, endogenity-checking estimation methods). A list of the studies referred to can be found in the Appendix.

Much more ambivalent are the results of the TFP regressions and other empirical studies of the GPT hypothesis. Brynjolfsson and Hitt (2003), Baily and Lawrence (2001) and Basu (2003) find positive empirical evidence for the existence of spill-over effects and for ICT as GPT for the USA. Some take productivity comparisons between industries as indirect verification of the spill-over theory (Bosworth and Triplett, 2003, Stiroh, 2002), while others see no evidence for this at all (Inklaar et al., 2008, Van Ark and Inklaar, 2005). Other studies use various descriptive statistics to compare ICT with previous ground-breaking technologies such as electricity. While Crafts (2002) and Jovanovic and Rousseau (2005) stress that ICT need not fear comparison with other major technological innovations, Gordon (2000) draws rather a skeptical conclusion as to the GPT character of ICT. Despite the abundance of anecdotal evidence of innovations arising from the use of ICT (Brynjolfsson and Saunders, 2010), and the assertion that "the suspect's fingerprints are all over the crime scene" (Basu et al., 2003), there is as yet no definite empirical proof of the GPT hypothesis.

Figure 7
Labor Productivity Growth by ICT Sectors



Source: Inklaar et al. (2003).

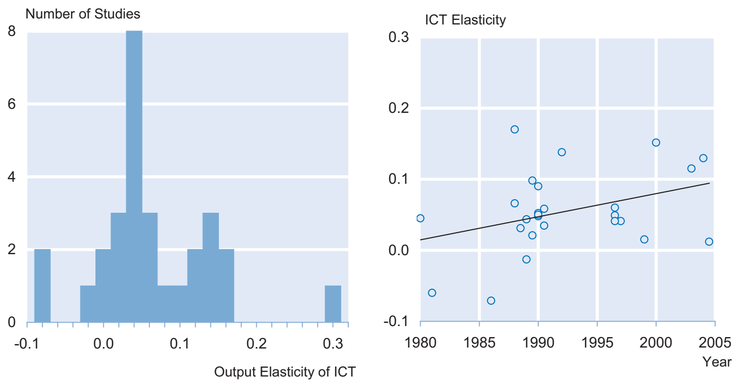
In the existing productivity studies, the mean output elasticity of ICT investments lies between 0.05 and 0.06: a 10% increase in ICT investment then raises output by 0.5–0.6%. This figure has tended to increase in the last few years.

Table 2
Overview table: contribution of ICT to labor productivity in %

	EU		USA	
	ICT contribution	Knowledge economy contribution	ICT contribution	Knowledge economy contribution
1990–1995	17	88	57	83
1995–2000	42	78	59–66	81–98
2000–2005	45	67	33–43	70–92
2003–2007	31	89		

Sources: USA data: 1990–95: Jorgenson (2001); 1995–2000: Cette (2009), Jorgenson (2001); 2000–05/6: Gordon (2010), Jorgenson (2008), Oliner (2007); EU data: 1990–95: Van Ark (2002); 1995–2000: O'Mahoney and Timmer (2009); 2005–05: EUKLEMS (2008), Van Ark and Inklaar (2005); 2003–07: EC (2011).

Figure 8
Frequency of Elasticities and Elasticities over Time



Linear estimation is derived from precision-weighted observations.

Source: Authors' calculations.

4. Summary and questions for the future

The roadmap set out here makes it clear that the contribution of ICT to productivity growth in individual companies, sectors or national economies is independent of the method of measurement or the level of aggregation. Both growth accounting and productivity studies arrive at findings that assign a leading role to ICT in securing sustainable growth.

Table 3
Elasticities by aggregation level and ICT product
(number of studies in brackets)

ICT product/ aggregation level	Company level	Industry level	Country level
Voice telephony (mobile/fixed network)	–	–	0.16 *(1)*
Dates (Internet/broadband)	–	–	0.045–0.16 *(3)*
IT (hardware/software)	0.015–0.39 *(15)*	–0.071–0.17 *(2)*	–
ICT	0.049–0.15 *(3)*	0.031–0.066 *(2)*	–0.013–0.138 *(2)*

Source: Studies consulted in the Appendix.

Still, there is no prevailing consensus in the literature on a number of questions:

What is the significance of complementary investments, particularly in the form of intangible (non-measurable) capital?

The existing studies show that some companies are able to deploy ICT more productively and hence to achieve a higher growth contribution from ICT. The important task is now to research the reasons for this further, and particularly to identify and quantify the "soft" organizational and strategic factors. Well-founded findings on the major complementary functions could be highly relevant to companies as well as policy-makers if we are to make optimum use of ICT investments and retain them as drivers for commercial success and productivity growth.

