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ICT Externalities: Evidence from cross country data

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Abstract
This paper reports the findings of an empirical study on the external effects of Information and Communication Technologies (ICT) on economic growth and productivity at an aggregate level. It focuses on possible network effects and spillovers emerging as externalities from investments in ICT. The existence of externalities is well described in theoretical work however empirical evidence is scarce. By using time series at the macro level for a panel of 15 countries I find positive externalities for investments in IT software and in telecommunication equipment, but not for IT hardware. The analysis, which accounts for cyclical effects and also takes external effects from non-ICT factors into account, points at considerable lags between the time of investing in these technologies and the time at which the externalities arise. Taking these externality effects into account, the paper shows that the impact of ICT on productivity is almost twice as high as compared to a model that does not include such effects.

Keywords: productivity, network effects, spillovers, Information and Communication Technologies, total factor productivity

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Introduction

Most studies that investigate the effects of Information and Communication Technologies (ICT) on productivity at the macro or the sectoral level are carried out in the tradition of growth accounting starting from the neoclassical model using a linear homogeneous production function with capital and labour as input factors and value added as a measure for output. [1,2] By assuming competitive markets for both inputs and outputs and by assuming neutral technical change, one can determine the contribution from each input factor to output or output growth. Since capital can be disaggregated into various sub categories like ICT capital, equipment, non-residential buildings, etcetera, the contribution of each of these sub categories to economic growth can be accounted for. This allows for the determination of the contribution of ICT to economic growth, or even of sub categories within the cluster of ICT technologies to economic growth, such as hardware, software, and telecommunication equipment. Such growth accounting analysis rules out the presence of market imperfections and externalities from the outset. There is an important and growing body of literature that argues that ICT induces externalities and that externalities are an important factor of economic growth and productivity growth. If this argument indeed holds true and if externalities are positive, then the impact of ICT on economic growth is underestimated in growth accounting studies. This paper focuses on the empirical relevance of externalities arising from ICT. By using time series at the macro level for a panel of 15 countries, I find positive externalities for investments in IT software and telecommunication equipment - not for IT hardware. The analysis, which also accounts for cyclical effects and takes external effects from non-ICT factors into account additionally, also points at considerable lags between the time of

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[1] In this case, the term Information and Communication Technologies (ICT) refers to the processing, storage and transfer of information, sometimes also referred to as Information Technologies (IT). ICT can be broken down into IT hardware, IT software and communication.

[2] For applications of this methodology on the impact of ICT (see e.g. Oliner and Sichel (1994), Jorgenson (2001), Daveri (2002), and Colecchia and Schreyer (2002)).

investment in these technologies and the time at which the externality effects are measurable in output growth and productivity growth.

The paper is organized as follows. The next section reviews the literature on ICT and externalities and shows that there are several reasons why ICT can generate externalities. It also briefly describes how the approach taken in this paper relates to the literature. The third section presents the model that is used for empirical analysis and section four shows the estimation procedures and the results. Section five discusses the findings and shows that including externalities into the analysis is actually quite significant given that the impact of ICT on economic growth doubles, even slightly more in Europe, but less in the US. The final section summarizes the main conclusions.

ICT and externalities

Many studies on the impact of new technologies such as ICT on economic growth start from a framework where ICT capital is one of the input factors next to other forms of physical capital and next to labour. Output growth can be broken down into contributions coming from these different input factors, and a remaining factor that represents the overall level of 'technology', commonly called total factor productivity (TFP) or multifactor productivity (MFP).[3] In such a framework, the contribution from ICT on economic growth comes from the use of ICT and the analysis is often further detailed by also looking at the ICT producing sectors and by attributing the contribution arising from TFP in these sectors to the overall contribution from ICT to economic growth. So the total contribution of ICT to economic growth is often related to both the production and the use of ICT in these growth accounting studies (see e.g. Jorgenson and Stiroh (2000), van Ark, Inklaar et al. (2003)).

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[3] The difference between the two terms refers to the question whether all relevant factors are taken into account (which would lead to the term total factor productivity) or not, thus referring to more but not necessarily all factors, i.e. multifactor productivity. Without discussing this in detail and without claiming that all factors are taken into account, this paper uses the most common following name: total factor productivity or TFP for short.

One of the basic assumptions in the growth accounting analysis is that the price of a factor is an indicator for its marginal product. In the case of capital goods it implies that the rental rate per unit of capital, or the user costs of capital, equals the marginal product. Aggregating over all capital goods yields the total amount paid for capital goods and this amount equals the user costs of capital times the total quantity of capital and this in turn is equal to the capital share in total income. The basic neoclassical model assumes that (current and future) marginal productivity of all relevant factors can be measured and more importantly that the aggregate of private and individual returns are equal to the social returns. So it is assumed that there are no externalities involved in the investment in and the use of ICT and this assumption can be doubted on several grounds. One argument is that ICT as a general purpose technology (GPT) induces various other innovations, diffuses widely across industries, and is embedded in a wide rage of applications. The benefits from these technologies and applications are not immediately clear from the outset and can lead to externalities as knowledge spillovers. A second main argument points at network effects of ICT which lead to externalities. Network effects exist when the utility of a product or technology for an individual user depends on the total number of users of that specific or a compatible, product or technology.

ICT as a General Purpose Technology inducing knowledge spillovers

Lipsey, Carlaw et al. (2005) review ICT as a GPT that has a major impact on process technologies, organizational technologies, and product technologies and also has social and political implications. While there are several definitions of GPTs, they all share the general idea that such technology is widely used, therefore not in a single sector or for a single production process, and that it leads to other innovations, new products and new productions processes. "GPTs are characterized by pervasiveness, inherent potential for technical improvements, and 'innovational complementarities', giving rise to increasing returns-to-scale" Bresnahan and Trajtenberg (1995), p. 83. These increasing returns-to-scale refer to spillovers that come from such generic and widely used technologies where in many cases, the spillovers are not internalised and thus show up as externalities. A main source of such spillovers originates from the learning-by-doing effects from other users of that technology thus, as knowledge spillovers. This notion is already introduced by Arrow (1962) however, in a dynamic, intertemporal setting that allows firms to learn from their own production and experience, and where Arrow assumes that the gains from learning are not incorporated into the initial decisions of the firm and thus show up as spillovers. Knowledge that spills over from firm to firm is introduced in the endogenous growth literature by e.g. Lucas (1988). Firms learn from the experiences with new technologies from other firms and knowledge accumulates so that learning leads to positive spillovers.

