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ICT AND GROWTH: THE ROLE OF RATES OF RETURN AND CAPITAL PRICES

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We revisit the widely discussed contribution of investment in ICT to economic growth, focusing on differences in productivity and quality of ICT across countries and time. In a growth accounting approach, we look at the way rates of return and rates of asset price decline measure these aspects. Conducting a sensitivity analysis with data from the EU KLEMS database for the years 1990–2007, we introduce a constant rate of return and a constant rate of ICT price decline. Both alternative measurements somewhat downplay the role investment played relative to growth in multifactor productivity in the U.K. and the U.S. during 1995–2000. Moreover, we show that more than half of the ICT contribution to labor productivity growth results from changes in capital quality and composition rather than from quantity.

JEL Codes: C43, E22, O47

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1. Introduction

The acceleration in U.S. economic growth during the mid-1990s is often attributed to the revolution in the field of information and communication technologies (ICT). Both the ICT producing sector and ICT investment in other sectors were larger in the U.S. than in continental Europe. After 2000, the U.S. continued to grow faster than many European countries, but the sources of growth shifted to a broader range of sectors. ICT-intensive service industries such as business services and trade experienced fast productivity growth (see Van Ark *et al.*, 2008).

In this paper, we take a closer look at the contribution of ICT investment in a growth accounting framework. The highest contributions so far were observed in the late 1990s. Does this mean that the countries with high growth after 1995

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invested a higher quantity of ICT capital than other countries? Or did they invest in better ICT and were more productive in using it? While it is well-known that ICT capital deepening is related to both more investment and strong quality improvement, we have less evidence on the variation of this effect across countries and time. In parallel to quality change, differing output elasticities of capital may affect the productivity growth attributed to ICT investment. In order to shed light on these questions we run three simulations including (1) a constant real rate of return to capital, (2) a constant quality improvement, and (3) a decomposition of net ICT investment into a quality and a quantity component. The purpose of the first two steps is to see how the ICT contribution to growth would have looked if there were no differences in return to capital or quality across countries, industries, and time. The purpose of the third step is to quantify the contribution of technical change embodied in ICT to economic growth.

Statistical measurement has gone a long way since the 1980s when accounting for quality improvement in computers represented a novelty in national accounting. Edward Denison, one of the founders of national accounting in the 1950s, strongly opposed this step. He considered that the new method of measuring computer capital would quantify capital via the output it produces and therefore impose a constant capital–output ratio (Denison, 1989). While Young (1989) and others continued to defend quality adjustment at the time, Denison's criticism shows how the idea of incorporating quality change into a measure of investment volume could be perceived as disruptive. Twenty-five years later, a growing amount of evidence on the contribution of ICT to economic growth is produced based on quality-adjusted measures of ICT investment.

With the publication of the EU KLEMS database (O'Mahony and Timmer, 2009), comparative analysis across countries and industries can be undertaken more easily than before. Much of the interest in the results of these studies lies in understanding the *differences* in productivity growth across countries, industries, and time periods. Since ICT has been discussed in a number of studies as an important driver of these differences, we ask which part of the differences in the ICT contribution to growth results from the quality and productivity of ICT rather than from the quantity. Quality increase is measured by decline in the prices of ICT. Marginal productivity of capital is measured by user cost in growth accounting. In our sensitivity analysis, we focus on the rate of return to capital as a variable that leads to differences in user cost. The rate of the return equally affects the output elasticity of non-ICT capital. For quality change, we assume that it only affects ICT capital, since the prices for non-ICT suggest that quality change has been low.

Computations of capital services and contributions to growth under alternative assumptions have been undertaken in previous studies. But there has been little systematic investigation into whether the conclusions from cross-country growth accounting change in an economically meaningful way when introducing alternative measures of returns to capital and ICT prices. In contrast to several previous studies, we do not intend to propose a particular improved measurement in this paper. We introduce a minimalistic measurement into a growth accounting setting and compare the results to those obtained with the EU KLEMS data for the years 1990–2007. Instead of the rate of return from EU KLEMS that is computed in a residual way, we introduce a constant external rate of return to capital that we set to a real value of 4 percent. In the sensitivity analysis for the rate of ICT price decline, we set all values equal to the average ICT price decline observed in the U.S. between 1990 and 2007.

There are two ways to read our analysis. On the one hand it can be read as an analysis of potential measurement error. Rental rates and investment prices are generally more prone to measurement error than nominal investment and output. Looking at our results through this lens starts from the presumption that price-based measures of marginal productivity and ICT quality change are probably good enough to gauge their general order of magnitude, but are not reliable in tracing differences across countries and time. Replacing them by measures that are constant in real terms gives an idea of the magnitude of measurement error in contributions to growth. Our analysis can also be read based on the contrary presumption that ICT quality measures and output elasticities in growth accounting contain important and reliable information on the extent to which it was not more ICT but better or more productive ICT that contributed to higher growth. Since a quality–quantity split is still not standard in the growth accounting literature, we also take an interest in the *total* contribution of better ICT quality to growth.

Our main results are that both the constant rate of return and the constant ICT price decline somewhat downplay the role investment played relative to growth in multifactor productivity (MFP) in fast growing countries during 1995–2000. The alternative rate of return has a stronger effect on the contribution of non-ICT capital than on the contribution of ICT capital. Moreover, we show that more than half of the ICT contribution to labor productivity growth results from growth in quality rather than quantity.

2. Previous Research

We are building on three strands of previous growth accounting research: work on rates of return, on ICT investment deflators, and on embodied technical change. The novel element in our analysis is to combine different pieces of evidence and to examine how far alternative measurements change results in a way that would affect the story told about drivers of growth between 1990 and 2007.

The rate of return to capital enters the user cost, which equals the sum of return to capital, depreciation, and capital devaluation. It appears in two steps of growth accounting: in aggregating up single assets to total ICT and non-ICT capital, and in assessing how output reacts to increases in capital. In growth accounting, the shares of compensation of total ICT and non-ICT capital in value added represent the output elasticities. The underlying assumption is the equality between user cost and marginal productivity.

In the standard growth accounting approach, the return to capital is computed as a residual, subtracting labor income from value added. The advantage of this so-called internal rate of return is the consistency between income and production accounts. If this rate is computed at the industry level, as in the EU KLEMS database, it implies that the total capital compensation of an industry equals its total value of capital services (EU KLEMS, 2007a). The goal of growth accounting is, however, not to measure income distribution but to assess the productivity of different inputs. The share of user cost in value added may not correspond to the output elasticity of an asset for two main reasons. First, the theoretical assumptions under which user cost equals marginal productivity may not hold. If competition is not perfect or if there is uncertainty about future returns when investing, marginal productivity may deviate from measured user cost. Second, an internal rate of return is particularly subject to measurement error, since its computation requires accurate estimates of investment, total capital income, and capital stock. The latter is usually hard to measure because it depends on the investment deflator and the depreciation rate. Also total investment is likely to be underestimated because of unmeasured assets (Inklaar, 2010). While there are different ways to compute an internal rate of return that allows growth accounting to relax the assumptions of perfect competition and foresight to some degree (see, e.g., the hybrid model by Oulton, 2007a), the problem of measurement error persists. Computing rates of return from a residual measure of capital income, Oulton and Rincon-Aznar (2012) find that they remain fairly constant across countries and time (with the exception for implausible overall magnitudes in Italy and Spain), while exhibiting implausible variation across sectors. Against this background, a number of researchers favor the use of external rates of return (Diewert, 2001; Balk, 2010; Inklaar, 2010; Schreyer, 2010). External rates of return are not derived from residual capital income but based on independent information. Using industry data for the EU and the U.S., Erumban (2008) finds that switching from an internal to an external rate of return has moderate effects on measured MFP growth. He mentions that it still may affect the interpretation of growth accounting results "because the productivity differences across countries are, sometimes, evaluated on a marginal scale" (p. 530).

Schreyer (2010) analyzes the computation of capital services and contributions to growth with external rates of return from a theory-based perspective. His aim is to "define a computable measure of productivity growth while allowing for the fact that it may reflect more than pure technology shifts" (p. 20). We will follow this approach by introducing an external rate of return to capital and computing an MFP measure that corresponds to what he terms apparent multifactor productivity. Apparent MFP is derived assuming that the cost function is linearly homogeneous in inputs and non-decreasing. This assumption does not imply the usually imposed constant returns to scale of the production function. Factor markets are assumed to be competitive while firms may charge a variable mark-up over costs in selling their products. In addition, the approach allows for the presence of unmeasured inputs. Under these assumptions, it is possible to derive a cost-based MFP measure using an external rate of return to capital. Apparent MFP includes not only the effects of technological progress shifting the production function but also the effects of non-constant returns to scale, mark-ups, and unmeasured inputs. Under additional assumptions, it is possible to disentangle these effects and identify a measure of pure technological change. Implementing several of these measures, Schreyer (2010) finds only a small difference to apparent MFP and recommends the latter as a pragmatic and relatively robust way of measuring MFP. Our choice for an external rate of return is based on a study by Diewert (2001). He introduces a constant real rate of return of 4 percent, which is close to the long-term OECD average. Inklaar (2010) proposes a more nuanced measure of the weighted average cost of capital for the external rate of return, taking into account both equity cost and debt cost.

