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Accounting for the Impact of Information and Communication Technologies on Total Factor Productivity:

Towards an Endogenous Growth Approach

Editor: Salvador Barrios
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The mission of the IPTS is to provide customer-driven support to the EU policy-making process by researching science-based responses to policy challenges that have both a socio-economic and a scientific or technological dimension.

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Preface

Extensive research has provided evidence on the positive impact of ICT on growth and productivity and, in particular, on the EU relative deficit in this respect as compared to the US. Although ICT adoption and productivity impact has been especially vigorous in certain Member States (e.g. Ireland, Finland), this effect has still not materialized in most EU countries. There is thus a growing awareness in both policy and academic circles that relatively low ICT diffusion is partly responsible for the EU productivity deficit. The existing evidence on the impact of ICT on productivity is far from satisfactory, however. Economists to date have essentially looked at the impact of ICT on productivity and growth, using a neoclassical framework where ICT is assumed to be equivalent to other types of capital. This framework of analysis appears to be too restrictive in the case of ICT. There are a number of reasons for this. For instance, ICT diffusion radically changes the way information flows. ICT also promotes interactions between agents through network effects. In this context, the economic impact of ICT cannot be understood properly without considering these interactions. From a policy perspective, the existence of interaction and spillovers suggests that the impact of ICT on productivity (and competitiveness) may require ICT diffusion to attain a certain level (or critical mass) and that it must be accompanied by measures fostering knowledge creation and diffusion. These issues have been largely discussed in endogenous-growth theories (often termed "new growth theories"), although not in the context of the macroeconomic impact of ICT diffusion on productivity. This literature has proved to be especially useful as it sets a rich analytical framework for identifying possible interactions and spillovers in new technology adoption and productivity dynamics.

This study, undertaken by Theo Dunnewijk, Huub Meijers, and Adriaan van Zon (MERIT, Maastricht Economic and social Research and training centre on Innovation and Technology, Netherlands) and edited by Salvador Barrios (IPTS, Joint Research Centre[1]), aims to contribute to the IPTS mission to provide customer-driven support to EU policy-making processes by providing research-based analysis of questions related to ICT diffusion, knowledge and innovation in the EU economy. The study reviews the literature on the impact of ICT on economic growth and productivity. It provides inputs to the discussion on extending the neoclassical growth framework to incorporate elements of the endogenous growth theories. In particular, the study provides arguments and empirical support for the idea that policy aimed at boosting ICT investment (because of the large potential spillovers related to ICT diffusion) can potentially create considerable economic benefits.

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[1] IPTS – the Institute for Prospective Technological Studies - is one of 7 research institutes that make up the Joint Research Centre, a Directorate-General of the European Commission.

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Executive Summary

The renewed Lisbon strategy puts special emphasis on the role Information and Communication Technologies (ICT) could play in meeting the challenges of boosting growth, competitiveness and cohesion throughout the EU. In particular, the i-2010 objectives to promote the information society and the diffusion of ICT to strengthen the competitiveness of the EU economy have translated into concrete policy proposals in a number of EU policy initiatives. In parallel to these policy developments, extensive research has provided evidence regarding the positive impact of ICT on growth and productivity. It has shown the EU's relative deficit in this respect, in comparison to the US. Although ICT adoption and productivity impact has been especially vigorous in certain Member States (e.g. Ireland, Finland), this effect has still not materialized in most EU countries, see van Ark and Inklaar (2005).

There is a thus growing awareness in both policy and academic circles that relatively low ICT diffusion is partly responsible for the EU productivity deficit. Up until now, however, economists have essentially looked at the impact of ICT on productivity and growth in a neoclassical framework where ICT is assumed to be equivalent to other types of capital. Here, the amount of money invested in ICT is linked to productivity growth in a given economy. This framework of analysis is far too restrictive in the case of ICT, however. There are a number of reasons for this. In particular, ICT diffusion radically changes the way information flows. ICT diffusion also promotes interaction between economic agents though network effects. This means that the economic behaviour of a particular firm, industry or country, cannot be understood properly without considering the specific context within which its activity takes place. These two features tend to support the view that the deployment of ICT does not face the same constraints as traditional physical production factors. Hence the neoclassic framework is necessarily limited for an analysis of the impact of ICT on productivity. Importantly, from a policy perspective, the existence of interactions and spillovers in ICT diffusion suggests that the productivity impact of ICT may require ICT diffusion to attain a certain level (or critical mass) and that it must be accompanied by measures fostering knowledge creation and diffusion. These issues have been largely discussed in endogenous-growth theories (often termed "new growth theories"), although not in the context of macroeconomic analysis of ICT diffusion and productivity. This literature has tended to focus attention on identifying possible interactions, i.e. spillovers, in productivity and innovation dynamics. Up to now, however, these views have rarely been connected with the information society. Significantly, the existence of spillovers in ICT adoption suggests the possibility that ICT investment can be lower in a given country than the optimum from an economic viewpoint.

The current study provides a review of the literature on the impact of ICT on economic growth and productivity. It also contributes to the discussion on extending the neoclassical growth framework to incorporate elements of endogenous growth theories, in order to take this impact into account. **Sections 2 and 3** provide an overview of the traditional growth accounting framework rooted in growth analysis. This contribution and the many studies that have followed, have led to the conclusion that the drivers of productivity growth were largely unknown and embodied in Total Factor Productivity (TFP), i.e. the residual term explaining productivity growth once production factors such as labour, capital and intermediate materials, are accounted for. This highly unsatisfactory conclusion gave rise to new directions in research. For instance, Arrow (1962) launched the idea of a "learning device" incorporating the knowledge aspect of capital. Romer's (1990) extension of the Sollow's framework introduced elements such as R&D expenditure and human capital accumulation. R&D, in particular, shares the characteristics of a public good in that the effect of private R&D expenditure of a given firm often spills over to other firms. For instance, a company which invents a new product or introduces new production methods thanks to its own research effort may expect its competitors to try to benefit and/or mimic the technological advances related to the corresponding innovation. This type of interaction in research and innovation activity is usually termed "research spillovers". It follows that, in presence of such spillovers, the social return from firm-level R&D may not be fully internalized in private agents' behaviour. The resulting situation, when considering the economy as a whole, is that the overall level of R&D may be lower than the optimum. Similarly to the R&D case just described, while the benefits of using ICT in terms of productivity are potentially large, the resulting aggregate use of ICT maybe too low to boost productivity significantly in a given economy. The presence of spillovers in ICT use may thus deter greater levels of ICT diffusion and, consequently, result in lower macroeconomic productivity and growth than what could be potentially achieved if these spillovers were taken into account.

Section 4 discusses the way ICT spillovers can be embodied in a traditional production function framework and discusses the impact of ICT on productivity growth when ICT-related spillovers are taken into account. This section also discusses possible interactions between ICT and elements such as human capital and R&D. Within this framework, ICT, seen as a product, is characterised by fast technological change and, as stated above, is likely to influence both the accumulation and transmission of knowledge. Hence, the relationship between ICT and productivity growth is likely to be more complex than, say, when considering traditional production factors. ICT is a general-purpose technology which means that the scope of application is wide, as are the variety of uses, and the number of potential improvements is high. Therefore, ICT takes time to implement, but it is also likely to lead to knowledge spillovers, faster diffusion and production of knowledge which are seen as decisive elements in generating long-term growth. It follows that, one would naturally think, ICT, human capital accumulation and research activity would interact in favour of greater innovative capability and higher productivity levels. Furthermore, the network-character of ICT suggests that the contribution of ICT capital to output as a direct factor of production exceeds its contribution to growth as measured simply by the variation in the ICT capital stock. The empirical results provided in this study show that ICT capital stock have indeed provided a significant contribution to productivity growth in a number of OECD economies with a 10% increase in ICT capital stock contributing to 1.3% annual average increase in productivity growth.

Section 5 summarizes the main lessons and findings of the study and addresses policy implications. In particular, the study provides arguments and empirical support for the idea that policies favouring ICT investment can create large economic benefits, due to the existence of large potential spillovers related to ICT diffusion. Because of the existence of network and spillovers effects, these benefits can hardly be directly perceived by individual firms taking investment decisions. However, these findings do not necessarily mean that higher ICT investment will yield greater productivity and growth levels. Indeed, existing microeconomic evidence suggests that the positive impact of ICT investment usually observed at the macroeconomic level is not systematic. The micro-literature tends to suggest that ICT investment is just one condition for greater productivity growth, and that much more is needed. A large number of microeconomic studies have shown that aspects such as skills, changes in business organisation and an innovation-friendly environment are all important components for promoting the effective impact of ICT adoption on economic efficiency, see for instance, Bertschek and Kaiser (2004) and Aubert et al. (2006). While these elements are not considered in this paper, the results and arguments provided here show that the context in which ICT diffuse conditions to a great extent the impact of ICT on productivity growth at a the macroeconomic level. From a policy perspective, the question arises as to how the economy's structural features and framework conditions (including institutions) could influence the adoption and expected impact of ICT on economic development. In particular, considering the Lisbon strategy, better working factors and product (and services) markets must be facilitated in order to favour the emergence of innovative forms of economic activities (new businesses, new products and services, new production organization processes, new markets, etc.) and adoption of new technologies (among which ICT is prominent).

1. Introduction

A country's production possibility frontier describes all combinations of outputs that it could produce given its available inputs. Efficient market-economies produce on their frontier. Consumption possibilities are ultimately bounded by that frontier, although international trade at non-autarky prices allow countries to consume packages of goods and services from outside their frontiers. A country's frontier (and therefore its consumption possibilities) can expand if its factors of production become more abundant, or (and this amounts to the same thing from a frontier-expansion point of view), if the productivity of these factors can be increased somehow. The bonus of increasing productivity rather than factor-abundance, however, is that output per head is also increased, which expands consumption possibilities, together with potential welfare per head.