Arrow's notion of learning-by-doing as a time consuming process is closely related to the notion that pervasive technologies such as ICT, demand for new views on organizational processes. Investing in ICT has major impacts for firms and organizations and goes beyond the direct and measurable productivity effects. It is well known that ICT demands a renewed organization of business processes, which may or may not be accompanied by initial productivity slowdowns and followed by positive effects later on. Examples of ICT induced organizational change include Brynjolfsson (1993), Brynjolfsson and Hitt (2000), Licht and Moch (1999), Bertschek and Kaiser (2004), Dewan and Min (1997), and Bresnahan, Brynjolfsson et al. (2002), all of whom show that such organizational changes are organic processes. The general finding is that it costs time (sometimes up to 5-7 years) before investment in ICT in general, and software in particular, pays off.

Finally, ICT also can facilitate the diffusion of knowledge and can enhance the knowledge generating process itself, such that the R&D process becomes more efficient. If the R&D process becomes more productive, then the output of the R&D sector in terms of new product and process designs (blueprints, patents, etc.), will increase and this in turn will lead to a permanent higher level of economic growth (see e.g. Zon (2001)). In this case, it is also likely that the gains coming from the improved R&D efficiency are not (entirely) internalised in the price of ICT and thus will show up as an externality.

Network effects and externalities

A second major argument on why ICT will lead to externalities comes from the concept of network effects. Network effects refer to the notion that the larger the network is, the more valuable it becomes to the individual user. It is argued by many authors that investments in ICT could generate network effects due to compatibility of communication protocols and due to hardware and software products. Standardisation plays an important role in the literature on network effects and network externalities. (Farrell and Saloner (1985), Katz and Shapiro (1985), Katz and Shapiro (1994), Liebowitz and Margolis (1994), Liebowitz and Margolis (1995)) and Church, Gandal et al. (2003)) If network effects are significant and if these effects are not internalised and thus not included in prices of capital, then the benefits from ICT investments will exceed costs. This implies that the additional productivity effects due to spillovers are not captured in factor prices and thus are not accounted for in traditional growth accounting analysis. The productivity effects are captured by the residual thus, included in growth of TFP. This also implies that expected private returns are lower than actual returns so that firms under-invest in these capital goods.

The following two types of network effects can be distinguished: direct, and indirect or virtual network effects. Direct network effects refer to the increase of the value of a network mainly through a physical effect of the number of users of that network. Examples include telephones, fax machines, and also the use of email and peer-to-peer file sharing networks. Each new user will add value for existing users of the network through its membership. Indirect or virtual networks refer to the market mediated effect as exemplified in the case of complementary products like printer cartridges and software add-ons. (Liebowitz and Margolis (1994), Katz and Shapiro (1994)). Larger networks, i.e. larger customer base for a certain product, will attract more firms supplying complementary products and these products will be sold at lower prices. The latter is the case if there are increasing returns to scale in the production process which is certainly the case for the production of software where initial costs are high and marginal costs are almost zero. This makes the software industry and software market different from for instance the market for spare products for automobiles. In both cases network effects are prevalent but the effect is much more emphasized in the software market. Network *externalities* arise from network effects as long as these effects are not internalised, therefore as long the positive impact of a larger customer base is not included in prices.

In summary, ICT can lead to spillovers and externalities through various channels: learning spillovers either being intertemporal or interpersonal/interfirm, and accompanied organizational change due to its pervasiveness and network externalities, are likely to play important roles. The second channel is via network effects. The concepts of learning-by-doing and organizational change also refer to lengthy processes which are needed to fully reap the benefits from investments in ICT. If this is indeed true and if externalities coming from ICT are indeed substantial, then the traditional growth accounting methodology underestimates the contribution of ICT to economic growth. In a growth accounting exercise, the effect of ICT on economic growth is only accounted through the direct effects. The remainder is captured as TFP. If however, parts of investments in ICT lead to externalities, then this will be captured by TFP as well. Next, I will use the relation between TFP and ICT investment and will show the results from an empirical investigation of externalities at the country level. Important issues in this analysis are considerable time lags which may occur between investment in ICT and the actual productivity effect.

The relation between investment in ICT and positive growth of TFP has been frequently discussed as an issue in the debate around the so called new economy. Opponents of the new economy view stressed that the impact of ICT was similar to other capital so that there was nothing new about the new economy. "Thus far we conclude that the impact of capital deepening has created a genuine revival in growth in output per hour (ALP) in the non-computer economy but that spillover effects on MFP in the non-computer economy are absent." Gordon (2000), p. 15. Continuing and refining his analysis, Gordon does indeed find some positive relation in some sectors but not in others: "Outside of durable manufacturing, the New Economy has been remarkably unfruitful as a creator of productivity growth." Gordon (2000), p. 46. It should however be stressed that the applications of growth accounting methodology rule out such positive relation between TFP and ICT investments so that spillover effects are absent in a growth accounting setting by definition.

Pilat and Lee (2001) show, albeit in a graphical way by relating average TFP growth to ICT use, that TFP is indeed positive related to the use of ICT goods and services. If the direct contribution of ICT is already accounted for in the measurement of total factor productivity, then this indicates an additional effect that goes beyond the standard neoclassical assumptions. Stiroh (2002) uses US manufacturing industry data in his econometric analysis based on the reduced form of the production function and relates ICT investments to output growth. He finds little evidence for production spillovers or network effects. In an econometric firm level based study, Brynjolfsson and Hitt (2003) show positive and significant contributions of computer capital (hardware) on TFP, thus beyond the 'standard' effect of capital on productivity. They also show that the lags can be considerable, even as much as up to 7 years.[4] O'Mahony and Vecchi (2005) employ a production function approach and use sectoral data for the US and UK on real value added, hours worked, ICT capital, and non-ICT capital, to estimate the productivity effect of ICT. Using a Pooled Mean Group estimator they show that the standard growth accounting methodology may understate the contribution of ICT to output growth and TFP. Meijers (2004) shows that the impact of changes in ICT capital stock on TFP growth is larger than one would expect from standard neoclassical theory. That analysis also shows that there can be significant lags before such effects are actually revealed. This could be the reason why Stiroh (2002), who does not include a lag structure in his analysis, fails to find such positive relation. If externalities are indeed present, then these findings imply that the social returns to ICT investments are higher than the private returns, as is, for example, the case in investments in R&D. Additionally, if adjustment costs are also present, then investment in ICT could even have a negative impact on TFP growth in the very short run due to organisational changes and due to a loss in productive working time because of the learning process which goes along with the introduction of new technologies.