Nowadays it is commonplace that a measure of real ICT investment has to adjust for rapid quality change. The implementation of adequate deflators, especially its harmonization across countries, continues to pose challenges, but the underlying concept is widely accepted and the kind of fundamental criticism expressed by Denison (1989) is rarely discussed anymore. Nevertheless the more complex meaning of "ICT capital deepening" that results from this methodological choice is not always explicit in the interpretation of growth accounting results. ICT capital deepening now means both more ICT and better ICT, and the sources of statistical information these two components rely on are quite different. The quantity of ICT invested corresponds to nominal investment adjusted for pure inflation. The measured quality of ICT investment depends on the investment deflators that are used to transform nominal ICT spending into real spending on constant-quality ICT. Around the year 2000, only a few national statistical offices had adopted advanced methods of constructing such deflators. Schreyer (2002) advocated the use of price deflators "harmonized" to the one in the U.S., where quality-adjusted measures were considered to be best implemented. Harmonization means that the decline of ICT prices relative to non-ICT capital prices is assumed to be identical in all countries, following the movement observed in the U.S. This method is also used in the EU KLEMS database for countries without adequate national measurement of ICT prices. If this approach is used at the level of different ICT categories (hardware, software, telecommunications equipment), aggregate real price decline may still differ across countries as a result of a different mix in ICT capital. One shortcoming of the harmonized deflator is that differences in national market structure are not taken into account.

Schreyer (2010) argues that the possible measurement error due to the usage of a harmonized price index is still smaller than the bias arising from the comparison of capital services computed with national deflators. While the relative merits of national and harmonized deflators may change with the spread of better methods, we consider that it remains important to examine whether differences in price change across countries look plausible. Moreover, the assessment of productivity effects of quality change in ICT does not only require the correct measurement of quality change. In growth accounting, it also relies on the assumption that better ICT is immediately translated into higher productivity in the ICT using sectors. Meanwhile there is evidence that firms need time to exploit the full potential of better ICT (O'Mahony and Vecchi, 2005; Brynjolfsson and Saunders, 2009). In our simulation, we use more uniform deflators than the EU KLEMS database, since we eliminate variations over time. Moreover, we introduce a constant decline relative to the value added deflator (following Oulton, 2012), while EU KLEMS computes a constant decline relative to the deflator for non-ICT investment.

When we account for quality change in ICT investment, we measure technical change that is embodied in ICT. Denison and other critics of hedonic measurement objected that this would blur the fundamental distinction between capital deepening on the one side and technical change measured by MFP on the other side. This concern gave rise to the so-called "embodiment controversy," which first emerged in the context of neoclassical growth theory in the 1960s (Solow, 1960; Jorgenson, 1966). At that time, ICT investment hardly existed and deflators accounting for technical change were not yet constructed. Without appropriate price information for investment goods of identical quality, it is impossible to distinguish disembodied and embodied technical change empirically. If prices are measured but with large error, the relative contributions of disembodied and embodied technical change are mismeasured (Jorgenson, 1966; Hercowitz, 1998). This is a problem revisited in our simulation exercise.

The second embodiment controversy was the subject of two articles in the *Journal of Monetary Economics* (Greenwood and Krusell, 2007; Oulton, 2007b) that took up issues raised by Greenwood *et al.* (1997) and Hercowitz (1998). Greenwood *et al.* (1997) assert that embodied technical change cannot act as an engine of growth in a one-sector general equilibrium with quality-adjusted investment because the optimal allocation between consumption and investment does not depend on the rate of embodied technical change in this case. The debate showed that some of the disagreement on the contribution of embodied technical change has to do with the difference between growth accounting and long-run growth theory (or "statistical" and "equilibrium" growth accounting, see Cummins and Violante, 2002).

In growth theory, investment choices are influenced by technical change and thus technical change has an effect on both the quality and the physical quantity of investment. Statistical growth accounting, which we consider in this paper, does not impose particular assumptions on drivers of investment. Growth accounting, however, does not contradict neoclassical growth models: the relation between disembodied and embodied technical change becomes transparent in a growth model with two or more sectors, where the price decline of investment goods results from disembodied technical change in an investment goods sector. This property is mirrored in multisector growth accounting analysis (see Oulton, 2012).

In order to assess the contribution of ICT capital quality, we rely on an approach first mentioned by Jorgenson (2001). Colecchia and Schreyer (2002) describe this method in more detail and apply it to a set of nine OECD countries. They evaluate changes in the quality of aggregate capital stemming from the shift in its composition towards highly productive but more short-lived assets. The effect of this compositional change is obtained as the difference between the change in capital services and the change in the capital stock, or, in other words, as the difference between measures of growth in capital input based on user costs and based on nominal asset shares. In addition, Bassanini and Scarpetta (2002) identify the effect that results from improved quality of capital through technological progress. These quality changes within categories of assets are measured by comparing the evolution of hedonic asset prices to the evolution of real acquisition prices. Since quality-adjusted deflators have become the standard for measuring ICT prices, direct information on real acquisition prices is not available to us. We use the deflator for non-ICT assets as a proxy.

TABLE 1
Industry Classification

Industry	NACE Revision 1.1
Market economy	1–67, 71–74, 90–93
Goods production	1–45
Electrical equipment	30–33
Market services	50–67, 71–74, 90–93
Trade	50–52
Hotels and restaurants	55
Transport and storage	60–63
Post and telecommunications	64
Financial intermediates	65–67
Business services	71–74
Other services	90–93

3. Data and Growth Accounting Methodology

3.1. *Basic Framework*

The main data source used for our research is the November 2009 release of the EU KLEMS database.[1] It consists of output data on a detailed industry level and, more importantly, in-depth capital input data for eight different types of assets. They are usually grouped into ICT (hardware, software, telecommunications equipment) and non-ICT assets (machinery etc.). The seven countries with sufficient coverage of input and price data for our analysis are Australia, Austria, Germany, Italy, Spain, the U.K. and the U.S. Time series for Germany start in 1991. Table 1 lists the industries covered. Under the usual assumptions of competitive markets and constant returns to scale, the industry-specific growth in real value added may be decomposed into the weighted sum of growth of inputs plus growth in multifactor productivity *MFP*:

$$(1)\qquad \Delta \ln Y_{j,t} = \bar{v}_{j,t}^{L} \Delta \ln L_{j,t} + \bar{v}_{j,t}^{ICT} \Delta \ln K_{j,t}^{ICT} + \bar{v}_{j,t}^{NICT} \Delta \ln K_{j,t}^{NICT} + \Delta \ln MFP_{j,t}$$

where $L_{j,t}$ stands for labor input in industry j in year t, $K_{j,t}^{ICT}$ for ICT capital input, $K_{j,t}^{NICT}$ for non-ICT capital input, and $\bar{v}_{j,t}$ for the two-period average of the shares of factor compensation.[2] Instead of growth in value added, we may use a similar expression for growth in labor productivity y, which is derived as value added Y over hours worked H:

$$(2)\qquad \Delta \ln y_{j,t} = \bar{v}_{j,t}^{L} \Delta \ln l_{j,t}^{L} + \bar{v}_{j,t}^{ICT} \Delta \ln k_{j,t}^{ICT} + \bar{v}_{j,t}^{NICT} \Delta \ln k_{j,t}^{NICT} + \Delta \ln MFP_{j,t}$$

where $\Delta \ln l_{j,t}^{L}$ is the growth rate of labor input per hour, $\Delta \ln k_{j,t}^{ICT}$ and $\Delta \ln k_{j,t}^{NICT}$ the growth rate of ICT and non-ICT capital per hour worked. The share of ICT capital compensation in total factor compensation is calculated as follows:

[1]See O'Mahony and Timmer (2009).
[2]Country subscripts are dropped unless country differences matter for definition.

$$v_{j,t}^{ICT} = \frac{\sum_{k \in ICT} q_{k,j,t} A_{k,j,t}}{\sum_{k \in ICT} q_{k,j,t} A_{k,j,t} + \sum_{k \in NICT} q_{k,j,t} A_{k,j,t} + LAB_{j,t}} \tag{3}$$

where $LAB_{j,t}$ denotes labor compensation in industry j, $q_{k,j,t}$ user cost of asset k, and $A_{k,j,t}$ real stock of asset k. Shares of other factors of production are obtained in an analogous way. If we use external measures of capital compensation, this leads to a cost-based measure of MFP that can be identified under the assumptions described by Schreyer (2010).

When aggregating over industries, we employ the direct aggregation approach of growth accounting described by Inklaar *et al.* (2005):

$$\Delta \ln y_t = \sum_j \bar{v}_{j,t}^{Y} \left(\bar{v}_{j,t}^{L} \Delta \ln l_{j,t}^{L} + \bar{v}_{j,t}^{ICT} \Delta \ln k_{j,t}^{ICT} + \bar{v}_{j,t}^{NICT} \Delta \ln k_{j,t}^{NICT} + \Delta \ln MFP_{j,t} \right) + R_t \tag{4}$$

where $\bar{v}_{j,t}^{Y}$ is the two-period average share of industry j in nominal aggregate value added. The term R_t is called reallocation of hours, which incorporates the difference between the share of an industry in aggregate value added and in hours worked. The industry-specific growth rate of ICT capital services is calculated as follows:[3]

$$\Delta \ln K_{j,t}^{ICT} = \ln K_{j,t}^{ICT} - \ln K_{j,t-1}^{ICT} = \sum_{k \in ICT} \bar{w}_{k,j,t}^{ICT} \Delta \ln A_{k,j,t} \tag{5}$$

where $\bar{w}_{k,j,t}^{ICT}$ denotes the two-period average share of asset k in ICT capital compensation:

$$w_{k,j,t}^{ICT} = \frac{q_{k,j,t} A_{k,j,t}}{\sum_{k \in ICT} q_{k,j,t} A_{k,j,t}}. \tag{6}$$

To calculate the shares in capital compensation $w_{k,j,t}$ as in equation (6) and $v_{j,t}^{ICT}$ as in equation (3), we need values for the user cost q_j of asset k at time t:[4]

$$q_{k,j,t} = p_{k,j,t-1}^{I} i_{j,t} + p_{k,j,t}^{I} \delta_{k,j} - \left[p_{k,j,t}^{I} - p_{k,j,t-1}^{I} \right]. \tag{7}$$

Equation (7) comprises the nominal rate of return $i_{j,t}$, the rate of depreciation $\delta_{k,j}$, and the asset revaluation term $p_{k,t} - p_{k,t-1}$.[5]

The real capital stock is calculated using the perpetual inventory method (PIM):

$$A_{k,j,t} = \left(1 - \delta_{k,j}\right) A_{k,j,t-1} + I_{k,j,t} / p_{k,j,t} \tag{8}$$

[3]Similar calculations are used for non-ICT capital.