Is the ICT-producing industry driving progress, or is it the diffusion of these technologies into other sectors? Is it embodied or disembodied technological progress?

The ICT-producing industry is making constant progress in developing and marketing new information and communications technology, and so constitutes a key driver for progress and growth. At least as interesting, however, is the question whether growth can be further stimulated by the diffusion and use of ICT (the "knowledge economy"). Confirmation of this theory, particularly at the sectoral level, would then equate the growth contribution of ICT with that of a "general purpose technology", serving as a stepping stone to further innovation.

What contribution can we expect from ICT in the future? Is there a second-round effect or has this already been exploited?

Empirical studies necessarily have to rely on historical data. New services and technologies such as mobile broadband or Ethernet for data transfer over shorter distances cannot yet be quantified in terms of their growth contribution. However, there is good reason to believe that the effect of ICT will be at least as great in the future, if not greater. Moreover, the literature often points to second-round effects of ICT investment with a certain time delay, which could increase the growth contribution still further.

Literature

Acharya, Ram; Basu, Susanto (2010): ICT and Total Factor Productivity Growth: Intangible Capital or Productive Externalities?
Aghion, P.; Howitt, P. (2007): Capital, innovation, and growth accounting. In *Oxford Review of Economic Policy* 23 (1), pp. 79–93.
Baily, Martin N.; Lawrence, Robert Z. (2001): Do We Have a New E-Conomy? In *American Economic Review* 91 (2), pp. 308–312.
Basu, Susanto; Fernald, John G.; Oulton, Nicholas; Srinivasan, Sylaja (2003): The Case of the Missing Productivity Growth, or Does Information Technology Explain Why Productivity Accelerated in the United States but Not in the United Kingdom? In *NBER Macroeconomics Annual* 18.
Bertschek, Irene; Kaiser, Ulrich (2004): Productivity Effects of Organizational Change: Microeconometric Evidence. In *Management Science* 50 (3), pp. 394–404.
Bloom, Nicholas; Sadun, Raffaella; van Reenen, John (2010): Americans Do I.T. Better: US Multinationals and the Productivity Miracle.
Bresnahan, Timothy F.; Brynjolfsson, Erik; Hitt, Lorin M. (2002): Information Technology, Workplace Organization, and the Demand for skilled Labour: Firm-Level Evidence. In *The Quarterly Journal of Economics* 117 (1), pp. 339–376.
Bresnahan, T.F. and M. Trajtenberg (1995), General Purpose Technologies: Engines of Growth? In *Journal of Econometrics* 65 (1), pp. 83–108.
Brynjolfsson, Erik; Hitt, Lorin M. (1995): Information Technology as a Factor of Production: The Role of Differences Among Firms. In *Economics of Innovation and New Technology* 3 (3), pp. 183–200.
Brynjolfsson, Erik; Hitt, Lorin M. (1996): Paradox Lost? Firm-Level Evidence on the Returns to Information Systems Spending. In *Management Science* 42 (4), pp. 541–558.
Brynjolfsson, Erik; Hitt, Lorin M. (2003): Computing Productivity: Firm-Level Evidence. In *The Review of Economics and Statistics* 85 (4).
Cette, Gilbert; Kocoglu, Yusuf; Mairesse, Jacques (2009): Productivity Growth and Levels in France, Japan, the United Kingdom and the United States in the Twentieth Century. In *National Bureau of Economic Research Working Paper Series* No. 15577.
Correa, Lisa (2006): The economic impact of telecommunications diffusion on UK productivity growth. In *Information Economics and Policy* 18 (4), pp. 385–404.
Conference Board (2011), The Conference Board – Total Economy Database, September 2011.
Crandall, Robert W.; Lehr, William; Litan, Robert (2007): The Effects of Broadband Deployment on Output and Employment: A Cross-sectional Analysis of U.S. Data.
Czernich, Nina; Falck, Oliver; Kretschmer, Tobias; Woessmann, Ludger (2011): Broadband Infrastructure and Economic Growth*. In *The Economic Journal* 121 (552), pp. 505–532.
Gordon, Robert J. (2000): Does the »New Economy« Measure up to the Great Inventions of the Past? In *Journal of Economic Perspectives* 14 (4), pp. 49–74.
Gordon, Robert J. (2010): Revisiting U. S. Productivity Growth over the Past Century with a View of the Future. In *National Bureau of Economic Research Working Paper Series* No. 15834.
Greenstein, Shane; McDevitt, Ryan C. (2009): The Broadband Bonus: Accounting for Broadband Internet's Impact on U.S. GDP. In *National Bureau of Economic Research Working Paper Series* No. 14758.
Greenstein, Shane; Spiller, Pablo T. (1995): Modern Telecommunications Infrastructure and Economic Activity: An Empirical Investigation. In *Industrial and Corporate Change* 4 (4), pp. 647–665.
Grimes, Arthur; Ren, Cleo (2009): The Need for Speed: Impacts of Internet Connectivity on Firm Productivity.