Basu and Fernald (2006) focus on the role of ICT as a general purpose technology and relate TFP growth to complementary investments and intangible capital. Although these

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[4] Their data does not allow for investigation of the effects of longer lags.

independent variables are unmeasured, their theoretical framework comes close to the one presented here. Using US industry data, they find that ICT investments are related to measured productivity growth with a very long lag of 5 to 15 years. The present analysis uses a broader set of countries and employs aggregate data.

The next section presents the model which is used to estimate the productivity effects of ICT. That model is elaborated by allowing for the underutilisation of input factors. In this case, I follow the network externality argument to setup the model. However, in the estimation procedures, a reduced form model is used and whether the measured externality actually comes from network effects or from other sources such as knowledge spillovers, learning-by-doing or other sources of increasing returns to scale, remains undetermined.

A simple model

There are several ways in which externalities can be modelled. In this case, I take the approach of externalities through network effects and spillovers.[5] In the simple model, I follow Barro (1999) and start from the initial production function, which, in order to articulate the social returns to ICT investments, is specified for each individual firm *i,* and is, for simplicity, written as a Cobb-Douglas production function:

$$Y_i = A \cdot K_i^{\alpha} \cdot K^{\theta} \cdot L_i^{1-\alpha} \qquad (1)$$

Where Y, A, K and L denote output (value added), the level of technology, capital input and labour input, respectively. $\theta \geq 0$ denotes the spillover effect from the social (economy wide) capital stock. (1) can be written in a labour-intensive form:

[5] I do not investigate sectoral and international spillovers and restrict the analysis to the pure macro economic spillovers emerging from own investments in ICT.

$$Y_i = A \cdot \left(\frac{K_i}{L_i}\right)^{\alpha} \cdot \left(\frac{K}{L}\right)^{\theta} \cdot L_i \cdot L^{\theta} = A \cdot k_i^{\alpha} \cdot k^{\theta} \cdot L_i \cdot L^{\theta} \qquad (2)$$

where k denotes capital per worker or capital intensity. In equilibrium, the capital intensity of all firms should be equal ($k_i = k \ \ \forall\, i$), yielding:

$$Y_i = A \cdot k^{\alpha+\theta} \cdot L^{1+\theta} \qquad (3)$$

Aggregating over all firms and using $k \equiv K / L$ gives:

$$Y = A \cdot k^{\alpha+\theta} \cdot L^{1+\theta} = A \cdot K^{\alpha+\theta} \cdot L^{1-\alpha} \qquad (4)$$

So the returns from capital at the aggregate level exceed the share of capital in total income if $\theta > 0$, i.e. if spillover effects are present. Note that the private returns to scale, for a given *K*, are still constant and equal to 1. The parameter α denotes the capital elasticity of output and assuming competitive input and output markets and assuming a production function with constant returns to scale and neutral technological progress (like Cobb-Douglas) this parameter is equal to the capital share in total income (see e.g. the seminal Solow (1957) paper for a discussion).

Taking the logarithm of (4) and assuming that the capital elasticity equals the capital share in income (v_k) and similarly that labour elasticity of output equals the labour income (v_l), (4) can be simply rewritten as:

$$\ln Y = \ln A + \theta \cdot \ln K + v_k \cdot \ln K + v_l \cdot \ln L \qquad (5)$$

As done by many authors, aggregate capital can be broken down into various ICT capital goods such as IT hardware, IT software and telecommunication equipment. Following common practice, the factor shares in total income are averaged over two years so that we obtain:

$$\ln Y = \ln A + \sum_j \theta_j \cdot \ln K_j + \sum_j \overline{v}_{kj} \cdot \ln K_j + \overline{v}_l \cdot \ln L \qquad (6)$$

where θ_j denotes the factor specific elasticity with respect to spillovers and network effects on output growth and where $\overline{v}_{kj}$ and $\overline{v}_l$ denotes moving averages of factor shares in total income as common used in growth accounting settings. Using first differences of the logarithms as growth rates equation (6) can be written as:

$$\hat{Y} = \hat{A} + \sum_j \theta_j \cdot \hat{K}_j + \sum_j \overline{v}_{kj} \cdot \hat{K}_j + \overline{v}_h \cdot \hat{L} \qquad (7)$$

From standard growth accounting literature where externalities are absent, TFP is measured as a residual as:

$$\hat{Y} = \hat{A}' + \sum_j \overline{v}_{kj} \cdot \hat{K}_j + \overline{v}_h \cdot \hat{L} \quad \text{such that} \quad \hat{A}' = \hat{Y} - \sum_j \overline{v}_{kj} \cdot \hat{K}_j - \overline{v}_h \cdot \hat{L} \qquad (8)$$

where $\hat{A}'$ denotes the growth rate of TFP using the traditional accounting method. Combining (7) and (8) yields:

$$\hat{A}' = \hat{A} + \sum_j \theta_j \cdot \hat{K}_j \qquad (9)$$

which says that the traditional measured TFP growth can be broken down into the 'real' TFP growth, and network and spillover effects. Equation (9) is basically the equation which will be estimated below. However, as reported by e.g. Basu, Fernald et al. (2001), among others, other influences such as changing rates of capacity utilisation may affect the estimates, especially when these estimates are based on relative short time series. Solow (1957) also included a capacity utilisation effect into his analysis but he simply assumed that the rate of unutilised capital is equal to the unemployment rate. The business cycle literature on productivity analysis obviously includes such effects too (see e.g. Greenwood, Hercowitz et al. (1988) and Basu, Fernald et al. (2004)).

