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Abstract

This paper studies the impact of the information and communication technologies (ICT) on U.S. economic growth using a dynamic general equilibrium approach. We use a production function with six different capital inputs, three of them corresponding to ICT assets and other three to non-ICT assets. We find that the technological change embedded in hardware equipment is the main leading non-neutral force of the U.S. productivity growth and accounts for about one quarter of it during the period 1980-2004. As a whole, ICT-specific technological change accounts for about 35% of total labor productivity growth.

JEL classification: E22, O30, O40.

Keywords: New economy, information and communication technologies, specific-technological change, neutral-technological change.

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1 Introduction

The U.S. has experienced a robust acceleration in its productivity growth rate during the 1990s in a context in which Information and Communications Technologies (ICT) investment have been very important. Jorgenson and Stiroh (2000) and Jorgenson (2001), among others, have related the increase in the U.S. productivity growth since the mid-1990s to the growth rate of investment in ICT and the rise in total factor productivity (TFP) growth, mainly in ICT-goods production sector. Oliner and Sichel (2000) and Baily and Lawrence (2001) have extended these positive effects to the non-ICT production sector of the U.S. economy.

However, in spite of the general view that ICT implies a new technological revolution, the measured impact of ICT on aggregate productivity has been very limited so far and their effects take long to become visible in the macro-economic aggregates. In this regard, the statement by Robert Solow is probably one of the most categorical: "You can see the computer age everywhere these days, except in the productivity statistics" (New York Times Book Review, July 12th 1987). Even for the successful cases, some papers have found that the positive impact of ICT on growth is not as straightforward as expected, but a number of issues appear as necessary conditions to be hold. For instance, according to Hornstein and Krusell (1996), an increase in the technological change can produce a temporary productivity slowdown given that average knowledge goes down because relatively more resources are allocated to the new capital (see also Greenwood and Yorukoglu, 1997, and Yorukoglu, 1998). Other papers have emphasized that the answer might be related to changes in new forms of organization at plant level which are required to obtain the full benefits from ICT (Samaniego, 2006). In fact, this historical episode has already taken place in other economies (see Kiley, 2001, for a survey). In general, many of them present the adoption of ICT as a technological revolution with substantial short-run negative effects until the new equipments have been completely adapted. The transitional dynamics from changes in technological progress lead to a slowdown in capital accumulation and thus in productivity during the transition period. According to this line of research, Pakko (2002a and b) using a model with stochastic growth trends, shows that changes in the growth rate of technological progress may not affect productivity contemporaneously, but with a lag.

In the literature we find two different approaches to study the effects of technological change on output and productivity growth. The first approach and the more widely used is the traditional growth accounting, in which output or productivity growth is decomposed in terms of the share-weighted growth in inputs. Examples of this approach are Jorgenson and Stiroh (2000), Oliner and Sichel (2000), Daveri (2002), Colecchia and Schreyer (2002), Jalava and Pohjola (2002) and Timmer and van Ark (2005), among others. The other approach use dynamic general equilibrium models to quantify the contribution to growth of specific-technological change. As pointed out by Cummins and Violante (2002), one disadvantage of traditional growth accounting is that it does not isolate the underlying sources of capital accumulation.

This paper studies the impact of ICT on the U.S. productivity growth using a computable dynamic general equilibrium model. Papers by Greenwood, Hercowitz and Krusell (1997, 2000), Kiley (2001), Pakko (2005) -all of them calibrated for the U. S. economy-, Carlaw and Kosempel (2004) for the Canadian economy, Bakhshi and Larsen (2005) for the U.K. economy and Martínez, Rodríguez and Torres (2008) for the Spanish economy, provide examples of this methodology applied to technological changes. Greenwood et al. (1997) for the period 1954-1990 obtained that neutral-technological change accounts for a 42% of total productivity growth, whereas the remaining 58% of productivity growth can be attributed to specific-technological change. Using a similar analysis for the U.K. economy, Bakhshi and Larsen (2005) obtained that specific technological change was around 20-30% of total labor productivity growth for the period 1976-1998. Both papers consider that capital is disaggregated into ICT and non-ICT assets, where specific-technological progress is solely motivated by the ICT capital. Finally, in analyzing the Spanish productivity slowdown during 1995-2004, Martínez et al. (2008), using an extended framework of that of Greenwood et al. (1997), find that despite of a rapid growth rates of ICT investment, specific technology growth in those assets is not providing much support for overall output growth in Spain. When the dynamics of productivity is decomposed into implicit and neutral technological progress, the former exerts a positive impact while the latter has a clear negative dominant effect. Behind the small contribution of implicit technological change, they find a modest negative impact coming from the traditional capital inputs, while communications and mainly hardware equipment appear as significant growth-enhancing assets.

This paper extends the work of Greenwood et al. (1997) for the U.S. economy where productivity is decomposed along the balanced growth path of the economy into investment-specific technological change and neutral technological progress. They distinguish between two types of capital: equipment and structures, where specific technological progress is only associated to equipment. On this basis, we use a more disaggregated production function with six capital assets, three of them corresponding to ICT assets (hardware, software and communications equipment) and three non-ICT capital goods (constructions and structures, machinery and transport equipment). Moreover, we consider the existence of investment-specific technological progress to all capital assets. Therefore, we split the labor productivity growth into seven factors: neutral technological change plus six-specific or embodied technological changes. These extensions are crucial because they provide a more appropriate measure of the sources of productivity growth. This way allows us studying the contribution to growth from ICT versus non-ICT capital assets.