[4]See Jorgenson (2005, pp. 154–5).

[5]In practice, we follow EU KLEMS and smooth the asset revaluation term of the user costs formula: $q_{k,j,t} = p_{k,j,t-1}^{I} i_{j,t} + p_{k,j,t}^{I} \delta_{k,j} - 0.5\left(\ln\left(p_{k,j,t}\right) - \ln\left(p_{k,j,t-2}\right)\right) p_{k,j,t-1}$.

with $I_{k,j,t}$ the nominal investment and $p_{k,j,t}$ the hedonic investment price index of asset k at time t.

3.2. *Specifications Used in Sensitivity Analysis*

The sensitivity analysis of the contributions of ICT capital, non-ICT capital, and multifactor productivity to labor productivity under alternative rates of return in equation (7) is carried out using two different nominal rates of return $i_{j,t}$:

1. *The internal rate of return of the EU KLEMS database*
   This rate of return is calculated in a two-step procedure via an ex-post method. The first step consists of computing the industry-specific total capital compensation, which is obtained as a residual:

$$CAP_{j,t} = VA_{j,t} - LAB_{j,t} \tag{9}$$

   where VA denotes value added and LAB labor compensation. The nominal rate of return i for industry j is then defined as:

$$i_{j,t} = \frac{CAP_{j,t} + \sum_k p^I_{k,j,t} - p^I_{k,j,t-1} A_{k,j,t} - \sum_k p^I_{k,j,t} \delta_{k,j} A_{k,j,t}}{\sum_k p_{k,j,t-1} A_{k,j,t}} \tag{10}$$

   where $p^I_{k,j,t}$, $\delta_{k,j}$ and $A_{k,j,t}$ are the investment price index, the depreciation rate, and the real stock of asset k.
2. *A 4 percent external real rate of return plus country-specific inflation*
   Our approach for an external rate of return is based on a 4 percent real rate of return combined with a 5-year centered moving average growth rate of the consumer price index (CPI) obtained from OECD data (OECD, 2010):

$$i_t = 0.04 + \sum_{s=-2}^{s=+2} \Delta CPI_{t-s}. \tag{11}$$

   This specification drawn from Diewert (2001) does not lead to industry-specific rates of return.

Our second focus lies on the sensitivity of growth accounting results to different ICT investment price indices $p_{k,j,t}$. They appear in equations (7), (8), and (10) of the growth accounting setting. Again we first consider the values from EU KLEMS. As alternative measures we introduce two economy-wide price indices for IT, CT, and software investments, which are inspired by Oulton's (2012) calibration. Thus, we conduct growth accounting with three specifications:

1. The EU KLEMS industry-specific investment price index.
2. A constant decline in IT (20 percent), CT (5 percent), and software (4 percent) investment price indices plus the country-specific growth rate of the value added deflator.
3. A constant decline in IT, CT, and software investment price indices of 10 percent plus the country-specific growth rate of the value added deflator.

The constant values in specification 2 are obtained from the mean price changes for IT (information technology hardware), CT (communications technology equipment), and software investment relative to the mean change in the value added deflator in the U.S. for the period 1990–2007. In specification 3, the 10 percent decline is the growth rate of the combined ICT price index relative to the mean change in the value added deflator in the U.S.[6] In order to obtain ICT output and input measures consistently, we need to adjust output prices for ICT-producing industries in cases 2 and 3. We follow the method of Inklaar *et al.* (2005), who apply U.S. double-deflated value added deflators adjusted for differences in overall price levels:[7]

$$(12)\quad \Delta \ln VA\_P^{X}_{NACE\,30-33,t} = \Delta \ln \overline{VA\_P}^{US}_{NACE\,30-33} - \left(\Delta \ln VA\_P^{US}_{t} - \Delta \ln VA\_P^{X}_{t}\right)$$

where $\Delta \ln VA\_P^{X}_{NACE\,30-33,t}$ denotes the growth rate of the value added deflator of industries 30–33 and $\Delta \ln VA\_P^{X}_{t}$ the total economy growth rate of value added deflator in country *X*. $\Delta \ln \overline{VA\_P}^{US}_{NACE\,30-33}$ is the geometric mean of value added deflator growth rates in industry 30–33 in the U.S. The average decline is about 9 percent for the period 1990–2007.

The different specifications used for rates of return and ICT deflators in our simulations are summarized in Table 2.

In addition to the simulation with alternative ICT deflators, we decompose the contributions of ICT capital to labor productivity growth into changes in quantity, asset composition, and quality of ICT capital. This is related to the use of hedonic price indices, which control for differences in quality. The real IT, CT, and software capital stocks based on (non-hedonic) acquisition prices are calculated as follows:

$$(13)\quad S_{k,j,t} = \left(1-\delta_{k,j}\right) S_{k,j,t-1} + I_{k,j,t} / p_{NICT,j,t}$$

with $p_{NICT,j,t}$ being the investment price index of non-ICT capital goods. We assume that $p_{NICT,j,t}$ is a non-hedonic price index. With average price index growth rates between 1.2 percent (DE) and 4.3 percent (ES) for the period 1990–2007, this seems to be an appropriate assumption. Following approaches by Colecchia and Schreyer (2002) and Bassanini and Scarpetta (2002), the weights for the calculation of a combined ICT capital stock index are now based on assumed acquisition prices rather than on user costs as in equation (6):

$$(14)\quad z^{ICT}_{k,j,t} = \frac{p_{NICT,j,t} S_{k,j,t-1}}{\sum_{k \in ICT} p_{NICT,j,t} S_{k,j,t-1}}.$$

The industry-specific growth rate of non-hedonic ICT capital stock $\Delta \ln S^{ICT}_{j,t}$ (i.e., capital quantity) is therefore calculated as follows:

[6] The exact values are –0.20209, –0.0479, and –0.0374 for case 2, and –0.10165 for case 3, and are based on EU KLEMS data.

[7] Inklaar *et al.* (2005, p. 510), ICT output is defined as NACE revision 1.1 30–33.

TABLE 2

Specifications of Basic Model and Sensitivity Analysis

Variable	Basic Model (1)	Model with External Rate of Return (2)	Model with Constant Deflator for ICT (3)	Model with Constant Deflator for IT, CT, and Software (4)
Rate of return	Residual (internal) rate of return from EU KLEMS $i_{j,t} = \frac{CAP_{j,t} + \sum_k p^I_{k,j,t} - p^I_{k,j,t-1}A_{k,j,t} - \sum_k p^I_{k,j,t}\delta_{k,j}A_{k,j,t}}{\sum_k p_{k,j,t-1}A_{k,j,t}}$	$i_t = 0.04 + \sum_{s=-2}^{s=+2} \Delta CPI_{t-s}$	see column (1)	see column (1)
IT deflator	Deflators from EU KLEMS which are "harmonized" to U.S. deflators for AUT, ESP, ITA	see column (1)	$p_{IT,t} = -0.10 + \Delta \ln VA\_P_t$	$p_{IT,t} = -0.20 + \Delta \ln VA\_P_t$
CT deflator	Deflators from EU KLEMS which are "harmonized" to U.S. deflators for AUT and ESP	see column (1)	$p_{CT,t} = -0.10 + \Delta \ln VA\_P_t$	$p_{CT,t} = -0.05 + \Delta \ln VA\_P_t$
Software deflator	Deflators from EU KLEMS	see column (1)	$p_{SFT,t} = -0.10 + \Delta \ln VA\_P_t$	$p_{SFT,t} = -0.04 + \Delta \ln VA\_P_t$
Output NACE 30–33	from EU KLEMS	from EU KLEMS	$\Delta \ln VA\_P_{NACE\,30\text{–}33,t} = \Delta \ln \overline{VA\_P}^{US}_{NACE\,30\text{–}33} - (\Delta \ln VA\_P^{US}_t - \Delta \ln VA\_P_t)$	see column (3)

Notes: j indicates the industry and k the asset. All variables except those denoted by the superscript US are country-specific.

$$\Delta \ln S_{j,t}^{ICT} = \ln S_{j,t}^{ICT} - \ln S_{j,t-1}^{ICT} = \sum_{k \in ICT} \bar{z}_{k,j,t}^{ICT} \Delta \ln S_{k,j,t}. \tag{15}$$

In order to separate quality and compositional effects, we need to calculate industry-specific growth rates of quality-adjusted (hedonic) ICT capital stocks $\Delta \ln HS_{j,t}^{ICT}$:

$$\Delta \ln HS_{j,t}^{ICT} = \ln HS_{j,t}^{ICT} - \ln HS_{j,t-1}^{ICT} = \sum_{k \in ICT} \bar{b}_{k,j,t}^{ICT} \Delta \ln A_{k,j,t} \tag{16}$$

with $\Delta \ln A_{k,j,t}$ the productive stock of asset k based on quality-adjusted prices as defined in equation (8). In contrast to the growth rate of ICT capital services defined in equation (5), the aggregation to hedonic ICT capital stock is based on nominal asset shares $b_{k,j,t}^{ICT}$:

$$b_{k,j,t}^{ICT} = \frac{p_{k,j,t} A_{k,j,t-1}}{\sum_{k \in ICT} p_{k,j,t} A_{k,j,t-1}}. \tag{17}$$

The growth rate of ICT capital quality $\Delta \ln Q_{j,t}^{ICT}$ is derived as a residuum:

$$\Delta \ln Q_{j,t}^{ICT} = \Delta \ln HS_{j,t}^{ICT} - \Delta \ln S_{j,t}^{ICT}. \tag{18}$$

ICT capital quality is defined as the difference between the growth rate of ICT capital stock based on hedonic prices $\Delta \ln HS_{j,t}^{ICT}$ and the growth rate of ICT capital stock based on non-hedonic prices $\Delta \ln S_{j,t}^{ICT}$.