Including the rate of Capacity utilisation

Since physical capital will not be adjusted instantaneously to new capacity levels as output changes, measured inputs may differ from effective inputs. As TFP is measured as the difference between output and inputs, mismeasurement of inputs leads to a mismeasurement of calculated TFP. The same holds true if other factors of inputs such as labour are not correctly determined. Adjusting the employed labour force involves adjustment costs so that the utilisation rate of labour can differ from unity, meaning that effective labour input differs from measured labour input. The real business cycle theory tries to endogenize the factor utilisation rates by taking for example, adjustment costs into account, but in this case, I simply assume that capital and labour may be underutilised. So as to include the possibility of underutilisation, I simply assume that capital and labour inputs are adjusted for their actual utilisation rates, so that equation can be written as:

$$Y = A \cdot (q_k \cdot K)^{\alpha} \cdot (q_l \cdot L)^{1-\alpha} K^{\theta} \tag{10}$$

where q_k and q_l denotes the rate of capacity utilisation of capital and labour respectively. The latter can be seen as labour hoarding due to e.g. costs of hiring and firing etcetera. Since this rate is not known directly from data, I assume that this rate depends on the rate of capacity utilisation of physical capital as:

$$q_l = 1 - \gamma(1 - q_k) \tag{11}$$

which says that the rate of capacity utilisation with respect to labour is a fraction of the rate of capacity utilisation of capital. If γ is equal to zero, then we have no labour hoarding at all so that labour is always adjusted instantaneously to final demand. If γ is equal to one, then labour is quasi fixed in the short run similar to physical capital. For ease of exposition, I assume that the levels of both rates are not that different, so that this relation can be expressed in growth rates as: $\hat{q}_l = \gamma \cdot \hat{q}_k$. Note that in equation (10) the spillover effects are modelled as long-term effects which are not directly affected by short-run changes in the rate of capacity utilisation.

Substituting equation (11) in (10) and following the same derivation as exposed above, equation (9) can be rewritten as:

$$\hat{A}' = \hat{A} + (\alpha(1-\gamma)+\gamma)\cdot\hat{q} + \sum_j \theta_j \cdot \hat{K}_j = \hat{A} + \beta\cdot\hat{q} + \sum_j \theta_j \cdot \hat{K}_j \tag{12}$$

Where β is implicitly defined in (12). If there is no labour hoarding we get:

$$\hat{A}' = \hat{A} + \alpha\cdot\hat{q} + \sum_j \theta_j \cdot \hat{K}_j \tag{13}$$

And with full or maximum labour hoarding:

$$\hat{A}' = \hat{A} + \hat{q} + \sum_j \theta_j \cdot \hat{K}_j \tag{14}$$

If the capital share in total income (α) is about equal to one-third, then β will be in the range between 1/3 and 1.

Equation (12) says that the measured rate of total factor productivity growth can be broken down into a capacity utilisation effect, various spillover effects and a remaining 'true' growth rate of TFP. The latter obviously can be regarded as the remaining Solow residual.

Estimation procedure and results

As mentioned above, reaping the benefits from ICT investments often takes quite some time due to for example, network effects and organisational adjustments. In order to capture such lagged influences of net ICT investments of TFP growth, equation (12) is expanded by including lags for the various inputs $\hat{K}_{j,t-n}$ where the lag length *n* can differ for each factor *j*. This specification implies that a change in the stock of a capital good *j* has an effect on the rate of total factor productivity growth after *n* years.[6] So the equation that is estimated reads as:

[6] Note that this specification differs from Brynjolfsson and Hitt (2003) who assume that the difference of the stock of a capital good now and n years ago has an effect on the difference of total factor productivity now and n years ago. Thus they assume: $\ln A_t - \ln A_{t-n} = c + \eta.(\ln K_t - \ln K_{t-n})$

$$\hat{A}_t' = \hat{A} + \sum_{n_q} \beta_{n_q} \cdot \hat{q}_{t-n_q} + \sum_j \sum_{n_j} \theta_{n_j} \cdot \hat{K}_{j,t-n_j} \qquad (15)$$

where the factor *j* includes IT hardware, IT software, telecommunication equipment, non-IT capital, and labour input. The model is estimated by employing the updated dataset from Timmer, Ypma et al. (2003).[7] This dataset includes data on real GDP growth: growth rates of capital stocks for non-IT equipment, IT hardware, IT software, Telecommunication equipment, labour input in hours worked, and measured TFP growth using the growth accounting methodology. As is common in growth accounting exercises, TFP is measured using capital services rather than capital stock and capital services are modelled as the two year moving average of the capital stock (see e.g. OECD (2001). Capital prices are measured by using harmonized hedonic price indices in the determination of the user costs of capital. For a description of the data and the employed methodologies to determine capital stocks and harmonized prices (see Timmer, Ypma et al. (2003)). Data on the rate of capacity utilisation is obtained from the OECD Economic Outlook database as the ratio of actual and potential output. Data are available for the time period 1980-2004 and for 14 EU countries plus the US.[8] Since lags of up to 10 years are to be expected, the model is estimated on the time period 1990-2004 in all estimates.

Given the number of variables to be estimated and the relative short length of the time series per country of 15 observations, a panel approach is employed. This increases the number of data points considerably, however, at the cost of flexibility. In the panel estimate, the coefficients β and θ_j are pooled, whereas a fixed effect specification allows for country specific constant terms. The constant terms reflect the remaining rate of TFP growth after correcting for spillovers and cyclical adjustments. So by applying a panel

where η is to be estimated whereas the model estimated here reads as (leaving aside the different ICT categories *j*): $\ln A_t - \ln A_{t-1} = c + \sum_n \theta_n \cdot (\ln K_{t-n} - \ln K_{t-n-1})$.

[7] See www.ggdc.net.

[8] The 14 EU countries comprise the EU-15 except for Luxembourg.

approach, the influence of spillovers and cyclical effects are assumed to be the same for all countries but the corrected rate of TFP growth can differ between countries.

Under the assumption that the values of the elasticity parameters of non-ICT inputs equal their theoretical values we can use Equation (15) to estimate the additional impact of ICT and the impact of the rate of capacity utilisation on TFP growth. The elasticity of non-IT inputs might differ from their theoretical values and one could argue that this can bias the estimation results of β and the θ_j's. In the first estimation rounds lags up to 4 years were included for all variables, thus, including non-ICT factor inputs. I expanded maximum lag length by one year for the variables for which I found significant effects of *t-1* on the TFP growth at time *t*. This was repeated until the fourth year.