From a welfare perspective then, productivity growth is important. The question naturally arises as to how one could secure a continuously high rate of productivity growth. This amounts to pinpointing the respective sources of productivity growth first and then indicating how these sources can be manipulated to get the highest return in terms of overall economic growth. In this paper, we will focus first in very general terms on the sources of economic growth. In Section 2 below, we provide a short historical overview of the evolution of growth models that have looked at different sources of growth, and that have concluded that technical change is responsible for per capita growth of output. This does not explain much by itself, since it simply shifts the need to find out about the sources of growth per se to finding out about the sources of technological progress. Indeed, that is what the new growth theorists of the 1980s set out to do. Their activities were inspired by the notion that technological change was by far the most important source of welfare growth, and that nothing much, let alone definite, was known about it. In order to fill this knowledge gap, many empirical studies were performed to find out more about the drivers of productivity growth, i.e. one wanted to measure the impact of an extensive set of factors (see Denison (1962, 1967) for example) on productivity growth. However, the act of measuring implies that one has a measuring device. In addition, one needs to have a notion about what is a normal value for productivity (i.e. one needs to 'calibrate' the actual measuring rod), so as to be able to determine how big the part is of productivity that deserves closer scrutiny since it defies the 'normal' explanation (i.e. in terms of the 'normal' inputs). A measuring device in the form of a production function links a set of inputs to a corresponding level of output and is presented in Section 3. Section 4 then addresses the issue of the extension of that measurement device to include the impact of ICT. It covers the different mechanisms through which this may happen, and it also provides some empirical evidence as to why such an extension is relevant in the first place in addition to a theoretical framework that includes the most important mechanisms through which ICT may influence productivity growth. Finally, Section 5 contains a short summary and some concluding remarks.

2. Technical change and productivity growth: an overview

Technology-driven economic growth comes from continuous productivity improvements in a broad sense. There is a rich tradition in modelling the process of economic growth. Starting in the 1930's Harrod (1939) and Domar (1946) came up with growth models that focussed on capital accumulation as a source of growth. The rate of growth of output matched that of the capital stock and was given by the product of the constant saving rate and the (again constant) productivity of capital. [2] But only if the rate of growth of the capital stock coincided with that of the labour force, growth was 'warranted'. Lower or higher growth than the warranted rate of growth, would inevitably lead to under or over utilisation of productive capacity, while there was no mechanism to return to a steady state growth path. These stability problems –or Harrods knife-edge problem - inspired many authors to modify Harrods' growth model.[3] The degree of utilisation of productive capacity was an equilibrating device stabilising the economy when it was running at a pace that did not coincide with warranted or sustainable growth. Over utilisation led to inflation which produced less real demand, while under utilisation led to deflation which boosted real demand through lower prices. But other mechanisms to solve this instability problem have been considered too, like e.g. Malthusian demographic reactions towards capital shortages or surpluses, or the Kaldorian saving function, where the distribution of income in times of capital surpluses/shortages changes in favour of profits/labour income and the effective saving rate changes accordingly (assuming a higher propensity to save out of profits than out of labour income). Nonetheless, the most popular way out of the growth instability problems has been that of a variable capital productivity,[4] as it is implied by the use of a neo-classical production function that links a set of inputs to a volume of output, and where each input faces a decreasing marginal product, i.e. the more of that input is used, ceteris paribus, the lower the productivity of the last unit used will be. In case of capital accumulation, this implies that the marginal product of capital will fall, and therefore also the average product of capital. So, a neo-classical production function entails an automatic 'break' on the over-accumulation of capital. First because the decrease in the marginal product of capital, for a given saving rate, leads to a lower level of savings per unit of capital when output grows, and therefore to lower growth of the capital stock, and secondly because the drop in the marginal product of capital also removes the incentive for the further accumulation of capital.

Based on the properties of the neo-classical production function, Solow (1956) was the first to formulate the fundamental equation of neo-classical growth theory[5] and constructed a neo-classical growth model featuring a stable steady state growth path, while labour productivity as well as the capital intensity of production was continuously growing at the rate of labour augmenting technical change.[6] Other parameters of the model, like the saving rate, do not

[2] Based on the work of S. Kuztnets the savings rate was deemed to be constant in the long run, see Deardorff (1970) Duessenberry (1949) gave a theoretical foundation for such a long run savings rate.

[3] Alexander (1950) and Allen (1960) analysed the structure of the model more deeply, Duessenberry (1958) gave it the dynamics of the business cycle, Jorgenson (1960) defined Harrods stability, while Phillips (1961, 1962) introduced the unemployment - inflation trade-off, Rose (1959) investigated the possibility of warranted growth, while Treza (1966) commented on Hahn & Matthews (1964) survey of the literature on growth economics. These publications all made the Harrod-Domar model more realistic is some sense or another by eliminating the instability of the original model.

[4] See for instance Solow (2000) on this issue.

[5] Stating that the growth of the capital stock equals the output produced with that stock minus depreciation and consumption.

[6] This is the type of technical change that works as if it enhances the quality of labour. There are many definitions of the rate of technical change, depending on their impact on the distribution of income between

affect its long-term growth performance, but they do have an impact on the long-term level of productivity. In addition, either the saving rate or the technology parameters other than the rate of technical change itself do have transitory growth effects as the economy moves towards a new steady state. However, the period of transition may by quite long in practice[7], so that for all intents and purposes the difference between growth-effects and level-effects of some policy shock becomes a matter of degree rather than a matter of principle.[8]

In the original Solow model, all long-term productivity growth results from technical change and capital accumulation is simply supporting the growth process rather than driving it, as opposed to the Harrod-Domar model. The reason is that due to the decreasing marginal product of capital the process of capital accumulation sec will drive down the marginal product of capital to zero (in the limit). As stated above, this poses two problems: first the average product of capital would go down too, resulting in less savings per unit of capital for a given saving rate, hence less growth of the capital stock. The second problem is that with a zero return on capital there would be little reason to save in the first place. Solow cured this problem by introducing labour saving technical change, that effectively increases the marginal product of capital by as much as is lost by the process of capital accumulation itself. Thus, capital accumulation does not lead to a continuous fall in the marginal product of capital, hence capital accumulation can continue to go on, both in physical terms as well as in terms of incentives. A big drawback of the Solow model, however, is that the rate of labour augmenting technical change is an exogenously given number, which is hardly satisfactory from the point of view that a growth model should not assume the existence of steady state growth (at least not in such an obvious manner), but instead should somehow be able to explain what kind of (economic incentive driven) behaviour would result in steady state growth.

In a very early attempt to solve this exogeneity problem, Kaldor and Mirrlees (1962) defined a 'technical progress' function as a function of per capita investment, and learning was thought to be the underlying factor. They regarded this technical progress function as a functional relationship more basic than the production function itself. Around the same time Arrow (1962) came up with a 'learning function' with (cumulative) past investment as a proxy for all the productive things that had been learned. Arrow asserted that new machines are improved machines and are more productive compared to old machines. So gross fixed capital formation does not only lead to labour productivity growth on existing capital, but it would also improve the productivity of labour associated with all subsequent vintages of capital made in the economy. In the Arrow (1962) model, capital as a production factor provided the opportunities for labour to learn to use the capital (and future generations of capital goods) more and more productively, leading to inter-temporal knowledge spillovers that were able to generate growth. Unfortunately, the Arrow-model was rather complicated, also because he chose a vintage setting, explicitly accounting for differences in productivity

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labour and capital. Harrod-neutral technical change, for instance, is the type of technical change that, for a given capital output ratio, leaves the distribution of income between labour and capital unchanged. Harrods labour saving technical change changes the distribution of income in favour of capital, again for a given value of the capital output ratio. For and extensive exposition on the types of technical change see Jones (1975). Most significantly, Harrod-neutral technical change can be represented as purely labour augmenting technical change, and because of that, a growth model having only labour augmenting technical change can actually reproduce Kaldor's stylised facts of growth, i.e. constant capital and labour shares, growing labour productivity and capital intensity of production and a constant capital output ratio. (Kaldor (1961)).

7 Formally, the transition period is infinitely long, while the actual growth rate of an economy asymptotically approaches its steady state value.

8 See also Solow (2000), p. 182-183, on this subject.

of the yearly additions to the capital stock.[9] The latter was a logical decision from the point of view that different generations of capital provided the objects of learning, but the vintage setting somewhat obscured the message of the importance for growth of knowledge spillovers by them selves. By contrast, the original Solow model was relatively simple, and its neo-classical features provided enough modelling entry points to try to endogenise growth processes as the result of decisions made by people acting on economic opportunities and incentives.

This is exactly what the new growth theorists of the 80s and 90s set out to do. Lucas (1988) is a relatively straight forward example of an endogenous growth model based on the original Solow aggregate production framework, where labour augmenting technical change was endogenised by linking it to incentive driven human capital accumulation. Romer (1990) and Aghion and Howitt (1992) are other examples that focussed more on the role of capital as carriers of technological improvements, and the differences between capital goods that created market niches for these capital goods. The latter in turn generates profit opportunities that fuels economic incentive driven R&D activities into improving the quality of capital goods and so creating 'new' goods that fit into new niches and that build on the experience attained with inventing the old ones. Grossman and Helpman (1991) built an endogenous growth model that shares many features with the Aghion and Howitt model of growth of creative destruction[10], but that concentrates on the production of welfare directly, and the role of love-of-variety by consumers -for as many product varieties as possible- in generating endogenous growth of welfare through R&D for a given volume of resources.