On the basis of model calibration over the period 1980-2004, our main results show that ICT-specific technological change accounts for about 36% of total productivity growth, whereas non-ICT-specific technological change accounts for only 7% of total productivity growth. These results imply that neutral technological change accounts for a 57% of total labor productivity growth, whereas 43% of productivity growth can be attributed to specific technological change (*i.e.* 36% + 7%), most of them due to technological change embedded in hardware equipment. When the sample is spitted into two sub-periods, 1980-1995 and 1995-2004, we obtain that ICT contribution to productivity growth increases, whereas non-ICT contribution decreases. These results support the view of the increasing importance of ICT as a leading force of the U.S. productivity growth over the last years. We also find that TFP contribution is larger in the second subperiod. Therefore, the discrepancies in our findings with respect to those achieved by Greenwood et al. (1997) mainly reflect differences in the sample period. Provided that we use a more disaggregated portfolio than the one proposed by them, that decompose capital into structures and equipment, we check whether our results are due to this particular portfolio, and find that our results are fairly robust to the disaggregation.

The paper is organized as follows. Section 2 presents the theoretical model, in which six types of capital are considered, with the characterization of its balanced growth path. Section 3 shows the calibration exercise. Section 4 presents the results. Section 5 provides some additional evidence using different levels of aggregation of capital assets. Finally, Section 6 concludes.

2 The model

Following Greenwood et al. (1997) we use a neoclassical growth model in which two key elements are present: the existence of different types of capital and the presence of technological change specific to the production of capital. In particular, we use the extension of the model developed in Martínez et al. (2008), which incorporate two new features. First, while Greenwood et al. (1997) disaggregate capital assets in structures and equipment, we distinguish among six different types of capital inputs. This implies a larger disaggregation of capital inputs than the one used in previous similar works. Therefore, our production function relates output with seven inputs: L is labor in hours worked; K_1 constructions and non residential buildings; K_2 transport equipment; K_3 machinery and other equipment; K_4 hardware and other office equipment; K_5 software; and K_6 is communications equipment. The first three types of capital are grouped into non-ICT capital inputs, whereas the remaining three ones are ICT inputs.

Second, we consider the investment-specific technological change associated to each capital input. Denote Q_i as the price of asset i in terms of the amount of it which can be purchased by one unit of output. This price reflects the current state of technology for producing each asset. Greenwood et al. (1997) consider that this price is constant for structures, but is allowed to vary for equipment assets. Note that, according to this definition, equipment embodies both ICT and non-ICT inputs.

2.1 Household

The economy is inhabited by an infinitely lived, representative household who has time-separable preferences in terms of consumption of final goods, $\{C_t\}_{t=0}^{\infty}$, and leisure, $\{O_t\}_{t=0}^{\infty}$. Preferences are represented by the following utility function:

$$\sum_{t=0}^{\infty} \beta^t \left[\gamma \log C_t + (1-\gamma) \log O_t\right], \tag{1}$$

where β is the discount factor and $\gamma \in (0, 1)$ is the elasticity of substitution between consumption and leisure. Private consumption is denoted by C_t. Leisure is $O_t = N_t H - L_t$, where H is the number of effective hours in the year ($H = 96 \times 52 = 4992$), times population in the age of taking labor-leisure decisions (N_t), minus the aggregated number of hours worked a year

($L_t = N_t h_t$, with h_t representing annual hours worked per worker).

The budget constraint faced by the consumer says that consumption and investment cannot exceed the sum of labor and capital rental income net of taxes and lump-sum transfers:

$$(1+\tau^c) C_t + \sum_{i=1}^{6} I_{i,t} = \left(1-\tau^l\right) W_t L_t + \left(1-\tau^k\right) \sum_{i=1}^{6} R_{i,t} K_{i,t} + T_t, \tag{2}$$

where $I_t = \sum_{i=1}^{6} I_{i,t}$ is total investment in the six types of capital, T_t is the transfer received by consumers from the government, W_t is the wage, $R_{i,t}$ is the rental price of asset type i, and τ^c, τ^l, τ^k, are the consumption tax, the labor income tax and the capital income tax, respectively. Note that capital income has six components, each of them with a different rental rate, $R_{i,t}$.

A key point of the model is that capital holdings evolve according to:

$$\{K_{i,t+1} = (1-\delta_i) K_{i,t} + Q_{i,t} I_{i,t}\}_{i=1}^{6}, \tag{3}$$

where δ_i is the depreciation rate of asset i. Following Greenwood et al. (1997), $Q_{i,t}$ determines the amount of asset i than can be purchased by one unit of output, representing the current state of technology for producing capital i. In the standard neoclassical one-sector growth model $Q_{i,t} = 1$ for all t, that is, the amount of capital that can be purchased from one unit of final output is constant. Greenwood et al. (1997) consider that structures can be produced from final output on a one-to-one basis but equipment are subject to investment-specific technological change. However, in our model, $Q_{i,t}$ may increase or decrease over time, representing technological change specific to the production of each capital. In fact, an increase in $Q_{i,t}$ lowers the average cost of producing investment goods in units of final good.