The number of cross-sections is equal to the length of the time series and both are relatively small so that standard OLS estimates will yield over-optimistic standard errors. Following Beck and Katz (1995), panel corrected standard errors (PCSE) are presented in the results. EGLS is used to control for heteroscedasticity. Table 1 presents the results for the model including lags of 4 years for the ICT variables and 2 years for the non-ICT variables. Model A includes all variables and shows that only the rate of capacity utilisation is significant. The constant, which describes the remaining average TFP growth rate for all countries, is positive and significantly different from zero. Calculating long-run parameter values using a standard Wald-test shows that only the rate of capacity utilisation is significant. The (unweighted) average wage share in total income (1-α in the model) over the entire sample and over all countries is 0.68 so the average capital share is equal to 0.32. The estimated cyclical parameter of 0.51 (the long run estimate of β) differs significantly from the capital share indicating some labour hoarding. The parameter γ is equal to 0.28 (see equation(11)) so the rate of underutilisation of labour is roughly a quarter of the underutilisation of capital.

[Insert Table 1 about here]

Starting from model A we can reduce the number of parameters according to the Hendry or LSE approach (general-to-specific modelling approach) in which the least significant parameters are dropped one by one until all individual (short run) parameters are significant at the 10 percent level. The resulting model is displayed as model B in Table 1. The parameters on the rate of capacity utilisation are similar to the ones in model A, however, the one and two year lagged growth rates of IT hardware are now also significant. The sign of the parameter changes from negative to positive suggests that investments in IT hardware have a negative impact on productivity in the very short run however, this is compensated afterwards. Note that the long-run parameter on the effect of IT hardware is insignificant. If one is mainly interested in long-run parameter values, then the abovementioned procedure to reduce the model may be inappropriate since only significance of short-run parameters are taken into account when deciding whether a variable has to be removed from the equation and if so, when determining which has to be removed first. The same general-to-specific modelling approach can also be applied on long-run parameter values and their significance. The resulting parameter values are described under model C. It should be no surprise that this model is similar to model B except for the short run effect of IT hardware.

From these estimates one could conclude that ICT does not have an additional effect on productivity growth that goes beyond the standard neoclassical view. The only significant variable is the rate of capacity utilisation which is positive and highly significant. One could argue that the estimation period covers mainly the upward phase in the business cycle in most countries but the (unweighted) average of the growth rate of capacity utilisation over the period 1990-2004 is even slightly negative but very close to zero (-0.0019 so about -0.2%). The estimation period of 15 years is apparently sufficiently long enough to overcome this cyclical problem.

The presented general-to-specific modelling approach would be an appropriate methodology to reduce the number of parameters in absence of multicollinearity. This is however highly unlikely since we can expect complementarity between changes in the capital stock of different types of (ICT) capital, substitutability between e.g. labour and

(ICT) capital, but also possible correlations over time of individual variables so that the applied lag structure in the model can lead to multicollinearity. Stepwise elimination of the least significant coefficients from the model may result in a wrong model specification if multicollinearity is present. In order to avoid this procedural effect, the model is re-estimated using all possible combinations of explanatory variables after which the best result can be selected. This implies that all possible combinations of 18 explanatory variables are estimated and only those models for which long-run parameter values are significant at the 10 percent level are used for further analysis.[9] To select the best performing model I employed the adjusted R-squared, the Akaike information criterion (AIC) and initially, I also employed the Schwarz and Hannan Quinn criterion as selection criteria. These criteria all use different weights for model complexity and the Schwarz and Hannan Quinn criterion lead to parsimonious models including the rate of capacity utilisation as remaining relevant explanatory variable. These criteria were further excluded in the analysis.

Table 2 displays the result of this alternative analysis. Only relevant variables are presented but all 18 variables that are presented in Table 1 are included in the analysis. Model A describes the resulting model that shows the highest adjusted R-squared. In contrast to the previous results telecommunication shows up in the analysis as a significant variable as well as labour input. The latter finding indicates that employment is too high given the growth rate of output or that there is some dynamic adjustment such that marginal productivity not always meets marginal costs. The latter case indicates that the inclusion of the rate of capacity utilisation (and labour hoarding) is not sufficient to capture the effects of adjustment costs on the demand for labour. The estimation results for telecommunication show that there is a positive effect after three years and subsequently an adjustment of this effect in the fourth year. The long run coefficient for telecommunication is slightly above 3%. The rate of capacity utilisation remains significant and is of comparable size as found in Table 1. Note that the parameter of the 4 year lagged effect of telecommunication is insignificant but considerable in size and thus

[9] This implies that 2^18-1, i.e. more than 260 thousand variants are estimated.

has a high impact on the ultimate long run estimate of the impact of telecommunication on TFP growth. To investigate the implication of telecommunication on TFP growth model A′ shows the same specification without the 4 year lagged value of telecommunication. Now the three year lagged parameter is reduced such that the long run effect remains approximately the same. The other parameters do not change either.

[insert Table 2 about here]

An alternative to the adjusted R-squared criterion, is the Akaike information criterion (AIC). According to this criterion, model B in Table 2 is the best model from all possible parameter combinations. In this case, labour no longer shows up as a relevant variable, instead IT hardware becomes relevant. As before, the one year lagged coefficient is negative however, this is not corrected anymore by positive values of subsequent lags such that the long-run effect of IT hardware is negative. The lag structure of telecommunication changes now, but the parameter value is roughly the same. The coefficient of the rate of capacity utilisation is slightly reduced, but the order of magnitude remains the same. All three models show a rather stable effect of telecommunication on productivity of about 3 to 3.5%. The estimates on the impact of the rate of capacity utilisation also show a stable pattern.

Though the Durbin-Watson test does not point at autocorrelation, a lagged dependent variable might pick up path dependency and may serve as a better explanation of TFP growth, and may overrule other explanations. For that reason, the model is re-estimated by including the lagged dependent variable in the set of explanatory variables. Out of all possible combinations, model C in Table 2 performs best according to the adjusted R-squared criterion while model D performs the best according AIC criterion. Both models are nearly the same and differ only in the lag structure of the telecommunication variable, a lag of two year versus three year, however, the long-run values of the parameters are the same. The influence of the rate of capacity utilisation is slightly lower as compared to the other models, but this difference is not significant. The model is still estimated with employing EGLS. I show that employing a GMM approach does not change the results dramatically. Note that again in this case, all models presented in Table 2 are very similar to each other whereas they are selected as best performing models out of millions of possible model specifications, including non-lagged variables.