Changes in the composition of ICT capital $\Delta \ln C_{j,t}^{ICT}$ (i.e., changes in the share of different ICT assets) are again calculated as a residuum:

$$\Delta \ln C_{j,t}^{ICT} = \Delta \ln K_{j,t}^{ICT} - \Delta \ln HS_{j,t}^{ICT}. \tag{19}$$

This is the difference between the growth rate of ICT capital services $\Delta \ln K_{j,t}^{ICT}$ and the growth rate of quality adjusted ICT capital stock $\Delta \ln HS_{j,t}^{ICT}$. The sum of the growth rates $\Delta \ln S_{j,t}^{ICT}$ (ICT capital quantity), $\Delta \ln Q_{j,t}^{ICT}$ (ICT capital quality), and $\Delta \ln C_{j,t}^{ICT}$ (compositional change) equals the growth rate of ICT capital services.

3.3. *Properties of Rates of Return and Capital Prices in EU KLEMS*

To understand by which mechanisms our simulations affect the growth accounting results, it is useful to first look at some characteristics of the original EU KLEMS data. With the direct aggregation approach for growth accounting, we do not use rates of return and deflators at the level of the market economy but at the level of 26 industries for the computations. Looking at average rates of return at the level of the aggregate market economy during the periods of observation offers a summary picture of how our simulations change the rate of return (see Figure 1).

The internal rates of return are larger than the external rate that we specify based on Diewert (2001). The largest differences are found for Spain and the U.S., and in the period between 2000 and 2007. The average internal rates at the sectoral

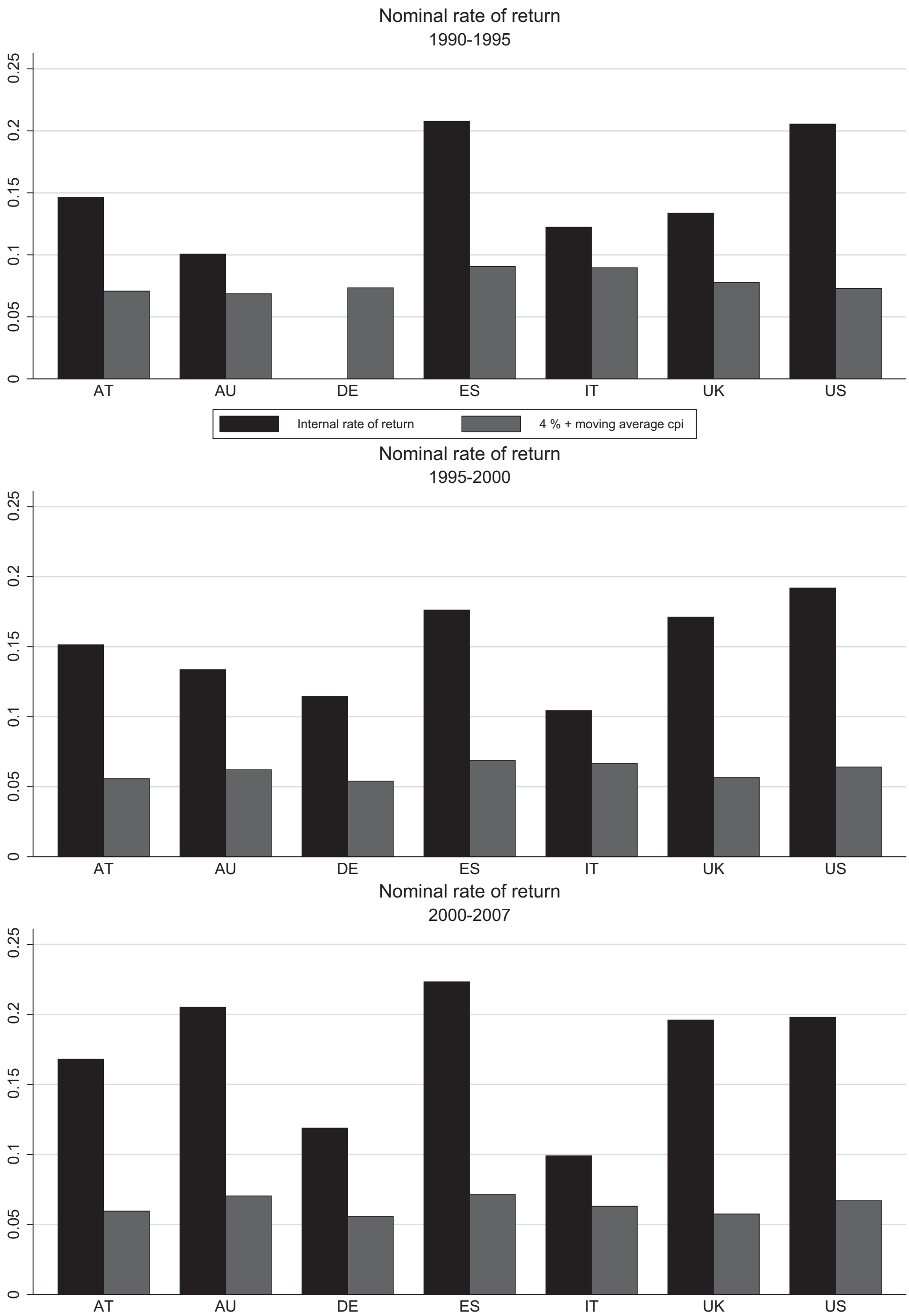

Figure 1. Different Methods of Measuring Rates of Return; Market Economy
Source: EU KLEMS, November 2009 release. Own calculations.

level within countries are generally not inconsistent from a theoretical point of view: less than 10 percent of the values observed are negative. This concerns most frequently the sector “transport equipment” (NACE rev. 1.1 34t35). As a country, Germany is most frequently concerned, one of the reasons being its low inflation rate. Negative rates of return do not necessarily lead to negative user cost, since the depreciation rate and the asset reevaluation terms enter in addition (see equation (7)). Moreover, user cost was adjusted in the EU KLEMS database in a way that it does not assume any negative values (EU KLEMS, 2007a). But even if negative values are excluded, high variation in rates of return may imply an implausibly high variation in output elasticities. To gauge this effect, we compute the standard deviation of the nominal rate of return within industries, taken over all countries and years. It lies between 7 and 14 percentage points for most industries, which is more than can be explained by differences in inflation. The highest standard deviation is observed in the real estate sector with 25 percentage points, followed by the business services and the financial intermediation sectors with 15 percentage points. The external rate of return used in our simulation implies that nominal rates of return only vary through inflation.

For ICT deflators, the EU KLEMS database pursues a mixed approach, using national deflators if they are quality-adjusted and deflators harmonized to U.S. values in other cases. National deflators are used for Australia, Germany, the U.K., and the U.S. (EU KLEMS, 2007b). For software they are also used in the other countries. For Austria and Spain, the IT and the CT deflator are harmonized to the U.S. deflator published by the BEA. For Italy, only the IT deflator is harmonized.[8]

Figure 2 compares the deflators observed in the database for three different periods to the constant decline of ICT prices that we assume in alternative specifications. We transform the constant decline in real terms (relative to the value added deflator) back into nominal terms in order to make values comparable to the deflators from the database. For hardware, the lower line represents the specific hardware deflator and the upper line represents the average ICT deflator. For communications equipment (CT) and software the upper line represents the specific deflator. The difference between our hypothetical deflator and the harmonized deflators is that the latter is not constant over time. Also it is taking into account U.S. price decline relative to the country’s non-ICT investment deflator, not relative to the value added deflator. For the U.S. and Austria, the EU KLEMS deflators are very similar for IT and CT. For Italy and Spain, the deflators are lower most of the time, indicating higher inflation for non-ICT investment goods. Among the national quality-adjusted deflators we focus on hardware, since the price decline is most important there and measurement problems are known to be more substantial for CT and software. For Australia, Germany and the U.K., the strongest decline in hardware prices is observed later than in the U.S. Both later

[8]To treat the input and output side consistently, we use adjusted output deflators (see equation (12)) for the sector NACE 30–33 in our simulations. Because the direct identification of the ICT hardware sector (NACE 30) is not possible in the data, we refrain from discussing the magnitude of the various national output deflators. Generally the adjustment in MFP growth will be overstated, since the ICT sector experiences unusually strong productivity growth and is relatively large in the U.S.