The problem faced by the consumer is to choose C_t, O_t, and I_t to maximize the expected utility (1), subject to the budget constraint (2) and the law of motion (3), given taxes $\left\{\tau^c, \tau^k, \tau^l\right\}$ and the initial conditions $\{K_{i,0}\}_{i=1}^{6}$.

2.2 Firms

The problem of firms is to find optimal values for the utilization of labor and the different types of capital. The production of final output Y requires the services of labor L and six types of capital K_i, $i = 1, ...6$. The firms rent capital and employ labor in order to maximize profits at period t, taking factor prices as given. The technology is given by a constant return to scale Cobb-Douglas production function,

$$Y_t = A_t L_t^{\alpha_L} \prod_{i=1}^{6} K_{i,t}^{\alpha_i}, \tag{4}$$

where A_t is a measure of total-factor, or sector-neutral, productivity and where $\{0 \leq \alpha_i \leq 1\}_{i=1}^{6}$, $\sum_{i=1}^{6} \alpha_i \leq 1$, and $\alpha_L = 1 - \sum_{i=1}^{6} \alpha_i$. Final output can be used for seven purposes: consumption or investment in six types of capital,

$$Y_t = C_t + \sum_{i=1}^{6} I_{i,t}, \tag{5}$$

where both output and investment are measured in units of consumption.

2.3 Government

Finally, we consider the existence of a tax-levying government in order to take into account the effects of taxation on capital accumulation. For simplicity, we assume that the government balances its budget period-by-period by returning revenues from distortionary taxes to the agents via lump-sum transfers T_t. The government has no role in our model and obtains resources from the economy by taxing consumption and income from labor and capital. Consequently, the government budget constraint in each period is:

$$\tau^c C_t + \tau^l W_t L_t + \tau^k \sum_{i=1}^{6} R_{i,t} K_{i,t} = T_t. \tag{6}$$

2.4 Equilibrium

The first order conditions for the household are:

$$\begin{aligned} \gamma \frac{1}{C_t} - \lambda_t \left(1 + \tau^c\right) &= 0, &(7)\\ -\left(1-\gamma\right) \frac{1}{N_t \overline{H} - L_t} + \lambda_t \left(1 - \tau^l\right) W_t &= 0, &(8)\\ E_t \beta^t \lambda_{t+1} \left[\left(1 - \tau^k\right) R_{i,t+1} + \frac{(1-\delta_i)}{Q_{i,t+1}}\right] - \frac{\lambda_t}{Q_{i,t}} \beta^{t-1} &= 0, &(9) \end{aligned}$$

for each $i = 1, ...6$. λ_t is the Lagrange multiplier assigned to the constraint dated at t. Combining (7) and (8) we obtain the condition that equates the marginal rate of substitution between consumption and leisure to the opportunity cost of one additional unit of leisure:

$$\frac{1}{N_t\overline{H} - L_t} = \frac{\gamma}{(1-\gamma)} \frac{\left(1-\tau^l\right)}{(1+\tau^c)} \frac{W_t}{C_t}. \tag{10}$$

Equation (9) is a set of Euler equations that equate the marginal cost of additional capital with the expected return to the investment for each type of capital. Combining (7) with (9) yields:

$$\frac{1}{\beta} \frac{C_{t+1}}{C_t} = \left(1-\tau^k\right) Q_{i,t} R_{i,t+1} + (1-\delta_i) \frac{Q_{i,t}}{Q_{i,t+1}}. \tag{11}$$

Condition (11) implies that marginal rate of consumption equates the rates of return of the six investment assets.

The first order conditions for the firms profit maximization are given by

$$\left\{ R_{i,t} = \alpha_i \frac{A_t}{K_{i,t}} L_t^{\alpha_L} \prod_{i=1}^{6} K_{i,t}^{\alpha_i} = \alpha_i \frac{Y_t}{K_{i,t}} \right\}_{i=1}^{6}, \tag{12}$$

and

$$W_t = \alpha_L A_t L_t^{\alpha_L - 1} \prod_{i=1}^{6} K_{i,t}^{\alpha_i} = \alpha_L \frac{Y_t}{L_t}, \tag{13}$$

that is, the firms hire capital and labor such that the marginal contribution of these factors must equate their competitive rental prices.

Additionally, the economy satisfies the feasibility constraint:

$$C_t + \sum_{i=1}^{6} I_{i,t} = \sum_{i=1}^{6} R_{i,t} K_{i,t} + W_t L_t = Y_t. \tag{14}$$

First order conditions for the household (10) and (11), together with the first order conditions of the firm (12) and (13), the budget constraint of the government (6), and the feasibility constraint of the economy (14), characterize a competitive equilibrium for the economy.

2.5 The balanced growth path

Next, we define the balanced growth path, in which the steady state growth path of the model is an equilibrium satisfying the above conditions and where all variables grow at a constant rate. The balanced growth path requires that hours per worker must be constant. Given the assumption of no unemployment, this implies that total hours worked grow by the population growth rate, which is assumed to be zero.