The developments as outlined above point at an increasing complexity in explaining technological developments. Endogenous growth theories replaced the exogenous growth theories – like the Harrod-Domar type of models embodied - that assumed that the relevant growth rates were given, i.e. the population growth rate, the deprecation rate and the rate of technological progress were determined by "God and the engineers".[11] To increase complexity even further, it should be noted that it's not just saving rates and technical change parameters that implicitly 'define' growth performance. Institutional factors, politics, democracy and history shaping micro policies like regulation of specific industries (like financial services), patent policies, R&D policies, education policy, policies aimed at institutional quality and democracy are important too Denison (1962, 1967), Griffith et. al. (2003), Mauro (1995), Chong & Calderon (2000), Knack & Keefer (1995) Nonetheless, in this paper we focus on linking growth performance to economic factors that are more tangible than the ones listed above, and that are relatively easily incorporated into a measurement framework as hinted at above.

9 Minus the yearly depreciations that scrap the least productive parts of the capital stock.
10 See Aghion and Howitt (1992)
11 Robinson (1962)

3. Measuring productivity growth

3.1 The measurement framework

If one wants to measure something, one has to have a frame of reference, i.e. a measuring device. Since in economics we are dealing with 'soft' relations between groups of agents, direct measurements are often not possible, as opposed to a field like physics or astronomy, for instance. So, instead of a true measuring rod, one uses a theoretical framework that tells us how much output the use of a set of resources would 'normally' produce. The characteristics of such a framework are important for three main reasons (Greenwood and Jovanovic, 1999):

1. To be able to predict the consequences of out of sample variation in policies and other exogenous variables;
2. To guide the measurement of variables;
3. To allow one to deal with simultaneities.

Point 1 is highly important from a policy point of view, certainly if policy makers are discontent with within sample performance. Point 2 reflects the adagio of 'no measurement without theory', while Point 3 refers to the completeness of a measurement framework, that allows one to infer the existence of relations between variables of particular interest that in turn (and in accordance with Point 2 above) can be used to help determine the practical/numerical importance of those variables.

The measuring framework that Solow (1956) used was essentially the production side of his neoclassical growth model expanded with exogenous technical change. In fact, anything that shifted the production function itself was 'technical change' by assumption. Solow's direct measurements showed that roughly 80 percent of labour productivity growth was due to technical change, rather than an increase in capital per head. This underlined the significance of technical change in 'explaining' productivity growth, but it also showed how little we actually knew then about the 'true' drivers of economic growth. Abramowitz (1956, 1993) called this 'some sort of a measure of our ignorance' and as a consequence: 'some sort of indication of where we need to concentrate our attention'.

Of course, labour productivity growth depends not only on technical change. A growing amount of capital per head would, according to neo-classical production theory, also result in labour productivity growth, thus obscuring somewhat the true impact of technical change on economic growth. In order to clarify things, empiricists (including Solow himself who made the first contribution in this area (Solow (1956)) came up with the notion of total factor productivity, or TFP for short, and means to measure this concept. The growth of total factor productivity then provides a (sometimes somewhat implicit) link with the 'rate of technical change'.

Total factor productivity denotes the productivity of a complex of input factors, rather than a single input factor. It originates from the concept of a technology represented by a production function, say f(L,K), describing how certain volumes of inputs -in this case labour (L) and capital (K) that together are aggregated into a 'volume' of the ensemble of L and K, i.e. f(L,K). This ensemble, or all factors taken together or the 'total factor', is then to be transformed into in corresponding volumes of output Y. The productivity of the input factors equals then by definition the ratio of the output volume and the measure of the input volume, which can be symbolised by Y/f(L,K). The latter ratio is TFP, and as such it is an extremely important concept because it measures how much output one would obtain per unit of a composite input or resource that is spent producing that output. As suggested in the introduction, a rise in TFP then represents an outward shift[12] of a country's production possibility frontier. TFP-growth therefore also implies an increase in a country's potential welfare (disregarding distribution issues).

But the fact that TFP is a ratio of two things – i.e. actual output (Y) on the one hand and an aggregate of total inputs f(L,K) - implies that the measurement of its actual value depends on the accuracy of the measurement of the composing parts, i.e. the output-side (Y) as well as the input-side f(L,K). However, both output and inputs are composite entities rather than the homogeneous concepts that a production function normally refers to, and so one needs to aggregate all outputs produced by a production unit and all inputs used by that production unit. This implies of course those aggregation schemes, both at the input side and the output side become more important, the 'bigger' and 'varied' the production units are (national economies versus small firms producing just one good).

3.2 Aggregation issues

There are aggregation issues that have an impact on the actual measurement of total factor productivity. Let us first deal with the output-side. A very important problem these days is that a growing part of today's economic activities consist of the rendering of services. The problem with services is that a volume measure of the production of the most important services, like banking and insurance, is hard to obtain. This is less the case with haircuts, of course, since a haircut is a haircut is a haircut, although people these days look distinctly different from people in the old days when they just had one. Another important issue is the fact that market prices may not reflect the intrinsic quality (-improvements) of a good or service. Given standard aggregation practices, where an aggregate price-index of a set of outputs is obtained by evaluating a given (old) basket of goods and services at new prices and evaluating that same basket at old prices (Laspeyres-aggregation) or doing the same thing but then with the current basket of goods (Paasche-aggregation), it follows that the volume measure of a good obtained by dividing total expenditures on that good by its price (-index), will be severely underestimated if the price-index of the good does not develop pari passu the intrinsic quality of the good under consideration. After all, a volume measure of a good should somehow take into account the way in which the good succeeds in performing its function.

In the case of the ICT several researchers have made a case for hedonic pricing.[13] That is a pricing scheme that does take into account changes in the intrinsic characteristics of a good. For computers, the change in characteristics (speed of operation, memory capacity, operating system usability and stability) has been tremendous, while prices of computers as such have even fallen, let alone therefore the costs of a computer in terms of a bundle of relevant characteristics. Without hedonic pricing, the contribution of ICT volume measures to output volume measures would be understated, because of the understatement of ICT volumes. Conversely, the input of ICT as a production factor would also be severely underestimated but for the use of hedonic pricing.

There are many issues involved in measuring inputs. The notion of a 'capital stock' is a heroic one, and epic battles have been fought around this issue (during the Cambridge capital

[12] Implying that more can be produced with the same measured inputs.

[13] See e.g. Jorgenson (2001), Schreyer (2000) and Colecchia and Schreyer (2001) for a general discussion, Parker and Grimm (2000) for revised quality adjusted data on software and Hollanders and Meijers (2001) for an overview of the techniques employed and an application for seven European countries.

controversy[14]), with no conclusive outcome. In practice, though, people do construct capital stocks, even though there are important theoretical and practical problems involved. “Only in very special cases will it be possible to define a consistent measure of capital-in-general. Some comfort may be gleaned from the reflection that when capital-labour ratios differ widely we hardly need a subtle index to tell us so, and when the differences are slight we are unlikely to believe what any particular index says”.[15] Not only capital but also other inputs than capital have their own measurement problems as well. Labour too comes in many functional varieties and sub-varieties distinguished accordance to sex, age, level of schooling etcetera. It is hard to say a priori which mix of properties of labour is decisive in determining labour productivity on its own. A posteriori this may be even harder because of the degrees of freedom lost in finding the right amount of detail, if econometrics leads to a decisive answer in the first place. A priori detail on the other hand may put too much structure on the TFP-data that may then bias the estimates of TFP.

In this paper however, we will not go into these measurement issues. These are extensively covered elsewhere (cf. Gordon, 2002). Instead, we focus on broader measurement issues, i.e. which general transmission mechanisms to include in a framework that is meant to account for economic growth that may be driven by ICT.

3.3 Spillover issues

The actual use of ICT in an economy may make the economy as a whole more productive (Bartelsman, et al 1998), since an economy becomes more integrated through extensive communication networks, enabling the individual parts of that economy to concentrate more on their core capabilities, just like the opportunity of international trade, at least according to international trade theory, enables countries to concentrate on their respective comparative advantages, and so reap the benefits from international specialisation. Something similar also holds for ‘ICT-integrated’ domestic economies, and it even holds in an ‘ICT-integrated’ international context (Harris, 1998). But these productivity effects of ICT use go beyond the productivity effects that are to be expected from the use of individual units of ICT goods. The fact that others (and especially business partners) are using ICT goods as well makes for positive spillovers of the use of ICT, i.e. they make other ICT users more productive, without them having to pay for that.

In a growth economics context, spillovers are taken into account in many different ways. First the accumulation of knowledge is typically an activity where one ‘stands on the shoulders of giants’ and so tries to improve on the results inherited from the past, without having to start from scratch again. These spillovers then have a typical temporal character, and are called intertemporal spillovers. They feature prominently in all endogenous growth models built so far, and with good reason, for without these spillovers it is simply not possible to have steady state endogenous growth from a given volume of resources. Besides, in reality we do not have to reinvent the wheel each new generation, we simply borrow our father's bike and with some reverse engineering and luck it becomes a lot easier to build the next generation better to use bikes. But even with basic R&D we build on the notions of our ancestors, although sometimes a complete break with the world-view of our ancestors may work wonders.[16]

[14] See Harcourt (1972)
[15] Solow (1956)
[16] One only has to think of quantum mechanics and Schrödingers cat as opposed to the mechanistic and deterministic world view of René Dèscartes.