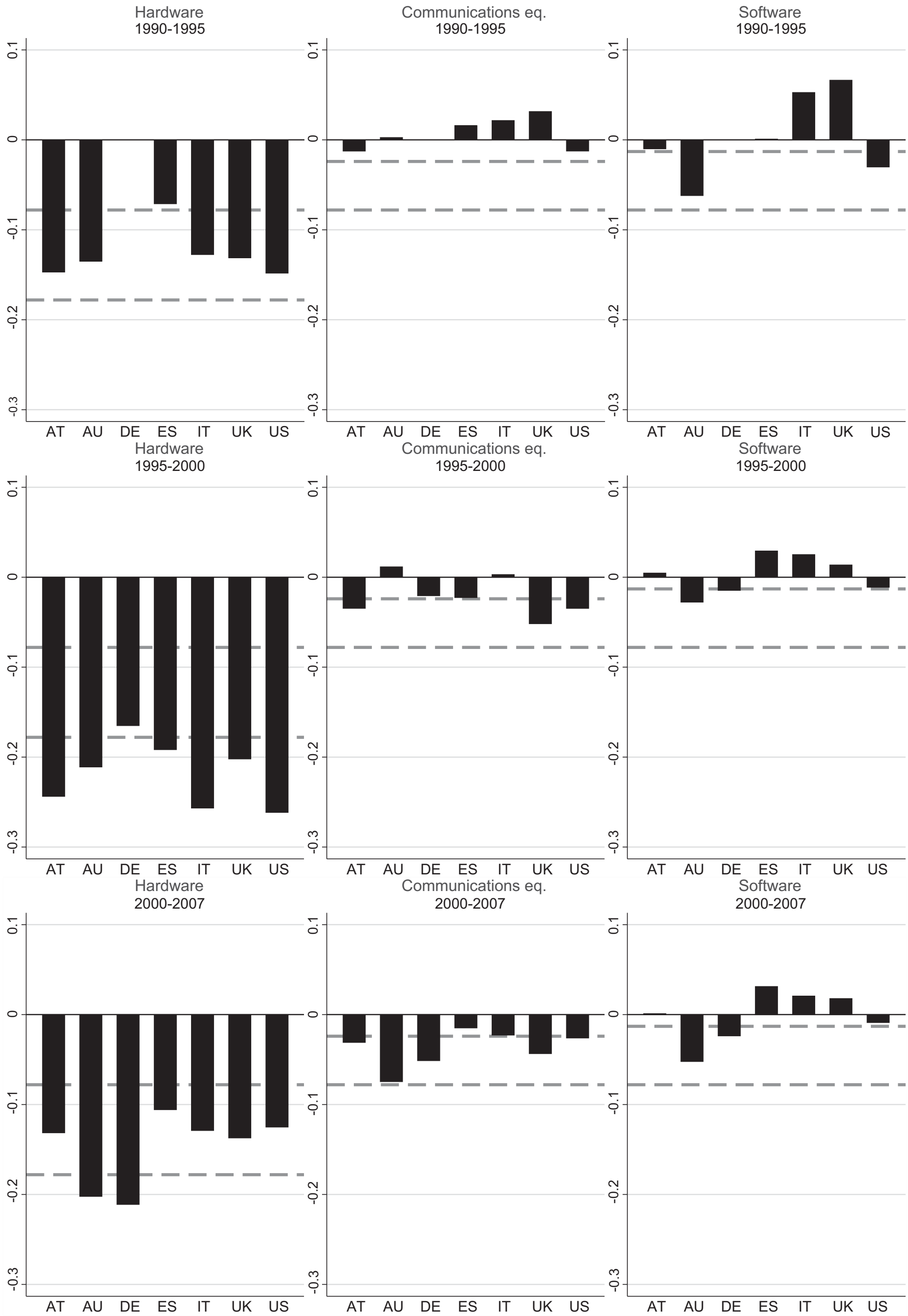

Figure 2. Different Assumptions on ICT Price Changes; Market Economy

Notes: Bars: average annual nominal ICT price decline from EU KLEMS, dashed lines: annual nominal ICT price decline in two alternative simulations.

Source: EU KLEMS, November 2009 release. Own calculations.

diffusion of powerful computers and changes in national methods used seem plausible explanations of this development. At least in Germany, the jump in the price decline after 2000 looks quite high, suggesting that it may not have been possible to backcast the new hardware deflator to a sufficient extent.[9] In Australia, the price decline for software is much stronger in all three periods than in the U.S. This also seems to result from differences in methods rather than from differences in the evolution of software quality.

4. Results

In this section, we discuss the growth accounting results under alternative rates of return and alternative investment prices as well as a breakdown of the ICT contribution into quality change, compositional change, and quantity change. We present diagrams with results at the level of the market economy for the periods 1990–95, 1995–2000, and 2000–07. An online appendix summarizes results for the goods producing sector and the market services sector.

4.1. *Different Rates of Return*

We compare growth accounting results with the EU KLEMS internal rate of return and an external real rate of return of 4 percent. The results show that with the external rate of return, the contribution of capital to labor productivity growth is lower in most cases. This is in line with the fact that the external rates of return are lower than the internal rates. The differences between both variants turn out to be higher for the contribution of non-ICT capital. For the ICT contribution, rates of return make less of a difference because its user cost is dominated by the decline in ICT prices. If we regard our sensitivity analysis as an exercise to gauge the size of potential measurement error, differences in the capital contribution of around 5 to 30 percent appear large (Figures 3–5). But they remain small in most cases when compared to the differences in growth of labor productivity and MFP across countries. For the period 1990–95, differences arising from the external rate of return are small at the level of the market economy in all countries except Spain and the U.S.

We observe the most visible effect during 1995–2000 in the U.S. and the U.K. (Figure 4). In this period, the decline in the capital contribution is also notable for ICT. In U.S. market services, the average decline in the contributions of ICT and non-ICT capital between 1995 and 2000 attains the same value of 0.18 percentage points (with, however, a higher overall level of the ICT contribution). With the external rate of return, MFP growth in U.S. and U.K. market services increases by

[9]Australia, Germany, and the U.K. introduced hedonic deflators for computers between 2003 and 2005. Australia had used an adjusted version of the U.S. deflator before, Germany a matched-model index, and the U.K. a cost-based method. Investment deflators for computer equipment are generally based on the producer price index and the import price index. For the U.S., information on producer prices is obtained from producer websites (BLS, 2011; BEA, 2014). For the other countries the number of producers of computer equipment that could be observed is too small and prices are taken mainly from wholesale or retail trade (Ball and Allen, 2003; ABS, 2005; Linz *et al.*, 2006).

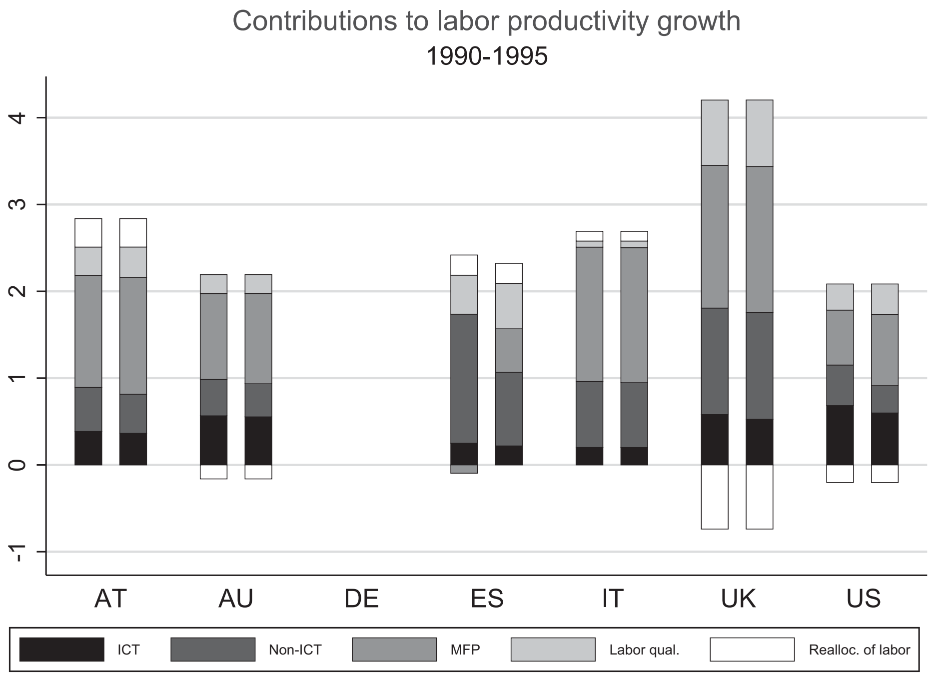

Figure 3. Contribution to Labor Productivity Growth for Different Rates of Return; Market Economy

Notes: Left bar: internal rate of return, right bar: 4% + moving average CPI growth rate.
Source: EU KLEMS, November 2009 release. Own calculations.

0.3 to 0.4 percentage points. A similar increase, but at a much lower overall level, can be observed in Italy. In Germany, negative MFP growth in market services nearly vanishes. In the other countries, the increase in market services MFP growth turns out to be lower (see online appendix). Looking at individual services industries (results not reported), we find that a broad range of services share the increase in MFP growth under the external rate of return in the U.K. Changes in MFP growth above 0.3 percentage points are observed in trade, hotels and restaurants, financial intermediation, and business services. In the U.S., large changes in services MFP growth are confined to financial intermediation and business services. In the business services sector of both countries, the ICT contribution to labor productivity growth declines by more than 0.4 percentage points with the external rate of return. Meanwhile, the level of the contribution remains high at more than 1.5 percentage points.

Taken at face-value, the results for 1995–2000 would attenuate the frequently emphasized switch from ICT-driven growth before 2000 to MFP-driven growth afterwards. The results from our specification attribute more of labor productivity growth in the U.K. and the U.S. between 1995 and 2000 to MFP growth. With the EU KLEMS internal rate of return, the ICT contribution exceeds the MFP contribution by more than 0.3 percentage points. With the 4

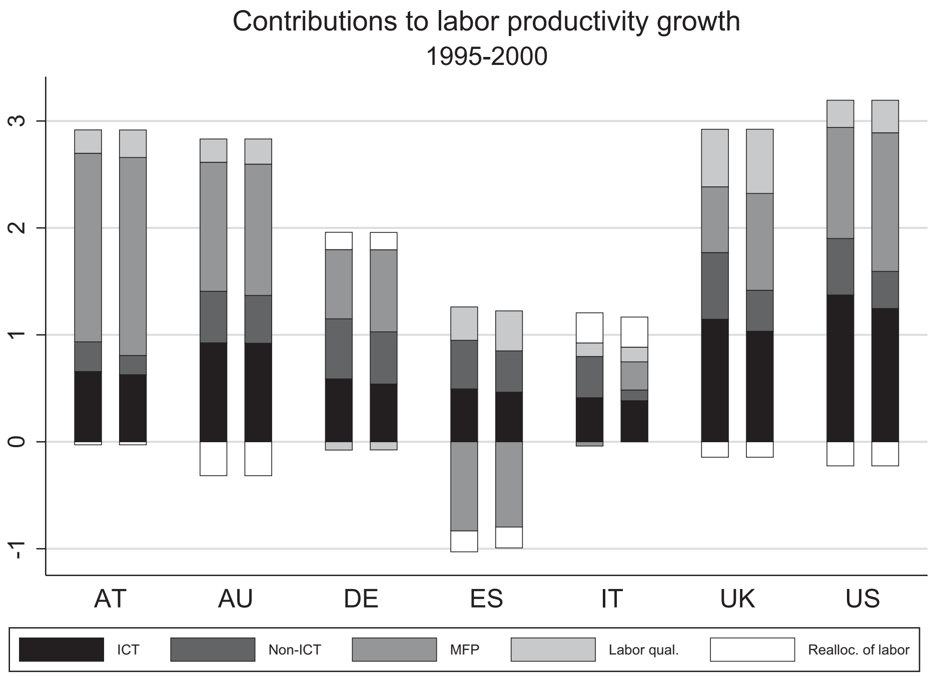

Figure 4. Contribution to Labor Productivity Growth for Different Rates of Return; Market Economy

Notes: Left bar: internal rate of return, right bar: 4% + moving average CPI growth rate.
Source: EU KLEMS, November 2009 release. Own calculations.

percent external rate of return, both contributions are of similar magnitude. In this context, higher MFP growth is fueled to a large extent by a decline in the non-ICT contribution.