Inspection of the estimation results of all possible combinations of parameters shows that the long run effect of IT hardware is only significant in 9% of all significant results.[10] IT software is significant in 68% of the cases, telecommunications in 55%, non-ICT equipment in 23%, hours worked in 70%, and the rate of capacity utilisation in 37%. IT software is the only variable for which the number of significant parameters increases for longer lags. This could indicate that the spillover effect of IT software on productivity appears even after more than 4 years. To investigate this possibility, I increased the number of lags of IT software until the number of significant coefficients started to decline. This occurred after 7 lags.[11] I also expanded the number of lags for IT hardware and Telecommunication to 5 to avoid a possible a priori selection bias and also included the non-lagged coefficients for all variables. This implies that the same analysis is repeated including 5 parameters for IT Hardware, 9 for IT Software, 5 for Telecommunication, 3 for non-ICT equipment, 3 for hours worked and 2 for the rate of capacity utilisation. Additional inclusion of the fixed effects parameters implies that 42 coefficients must be estimated of which combinations of 27 parameters must be tested to select the final model. This implies that roughly 134 million possibilities are tested.

Table 3 shows the result of this exercise and again in this case, only the variables which are included in the resulting models are presented. Model A displays the best performing parameter combination according to the highest adjusted R2 criterion. As is the case in Table 2 above, the hours worked are significant in model A and the parameter values are in the same order of magnitude. Model B is the best model according to Akaike Information Criterion. Surprisingly both models are rather similar so that out of all

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[10] Out of all 262143 possible combinations only 533 (0.20%) models show significant long run coefficients.

[11] Note that the number of possible combinations doubles for each parameter that is added to the set so that it is impractical to include so many lags for all variables.

possible combinations, the adjusted R2 and Akaike Information Criterion select the same model, except for the hours worked. Telecommunication also remains a relevant factor and the long run parameter value is slightly higher as before but in the same order of magnitude. Next to Telecommunication, IT software now also appears to have positive and significant long run effects on output and TFP growth. One of the most striking results, is that I find a lag of 7 years, similar to the findings of Brynjolfsson and Hitt (1996) and Brynjolfsson and Hitt (2003) even though they use US based firm level data in their analysis.

IT hardware and non-ICT equipment do not show up in the model. Out of all significant models IT hardware is included only in 2% of the cases and non-IT equipment in 10%.[12] Comparing this with IT software which is included in 97% of the significant models and Telecommunication in 76%, this also indicates that IT hardware does not lead to additional productivity effects.

If the lagged dependent variable is included in the analysis, then both the adjusted R-squared criterion and the AIC lead to the same model specification. This is presented as model C in Table 3 where, as before, there is no difference at all in the model specification of the best performing model as compared to the models without lagged dependent variable and where also, the estimated parameter values remain the same. Finally, the GMM estimation procedure as introduced by Arellano and Bond (1991), is employed to investigate the possible error if EGLS is used in presence of a lagged dependent variable. Model C is re-estimated and the resulting parameter estimates are presented in the last column in Table 3. Now the impact of telecommunication of TFP growth is increased and the impact of software is decreased however, the order of magnitude remains the same and all parameters remain significant.

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[12] Only 2670 (=0.002%) models show significant long run coefficients.

Discussion

The results indicate that there is a positive relation between the growth of IT software and Telecommunication services and TFP growth. This implies that productivity gains from software and from telecommunication equipment are larger than one would expect from a standard neoclassical growth accounting approach. This result is obtained after allowing for considerable time lags in the econometric analysis. The elasticity of the growth of Telecommunication equipment on economic growth and on productivity growth varies between 3 and 5 percent with a lag of 2 to 3 years. The impact of software investments, or more precisely, of changes in the services arising from the software capital stock, is roughly 2-3% with a lag even up to seven years. IT hardware does not seem to have an effect that goes beyond the neoclassical paradigm and if there is a significant long run effect, it is negative but relatively small (1.5%). Non-ICT equipment investments do not show up at all in the estimates as a relevant factor, whereas labour does sometimes. If labour is included in the model, then the effect of rate of capacity utilisation on TFP growth is larger. This could indicate that the model does not capture labour hoarding effects to the full extent or that the model specification is not precise regarding labour hoarding. The cyclical effect of TFP growth clearly shows up in all estimates. This implies that firms are able to expand output without adjusting the input factors in the short run and this leads as a result to an underestimation of factor inputs and thus an overestimation of TFP growth in the upward phase of the business cycle. Similarly in a downward phase, firms do not scrap capital or fire workers in the short run so that TFP growth is underestimated in that phase.

The long lag of the effect of software investments on TFP growth is striking. First of all it precisely resembles the findings of Brynjolfsson and Hitt (2003) though they base their finding on a different methodology, a different dataset and on ICT as aggregate technology not IT software specific. Second, comparing the depreciation rate and this lagged influence clearly opens the discussion as to how this effect can materialize. Following Jorgenson and Stiroh (2000), Timmer, Ypma et al. (2003) assume a depreciation rate of software of 31.5% in the construction of the dataset used here. This implies that after 7 years, only 7 percent of the initial software capital stock remain in operation, which implies that it is not likely that this small amount can cause such large productivity effect. This indicates that other influences are important. The notion of ICT as a general purpose technology and the demand for organisational adjustments and learning processes are obvious candidates. ICT as general purpose technologies open new possibilities and new potential innovative routes to be explored. But exploring these new routes and implementing new production processes often induce other changes such as transformations of workplaces and changes in hierarchies. Such conversion processes obviously take time. From this perspective, investments in IT software may also be regarded as a rationale for workplace reorganisations.

[Insert Table 4 about here]

What do these results mean for the impact of ICT on economic growth and productivity growth? Table 4 provides an answer by including the additional effects of software and telecommunication and of changes in the rate of capacity utilisation on TFP growth in a traditional growth accounting framework for the EU and for the US. The analysis is carried out along the standard growth accounting exercises (e.g. Timmer, Ypma et al. (2003) for EU and the US, Jorgenson and Stiroh (2000) for the US). Labour productivity growth is broken down into capital deepening and TFP growth, as is done in standard analysis where TFP growth is measured as a residual. The non-italics numbers in Table 4 refer to outcomes coming from a traditional growth accounting exercise. Additionally, I also include spillover effects and effects due to changes in the rate of capacity utilisation, as displayed in italics in Table 4. The remaining contribution from TFP growth on labour productivity growth declines if this additional effect is positive, which is the case for both periods 1996-2000 and 2001-2004 and for both regions. A striking result is that the effect of ICT on labour productivity are almost doubled as compared to the direct capital deepening effects as measured in standard growth accounting models. This indicates that network and spillover effects are as important as the initial direct productivity effect of ICT investments. Ignoring these effects clearly underestimates the importance of ICT on productivity growth. Is IT hardware the most prominent source of ICT driven growth in standard analysis? These results show a different picture. In both regions and in both periods, the impact arising from IT software is similar to the impact of IT hardware. The impact of Telecommunication equipment even exceeds the impact of IT hardware.