According to the balanced growth path, output, consumption and investment must all grow at the same rate, which is denoted by g. However, the different types of capital would grow at a different rate depending on the evolution of their relative prices. From the production function (4) the balanced growth path implies that:

$$g = g_A \prod_{i=1}^{6} g_i^{\alpha_i}, \tag{15}$$

where g_A is the steady state exogenous growth of A_t. Let us denote g_i as the steady state growth rate of capital i. Then, from the law of motion (3), we have that the growth of each capital input is given by:

$$\{g_i = \eta_i g\}_{i=1}^{6}, \tag{16}$$

with η_i being the exogenous growth rate of $Q_{i,t}$. Therefore, the long run growth rate of output can be accounted for by neutral technological progress and by increases in the capital stock. In addition, expression (16) says that the capital stock growth also depends on technological progress in the process producing the different capital goods. Therefore, it is possible to express output growth as a function of the exogenous growth rates of production technologies as:

$$g = g_A^{1/\alpha_L} \prod_{i=1}^{6} \eta_i^{\alpha_i/\alpha_L}. \tag{17}$$

Expression (17) implies that output growth can be decomposed as the weighted sum of the TFP (neutral technological progress) growth and embedded technological progress, as given by $\{\eta_i\}_{i=1}^{6}$. Along the balanced growth path, growth rate of each capital asset can be different, depending on the relative price of new capital in terms of output. A particular capital asset with decreasing prices (specific technological progress) will display a growth rate higher than the output growth rate. On the contrary, capital assets whose relative prices increase, will grow over time at a lower rate than output.

On this basis, the following steady state ratios can be defined:

$$\rho_i \equiv \left(Q_i \frac{Y}{K_i}\right)_{ss} > 0, \tag{18}$$

$$s_i \equiv \left(\frac{I_i}{Y}\right)_{ss} \in (0,1), \tag{19}$$

$$c \equiv \left(\frac{C}{Y}\right)_{ss} \in (0,1), \tag{20}$$

$$v \equiv \left(\frac{L}{NH}\right)_{ss} = \left(\frac{h}{4992}\right)_{ss} \in (0,1), \tag{21}$$

where the subscript ss denotes its steady state reference.

The balanced growth path is finally characterized by the following set of equations:

$$\left\{\eta_i g = \beta\left[\left(1-\tau^k\right)\alpha_i \rho_i + 1 - \delta_i\right]\right\}_{i=1}^{6}, \tag{22}$$

$$\left\{\eta_i g = \rho_i s_i + 1 - \delta_i\right\}_{i=1}^{6}, \tag{23}$$

and

$$1 = c + \sum_{i=1}^{6} s_i, \tag{24}$$

$$1 = \alpha_L + \sum_{i=1}^{6} \alpha_i. \tag{25}$$

$$c = \alpha_L \frac{\gamma}{1-\gamma} \frac{1-\tau^l}{1+\tau^c}\left(\frac{1}{v} - 1\right). \tag{26}$$

3 Data and Calibration

Expressions from (22) to (26) define a system of fifteen equations, which is used in the calibration exercise. Values must now be assigned to the parameters of the model. These are two related to preferences, three for taxes and thirteen for technological parameters. The above system of fifteen equations expressions is solve for the fifteen unknowns $\left\{\{\alpha_i, \rho_i\}_{i=1}^{6}, c, \beta, \gamma\right\}$, given

$$\left\{\{\delta_i, s_i, \eta_i\}_{i=1}^{6}, \alpha_L, g, v, \tau^c, \tau^k, \tau^l\right\}.$$

Data on GDP, labor (employees and hours), capital assets, (real and nominal) investment series, and cost shares are taken from the Database of Groningen Growth and Development Centre (GGDC). Prices $\{Q_i\}_{i=1}^{6}$ are calculated as:

$$Q_i = CPI \times \frac{\text{Real investment in asset } i}{\text{Nominal investment in asset } i}, \tag{27}$$

where CPI is the consumption price index (line 111.64 of IMF-IFS). This represents the amount of asset i that can be purchased by one unit of the consumption good. The first column in Table 1 reports the changes in average price of the six assets, $\eta_i = \frac{1}{T}\sum_{t=1}^{T} Q_{it}/Q_{it-1}$, for observations from 1980 until 2004. While implicit technological change from the non ICT assets is apparently negligible across the period, i.e. $\{\eta_i \simeq 1\}_{i=1}^{3}$, price changes are considerable for the ICT inputs. The amount of hardware equipment that can be traded by one unit of output has increased by 16% per year. This increase is over 3% per year for communication equipment and software. Implicit technological change, as measured by the evolution of Q_i, seems to be specific to the ICT equipment.

The depreciation rates $\{\delta_i\}_{i=1}^{6}$ have been computed as the ratio of investment resources devoted to depreciation over the gross capital stock, using the GGDC data base. These estimates are shown in the second column of table 1. Structures depreciate by 2.8% a year. This rate represents the half of that assumed by Greenwood et al. (1997) of 5.6%. The rates of depreciation of ICT equipment are high. A brand new software license depreciates in about two years. This time length is four years for hardware equipment.