During the period 2000–07, moving to an external rate of return does not have a notable effect on productivity contributions in the aggregate market economy (see Figure 5). The overall capital contribution is quite small and changes in the sensitivity analysis are also small in absolute value. Goods production in Australia, the U.K., and the U.S. experiences a relatively high effect. The overall change is highest in Italy and Spain, where internal rates of return are known to be implausible (Oulton and Rincon-Aznar, 2012). Sensitivity analysis with other rates of return (real 3 and 6 percent, average of short and long-term interest rate—results available upon request) shows that the impact of different rates on the capital contribution may be high relative to the contribution itself, but it is often small relative to aggregate labor productivity growth, especially before 1995 and after 2000.

4.2. *Different ICT Investment Prices*

We now consider the effect of replacing the ICT investment price indices from EU KLEMS with average U.S. values of price decline relative to the U.S. value

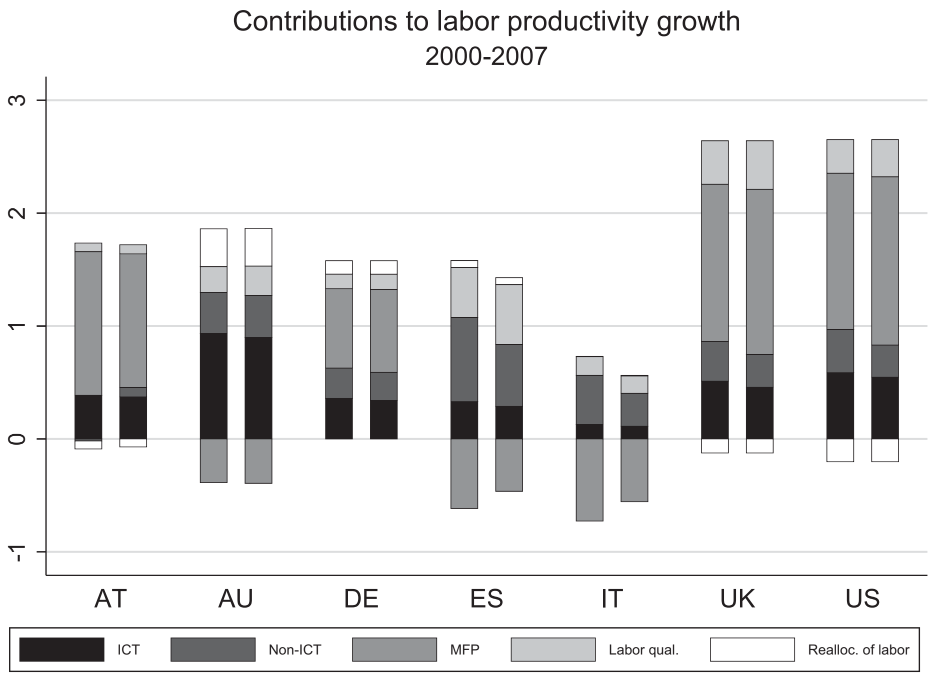

Figure 5. Contribution to Labor Productivity Growth for Different Rates of Return; Market Economy

Notes: Left bar: internal rate of return, right bar: 4% + moving average CPI growth rate.
Source: EU KLEMS, November 2009 release. Own calculations.

added deflator. We discuss two variants: the first introduces different price declines for IT hardware, software, and telecommunications equipment; the second applies a unique rate of price decline of 10 percent to all ICT capital goods. The aim of this sensitivity analysis is to eliminate differences in the ICT contributions that result solely from differences in price decline across countries and time, that is from presumed differences in embodied technical progress. When introducing a constant price decline to ICT inputs, we also introduce a constant price decline to the output of ICT production, which affects labor productivity.[10]

If average U.S. investment price decline implies stronger technical progress than price decline in a given country or period, our procedure will raise ICT contributions. On the other hand, if growth in ICT production is lower with national deflators, introducing average U.S. price decline will raise it and, ceteris paribus, raise MFP growth.

Our alternative specifications have first of all a time-specific effect. The U.S. price decline for hardware and communications equipment is strongest during

[10]The online appendix reports labor productivity with average U.S. price decline for the electrical and optical equipment sector corrected for the difference in inflation between the U.S. and the respective country.

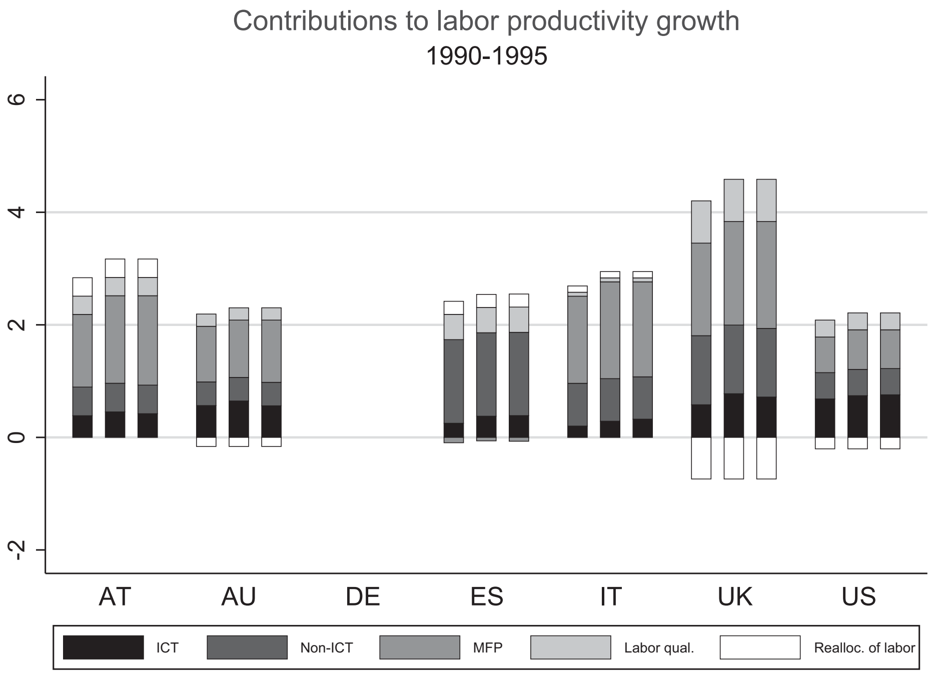

Figure 6. Contribution to Labor Productivity Growth for Different Investment Prices; Market Economy

Notes: Left bar: EU KLEMS investment prices, middle bar: −5% (CT), −20% (IT), −4% (Software) + GDP deflator, right bar: −10% + GDP deflator.
Source: EU KLEMS, November 2009 release. Own calculations.

1995–2000. In most other countries, the strongest price decline is also observed during this period. So using average U.S. deflators tends to increase ICT contributions before 1995 and after 2000, while it tends to decrease ICT contributions in the middle period. Some notable country differences discussed in Section 3.3 translate into changes in ICT contributions. The Australian ICT contribution decreases after 1995 using average U.S. price decline. The Spanish contribution increases in all three periods.

Turning now to effects in specific periods, we can see that the ICT contribution is overall relatively small during 1990–95. Even large changes in deflators like in Spain do not affect the ICT contribution substantially compared to the magnitude of labor productivity growth (Figure 6). The effect on MFP growth from changing the output deflator in the sector of electrical and optical equipment turns out to be higher than the effect on ICT contributions. However, the MFP effect is likely to be overstated.