As early as the Sixties, people have focussed on (inter-temporal learning-) spillovers as a source of growth (Arrow (1962)). And with the advent of new growth theory in the eighties of the previous century, the decisive role of inter-temporal knowledge spillover in fuelling steady state growth became very clear indeed. In Lucas (1988), interpersonal (as opposed to inter-temporal) human capital spillovers are also an important feature of the model, although they only add to growth and do not cause growth (that is what the inter-temporal knowledge spillovers already do!) Nevertheless, they serve to illustrate a notion of spillovers that is connected with the productivity effect of a network. Roughly speaking, a network becomes more valuable to individual participants in a network, the larger the network is. Its overall value rises therefore more than proportionally with its size. And if an input, like ICT capital for instance, exhibits network features, then its contribution to output may be expected to rise more than proportionally with the volume of the input itself. In Lucas (1988) this notion is captured by the addition of human capital per person that directly and proportionally influences the productivity of individual persons, but it also influences the productivity of all factors taken together, simply because smarter people become even smarter than they already are by communicating with each other and benefiting from each others' experiences.[17] If these spillovers are not taken into account in economic decision-making (for instance in decisions regarding the allocation of time between human capital formation and final output production), then a Lucas (1988) type of economy will under-invest in human capital formation. By contrast, in the Aghion and Howitt (1992) model there are actually negative rent spillovers in that new firms steal the business of old firms. This kind of innovation is often called Schumpeter mark I, the most drastic type of innovation, rendering the old versions of products and firms obsolete (Aghion & Howitt, 1998). The welfare effect simply is the welfare gain of the new products minus the loss of the old ones. For individual entrepreneurs the entire rent-stream is available if one succeeds in finding a new instance of a production technology, but for society as a whole it is only the incremental productivity increase that is available. So, from a societal welfare point of view, the gain of allocating R&D resources to finding the next instance of a technology is much smaller than for the individual that actually succeeds in finding it and taking over the market. Hence, from a societal welfare point of view, there is over-investment in R&D activities, because of the negative effects that a new instance of a technology has on existing instances of that technology.

3.4 The theory of TFP measurement

As stated above, any factor that increases the productivity of an economy's 'ensemble' of resources may actually improve the welfare of the economy under consideration. The question naturally arises how to 'measure' this productivity of all resources/production factors taken together, i.e. how to measure 'total factor' productivity. Solow's (1956) answer to this question was straight forward: One takes an aggregate production function,[18] mixes it with some assumptions regarding the efficiency by which production factors are used as well as some assumptions about the degree of competition on the relevant markets, and one can directly calculate what the contribution of the production factors to output should be. Then TFP is defined as the contribution of the 'rest' (which has not been specified explicitly) by taking the difference between total output and the contribution to output of all 'known' factors (like the input of labour, capital and so on). The bigger this difference is, the more important the factors are that we do not know! From that perspective, a high value of total factor

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[17] Of course this presupposes a kind of variety of the knowledge contained in individual persons, so that the union of all knowledge is bigger than the 'knowledge-set' of each individual.

[18] With certain mathematical characteristics, see Takayama, p 436

productivity is not necessarily a good thing, since that also means that there are factors at play that are important for the actual development of welfare in a country, but that we don't know anything about, and that we therefore can not hope to influence through directed policy actions. So total factor productivity is not only a measure of our ignorance, but also, to some extent, a measure of our policy impotence.

The above can be formalised by defining a neo-classical production function:

(1) $$Y = Z.f(L,K)$$

where Y is output, L is a labour aggregate (number of working hours, for instance), and K is 'the' capital stock.[19] f(L,K) is a meaningful aggregate of all inputs, meant to represent a volume measure of all inputs taken together, i.e. f(L,K) measures the volume of the total factor in terms of the volumes of its individual components (in this case L and K). Z=Y/f(L,K) then represents the output per unit of the total factor, and is therefore equal to total factor productivity.

It follows directly from (1) that anything that contributes to output but that is not subsumed under f() would reduce z if it were indeed subsumed under f(). From the perspective of reducing the residual, i.e. increasing the knowledge about the inner-structure of the black box that is total factor productivity, f() itself therefore should be expanded to 'account' explicitly for quality changes in inputs, quality changes in the organisation of production units and so on. This means that the measurement of inputs needs to reflect more closely the way in which these inputs themselves succeed in performing their tasks, or in which the organisation of the production process itself influences their performance. The way to improve the correspondence between measurement and actual contribution is to account for more defining characteristics of production factors. In the case of labour, for instance, this may be done by distinguishing different classes of labour in accordance with type and level of education, experience, age, sex and so on.

Usually, however, one follows a two-stage approach. First one defines f(), then obtains z or even the growth rate of z, i.e. $\hat{Z}$, and then tries to link variations in $\hat{Z}$ to variations in other (characteristics of) variables not subsumed under f().[20,21] Hence, taking the time derivative of (1), it follows immediately that:

(2) $$\dot{Y}/Y = \dot{Z}.f/Y + Z.\dot{f}/Y = \hat{Z} + \hat{f}$$

Where a dot over a variable denotes its instantaneous change over time, and a hat over a variable denotes its proportional rate of change over time, i.e. the instantaneous growth rate. Total factor productivity growth $\hat{Z}$ is therefore equal to the difference between the growth of total output and the growth of f() as a measure of total inputs.

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[19] The measurement of capital is by no means an easy task (Harcourt, 1972 who overviews the Cambridge Debate in his excellent *Some Cambridge controversies in the theory of capital*), but in TFP measurement exercises one usually takes a practical stance and uses the Perpetual Inventory Method to construct capital stock time-series, accounting for heterogeneous qualities of those machines as time dependent.

[20] In an econometric sense, one tries to 'explain' $\hat{Z}$.

[21] But if these characteristics are really linked to f() itself or to the variables in f(), then this two-stage procedure implicitly assumes the existence of some aggregate functional form linking the development of output and the use of inputs in a way that may be different from the aggregate relations that are implied by the structural model in which the additional determinants of z are taken into account from the outset (and more importantly in the 'proper' way).

By assuming that TFP-growth $\hat{Z}$ depends on all kinds of things, like a trend, R&D performance per unit of output (Krusell, 1998), changes in the level of education of the working population (Barro, 1991, Parente, 1994) or the quality of the workforce, (Hanushek & Kimbo, 2000) changes in infrastructure per head (Barro 1991), and so on, one tries to reduce the unknown residual present in total factor productivity growth. The additional bonus of accounting for various contributing factors to total factor productivity growth is that one also obtains potential policy entry points that may be useful from a welfare maximization point of view. Hence, the actual identification of the factors that contribute to TFP-growth in the first place, and secondly the measurement of their contributions to growth and third an assessment of the 'costs' in a broad sense of changing the volume and/or nature of the contributing factors through alternative economic policies, provides valuable information as to which policies would be the most effective, and how an 'optimum' policy-mix would look like. This leads directly to the conclusion that it is important from a practical point of view to obtain direct estimates of the contribution of different factors to total factor productivity growth. It also underlines the notion that a measurement framework is needed that contains the most important mechanisms through which technology may influence macro-productivity growth, if only to be able to identify the most important entry-points from a policy perspective.

It should be noted that in the standard TFP measurement approach, a high value of TFP represents a high impact of technical change on productivity, whatever technical change may be. Nonetheless, a high value of Z is desirable, because it signals how much output could be obtained from a crude measure of all inputs available. However, if f() has the interpretation of an input measure in which all the qualifying characteristics of these inputs, as well as the organisation of the production process are taken into account, then a high value of Z also indicates that an important part of the defining elements of productivity are not known, or at least not accounted for by f(), and from that perspective a high value of Z implies a high level of Abramowitzian 'ignorance'. If on the other hand if Z is relatively low (i.e. as close to one as possible), then productivity growth depends on what happens to the components of f(), and more specifically on how these components change over time. The reduction of our ignorance about the relevant sources of growth then boils down to explaining changes in the measurement of total factor productivity growth in terms of changes in (economic) factors that can be explicitly and formally included in f() and which inclusion is backed up by econometric evidence or convincing a priori theorising.

3.5 The practice of TFP measurement

Most TFP measurement frameworks are built around the (implicit) notion of a production function that describes the ways in which factors of production can be used efficiently. Indeed, even dual approaches towards measuring TFP growth, rests implicitly or explicitly on the assumption that a minimum costs function exists that can be used to derive the cost minimising factor demands and hence the cost minimising contributions of these factors to output. This is only possible because the minimum cost function contains the same amount of (economically relevant) information as the (implicitly) underlying production function. (Jorgenson, 1967)

Many TFP growth measurement exercises use – for the sake of simplicity- a Cobb-Douglas production function framework (further called CD-function). This production function has many desirable features.[22] In a growth setting, one of the most convenient features is that growth calculations become relatively easy with a CD-function, because the growth rate of output that is implied by a CD-function simply is the sum of the growth rates of all inputs.

Because of its econometric convenience (estimation of linear systems), the growth in total factor productivity is often assumed to depend linearly on the growth in other factors while using the assumption of constant parameters, hence implying a contribution of the factor concerned to output that has the same general mathematical shape as the contribution of the 'standard' factors of production labour and capital. Hence, also for this reason, one often finds 'generalised CD-functions', where other factors feature in much the same way as labour and capital. Examples of additional factors are R&D stocks, different types of capital-stocks, different types of labour distinguished by skill, sex, age and so on.

Such a generalized production function is provided in equation (3) below in which we have homogenous labour L and j different kinds of capital and a scale coefficient A that is completely comparable to z in (1), just like f(). The only difference between the two f()'s are the number of inputs subsumed under f() (and potentially the way in which they aggregate into one unit of the composite input, i.e. the exact mathematical form of f() itself). We can write this generalized function as:

(3) $$Y = A.f(K_1, K_2, ..., K_j, L)$$

where Y represents output and *Kj* represents the level of the j-th capital stock. In a perfectly competitive environment, all factors are paid their marginal product, the growth rate of output (e.g. value-added) can be written as:

(4) $$\hat{Y} = \hat{A} + \sum_j (\partial Y / \partial K_j).(K_j / Y)\hat{K}_j + (\partial Y / \partial L).(L/Y)\hat{L}$$

with $\hat{Z}$ is the proportional growth rate of the Solow residual or total factor productivity growth. In equation (4) the weights of the growth rates of the various capital stocks are the partial output elasticities of the factors concerned.[23] One of the properties of a CD-function is that these partial output elasticities are constant. At the same time they are also equal to the value share in output of the factors concerned if these factors are paid their marginal product. If we assume the latter, then we can simply calculate the contribution of the growth in all factors of production to output growth by calculating a weighted average of the growth rate of individual inputs, with the factor shares in output as weights, as is readily apparent from (4).