The third column of table 1, finally, reports the portfolio weights as averaged over 1980-2004, $\sum_{i=1}^{6}\omega_i = 1$. Note that three quarters of total investment is allocated on non ICT inputs, $\sum_{i=1}^{3}\omega_i = 0.7666$, precisely the assets where technological change is not embedded. We also assume a long run saving ratio of 0.17, and that the gross long run growth rate for productivity is $g = 1.0183$ (*i.e.* 1.83%).

From to the GGDC data base, the labor income share is set to $\alpha_L = 0.7060$ as averaged over 1980-2004, which coincides with that used by Greenwood et al. (1997) for data that spread over 1950-1990. Tax rates are borrowed from Boscá et al. (2005), who extend the methodology proposed by Mendoza et al. (1994) to estimate effective average tax rates for U.S. for the period 1964-2001. Average values over 1980-2001 are $\tau^c = 0.0465$, $\tau^l = 0.2300$ and $\tau^k = 0.3302$.

Table 1: Calibrated parameters values

Asset	Prices	Depreciation	Weights
Constructions and other structures	$\eta_1 = 1.0008$	$\delta_1 = 0.0278$	$\omega_1 = 0.361$
Machinery and other equipment	$\eta_2 = 1.0094$	$\delta_2 = 0.1302$	$\omega_2 = 0.295$
Transport equipment	$\eta_3 = 1.0075$	$\delta_3 = 0.1879$	$\omega_3 = 0.110$
Hardware and other office equipment	$\eta_4 = 1.1645$	$\delta_4 = 0.2417$	$\omega_4 = 0.086$
Software	$\eta_5 = 1.0380$	$\delta_5 = 0.1088$	$\omega_5 = 0.070$
Communication equipment	$\eta_6 = 1.0439$	$\delta_6 = 0.4188$	$\omega_6 = 0.076$

Finally, the remaining parameters will be determined through a calibration exercise, using the steady state representation of the first order conditions: $\{\alpha_i\}_{i=1}^{6}$ and $\{\beta, \gamma\}$.[1] Technology parameters are found as $\alpha_1 = 0.1167$, $\alpha_2 = 0.0823$, $\alpha_3 = 0.0305$, $\alpha_4 = 0.0233$, $\alpha_5 = 0.0205$, $\alpha_6 = 0.0198$, and preference parameters are found as $\beta = 0.9895$ and $\gamma = 0.4879$.

4 ICT contribution to productivity growth

Using the parameters calibrated in the above section, we proceed to study the quantitative importance of investment-specific technological change in explaining labor productivity growth in the U.S. over the period 1980-2004. The period is also spitted into two intervals, 1980-1994 and 1995-2004, in order to investigate possible changes in the contribution of the different factors over the sample period. Expression (17) allows us to identify the contribution to growth of these six capital assets embodied technological progress plus the contribution to growth from neutral technological change. The contribution to growth from each production factor technological progress and the contribution to growth from neutral-technological change have been calculated by assuming that the impact of remaining factors is zero (Greenwood et al., 1997).

[1] A more formal description of these conditions is available upon request to the authors.

Table 2 shows the estimated values of the calibration exercise, given the growth balance path. We present both the observed rate of labor productivity growth and the calibrated one, in order to see the accuracy of this exercise. While the actual observed average growth rate of productivity is 1.83%, our calibration reports a value of 2.06% a year for this variable. This slight difference between both growth rates comes from the fact that we calibrate the balanced path of the U.S. economy, which is unlikely to be the same than the actual one. This result indicates that over the period 1980-2004 the labor productivity in U.S. had grown at a lower rate than its long-run productivity growth rate.

The contribution to productivity growth of neutral-technological change is larger than that of the specific-technological change. With only neutral (TFP) technological change, output per hour worked would have grown at 1.17% per year whereas with only specific-technological change labor productivity would have grown at 0.89% per year. This result implies that about 57% of labor productivity growth over the period 1980-2004 was due to neutral-technological change, with specific-technological change providing the rest. This result contrasts with the one obtained by Greenwood et al. (1997), where productivity growth in the period 1954-1990 is dominated by specific-technological change, which accounts for about 60% of productivity growth, with neutral-technological change accounting for the rest. However, it is important to note that the sampled period used by Greenwood et al. (1997) is mainly governed by the total factor productivity slowdown since the early 1970s. In contrast, our sample period is characterized by an important recovery in TFP growth in the U.S. economy from the mid 1990s.

The effect of non-ICT technological change on output per hour worked is negligible, 0.16 percentage points, mainly due to the technological change embodied in machinery equipment (0.11 percentage points). The contribution of structures is zero, confirming the assumption of Greenwood et al. (1997) that structures are produced from final output on a one-to-one basis, evincing no specific technological progress. The contribution to productivity growth from transport equipment is also insignificant, merely 0.03 percentage points.

Results reported in Table 2 reveals the importance of ICT capital assets in explaining productivity growth for 1980 to 2004. With only ICT-specific technological change output per hour would have grown by 0.73% per year. Therefore, ICT technological change accounts for about 35% ($= 100 \times 0.73/2.06$) of total productivity growth during the period 1980-

2004. However, this ratio increases across the sample period. "Hardware" is the capital asset with the largest contribution. With only hardware technological change, output per hour would have grown at 0.50% per year, that is, technological change associated to hardware equipment contributes about a quarter of all productivity growth in the U.S. during this period.[2] Software contribution to productivity growth is around 0.10 percentage points whereas the contribution from communication equipment is 0.12 percentage points.