Comparing the regions demonstrates that the spillover effect relative to the direct effect is larger in the EU such that the overall contribution from ICT on labour productivity growth is still larger in the US, however the difference between the two regions is less pronounced. The effect of the rate of capacity utilisation on labour productivity is positive in the first period and negative afterwards. The upward phase in the business cycle at the end of last century clearly had a positive effect on labour productivity indicating that if demand increases, firms and workers are able to absorb parts of the increased demand in the short run. The opposite holds true for the period after 2001.

Conclusions

This paper investigates the influence of ICT investments on economic performance and productivity growth. The main question addressed is whether ICT induces productivity outcomes that go beyond the effects that arise from a standard growth accounting analysis. The results evidently show that investment in IT software and in telecommunication equipment lead to positive additional productivity effects. This is not the case for IT hardware. The paper also shows that these additional effects can come after considerable delays. The delay of Telecommunication of productivity growth is three years and for IT software is even up to seven years.

Next to externality or learning-by-doing effects arising from ICT, the paper shows considerable short run effects of changing rates of capacity utilisation on labour productivity and consequently on short run measured total factor productivity. In an upward phase of the business cycle, labour productivity will increase due to increased efficiency rather than due to increased technology. This reduces the measured impact of TFP growth on economic growth and labour productivity growth. The opposite holds true for a downward phase in the business cycle. However, the long run measurement of TFP growth is not affected.

The results also demonstrate the differences in results between the Hendry approach of a general-to-specific econometric modelling method and the 'brute force method' where simply all possible combinations are estimated. Multicollinearity between explanatory variables and between different lagged values of similar variables, leads to non-optimal model specifications in the case of the Hendry approach. In terms of performance, these models are merely the same indicating a relative flat objective function but in terms of final parameter selection and sign and size of the parameters, they differ considerably except for the rate of capacity utilisation. The latter remains highly robust in all findings.

If network effects are relevant, what policy conclusions can be drawn from this finding? If the social returns on investment exceed the private return, as is relevant in the case of network and spillover effects, entrepreneurs will invest too less in ICT from a social perspective. This demands a policy to stimulate investment in ICT. However, the present study also shows that there is a considerable time lag between investment and the ultimate pay-off. In the literature, this time lag is attributed to adjustment of the organisation, schooling and retraining. This indeed implies that the labour force, organisational structures, etc., should be able to keep up with technological change.

A drawback of the present analysis is that estimated parameters are assumed to be the same for all countries. The inclusion of long lag structures reduces the degrees of freedom considerably such that a panel approach had to be employed. Spillover effects and productivity impacts from fluctuations of the business cycle due to e.g. labour hoarding, are likely to differ between regions and countries. The use of longer time series would relax the need for such panel approach. Finally, the present analysis cannot clearly distinguish spillover effects from influences that arise due to adjustments such as organisational change, learning-by-doing or other causes of increasing returns to scale. More detailed data and a different level of analysis could shed light on this issue however, this is left for further research.

Table 1. Estimation results of the full model, lags ICT variables up to 4 years.

	model A	model B	model C
IT hardware -1	-0.0315 (0.0194)	-0.0385 (0.0148)**	
IT hardware -2	0.0251 (0.0295)	0.0290 (0.0139)**	
IT hardware -3	-0.0049 (0.0297)		
IT hardware -4	-0.0056 (0.0200)		
IT Software -1	-0.0089 (0.0234)		
IT Software -2	-0.0005 (0.0329)		
IT Software -3	0.0218 (0.0323)		
IT Software -4	-0.0158 (0.0229)		
Telecommunication -1	0.0021 (0.0455)		
Telecommunication -2	-0.0200 (0.0794)		
Telecommunication -3	0.0703 (0.0810)		
Telecommunication -4	-0.0418 (0.0496)		
Non-IT equipment -1	-0.0293 (0.0890)		
Non-IT equipment -2	0.0296 (0.0886)		
l -1	-0.1036 (0.0759)		
l -2	0.0520 (0.0657)		
q	0.7148 (0.0598)***	0.7139 (0.0480)***	0.6790 (0.0474)***
q -1	-0.2012 (0.0727)***	-0.2668 (0.0495)***	-0.3021 (0.0467)***
c	0.0145 (0.0031)***	0.0133 (0.0017)***	0.0115 (0.0007)***
R2	0.5678	0.5875	0.5760
AIC (*10^4)	1.771	1.664	1.679
DW	1.93	1.81	1.78
F-statistics	10.20***	18.72***	20.02***
Computed long run parameter values:			
IT hardware	-0.0169 (0.0129)	-0.0095 (0.0086)	
IT Software	-0.0033 (0.0191)		
Telecommunication	0.0106 (0.0253)		
Non-IT equipment	0.0003 (0.0473)		
l	-0.0515 (0.0715)		
q	0.5135 (0.0876)***	0.4472 (0.0577)***	0.3769 (0.0516)***

Note: Dependent variable: growth rate of TFP. All variables are in growth rates. Standard errors in brackets; ***, ** and * indicate significant at the one, five and ten percent level, respectively. Sample is 1990-2004, 15 cross sections included, total balanced panel observations is 225, fixed effects estimate is employed using EGLS with cross section weights (PCSE). All variables are in (logarithm based) growth rates. Model A includes all variables, model B is the model for which all coefficients are significant at the 10 percent level using stepwise elimination of the least significant variable (the LSE or Hendry approach), model C is the same but on the condition that all long run coefficients are significant at the 10 percent level.