3.6 Including spillovers in the standard TFP measurement framework

Above, we have stated that spillovers are an important element of modern growth economics. And Arrow (1962) provides an excellent starting point for the integration of such spillovers in a 'common practice' TFP measurement framework. Recall that Arrow did strongly suggest that the contribution of a factor to output might go beyond their direct productive contribution if (inter-temporal) learning effects are involved. In a CD-function setting this boils down to the conclusion that the sum of the long-term partial output elasticities of all factors concerned is bigger than the sum of the instantaneous partial output elasticities of these factors. In fact, and following Arrows spillover suggestion, one way to explain total factor productivity

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[22] However in Kaldor & Mirrlees, 1962, there doesn't exist a production function as a single valued relationship between some measure of capital the workforce and output. Output will be grater the more recent the capital stock is.

[23] So, $(\partial Y / \partial K_j).(K_j / Y)$ is the partial output elasticity of capital of type j

growth in terms of these spillovers is to use a CD production function for each individual firm:

(5) $Y = A_i . L_i^{\alpha} K_i^{1-\alpha}$

Now the learning function can be described in terms of the total capital stock (CS) as an approximation of accumulated experience with past gross fixed capital formation. The total capital stock is equal to the capital stock obtained by aggregating over all individual firms. Firm total factor productivity is then assumed to be a positive (power-) function of this total (aggregate) capital stock CS.

(6) $A_i = CS^{\theta}$

Equation (6) states that what is learnt from past investment is an externality to all firms. The ability to learn from the existing capital stock depends on each firm's capacity, therefore A is indexed with i. With the aggregate production function in mind we can substitute CS by K because they are identical.

(7) $Y = L^{\alpha} K^{1-\alpha+\theta}$

Arrow assumed that $\theta - \alpha < 0$. Therefore, increasing only capital (or only labour) does not lead to increasing returns. For a given value of the labour force L, we can avoid the fall in the marginal product of capital during the process of capital accumulation if $1-\alpha+\theta >= 1$. Arrow assumed that this was not the case, but Romer (1986) did not accept this restriction since a higher capital/output ratio (K/Y) in an economy will lead to a greater incidence of technological spillovers and therefore the marginal product of capital would tend to be higher too.

Taking the growth rates of (7), while assuming that the 'total factor contribution' to growth can be measured as in (4), we immediately obtain:

(8) $Y = L^{\alpha} K^{1-\alpha+\theta} = L^{\alpha} K^{1-\alpha} . K^{\theta} \Leftrightarrow \hat{Y} - \alpha \hat{L} - (1-\alpha)\hat{K} = \hat{A} = \theta \hat{K}$

Equation (8) shows that the Arrow model can be used to explain why total factor productivity growth (measured in the 'ordinary' way and defined by $\hat{A}$) would be correlated with the growth in the capital stock K, namely as $\theta \hat{K}$ if the latter would indeed be the case.

In fact, it is essentially this conceptual framework that Meijers (2002) has used only recently to re-confirm Solow's (1957) results that TFP growth is still by far the most important factor behind output growth. Meijers shows this for several European countries and the US. He uses data on capital ICT capital and labour of nine European countries and the US during 1990 – 2000 and shows that TFP contributed on average more than 50% of output growth, while capital contributed 38%, with ICT capital contributing 16% and other capital 22%.[24] The contribution of ICT-capital to output growth is therefore of the same order of magnitude as that of 'ordinary' capital. A closer look into the contribution of ICT to growth, seems therefore warranted, and in order to do that we have to state which mechanisms we want to take into account in actually quantifying[25] the contribution of ICT.

[24] Meijers, 2001, p 26, table 4.1, the remaining part (9%) comes from labour. Differences between countries arfe considerable, e.g. TFP contribution to the US is 'only' 38% and labour 31%. The latter figures are comparable with the results of Jorgenson & Stiroh (2000) and Daveri (2000).

[25] The use of the term 'quantifying' is on purpose here, since the use of the term 'measuring' would suggest the availability of a tested and tried 'measuring rod'. Indeed the TFP measuring rod we have at our disposal ís tested and tried, but in other circumstances than we would expect to prevail especially in the context of ICT use.

4. Incorporating ICT in a TFP measurement framework

4.1 Introduction

As stated above, an extension of the framework calls for an extension of the content of f() such that the most important mechanisms of ICT linked endogenous growth are covered. So we do not only have to expand the number of production factors subsumed under f() to include ICT-capital stocks, but there are also many other transmission channels to consider. Below we list the most important ones found in the literature.

There are institutional aspects of ICT that are thought to influence/shape growth processes in the following ways:

- ICT and especially the Internet is sometimes perceived as a technology that has either no or slight impact because people like to meet each other physically (Thurow, 1997) or – on the contrary - socially alienates people. Evidence suggests that the contrary is the case: it supports new forms of social relationships (Anderson & Tracy 2003) and not necessarily globally but "glocally". (Castells, 1997), (Smoreda, Z. & F. Thomas, 2001), (Mante-Meijer & Ling, 2001);
- ICT may improve the institutional quality of a country or region facilitating and stimulating economic growth. It is probably a simultaneous relation, so institutional quality enhances the societal effects of ICTs. (Romer, 1986, 1990) (Lucas, 1988), (Chong & Calderon, 2000), (Ehrlig, 1990), (Verspagen, 1992).

In terms of 'harder' but still pretty general economics, one may consider that:

- ICT regarded as a general-purpose technology is able to create new 'markets' and the corresponding products and services. (Helpman, 1998);
- ICT-investment may have growth-effects through its (potential) impact on the variety of products,[26]
- ICTs like the Internet enhance the (virtual) mobility of (skilled) labour, and so improving the efficiency of production at a more aggregate level. (Harris, 1998);
- ICTs can lead to more efficient education and health care alleviating "Baumol's disease". (Bryderup & Kowalski, 2002);

And in terms of impacts on the level of total factor productivity, one has to take into consideration that:

- ICT use leads to lower transaction costs as well as lower search costs, and hence to more efficient matching of demand and supply on various markets, including the labour market. (Bartelsman & Hinloopen, 2000);
- At the micro-level at least, the use of ICT investment raises TFP itself, and there are indications that the contribution of ICT-investment to output growth has indeed increased especially during the second half of the Nineties. (Bartelsman et. al, 1998) (Oliner & Sichel, 2000). But this is probably not independent of other factors like R&D expenditure and the business climate (OECD, 2002).

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[26] If, for instance, in the context of the Romer (1990) model, the marginal productivity of knowledge workers in product innovation would be positively affected by ICT-investment, there would be a direct impact of ICT-investment on growth in a love-of-variety setting. Note, however, that ICT-itself also gives rise to new products directly. The latter aspects of ICT-could be integrated with a GPT approach, as described (in general terms) in Helpman (1998).

- ICT use enables more efficient communication that allows firms to concentrate on their core-business and so lower fixed costs. (Groot, 2001).

And from a direct growth-promotion point of view, one has to take into account that:

- ICT-equipment may actually increase the marginal productivity of knowledge workers, and so extend the 'growth base' of the economy. (Bartelsman & Hinloopen, 2000);
- Knowledge spillovers from ICT-use in education to ICT-use elsewhere, provide some scope for policy intervention by raising the 'effective computer literacy spillover potential' of formal education, thus positively influencing growth performance. (Van Zon, 2001).

Of course, we cannot hope to formulate a framework in which all of these factors are featuring equally prominently. Instead, we have to focus on just a few, while at the same time not diverging too much from the original TFP measurement exercises. So, in order to limit our modelling efforts, we state what we consider to be the minimum features of a framework that is supposed to measure (a large part) of the impact of ICT on economic growth, while taking into account (most of) the literature references listed above, except for the market-niche/variety literature, as well as the 'institutional' literature.

First, ICT capital is a factor of production, just like other capital goods. Computers and office equipment perform functions that are necessary to conduct business on the one hand, while on the other hand ICT hardware is an output of our production system as much as it is an input to it. Nonetheless, its contribution to growth through *using* ICT, certainly for the non-leading ICT countries, is generally deemed much more important than its contribution to growth via the *production* of ICT itself. This suggests the possibility of formulating a framework that does not explicitly distinguish between the production of ICT goods and the production of other goods and services, but rather a framework that distinguishes between different uses of ICT.