During 1995–2000, introducing average U.S. price decline again has a high effect on labor productivity growth in the optical and electrical equipment sectors of all other countries. This effect mainly drives the observed increases in market sector MFP growth (Figure 7). In particular the large increase in German MFP growth from around 0.7 to over 1 percent in this and the following period has to

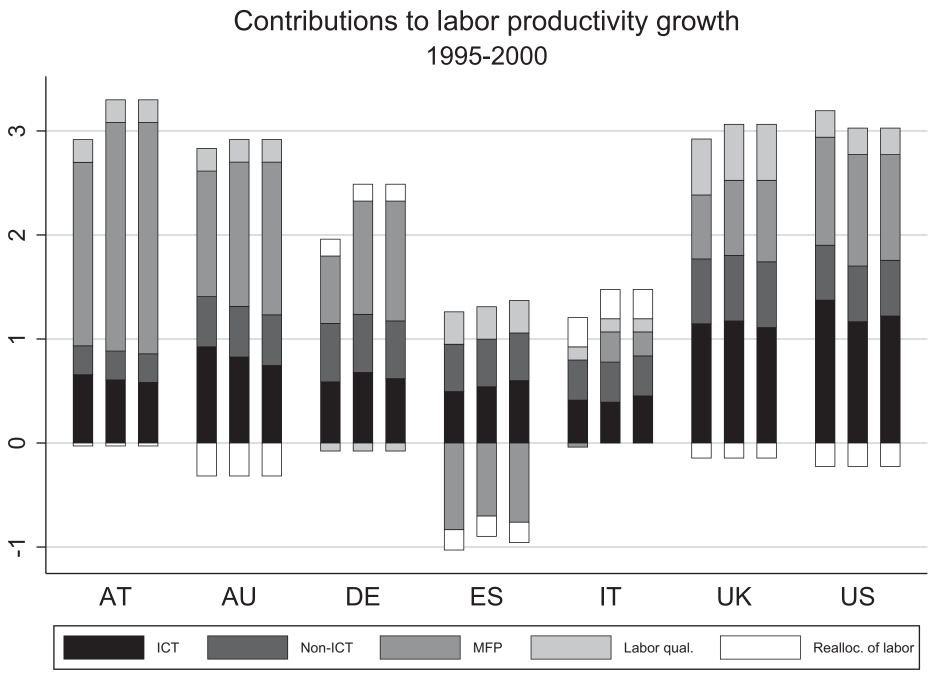

Figure 7. Contribution to Labor Productivity Growth for Different Investment Prices; Market Economy

Notes: Left bar: EU KLEMS investment prices, middle bar: −5% (CT), −20% (IT), −4% (Software) + GDP deflator, right bar: −10% + GDP deflator.
Source: EU KLEMS, November 2009 release. Own calculations.

be interpreted with caution. In the U.S. itself, the MFP effect in negative. Meanwhile, we observe little systematic change in the ICT contributions to labor productivity growth. One reason is that the combined effect of hardware, software, and communications technology price decline in this period is close to the average U.S. price decline (see Figure 2). In Australia and the U.S., we observe the strongest decline in ICT contributions. In Australia, changes in goods production and market services are of approximately equal size. In the U.S., the decline is mainly driven by market services (see online appendix).

During 2000–07, strong increases in labor productivity growth from adjusting deflators in the ICT sector are observed in Austria, Germany, and Italy (Figure 8), again most likely being overstated. These increases entail an increase in MFP growth, which is also observed at a more moderate scale in Australia, Spain, and the U.K. MFP growth in the U.S. market economy declines by 0.1 to 0.2 percentage points with the introduction of the averaged price deflators, since labor productivity growth remains nearly unchanged and the ICT contribution rises.

As the sensitivity analysis with different rates of return, the results with alternative investment deflators show a lower contribution of capital deepening to growth in the U.S. between 1995 and 2000 than the results from EU KLEMS data. Since, in addition, U.S. MFP growth turns out to be lower after 2000, the

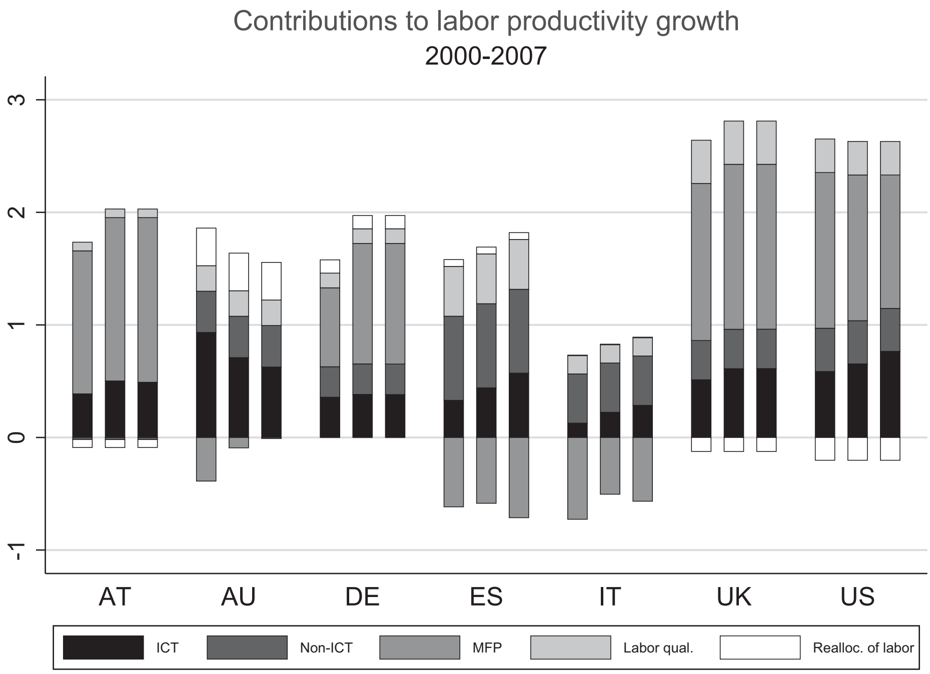

Figure 8. Contribution to Labor Productivity Growth for Different Investment Prices; Market Economy

Notes: Left bar: EU KLEMS investment prices, middle bar: −5% (CT), −20% (IT), −4% (Software) + GDP deflator, right bar: −10% + GDP deflator.
Source: EU KLEMS, November 2009 release. Own calculations.

alternative measures again reduce the contrast between ICT-based growth before 2000 and MFP-based growth afterwards. In both cases, the effect in market services plays an important role. However, the parallel between sensitivity analysis in rates of return and in investment prices only holds for the U.S., not for the U.K. It may be related to the fact that we use average U.S. price decline as a benchmark. The contribution of non-ICT is virtually unaffected by different ICT deflators. A few slight differences arise from changes in total capital income and thus in the income share of non-ICT capital.

Two remarks are at order concerning the potential effect of different price deflators on overall GDP, which is discussed in Schreyer (2002). We only look at market sector value added, which may, for example, be increased if a higher price decline is applied to ICT output. If the price decline for ICT imports also increases, this has a counteracting effect on GDP. Meanwhile for the ICT capital contribution the difference between national supply and imports does not matter in any fundamental way. Properly constructed national deflators should already be using information on both producer prices and import prices for ICT capital. A second effect counteracting output increase in the ICT sector is the increase in real intermediate input of ICT goods. Since we are using average value added deflators for our output adjustment, we should already observe the net effect.

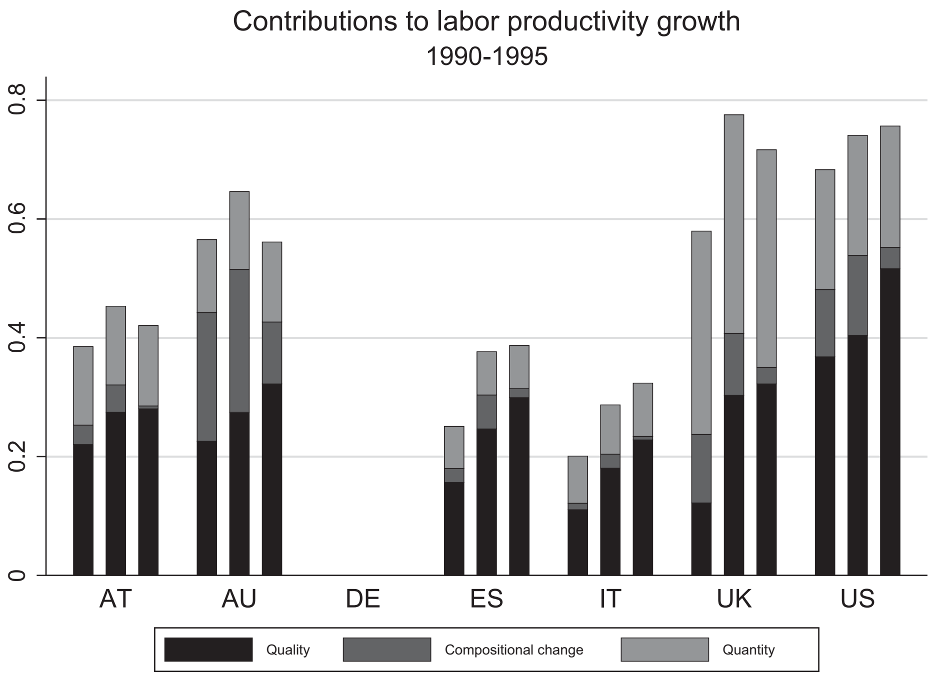

Figure 9. Contribution to Labor Productivity Growth by ICT Capital Quality, Composition, and Quantity; Market Economy

Notes: Left bar: EU KLEMS investment prices, middle bar: −5% (CT), −20% (IT), −4% (Software) + GDP deflator, right bar: −10% + GDP deflator.
Source: EU KLEMS, November 2009 release. Own calculations.

4.3. *Contributions of ICT Capital Quantity, Composition, and Quality*

In the previous section, we examined how alternative ICT deflators representing alternative rates of embodied technological progress affect the contribution of ICT and MFP to labor productivity growth. In this paragraph we make further use of the information contained in ICT deflators in order to break down the ICT contribution into embodied technological progress (quality change), compositional change, and quantity change. We do this for all three ICT deflators used.