The last two rows in Table 2 compute how much of the technological progress is accounted for the neutral source and the implicit source. For the overall period, about 43% percent of technical progress is associated to the implicit change within these assets. These results sensibly contrast with that obtained by Greenwood et al. (1997), where the implicit change is 58% of labor productivity growth. Also, our result approaches to that of Bakhshi and Larsen (2005) for the U.K. economy, where implicit technological change ranges within an interval from 20% to 30%.

The larger average productivity growth in 1995-2004, compared to that of the period 1980-1994, was mainly due to neutral technological change, given that contribution from specific-technological change was fairly stable during both periods. In fact, specific-technological change contribution to productivity growth was 0.85 and 0.95 percentage points in both periods, respectively. Contrary, contribution from neutral-technological change was 0.74 percentage points in the first subperiod but 1.89 points in the second. Therefore, the larger labor productivity growth in the U.S. since the mid 1990s is mainly due to the recovery of the TFP growth.

The larger level of disaggregation used in this analysis reveals that the approximately constant contribution to productivity growth from capital deepening is due to the decreasing contribution from non-ICT assets and the increasing contribution from ICT assets. As we can observe, the contribution of non-ICT assets to productivity growth is close to zero in the period 1995-2004, from a value of 0.23 percentage points in the period 1980-2004. This change is mainly causes by the technical change embedded in structures, with a negative contribution to productivity growth in this second period. Overall, the contribution of specific-technological change increases in the second period thanks to ICT assets. Contribution to productivity growth from

[2] Jorgenson and Stiroh (2000) and Oliver and Sichel (2000) for the U.S. and Jalava and Pohjola (2002) for Finland, all of them using a traditional growth accounting approach, also find that the contribution from hardware was the highest of the ICT assets.

machinery and transport equipment through technological progress increases in the second period with respect to the first period.

Table 2: Productivity growth and sources of technological progress. U.S. economy, 1980-2004.

	1980-1994	1995-2004	1980-2004
Productivity growth			
Observed	1.41	2.52	1.83
Calibrated	1.59	2.84	2.06
Specific-technological change	**0.85**	**0.95**	**0.89**
Non-ICT	0.23	0.02	0.16
Structures	*0.13*	*-0.19*	*0.01*
Machinery equipment	*0.07*	*0.16*	*0.11*
Transport equipment	*0.02*	*0.04*	*0.03*
ICT	0.62	0.93	0.73
Hardware equipment	*0.39*	*0.68*	*0.50*
Software	*0.07*	*0.15*	*0.10*
Communications equipment	*0.14*	*0.09*	*0.12*
Neutral-technological change	**0.74**	**1.89**	**1.17**
Decomposition			
Specific	**53.5%**	**33.5%**	**43.2%**
Non-ICT	14.5%	0.7%	7.8%
ICT	39.0%	32.8%	35.4%
Neutral	**46.5%**	**66.5%**	**56.8%**

The contribution to productivity growth from ICT assets increases significantly from a value of 0.62 percentage points in the first period to a value of 0.93 percentage points in the second period. This implies that the importance of ICT capital assets as factors driving the productivity growth in the U.S. economy has increased from the mid 1990s.[3] As noted above, the larger contribution corresponds to hardware and other office equipment with a value of 0.39 percentage points in the first period and 0.68 percentage points in

[3] Jalava and Pohjola (2002) also obtain that the contribution to output growth from ICT in Finland has increased from 0.3 percentage points in the early 1990s to 0.7 points in the late 1990s.

the second. Interestingly, whereas the contribution of software also increases (from 0.07 to 0.15 percentage points), the contribution of communication equipment decreases (from 0.14 to 0.09 percentage points).

5 Robustness of the results

In order to check whether these results are robust to some calibrated values, we now perform a sensitivity analysis. There are important differences between our analysis and previous analysis in the literature using this methodology. First, we compute specific-technological progress to all capital assets. By contrast, for Greenwood et al. (1997) this type of technological change is only associated to equipment, assuming no specific-technological change in structures. In the contribution of Bakhshi and Larsen (2005) specific-technological change is only linked to ICT capital assets, on the basis that there is no specific-technological progress in the production of non-ICT capital assets.

The second important difference is the level of disaggregation of capital assets considered. One possible source of divergence of our results and those from Greenwood et al. (1997) can be due to the six-assets disaggregation we have implemented. Indeed, calibration of dynamic general equilibrium models use at most two assets. This the case of Greenwood et al. (1997), who distinguish between structures and equipment, and Bakhshi and Larsen (2005), with ICT and non-ICT capital assets.

Table 3 calibrates the model and compute contributions to productivity growth using three aggregated portfolios of physical assets: (1st) we only distinguish between structures and equipment as in Greenwood et al. (1997); (2nd) with three capital assets where equipment are disaggregated into ICT and non ICT equipment, while keeping structures as a third differentiated asset; and (3rd) with only two assets, ICT and non ICT assets (structures plus non-ICT equipment) as in Bakhshi and Larsen (2005). Importantly, these aggregations are calculated using the Törnqvist index that explicitly takes account into the variation in relative prices of assets. For all the cases, the aggregated capital stock and their implicit deflators are computed.