From endogenous growth theory it has become very apparent indeed that the decisive element in generating growth is the accumulation of productive knowledge. This has led to a logical combination of growth of the human capital stock as a factor that determines the rate of labour augmenting technical change in a context based on the original Solow model, and that therefore is able to generate steady state growth, driven by human capital accumulation and therefore ultimately driven by the determinants of the rate of human capital accumulation. The model referred to is the endogenous growth model by Lucas (1988) that differs in a number of respects from the original Solow model. First, a labour force that is growing more efficient through its endogenous accumulation of productive knowledge notionally replaces labour augmenting technical change. The rate at which this knowledge is accumulated depends on economic decision making, in which the costs of learning (the loss in output due to a reduction in production time that is implied by an increase in the time spent learning) are balanced by the benefits of learning, i.e. increases in the real marginal product of physical labour, and therefore increases in future real wages. This trade off between costs that have to be born in the present (current losses of output and hence consumption and investment possibilities) and benefits that occur in the future (increased future consumption possibilities through higher real wages) is taken into account by means of an inter-temporal utility function, in which the valuation of (the loss of) consumption possibilities at different moments in time (roughly speaking 'now' and 'the future') define personal and societal welfare. For somewhat opportunistic reasons, the mathematical form of the utility function is such that an inter-temporal welfare maximisation problem results in a constant (long term) saving rate, and so essentially reduces the model to the 'old' Solow model again, at least with respect to its steady state features, but with the behavioural parameters from the Solow model linked to 'deeper'/more fundamental structural parameters such as (time-) preference parameters. In addition to this, the actual allocation of scarce time between learning and working depends on these preference parameters too, as well as the relative benefits of both uses of time, and therefore on the productivity of the learning process too. Actually, the rate of (endogenous productivity) growth depends directly and positively on the productivity of the learning process in the Lucas model. This suggests that there is a direct entry point for ICT use as a determinant of the rate of economic growth, in as far as it would influence the productivity of the learning process. The latter seems hard to deny in practice, certainly for people involved in the production of knowledge at Universities and other Research Institutes. It's not just that the use of computers have indeed increased one's possibilities to do research in the first place, but also that the Internet plays a decisive role in learning about what other people have done/found, so interpersonal knowledge spillovers are more complete and take place at a faster rate. This definitely leads to time savings and hence to productivity improvements.

Several different spillover mechanisms need to be taken into account in the context of ICT use. First of all there is the network-character of ICT itself, which suggests that the contribution of ICT capital to output as a direct factor of production exceeds its contribution to growth as measured by the growth of the ICT capital stock weighed by its income share. Indeed Lucas (1988) took into account that human capital per person proportionally affects the productivity of each individual. But in addition to this, Lucas also accounted for an autocatalytic effect of human capital accumulation, in that, through the acknowledgement of network-like effects of human capital accumulation, further human capital accumulation becomes even more attractive from an economic point of view. Something similar also goes for the accumulation of ICT-capital. And by analogy with the human capital spillover in the Lucas model (i.e. being part of a (growing) network that makes being a member of the network more valuable), can be modelled by including a spillover term in the aggregate production function that is positively influenced by the stock of ICT-capital. In this way we may cover within final output sector spillovers between producers due to the network benefits of ICT use.

Secondly spillover to take into consideration is the fact that an increase in the ICT-intensity of the learning process, may actually raise the productivity of people using ICT later on in their jobs in the final output sector. Alternatively, a more ICT intensive production of knowledge may actually facilitate the timely absorption of new productive knowledge by the final-output sector, and may lead to higher levels of productivity than otherwise could have been attained.

4.2 Empirical evidence regarding the impact of ICT on economic growth

There are several approaches to measure the impact of ICT on economic growth and productivity. First as stated above one has to realise that ICT is an output of the economic system as much as an input to it. The ICT producing sectors have experienced a remarkable growth in both value added and in productivity. However, not every country can specialize in the production of ICT. As is the case in International trade, ICT production follows comparative advantage whether these are technological in nature or depend on factor abundance ((skilled) labour, physical capital, knowledge etc.) On the other hand, every country can become a user of ICT - and in fact they all did that in practice. So, if there is a positive relation between the use of ICT and economic growth and productivity growth, investment in ICT can become a source of growth everywhere.

Studies on the contribution of the production of ICT to economic growth (e.g. Gordon (2000), Oliner and Sichel (2000)) often take the form of growth accounting trying to pin down the importance of the use of ICT for economic growth (for a combined approach see e.g. Jorgenson (2001)). A considerable number of studies review the effect of the use of ICT on growth and productivity gains by applying the growth accounting framework set out by Jorgenson and Griliches (1967). European examples are Daveri (2000), van Ark et al. (2002), Colecchia and Schreyer (OECD countries, 2002). There are also some recent comparative studies focussing on ICT-investment and economic growth across countries (e.g. Pohjola 2002) and studies that concentrate on the correlation between ICT-investment and productivity across firms, often combined with organisational change. (e.g. Brynjolfsson and Hitt (2000)).

In this section, we concentrate on the empirical results that use the TFP measurement framework outlined in the previous sections. As was explained above, total factor productivity growth is computed as a residual after taking into account the contribution of several different input factors. Jorgenson and Stiroh (2000) for instance use quality-adjusted data for various types of ICT investments but also account for changes in labour quality. The quality adjustment for ICT investments is done by applying Hedonic pricing models. They entail the correction of ICT prices for quality differences between several investments of the same type, using imputed prices for disk size, cpu[27] speed, amount of memory, etc. in the case of computer hardware. These models are often combined with Matched models that use price development of exactly the same product over more years. Labour is quality adjusted by using information on gender, educational background, age groups, etc.

Jorgenson (2001) and VanArk et.al. (2002), among others, shows the decomposition of labour productivity growth for the US and EU. Comparing the first half of the 1990's with the second half, Jorgenson shows that in the US labour productivity growth increased from 1.2 percentage points to 2.1 as is shown in Table 1. He used three factors that explain this growth rate: capital deepening,[28] changes in labour quality and changes in TFP growth.[29] Van Ark et al (2002) do not employ quality-adjusted data for labour input which implies that the source of growth that arises from changes in the quality of labour is now included in the rate of TFP growth. However, it should be noted that the contribution of changes in labour quality on labour productivity growth has a limited effect especially in the late 1990s.[30] Leaving aside changes in labour quality, the contribution of capital deepening to labour productivity growth increased from 0.6 to 1.0 percentage points and that of TFP growth increased from 0.2 to 0.8 percentage points. So the increase of labour productivity by 1 percentage point from the first to the second half of the Nineties is explained for a considerable part by increases in TFP growth, closely followed by capital deepening, whereas the contribution from labour quality actually decreased. The decomposition of the capital deepening part into contributions by ICT and non-ICT capital indicates that the contribution by ICT capital dominates. Both Jorgenson and van Ark et al. use a sectoral approach and are able to compute TFP growth in the ICT producing industry and in the non-ICT producing industry. This implies that the total growth

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27 Central processor unit, the heart of a computer, beating several billion times per second.

28 Capital deepening occurs when the ratio of capital to labour increases.

29 Note that table 1 is based on VanArk et al. 2002 and does not include contributions of changes in labour quality.

30 In Jorgenson (2001) the contribution from labour quality decreased from 0.3 to 0.1 percentage points

rate of TFP can be decomposed into the TFP growth in both sectors. As is shown in the Table below, the contribution of the non-ICT producing sector to TFP growth is large compared to that of the ICT producing sector. However, it should be noted that the ICT sector itself is relative small. Taken together, the contribution of ICT (both through capital deepening and through TFP growth in the ICT producing sector) increased by 0.6 percentage points between the two time periods and the contribution of the non-ICT sector increased by about 0.4 percentage points. Given the small size of the ICT sector and the relative small amount of ICT investments in total investments the contribution of ICT is considerable.

Van Ark et al. (2002) show the results for the EU, which differ markedly from the ones obtained for the US.[31] First of all, labour productivity growth declined from 2.5 percentage points in the first half of the Nineties to 1.4 percentage points in the second half of the Nineties. So whereas labour productivity growth increased in the US, it declined in the EU. However, it should also be noted that the growth rate of EU labour productivity in the first half of the 1990s was even larger than the corresponding growth rate in the US in the second half of the 1990s. But the contribution of both capital deepening and TFP declined from the first to the second half of the 1990s. Again distinguishing between ICT and non-ICT contributions, the ICT capital deepening part actually increased from 0.3 to 0.4 percentage points and the decline in TFP growth can be attributed entirely to non-ICT capital services. In addition, the TFP growth in the ICT-producing industry increased from 0.1 to 0.2 percentage points whereas it decreased from 1.0 to 0.4 in the non-ICT producing sector. So for Europe we find mixed results. First of all, labour productivity growth decreased but this can be entirely explained by non-ICT. The contribution of ICT (both in capital deepening and in TFP growth in the ICT-producing sector) increased from 0.4 to 0.6 percentage points. However, this is less than experienced in the US (from 0.6 to 1.2 percentage points).

This leads to three conclusions. First of all ICT matters; the results shown here (and in many other studies) indicate that the contribution of ICT to both economic growth and labour productivity growth is considerable. Second, the contribution of ICT is much larger in the US than in the EU. For a large part this can be explained by the high ICT investment ratios in the US.[32] Finally, total factor productivity growth is considerable. In Europe almost half of the labour productivity growth is “explained” by the residual part. So there is definitely a need for further explanation, i.e. a reduction of the residual.

[31] Van Ark et al. exclude Belgium, Luxembourg and Greece in their analysis.

[32] The ICT share in capital services flows to total equipment is about 37% in the US and only about 24% in the EU.

Table 1 Contributions to Average Annual Labour productivity growth[33]

	1990-1995		1995-2000	
	EU	US	EU	US
Growth of labour productivity	2.45	1.19	1.43	2.21
Contributions from				
Capital deepening, of which	1.34	0.58	0.80	1.00
ICT Capital	0.28	0.40	0.40	0.75
Office and computer equipment	0.13	0.19	0.22	0.38
Communication equipment	0.06	0.04	0.07	0.11
Software	0.09	0.16	0.11	0.26
Other Non-Residential Capital	1.05	.019	0.40	0.25
Total Factor productivity, of which from	1.12	0.61	0.62	1.21
TFP in Production of ICT (excl. software)	0.14	0.23	0.20	0.40
TFP in Other Production	0.97	0.38	0.42	0.81
Total ICT Contribution	0.43	0.62	0.61	1.15

4.3 Reducing the residual through ICT spillovers

It is often claimed that ICT capital is different from non-ICT capital because ICT capital may be associated with spillovers and network effects. In order to account for such spillover in an otherwise 'standard' TFP measurement framework, an Arrow-like extension of the production function framework seems to be called for (see also Section 3.6). Such extensions also prominently feature in the Lucas (1988) model in the context of human capital spillover, and in in the model by van Zon (2001) that features both human capital spillover and several types of ICT-based spillover. Moreover, Barro (1999) has constructed a model in which each individual firm faces a neoclassical production function and in which spillovers only occur at the macro level. Since these spillovers are external from the point of view of each individual firm, they do not take them into account in their investment decisions. However, if a firm invests in ICT capital, other firms (who invested previously in ICT) can gain from this investment due to spillover effects. In other words, the individual firm considers the total ICT capital stock to be given and assumes that its own investments are too small to influence the total macro economic capital stock. At the macro level, however, the productivity effect of all these spilllovers at the micro-level could become visible which actually implies that parts of the TFP growth as measured in the growth accounting analysis can (and should) be related to changes in the ICT capital stock.