Hardy, Andrew P. (1980): The role of the telephone in economic development. In *Telecommunications Policy* 4 (4), pp. 278–286.
Hausman, Jerry A.; Pakes, Ariel; Rosston, Gregory L. (1997): Valuing the Effect of Regulation on New Services in Telecommunications. In *Brookings Papers on Economic Activity* 1997 (Special Issue Microeconomics), pp. 1–54.
Hempell, Thomas (2005a): Does Experience Matter? Innovations and the Productivity of Information and Communication Technologies in German Services. In *Economics of Innovation and New Technology* 14 (4), pp. 277–303.
Hempell, Thomas (2005b): What's Spurious, What's Real? Measuring the Productivity Impacts of ICT at the Firm-Level. In *Empirical Economics* 30 (2), pp. 427–464.
Hempell, Thomas; van Leeuwen, George; van der Wiel, Henry (2004): ICT, Innovation and Business Performance in Services: Evidence for Germany and the Netherlands.
Im, Kun Shin; Dow, Kevin E.; Grover, Varun (2001): Research Report: A Reexamination of IT Investment and the Market Value of the Firm — An Event Study Methodology. In *Information Systems Research* 12 (1), pp. 103–117.
Inklaar, Robert; O'Mahony, Mary; Robinson, Catherine; Timmer, Marcel P. (2003): Productivity and Competitiveness in the EU and the US. In Mary O'Mahony, Bart van Ark (Eds.): EU Productivity and Competitiveness: An Industry Perspective. Can Europe Resume the Catching-up Process? Luxembourg: Office for Official Publications of the European Communities, pp. 73–148.
Inklaar, Robert; Timmer, Marcel P.; van Ark, Bart (2008): Market services productivity across Europe and the US. In *Economic Policy* 23 (53), pp. 139–194.
Jorgenson, Dale W. (2001): Information Technology and the U.S. Economy. In *American Economic Review* 91 (1), pp. 1–32.
Jorgenson, Dale W. (2007): Industry Origins of the American Productivity Resurgence. In *Economic Systems Research* 19 (3), pp. 229–252.
Jorgenson, Dale W.; Ho, Mun S.; Stiroh, Kevin J. (2008): A Retrospective Look at the U.S. Productivity Growth Resurgence. In *Journal of Economic Perspectives* 22 (1), pp. 3–24.
Jorgenson, D.W., M.S. Ho and K.J. Stiroh (2005), Productivity – Information Technology and the American Growth Resurgence, 3, Cambridge: MIT Press.
Jorgenson, Dale W.; Stiroh, Kevin J. (1999): Information Technology and Growth. In *American Economic Review* 89 (2), pp. 109–115.
Mefford, Robert N. (1986): Introducing Management into the Production Function. In *The Review of Economics and Statistics* 68 (1), pp. 96–104.
Koutroumpis, Pantelis (2009): The economic impact of broadband on growth: A simultaneous approach. In *Telecommunications Policy* 33 (9), pp. 471–485.
Lehr, William; Osorio, Carlos A.; Gillett, Sharon E.; Sirbu, Marvin A. (2006): Measuring Broadband's Economic Impact.
Morrison, Catherine J. (1997): Assessing the Productivity of Information Technology Equipment in U.S. Manufacturing Industries. In *The Review of Economics and Statistics* 97 (3), pp. 471–481.
Oliner, Stephen D.; Sichel, Daniel E. (2000): The Resurgence of Growth in the Late 1990s: Is Information Technology the Story? In *Journal of Economic Perspectives* 14 (4), pp. 3–22.
Oliner, Stephen D.; Sichel, Daniel E.; Stiroh, Kevin J. (2007): Explaining a Productive Decade. In *Brookings Papers on Economic Activity* 1, pp. 81–137.
Röller, Lars-Hendrik; Waverman, Leonard (2001): Telecommunications Infrastructure and Economic Development: A Simultaneous Approach. In *American Economic Review* 91 (4), pp. 909–923.
Schreyer, P. and D. Pilat (2001): Measuring Productivity, *OECD Economic Studies* 33 (2), pp. 127-170.
Stiroh, Kevin J. (1998): Computers, Productivity, and Input Substitution. In *Economic Inquiry* 36 (2), pp. 175–191.
Stiroh, Kevin J. (2002a): Are ICT Spillovers Driving the New Economy? In *Review of Income and Wealth* 48 (1), pp. 33–57.
Stiroh, Kevin J. (2002b): Information Technology and the U.S. Productivity Revival: What Do the Industry Data Say? In *American Economic Review* 92 (5), pp. 1559–1576.
Tam, Kar Yan (1998): The Impact of Information Technology Investments on Firm Performance and Evaluation: Evidence from Newly Industrialized Economies. In *Information Systems Research* 9 (1), pp. 85–98.
Tambe, Prasanna; Hitt, Lorin M. (2011): The Productivity of Information Technology Investments: New Evidence from IT Labor Data. In *SSRN eLibrary*.
Timmer, M., G. Ypma and B. van Ark (2003), ICT in the European Union: Driving Productivity Divergence?, Groningen Growth and Development Center, Working Paper GD-67.
Van Ark, B., R. Inklaar and R.H. McGuckin (2003), ICT and Productivity in Europe and the United States: Where Do the Differences Come From?, In *CESifo Economic Studies* 49 (3), pp. 295–318.
Van Ark, B., J. Melka, N. Mulder, M.P. Timmer and G. Ypma (2002), ICT Investment and Growth Accounts for the European Union, 1980–2000, Groningen Growth and Development Center, Research Memorandum GD-56.