Table 2. Estimation results using ICT lags up to 4 years

	model A	model A'	model B	model C	model D
IT hardware -1			-0.0157 (0.0086)*		
Telecommunication -2			0.0306 (0.0158)*	0.0291 (0.0155)*	
Telecommunication -3	0.0722 (0.0354)**	0.0376 (0.0152)**			0.0293 (0.0151)*
Telecommunication -4	-0.0393 (0.0364)				
l -1	-0.1109 (0.0532)**	-0.1026 (0.0522)*			
q	0.6685 (0.0468)***	0.6666 (0.0472)***	0.6918 (0.0466)***	0.6611 (0.0466)***	0.6633 (0.0467)***
q -1	-0.2371 (0.0606)***	-0.2330 (0.0609)***	-0.2932 (0.0497)***	-0.3974 (0.0528)***	-0.3763 (0.0524)***
tfp -1				0.1561 (0.0609)**	0.1413 (0.0610)**
$R2$	0.5865	0.5841	0.5804	0.5886	0.5874
AIC ($x10^{-4}$)	1.683	1.671	1.668	1.665	1.663
DW	1.87	1.87	2.10	2.10	2.07
F	17.72***	18.48***	18.72***	18.72***	18.80***
long run					
IT hardware			-0.0157 (0.0086)*		
Telecommunication	0.0329 (0.0158)**	0.0376 (0.0152)**	0.0306 (0.0158)*	0.0345 (0.0186)*	0.0341 (0.0175)*
l	-0.1109 (0.0532)**	-0.1026 (0.0522)*			
q	0.4314 (0.0580)***	0.4337 (0.0582)***	0.3985 (0.0541)***	0.3125 (0.0629)***	0.3343 (0.0615)***

Note: Dependent variable: growth rate of TFP, all variables in growth rates. Standard errors in brackets; ***, ** and * indicate significant at the one, five and ten percent level, respectively. Sample is 1990-2004, 15 cross sections included, Total balanced panel observations: 225, fixed effects estimate using EGLS with cross section weights (PCSE). Statistics of long run parameters are estimated by a Wald-test. Model A is best fit according to adjusted R2 criterion, model B is the best according to AIC. Model A' is similar to A with the exception of the 4 year lagged value of telecommunication, which is insignificant as such but model A gave the best results (according to the R2 criterion) under the condition that all long run parameters are significant. If we include the one year lagged dependent variable as additional explanatory variable, model C gives best results according to R2 and model D gives best results according to the AIC criterion.

Table 3. Estimation results and model selection

	model A	model B	model C	GMM
IT Software -7	0.0244 (0.0114)**	0.0272 (0.0113)**	0.0252 (0.0109)**	0.0126 (0.0076)*
Telecommunication -3	0.0469 (0.0159)***	0.0421 (0.0158)***	0.0392 (0.0158)**	0.0774 (0.0144)***
l -1	-0.0898 (0.0522)*			
q	0.6856 (0.0480)***	0.7075 (0.0465)***	0.6822 (0.0473)***	0.5993 (0.0659)***
q -1	-0.2357 (0.0605)***	-0.3006 (0.0459)***	-0.3661 (0.0527)***	-0.3424 (0.0706)***
tfp -1			0.1354 (0.0602)**	0.2121 (0.0821)**
R2	0.5906	0.5853	0.5949	
AIC (*10^{-04})	1.658	1.657	1.648	
DW	1.87	1.81	2.08	
F	18.01***	18.57***	18.31***	
long run				
IT Software	0.0244 (0.0114)**	0.0272 (0.0113)**	0.0291 (0.0126)**	0.0160 (0.0094)*
Telecommunication	0.0469 (0.0159)***	0.0421 (0.0158)***	0.0454 (0.0181)**	0.0982 (0.0163)***
l	-0.0898 (0.0522)*			
q	0.4498 (0.0578)***	0.4069 (0.0517)***	0.3657 (0.0628)***	0.3260 (0.0933)***

Note: Dependent variable: growth rate of TFP, all variables in growth rates. Standard errors in brackets; ***, ** and * indicate significant at the one, five and ten percent level, respectively. Sample is 1990-2004, 15 cross sections included, total balanced panel observations is 225, fixed effects estimate is applied using EGLS with cross section weights (PCSE). Statistics of long run parameters are estimated by a Wald-test. From all possible combinations of parameters model A gives best results according to adjusted R2, model B is the best according to AIC. Model C gives the best result according to both R2 and AIC criteria if lagged value of tfp is included. Note that the Schwarz criterion is very restrictive on the number of parameters and leads in both cases, with and without inclusion of the lagged value of tfp at the right hand side to a simple model: $tfp=f(q,q_{-1})$ as the best result. The HQ criterion operates in between and selects the same as Schwarz criterion if tfp_{-1} is included but selects model B if the lagged dependent variable is not included. GMM estimate of model C is the dynamic panel estimator by Arellano and Bond (1991) restricting the number of lagged levels in the instrument set to 6 based. The estimated model is based on logarithms of the levels of the variables leading to an equivalent interpretation of the parameters.

Table 4. Contributions to labour productivity growth including network effects

	EU-15		US	
	1996-2000	2001-2004	1996-2000	2001-2004
labour productivity growth	1.78%	1.06%	2.32%	2.78%
ICT Capital deepening	0.61%	0.30%	0.98%	0.56%
IT Hardware	0.43%	0.18%	0.61%	0.28%
IT Software	0.12%	0.06%	0.26%	0.14%
Telecom equipment	0.07%	0.06%	0.14%	0.14%
Spillover effects	*0.59%*	*0.36%*	*0.77%*	*0.43%*
IT Software	*0.29%*	*0.12%*	*0.39%*	*0.13%*
Telecom equipment	*0.30%*	*0.24%*	*0.38%*	*0.29%*
non-ICT capital deepening	0.32%	0.40%	0.20%	0.51%
rate of capacity utilisation	*0.31%*	*-0.28%*	*0.21%*	*-0.15%*
total factor productivity	-0.05%	0.28%	0.16%	1.43%
Total contribution of ICT	(1.20%)	(0.66%)	(1.75%)	(0.99%)
(TFP contribution without additional effects)	(0.85%)	(0.36%)	(1.14%)	(1.71%)

Note: Capital deepening, both ICT and non-ICT, is based on the standard growth accounting methodology, using the updated data from Timmer, Ypma et al. (2003) (see www.ggdc.net). Other effects are calculated by using these data and by taking the following values as spillover/additional effects, c.f. Table 3: IT Software: 0.025; Telecom equipment 0.04; capacity utilization effects: 0.36. The additional effects are printed in italics. Total contribution of ICT on labour productivity comprises ICT capital deepening effects and spillover effects. For comparison the last row denotes the contribution of Total Factor Productivity growth on labour productivity without additional effects. These numbers are the same as presented by Timmer, Ypma et al. (2003).

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