Meijers (2002) investigates the size of these spillover effects. He argues that spillover effects will not arise instantaneously and that it takes some time before they will indeed become visible. The analysis is based on European time series on ICT capital, non-ICT capital and TFP growth. Since time lags are included in the estimation, and since time series on ICT

[33] Source: van Ark et al. (2002, revised 2003)

capital are rather short, Meijers uses a panel estimate to investigate spillover effects.[34] In order to test whether ICT capital differs from non-ICT capital, the latter is also included in the estimate whereas the former is sub-divided in the contribution from IT-Hardware, IT-Software and Telecommunication capital. Next to the contribution of capital to TFP growth, the rate of capacity utilisation is also included to capture the cyclical variation in the TFP growth rates. A (fast) growing economy uses its resources more efficiently than a slow growing or even shrinking economy. As the rate of capacity utilisation and the degree of labour hoarding is not taken into account in a standard growth accounting analysis, the TFP growth rate measurements resulting from those exercises include this cyclical effect. In Meijers (2002) therefore, TFP growth is to be explained by the growth rates of the various ICT capital stocks, the non-ICT capital stock and a cyclical variable, for which the change in the rate of capacity utilisation is used. As the effect of changes in the capital stock on productivity can take some time, the estimated equations contain several lagged values of the growth rate of the different capital stocks. For each variable, up to three-year lagged values are included and all possible combinations of these lagged variables are investigated. The estimated values of the contributions of the various capital stocks to TFP growth are comparable in nature to the parameter θ in equation (8), implying that they measure the contribution of the stocks under consideration in excess of the 'normal' contribution to TFP growth of these stocks. Note finally that the long-term effect can be computed from the individual estimates and Table 2 shows the long-term coefficients as well as the levels of significance.

Table 2 Long-run effects of growth of capital stocks on TFP growth

(estimation period 1993-2000)

	Long run coefficient	F-Statistic	P-value
IT-hardware	-0.009	0.116	0.733
IT-Software	0.127	5.49	0.022
Telecommunications	0.098	11.23	0.001
Non-ICT capital	0.132	0.79	0.377
Capacity Utilisation	0.644	64.39	0.000

The p-values denote the probability that the estimated coefficient is equal to zero.[35] It appears that the cyclical effect (measured by changes in the rate of capacity utilisation) is both considerable and highly significant. Moreover, the additional contribution of software and telecommunications to TFP growth is positive and significant. IT-Hardware and non-ICT capital do not show significant long-term effects on TFP growth. The estimation results indicate that a change in the capital stock of software (telecommunications) implies an additional contribution to TFP growth of 12.7% (9.8%). This finding strongly suggests that there are indeed spillover effects at work in the case of ICT investments (Software and Telecommunications in particular) which can be related to the theoretical work of e.g. van

[34] Countries included in the estimation are: Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Sweden, UK and the US. (Also Hungary was included initially but the data appeared to be less reliable).

[35] These are computed with a standard Wald-test.

Zon (2001) as described above. Again, it should be noted that the direct contribution of ICT investment to economic growth is already accounted for in the underlying growth accounting framework. Table 2 therefore represents the extra effects of ICT investments, or to be more precise, the extra effects of the growth rates of the capital stock of various input factors, on the residual part of TFP growth. In this context it is remarkable that investments in software and telecommunication in Europe is lagging more behind the US rates than investment in hardware. (see e.g. van Ark et al. 2002).

These results suggest that the framework set out by van Zon (2001), and explained in some detail below, is indeed relevant, since it can be used to ‘explain’ why and how ICT capital differs from non-ICT capital and why and how spillovers matter.

4.4 A theoretical framework for measuring the contribution of ICT to TFP

In van Zon (2001), a first implementation can be found of a model containing different stocks of ICT capital, and furthermore allowing for two different types of spillovers (namely inter-temporal knowledge spillovers, and the between sectors spillover effect of an increase in the ICT capital intensity of knowledge accumulation). In that implementation, within final output sector network-effects of ICT use have not been taken into consideration yet. But the first empirical results by Meijers (2003) suggest that the latter are a fairly robust feature of ICT use. Hence, because of its practical relevance, we indicate here how the framework suggested by van Zon (2001) can be extended to cover these intersectoral spillovers. Secondly, we will explain how this growth framework can be used to obtain parameter estimates of the underlying economic structures, based on cross-country estimations.

Essentially, the van Zon (2001) model is a direct extension of the Lucas (1988) model, where the productivity of the learning process depends directly and positively on the ICT-intensity of that learning process. Because of the latter, the van Zon (2001) model includes the Rebelo (1991) model as a special case, but its main features are directly comparable to those of the Rebelo model. In van Zon (2001), the final output sector uses ICT capital as a factor of production. Its network-effects need to be taken into account by allowing total factor productivity to depend positively on the stock of ICT capital itself (with weights that may differ between the sectors where the ICT capital is situated). We also assume that total factor productivity in the final output sector depends positively on the ICT intensity of the knowledge accumulation process, for the reasons given above. Finally, the growth rate itself may be positively influenced by an increase in the ICT-capital intensity of knowledge accumulation. The relative impact on growth of these mechanisms depends first and foremost on the relative sizes of spillover parameters, but also on the partial output elasticities of the various ICT-capital stocks in the sectors under consideration. But in order to be able to conclude anything at all about the relative importance of these mechanisms in determining growth, one has to have a framework that distinguishes explicitly between them and that enables their empirical ‘estimation’.

Using sensitivity analysis, Van Zon (2001) shows how growth performance depends on the various parameters of the structural model. A numerical analysis is called for, since the more intricate version of the van Zon (2001) model (i.e. the model where intersectoral spillovers are internalised) does not allow for a closed form analytical solution. Nonetheless, the analysis shows that especially the technology parameters describing the efficiency of the accumulation of knowledge, determine growth performance to a very large extent. This also holds for the intersectoral spillover parameters.

With respect to spillovers, van Zon (2001) distinguishes between two different cases. The *external spillover* case refers to spillovers between ICT use in knowledge accumulation and ICT use in final output production being treated as a purely external effect. So an individual firm ignores this effect in its investment decision. The internalised spillover case takes the existence of these spillovers into account from the outset. Interestingly enough, we see that an increase in the size of the spillover parameter associated with the use of ICT-capital also increases the steady state growth rate. However, if we change to the internalised spillover regime spillover, the time allocation balance shifts slightly in favour of final output production (thus consumption) rather than knowledge accumulation, thus lowering growth relative to the external spillover case. The reason is that due to these intersectoral spillovers emanating from the knowledge accumulation sector, a shift in the allocation of time in favour of knowledge accumulation is now seen to have higher opportunity costs than before: not only do we have to face the direct opportunity cost in terms of current output foregone due to the allocation of time to knowledge accumulation, but we also face the fact that a higher allocation of time towards knowledge accumulation, lowers ceteris paribus, the ICT-capital intensity of the learning process, which results in a lower (but still positive) impact of the ICT-capital use spillover effect on productivity in the final output sector. In addition to this, in the internalised spillover case, the model allows for two steady states in which the loss in marginal utility of consumption due to growth and the negative impact of the rate of discount on the valuation of future consumption is exactly offset by the actual rate of return on capital. So, the marginal benefits of postponing consumption (i.e. the rate of return on capital) exactly offset the marginal costs of postponing consumption (i.e. saving now and consuming later). The low growth equilibrium is unstable, though, since a small deviation from the steady state will lead to a divergence between the actual rate of return on capital and the rate of return required to make people accept the actual rate of growth that becomes bigger and bigger. The high growth equilibrium is stable.

4.5 Combining the van Zon model and the Meijers exercise

As suggested by the results outlined above, a formal link between the van Zon (2001) model and the Meijers (2001) TFP exercise seems to be in order since on the one hand Meijers points out: "… that the U.S. is not a unique case and that some European countries experienced a successful absorption of ICT investment goods too. Moreover, the combination of high rates of output growth, low unemployment and low inflation seems not to be just a coincidence but can be explained by the direct and indirect productivity effects of Information and Communication technologies."[36] This underlines the practical relevance of ICT as a source of (low inflation) growth. The van Zon (2001) model on the other hand, provides extensions of f() that would enable one to capture the ways in which ICT-investment actually brings about additional growth, and that allows us, in principle at least, to find out more about the relative importance of the different mechanisms that are directly relevant in this respect.

In the endogenous growth model that is used below (Van Zon, 2001) and starting from the notions above it is shown that the significance of ICT-(i.e hardware and complementary software) is not only in its use as a factor of production, but also, and maybe even more, in the generation of knowledge regarding the production of final output. Part of the relevance of this paper comes from noting that deliberate or 'managed' spillovers emanating from ICT-schooling may yield extra results and that it may well pay off not only to stimulate 'computer-literacy' among the population, but also to match ICT-schooling and ICT demands. Another reason is that improved access to information is potentially improving the overall productivity

[36] Meijers, 2002, p 44.

of the learning process as well as the economic transformation process in general. This idea is taken as a point of departure in van Zon (2001). Here output Y is produced using three different inputs, i.e. physical capital K_y, ICT-capital K_{iy} and human capital services $h.L_y$ where L_y is labour measured in physical units and used in final output production. h is an index of the human capital content of a physical unit of labour, further referred to as knowledge per worker. Like above in equation (3), van Zon uses a linear homogeneous Cobb-Douglas production function:

(9) $$Y = A.(h.L_y)^{\alpha}.(K_{iy})^{\beta_y}.(K_y)^{1-\alpha-\beta_y}$$

It should be noted that A in equation (9) represents total factor productivity. α and β_y are constant parameters reflecting the partial output elasticities of labour (measured in efficiency units) and ICT-capital used in final output production.