Appendix

Table A.1
Summary of elasticities

Original author	Year publ.	Elasticity	Unit	Dates		Region	No. obs./yr
				Start	End		
Black	2001	**0.050**	Company	1987	1993	AM	638
Black	2004	**0.296**	Company	1993	1996	AM	284
Bresnahan	2002	**0.035**	Company	1987	1994	AM	300
Brynjolfsson	1996	**0.044**	Company	1987	1991	AM	702
Brynjolfsson	1995	**0.052**	Company	1988	1992	AM	n.a.
Brynjolfsson	2003	**0.058**	Company	1987	1994	AM	1,324
Dewan	1997	**0.090**	Company	1988	1992	AM	773
Gilchrist	2001	**0.021**	Company	1986	1993	AM	580
Hitt	1996	**0.048**	Company	1988	1992	AM	370
Lichtenberg	1995	**0.098**	Company	1988	1991	AM	1,315
Tambe	2011	**0.041**	Company	1987	2006	AM	1,800
Bertschek	2004	**0.152**	Company	2000	2000	EU	212
Bloom	2010	**0.015**	Company	1995	2003	EU	4,809
Hempell	2004	**0.041**	Company	1996	1998	EU	972
Hempell2	2005	**0.060**	Company	1994	1999	EU	1,177
Mahr	2010	**0.130**	Company	2000	2008	EU	182
Hempell1	2005	**0.049**	Company	1994	1999	EU	1,222
Loveman	1994	**– 0.060**	Company	1978	1984	WW	60
Basant	2006	**0.115**	Company	2003	2003	AS	266
McGuckin	2002	**0.170**	Industry	1980	1996	AM	10
Stiroh	2002	**– 0.071**	Industry	1973	1999	AM	18
Acharya	2010	**0.031**	Industry	1973	2004	WW	384
Omahoney	2005	**0.066**	Industry	1976	2000	WW	55
Venturini	2009	**0.138**	Country	1980	2004	EU	15
Dewan	2000	**– 0.013**	Country	1985	1993	WW	36
Koutroumpis	2009	**0.012**	Country	2002	2007	WW	22
Madden	2000	**0.162**	Country	1975	1990	WW	43
Röller	2001	**0.045**	Country	1970	1990	WW	21
Sridhar	2007	**0.150**	Country	1990	2001	WW	63

Note: Region = AM: America, AS: Asia, WW: Worldwide.

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Tobias Kretschmer studied Business Administration at the University of St. Gallen and took a PhD in Economics from the London Business School. Before his professorship, he was employed as a post-doc at INSEAD (2000–2001), Fontainebleau, and as an associate professor at the London School of Economics (2001–2006).

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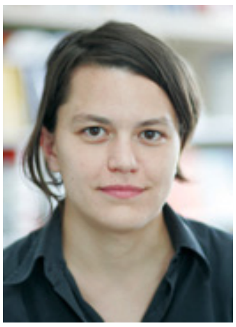

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