The results from these exercises are reported in Table 3. We present the evolution of the aggregated assets price in column η. Also, the calibrated Cobb-Douglas parameters are presented in column labeled as $\alpha-$shares. From Table 3, we would like to highlight the following results. First, productivity growth obtained in all the exercise is very similar to the previous calibration value, except for the 1st aggregation (only two assets: structures and equipment) where the calibrated productivity growth is 2.24%.

Second, the contribution of structures from the first and the second aggregations is very similar, 0.02 percentage points, consistent with the contribution obtained in the previous analysis. This implies that structures accounts for about 0.7% of productivity growth, indicating a technological progress of this assets close to zero. By contrast, using the first aggregation equipment accounts for about 40% of productivity growth. In fact, all aggregations are robust to our previous result that specific-technological change ranges within a narrow interval $[40\%, 43\%]$.

The third aggregation is similar to the one used by Bakhshi and Larsen (2005) for the U.K. over the period 1976-1998. While Bakhshi and Larsen (2005) allow specific-technological progress only in ICT capital assets, in our case, we do not restrict limit technological progress the ICT assets. However, we obtain that non-ICT specific-technological change contribution to productivity growth is only 0.17 percentage points, that is, only explains about 8% of productivity growth in the U.S. This result confirms the previous findings that traditional (non-ICT) capital assets show very limited specific-technological progress.

Therefore, the results derived from our analysis are very robust to the level of disaggregation in the capital assets. This implies that our level of disaggregation is more informative than those of previous approaches. In fact, this allows to study the contribution of different capital assets to productivity growth in a more detailed way, without suffering biases in the estimates of the impact of technological progress.

Table 3. Robustness check and portfolio aggregation, 1980-2004

	η	α-shares	Contribution	Percentage
	1^{st} aggregation			
	η	α-shares	Contribution	Percentage
Structures (a_1)	*1.0010*	*0.1167*	*0.02%*	*0.7%*
Equipment (a_2)	*1.0359*	*0.1773*	*0.89%*	*39.7%*
Specific-technological change $(a_3) = (a_1) + (a_2)$			0.91%	40.4%
Neutral-technological change (a_4)			1.33%	59.6%
Calibrated productivity growth $(a_3) + (a_4)$			2.24%	100%
	2^{nd} aggregation			
	η	α-shares	Contribution	Percentage
Structures (b_1)	*1.0010*	*0.1167*	*0.02%*	*0.8%*
Non-ICT Equipment (b_2)	*1.0090*	*0.1135*	*0.14%*	*6.9%*
ICT Equipment (b_3)	*1.0836*	*0.0638*	*0.73%*	*34.8%*
Specific-technological change $(b_4) = (b_1) + (b_2) + (b_3)$			0.89%	42.5%
Neutral-technological change (b_5)			1.20%	57.5%
Calibrated productivity growth $(b_4) + (b_5)$			2.09%	100%
	3^{rd} aggregation			
	η	α-shares	Contribution	Percentage
Non-ICT Assets (c_1)	*1.0054*	*0.2302*	*0.17%*	*8.3%*
ICT Assets (c_2)	*1.0836*	*0.0638*	*0.73%*	*34.7%*
Specific-technological change $(c_3) = (c_1) + (c_2)$			0.90%	43.0%
Neutral-technological change (c_4)			1.20%	57.0%
Calibrated productivity growth $(c_3) + (c_4)$			2.10%	100%

6 Conclusions

This paper has studied the importance of investment-specific technological change in explaining the U.S. productivity growth during the period 1980-2004. Capital inputs are disaggregated into six capital assets, in line with current typologies that distinguish between ICT and non-ICT inputs. This asset structure allows us to decompose the sources of productivity growth into a richer and more informative framework than previous studies do, also using dynamic general equilibrium model. We conclude that the contribution of the three non-ICT capital assets to productivity growth is close to zero. The contribution of "constructions and non residential buildings" is negative during the period 1995-2004 while the effect of the other two non-ICT assets is still positive but weak.

Specific–technological change in the U.S. economy over the period 1980-2004 is mainly due to technological progress embedded in ICT capital assets. While the contribution of ICT specific-technological change to productivity growth is about 0.73 percentage points, that of non-ICT capital assets is only 0.16 percentage points. More interestingly, whereas the contribution of ICT is increasing from the mid 1990s, the contribution of non-ICT capital inputs is decreasing.

By contrast, neutral-technological change is the main productivity growth force during the period. When this period is splitted, 1980-1994 and 1995-2004, we also find that TFP contribution is larger in the second subperiod. This is explained by the recovery in TFP growth of the U.S. economy from the late 1990s onwards. These results imply that neutral technological change accounts for a 57% of total labor productivity growth. About 43% of productivity growth can be attributed to specific technological change, most of them due to technological change embedded in hardware equipment. Comparing the subperiods 1980-1995 and 1995-2004, we obtain that ICT contribution to productivity growth increases, whereas non-ICT contribution decreases. These results support the view interpreting the increasing importance of ICT assets as a leading force of the U.S. productivity growth over the last decade.