The most striking observation in all periods is that the joint contribution of quality and compositional change tends to exceed the contribution of quantity by a factor of two or more (Figures 9–11). Some countries even experience a growth in ICT quantity close to zero while quality increases through the replacement of old capital (Austria, Germany, and Italy exhibit a contribution of quantity change close to zero in 2000–07, while the contribution of quality change lies around 0.2–0.3 percentage points.). Our results underline the importance of correctly reflecting the productive capacities of ICT in hedonic price measurement. The largest relative contributions of ICT quantity are measured in the U.K. and in the U.S. between 1990 and 2000. During 1995–2000, the overall ICT contribution in

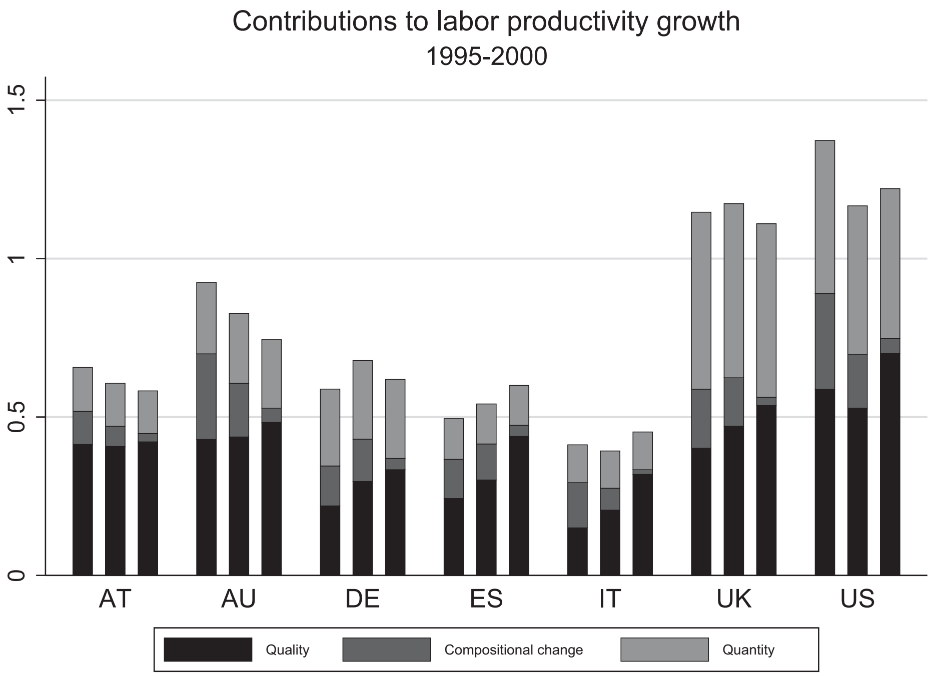

Figure 10. Contribution to Labor Productivity Growth by ICT Capital Quality, Composition, and Quantity; Market Economy

Notes: Left bar: EU KLEMS investment prices, middle bar: −5% (CT), −20% (IT), −4% (Software) + GDP deflator, right bar: −10% + GDP deflator.
Source: EU KLEMS, November 2009 release. Own calculations.

these countries was very high. During 1990–95, the contributions are similar to those observed in 2000–07. But in the latter period, the share of ICT quantity in the total contribution is much lower.

Moreover, we observe that constant price decline across the three ICT assets largely reduces compositional change, although it does not completely eliminate it (except in 2000 to 2007, where it virtually turns zero in the third variant considered). Compositional change turns out to be small compared to the other two components. This is not surprising, since we consider compositional change only within ICT capital. Still, there is a clear pattern with contributions ranging from 0.01 to 0.12 percentage points in the first period (with the exception of the high value observed in Australia), contributions from 0.10 to 0.30 percentage points during 1995–2000, and a decline to the range of 0.01 to 0.10 percentage points (again with an outlier in Australia) after 2000 (see online appendix). It is likely that the high values for 1995–2000 result from the decline in the share of traditional communication technology in total ICT capital. The movements of the ICT quality contributions across the three variants of deflators essentially reflect the changes in the overall ICT contribution discussed in the previous paragraph.

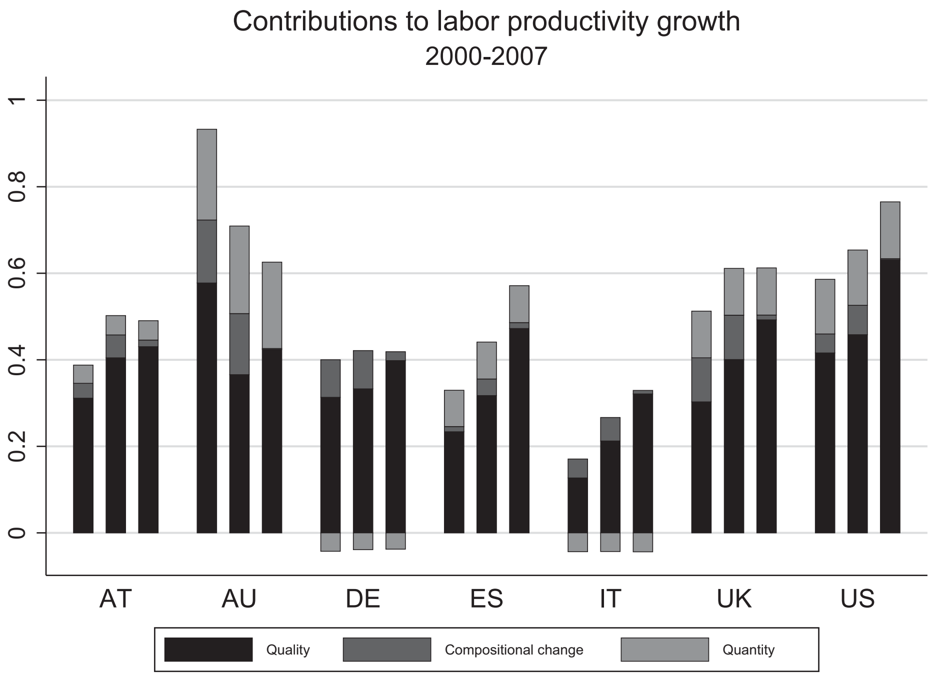

Figure 11. Contribution to Labor Productivity Growth by ICT Capital Quality, Composition, and Quantity; Market Economy

Notes: Left bar: EU KLEMS investment prices, middle bar: −5% (CT), −20% (IT), −4% (Software) + GDP deflator, right bar: −10% + GDP deflator.
Source: EU KLEMS, November 2009 release. Own calculations.

5. Conclusion

We have investigated the role rates of return, rates of ICT asset price decline, and changes in ICT quality play in explaining sources of productivity growth within a growth accounting framework. In order to conduct sensitivity analysis, we introduced a constant rate of return to capital and a constant rate of ICT price decline across sectors, countries, and time. The main result is that both alternative measurements somewhat downplay the importance of investment relative to growth in multifactor productivity in fast growing countries of our sample during 1995–2000. Different rates of return mainly affect the contribution of non-ICT capital since user cost of ICT capital is dominated by its price decline. In addition, we show that more than half of the ICT contribution results from growth in quality and change in composition rather than from growth in quantity.

The results point to the fact that between 1995 and 2000 a sizeable part of the conventionally measured capital contribution can be attributed to returns to capital and ICT price declines that exceed our benchmark values, rather than to the quantity of investment alone. On the other hand, the quality–quantity decomposition reveals that the relative influence of ICT quantity is high if the overall ICT contribution is high. One reason is that increases in the capital stock are larger and pure replacement of depreciated capital plays a lesser role in this case.

We think that external rates of return are useful to introduce at least as a robustness check in growth accounting, since observed differences in internal rates are not easily explained by plausible differences in marginal productivity. For some countries, like Spain, measurement problems have been noted before. For other countries, mismeasurement of capital stock could play a larger role. Recent research has shown that intangible investment that is not measured in national accounts is high in the U.S. and the U.K. (Corrado *et al.*, 2013). Overall, we find that the contributions to growth of non-ICT capital with different rates of return vary quite substantially when compared to their own magnitude but not when compared to total growth in labor productivity. The assumption of constant returns constrains this contribution. Potential spillovers from ICT and (unmeasured) intangible capital that could lead to increasing returns have been investigated in econometric estimation, but introducing them in growth accounting is not possible without strong ad hoc assumptions.

With regard to ICT deflators, our assumption of a time-invariant deflator is certainly not to be considered as a practical alternative. But the results show the importance of further promoting the standardization of ICT deflators at an international level. Some degree of harmonization to the U.S. deflators continues to represent a useful benchmark, though a deflator that also incorporates national information (such as the time lag relative to the U.S. in introducing new ICT) should be superior to simple variants of harmonized deflators. In addition, productivity effects of ICT may themselves occur with a time lag. The more the differences of productivity growth to be analyzed by growth accounting become fine-grained (an aspect also discussed by Erumban, 2008), the more it seems important to check the robustness of results with complementary, for example, econometric, methods.

The fact that both MFP growth in the ICT producing sector and quality change in ICT investment are driven by ICT prices and are important in magnitude underlines the importance of a multisector perspective in understanding embodied technical change. Finally we note that the distinction between capital deepening and MFP as distinct drivers of growth becomes less clear-cut if research progresses in the measurement of knowledge-based investment. Recent results by Corrado *et al.* (2013) show that accounting for a broader range of intangible assets (such as organizational capital and brand value) than those measured by national accounts generally reduces the importance of residual technical change in explaining productivity growth. Our results move the weights in the opposite direction, since they identify a large part of capital deepening as embodied technical change.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher’s web-site:

Table A.1: Contribution of ICT capital, non-ICT capital and MFP to labor productivity growth for different rates of return, period 1990–1995

Table A.2: Contribution of ICT capital, non-ICT capital and MFP to labor productivity growth for different rates of return, period 1995–2000

Table A.3: Contribution of ICT capital, non-ICT capital and MFP to labor productivity growth for different rates of return, period 2000–2007

Table A.4: Contribution of ICT capital, non-ICT capital and MFP to labor productivity growth for different investment prices, period 1990–1995

Table A.5: Contribution of ICT capital, non-ICT capital and MFP to labor productivity growth for different investment prices, period 1995–2000

Table A.6: Contribution of ICT capital, non-ICT capital and MFP to labor productivity growth for different investment prices, period 2000–2007

Table A.7: Contribution of ICT capital quality, composition and quantity to labor productivity growth for different investment prices, period 1990–1995

Table A.8: Contribution of ICT capital quality, composition and quantity to labor productivity growth for different investment prices, period 1995–2000

Table A.9: Contribution of ICT capital quality, composition and quantity to labor productivity growth for different investment prices, period 2000–2007

Table A.10: Sectoral contribution to market economy labor productivity growth for different investment prices, period 1990–1995

Table A.11: Sectoral contribution to market economy labor productivity growth for different investment prices, period 1995–2000

Table A.12: Sectoral contribution to market economy labor productivity growth for different investment prices, period 2000–2007