ICT can either increase the rate of growth of knowledge production or can enhance in broader sense productivity in general supportive activities not attached to factors of production factors but embodied in contextual variables like the quality of supportive activities and the quality of government. The rate of growth of knowledge accumulations $\hat{h}$ is assumed to be proportional to the time spent on schooling L_h (or accumulating knowledge) and the productivity of the learning process:

(10) $$\hat{h} = \delta_h^{'}.L_h / L$$

(10) is the same as in Lucas (1988), with the proviso that the productivity of the learning process is an obvious entry point for the impact of ICT use on growth performance. Actually, there are two obvious spots in the model where ICT-investments can be linked directly to productivity developments, i.e. the total factor productivity parameter A in final output generation, and $\delta_h^{'}$, i.e. the productivity of the knowledge accumulation process. In final output generation, the direct impact of ICT-investment is taken into account through $\beta_y > 0$. The potential knowledge spillovers are linked to the parameter A, which we reformulate as $A = \kappa_{ih}^{\sigma \cdot \beta_y}$ where σ is the spillover parameter and κ_{ih} is the ICT-capital intensity of human capital accumulation, i.e. $\kappa_{ih} = K_{ih} / (h.L_h)$. The exponent of κ_{ih} is the product of σ and β_y, since we don't want any spillovers to occur from knowledge accumulation to final output, if the final output sector itself does not use ICT-capital. For $\delta_h^{'}$ we postulate, very much as above $\delta_h^{'} = \delta.\kappa_{ih}^{\beta_h}$. Rewriting (9) while making use of the double role of the ICT-capital intensity of human capital accumulation, results in the following equation that clearly shows the contribution of human capital in the augmentation factor and the contribution of ICT capital in knowledge accumulation as well as the separate impact of physical capital:

(11) $$Y = A.(h.L_y)^{\alpha}.(\kappa_{ih}^{\sigma} K_{iy})^{\beta_y}.(K_y)^{1-\alpha-\beta_y}$$

and the percentage rate of growth of knowledge accumulation

(12) $$\hat{h} = \delta(\kappa_{ih})^{\beta_h}.L_h / L$$

These two modifications in the Lucas (1988) model, bring the model a lot closer to the Rebelo (1991) model, where van Zon (2001) differs from Rebelo in that more types of capital are used in the final output sector than in the Rebelo model.

If we compare the two approaches followed in (11) and in (3), it is obvious that they differ in the number of production factors and in the restrictions imposed on the parameters as well as the functional specification. Logarithmic differentiation of (11) results directly in:

(13) $$\hat{Y} = \hat{A} + \alpha \cdot (\hat{h} + \hat{L}_y) + \beta_y.\sigma.\hat{\kappa}_{ih} + \beta_y.\hat{K}_{iy} + (1 - \alpha - \beta_y).\hat{K}_y$$

Equation (13) describes what happens to output growth both during the transition towards the steady state and in the steady state it self. In the latter case, however, changes in the allocation of time between knowledge formation and final output production would be zero, just like the changes in the ICT-capital intensity of human capital formation. In that case the drivers of output growth are of course growth in A itself (what's left of total factor productivity after accounting for ICT) and in h (still linked to ICT investment because of (12)). Very much as in equation (8). As to cover the network effects thought to be associated with the ICT capital stock $\hat{A}$ is considered as linked to the ICT-capital stock in final output production. In this case it is not the inter-temporal learning by doing, as in Arrows (1962) model, that allows capital to contribute more than individuals expect, but it's the fact that individuals joining a network make the network itself more productive.[37]

As was explained above, Meijers (2002) used an equation much like (13), except for the direct influence of the ICT capital-intensity of production (which is zero in the steady state anyway), and where $\hat{h}$ was essentially subsumed under $\hat{A}$ Then the growth in A was correlated with the growth in the various capital stocks again, among which ICT-hardware and software-stocks. The growth in communication capital stocks explains about 10 percent of TFP growth, and the software stocks also contribute 13%. Other stocks do not contribute, including the stocks of computer hardware and the non-ICT capital stock. This suggests that the Arrow (1962) framework can be reinterpreted as underlining the practical importance of the network-effects associated with ICT capital use since they seem to account for a significant part of growth.

Obviously, Meijers (2002) and van Zon (2001), having been exercises that stood on their own, are not completely compatible as they are now. For one thing, the van Zon model is a structural model of the importance of ICT use, and the Meijers model is a reduced form model. Nonetheless, with an extension of the van Zon (2001) model to cover within final output sectors spillovers too, both analyses cover (in principle at least) exactly the same grounds, and the parameter estimates of the Meijers approach should provide valuable numerical information about the structural parameters of the van Zon (2001) model. Those structural parameters would provide indications about the relative impact of alternative policy actions that would support both the generation and the use of human capital in growth creating activities and final output production itself.

Fortunately, it proves to be possible to obtain the steady state solution of the van Zon (2001) model, although that's by no means easy to do. For the no-spillovers and the external spillovers case (see above) there is even an analytical solution. For the internalised spillover case, only a numerical solution exists. Nonetheless, it is possible to reduce the entire model to just three simultaneous, but strongly non-linear, differential equations. These differential equations describe the movement of the economy towards its steady state, in function of the structural parameters of the economy. By linearising this system of differential equations

[37] Formally, however, this should be included as part of the structural model f(), and the growth repercussions of this change in f() should be evaluated. So far we have not done this, but the Arrow (1962) approach provides a valuable illustration of what could be expected to happen.

around the steady state, one arrives at a simultaneous linear system that still (but implicitly) depends on the values of the structural parameters of the system, as well as on the actual distance of the system from the steady state.[38] This particular system also suggests that it should be possible to actually estimate the values of (transformations of) the system parameters through cross-country estimation of the adjustment coefficients in the linearised system. We can use these numbers to obtain numerical values (or ranges of values) for the structural parameters of the system. At present the latter procedure is still being developed.

[38] This implies that the speed of adjustment depends on the actual distance from the steady state, very much as in catching-up models of growth.

5. Summary and Conclusions

Growth is the source of increases in welfare per head. Economists now broadly agree on the fact that technical progress and technology dissemination constitute the ultimate source of sustained economic growth. In particular, the economic analysis in the context of the so-called endogenous-growth approach (often termed "new growth theories") has shifted towards elements such as human capital (education and training) and R&D. Extensive literature has provided arguments and empirical evidence showing that both elements do increase knowledge accumulation, technical progress and, by the same token, long-term growth. One of the features that distinguishes this strand of the literature compared to the neoclassical growth framework is the role played by interactions between economic agents, the so-called spillovers. In particular, a key finding of the endogenous growth literature is that, in the presence of spillovers, the return from firm-level R&D may not be fully internalized by a particular firm which results in a sub-optimum situation where the economy as a whole is concerned.

ICT investments contribute to growth in two different ways: the ‘classical’ way, since ICT equipment is used for normal production activities and the ‘network effect’. The latter, in particular, implies that a network entails more benefits for its individual users, the more users there are. So, being part of a growing network increases the value of the network more than proportionally for each individual member, and supports a self-sustaining ICT-based productivity growth process. Network effects in ICT adoption therefore tend to magnify the influence of spillovers in ICT. The present study provides a number of caveats for future research in order to analyse the interplay between ICT economic impact, market structure and spillovers. Considering the adoption costs of ICT for companies, a company might find little direct incentives to invest in ICT when costs appear to be far above expectable benefits. Consequently, one has to envisage that the presence of spillovers in ICT use may deter greater levels of ICT diffusion.

The above arguments suggest there is a strong case to be made for the design of policies promoting the use of activities that generate productivity growth through ICT diffusion. The results provided in this report show that the contribution of ICT investment to TFP growth through network effects is at least as important as ICT investments themselves. This result provides support for ICT investment promotion policies, given that the presence of ICT-related spillovers might tend to deter ICT investment in economies where the benefits linked to network externalities are insufficiently perceived by individual agents.

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Abstract

Economists now broadly agree on the fact that technical progress and technology dissemination constitute the ultimate source of sustained economic growth. In particular, economic analysis in the context of the so-called endogenous-growth (often termed "new growth theories") approach has shifted towards elements such as human capital (education and training) and R&D which could be both used to increase knowledge accumulation and technical progress. This paper provides a review of the literature on the impact of ICT on Economic Growth and Productivity and provides elements of discussion for extending the neoclassical growth framework to incorporate elements of the endogenous growth theories in order to consider the impact of ICT diffusion on growth and productivity. This study provides an overview of the traditional growth accounting framework rooted on Sollow's contributions and its extension considering the cases where situations of under-investment in growth-promoting items such as R&D, can be detected. Similarly to the R&D case, the resulting aggregate use of ICT maybe too low for pushing productivity up in a given economy given that private agents may under-invest in ICT if the private economic returns from these investments are too low. The overall macroeconomic outcome may therefore result in a situation where the growth potential of ICT investment is far from being fully realised. This outcome in particular would allow explaining why still many EU countries are lagging behind in terms of ICT investment and ICT impact on economic growth, in particular compared to the US. This present study provides a number of theoretical caveats to understand the main issues at stake.

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