Finally, this disaggregation of capital stock reveals that hardware equipment account itself for an important fraction of both productivity growth and the implicit technological growth. Particularly, the contribution of hardware to the U.S. productivity growth is of 0.50 percentage points for the whole period (0.39 points during 1980-1994 and 0.68 points during 1995-2004). This result contrasts with that of Greenwood et al. (1997), where implicit technological change plays a more relevant role. However, the discrepancies in our findings with respect to those of Greenwood et al. (1997) mainly reflect differences in the sample period. With respect to this, we have checked that our results are robust to different criteria by considering dissagregation. In that sense, the approach we follow points out the importance of using this disaggregation schedule since it can provide a more precise insights on the sources of productivity growth.

A major implication can be derived from this paper, namely, ICT have heterogeneous effects on economic growth through different channels depending on the stage in the process of introduction and use of new technlogies in which the economy is. The case of U.S., a pioneering country in the massive use of ICT, is revealing. At a first stage, the main positive effect of ICT capital inputs comes from using new equipments linked to new technologies.

Moreover, as some papers have shown (Samaniego, 2006), it may be usual paying a price for being innovative in terms of adjustment costs and smaller (even negative) TFP growth. The magnitude of the new techological revolution may be so intense that high organizational costs may arise at level plant. As the time goes by, new equipments begin to provide significant productive services and, what is more important, allow a more efficient organization of inputs, that is, a higher growth of TFP.

References

[1] Bakhshi, H. and Larsen, J. (2005): ICT-specific technological progress in the United Kingdom. *Journal of Macroeconomics* 27, 648-669.

[2] Baily, M. and Gordon, R. (1998): The productivity slowdown, measurement issues, and the explosion of computer power, *Brookings Papers on Economic Activity*, 347-420.

[3] Boscá, J., García, J. and Taguas, D. (2005): La fiscalidad en la OCDE: 1965-2001, *Documento de Trabajo Ministerio de Economía y Hacienda*, D-2005-06.

[4] Colecchia, A. and Schreyer, P. (2002): ICT investment and economic growth in the 1990's: Is the United States a unique case? A comparative study of nine OECD countries, *Review of Economic Dynamics* 5, 408-442.

[5] Cummins, J.G. and Violante, G.L. (2002): Investment-specific technical change in the United States (1937-2000): Measurement and macroeconomic consequences, *Review of Economic Dynamics* 5, 243-284.

[6] Daveri, F. (2002): Information technology and growth in Europe, *Università di Parma.*

[7] Greenwood, J., Hercowitz, Z. and Krusell, P. (1997): Long-run implication of investment-specific technological change, *American Economic Review* 87, 342-362.

[8] Greenwood, J., Hercowitz, Z. and Krusell, P. (2000): The role of investment-specific technological change in the business cycle, *European Economic Review* 44, 91-115.

[9] Hornstein, A. and Krusell, P. (1996): Can technology improvements cause productivity slowdowns? *NBER Macroeconomics Annual* 1996, 209-259.

[10] Jalava, J. and Pohjola, M. (2002): Economic growth in the New Economy: evidence from advanced economies. *Information Economics and Policy* 14, 189-210.

[11] Jorgenson, D. W. (2001): Information Technology and the US Economy, *American Economic Review* 91(1), 1-32.

[12] Jorgenson, D. W. and Stiroh, K. J. (2000): Raising the Speed Limit: U.S. Economic Growth in the Information Age, *Brooking Papers on Economic Activity* 1, 125-211.

[13] Kiley, M. (2001): Computers and growth with frictions: aggregate and disaggregate evidence, *Carnegie-Rochester Conference Series on Public Policy* 55, 171-215.

[14] Martínez, D., Rodríguez, J. and Torres, J. L. (2008): The productivity paradox and the new economy: The Spanish case. Forthcoming in *Journal of Macroeconomics.*

[15] Mendoza, E., Razin, A. and Tesar, L. (1994): Effective tax rates in macroeconomics. Cross-country estimates of tax rates on factor incomes and consumption, *Journal of Monetary Economics* 34, 297-323.

[16] Oliner, S. and Sichel, D. (2000): The resurgence on growth in the late 1990s: Is information technology the story?, *Journal of Economic Perspectives* 14, 3-22.

[17] Pakko, M.R. (2002a): What happens when the technology growth trend changes? Transition dynamics, capital growth and the "new economy", *Review of Economic Dynamics* 5, 376-407.

[18] Pakko, M. R.(2002b): "Investment-Specific Technology Growth: Concepts and Recent Estimates" *Federal Reserve Bank of St. Louis Review* (November/December), 37-48.

[19] Pakko, M. R. (2005): Changing Technology Trends, Transition Dynamics, and Growth Accounting, *The B.E. Journal of Macroeconomics, Contributions* 5 (1), Article 12.

[20] Samaniego, R. M. (2006): Organizational capital, technology adoption and the productivity slowdown, *Journal of Monetary Economics* 53, 1555-1569.

[21] Stiroh, K. (2002): Information technology and U.S. productivity revival: What do the industry data say?, *American Economic Review* 92, 1559-1576.

[22] Timmer, M. and van Ark, B. (2005): Does information and communication technology drive EU-US productivity growth differentials?, *Oxford Economic Papers* 57, 693-716.

[23] Yorukoglu, M. (1998): The information technology productivity paradox, *Review of Economic Dynamics*, 1, 551-592.