Macroeconomic Dynamics, **16**, 2012, 133–150. Printed in the United States of America.
doi:10.1017/S1365100510000489

TECHNOLOGICAL SOURCES OF PRODUCTIVITY GROWTH IN GERMANY, JAPAN, AND THE UNITED STATES

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In this paper we use a dynamic general equilibrium growth model to quantify the contribution to productivity growth from different technological sources in the three leading economies of the world: Germany, Japan, and the United States. The sources of technology are classified into neutral progress and investment-specific progress. The latter can be split into two different types of equipment: information and communication technologies (ICT) and non-ICT equipment. We find that in the long run, neutral technological change is the main source of productivity growth in Germany and Japan. For the United States, the main source of productivity growth arises from investment-specific technological change, mainly associated with ICT. We also find that a non-negligible part of productivity growth in the three countries has been due to the technology specific to non-ICT equipment.

Keywords: Productivity Growth, Investment-Specific Progress, Neutral Progress, Information and Communication Technology

1. INTRODUCTION

In this paper we investigate the contribution of different sources of technology change to labor productivity growth in three leading economies, Germany, Japan and the United States, for the period 1977–2006 using a general equilibrium approach. Technological change is decomposed into two sources: (i) neutral change and (ii) investment-specific technical change. Whereas the former is associated with total factor productivity (TFP), the later is the amount of technology that

For helpful comments and suggestions, we are grateful to R. Armendáriz, A. Bongers, J.C. Conesa, S. Danthine, G. Fernández de Córdoba, M. Lindquist, A. Moro, J.J. Pérez, L. Puch, J. Steinberg, and participants at the Workshop on the New Economy, Málaga 2008. We thank G. Violante for providing us with a data set of quality-adjusted prices. Two anonymous referees and the editors offered very helpful comments and suggestions that improved the paper. Financial support from the Proyecto Excelencia Junta de Andalucía P07-SEJ-02479 is acknowledged. Address correspondence to: Jesús Rodríguez-López, Department of Economics, Universidad Pablo de Olavide, Ctra Utrera, 1, 41013 Sevilla, Spain; e-mail: jrodlop@upo.es.

can be acquired using one unit of a particular capital asset. The aim of the paper is twofold. First, we seek to quantify the contribution to labor productivity growth from the three sources of technological progress considered: neutral, ICT equipment (information and communication technologies), and non-ICT equipment technological change. Second, we want to study the differences between the technological sources of productivity growth in these countries.

Comparison of the technological progress in these countries is particularly interesting for several reasons. First, they are the three leading economies in the world and their dynamics are taken as a reference of the overall world economic moment. Second, economic performance has been different in each of these three countries, especially during the last decade: whereas the German economy experienced a slowdown during the nineties, the U.S. economy has seen a resurgence of productivity ever since, and Japan productivity growth has evolved within a more stable pattern. Third, it seems important to quantify the contribution of investment-specific technical change derived from the two types of equipment (ICT versus non-ICT), as the portfolio choice of assets differs from one country to another.

To carry out this exercise, we combine two databases, the EU KLEMS database and the quality-adjusted investment prices estimated by Gordon (1990) and extended by Cummins and Violante (2002) (henceforth, the GCV database). From EU KLEMS we download data on nominal output, hours worked, and nominal investment. The quality-adjusted prices of the GCV database serve to deflate the EU KLEMS investment series and to construct valid measures of investment-specific-technical change associated with both the ICT equipment and the non-ICT equipment. The GCV prices were estimated for the U.S. economy and we harmonize these deflators for Germany and Japan by applying the methodology proposed by Schreyer (2002). In fact, the EU KLEMS database uses Schreyer's methodology to quality-adjust the ICT investment using the corresponding National Income and Product Account (NIPA) prices. However, the non-ICT equipment are not quality-adjusted in the EU KLEMS database. This is a key contribution of this paper, as both investment in equipment will be adjusted in the three countries. It is worth noting that when only the ICT assets are subject to this adjustment, growth accounting exercises tend to overstress its importance as a factor behind the 1995 upsurge in U.S. productivity growth [see, for example, Jorgenson and Stiroh (2000); Collechia and Schreyer (2001)].

Our results show some important differences in performance among these economies. For the period under consideration, 1977–2006, we find that neutral technical change is the force that drives productivity in Germany and Japan, accounting for 74% and 57% of their growth, respectively. For the U.S. economy, productivity growth is mainly accounted for by the investment-specific technical change, whereas the neutral change has made a negative contribution during this period. The contribution to average productivity growth from investment-specific technical change is only 0.69 percentage points for Germany, whereas it is about 1.5 percentage points for Japan and the United States. A relevant finding of the paper is that the diversity in the capital portfolio composition is a relevant issue in explaining the productivity dynamics across countries. The ICT technological progress contribution to average productivity growth is only 0.39 percentage points for Germany, 0.96 percentage points for Japan and 0.88 percentage points for the United States.

When the period is split into 1977–1995 and 1995–2006, we find that the resurgence in U.S. productivity after 1995 was due to a recovery of the neutral progress. Yet the role of investment-specific technical change increased in Germany and the United States but decreased in Japan. Importantly, we find that this increase cannot be associated solely with the ICT equipment, as conventional wisdom does, given that there is an important fraction of productivity that was originated from the quality improvement and technical advances incorporated into the non-ICT equipment.

In the literature, we find two different approaches to identifying technological progress: (i) the standard growth accounting decomposition and (ii) the calibration of a general equilibrium model.[1] Whereas most previous works, for instance, Timmer and van Ark (2005), use the "growth accounting" approach, in this paper we use the alternative "general equilibrium" approach. Greenwood and Krusell (2007) show that traditional growth accounting and equilibrium growth accounting report very different findings concerning the empirical importance of investment-specific technological progress for the growth process, the second approach being preferred to the first one. The reason is that, whereas the use of a general equilibrium model can isolate technological progress from other sources of output growth as capital accumulation, traditional growth accounting cannot. Output growth derives from both technological progress and capital accumulation. Traditional growth accounting quantifies the importance of both components in growth as independent from each other. The problem is that capital accumulation is affected by technological progress. So, in reality, traditional growth accounting is not able to quantify the importance of technological change, given that it is not possible to know the proportion of capital accumulation due to technological progress. Only a fully articulated general equilibrium model can do that. Along the same lines as the arguments of Greenwood and Krusell (2007), Cummins and Violante (2002) pointed out that the main disadvantage of traditional or statistical growth accounting is that it does not isolate the underlying sources of capital accumulation. On the opposite site, Oulton (2007) claims that the general equilibrium growth model with embodied technological change is a particular case of Jorgenson's approach, where the concept of investment-specific technological change is closely related to the concept of total factor productivity, where TFP grows at different rates in a two-sector model.

The remainder of the paper is organized as follows. In the following section we present a theoretical dynamic general equilibrium growth model with embodied technological progress and a characterization of its balanced growth path. Section 3 presents a description of the data set and the calibration exercise. Section 4 estimates the contribution of each type of technological change to labor productivity growth in the long run. Finally, Section 5 summarizes and concludes.

2. THE MODEL

Following Greenwood et al. (1997), we use a dynamic general equilibrium neoclassical growth model in which two key elements are present: the existence of different types of capital and the presence of technical change specific to the capital equipment. We use a simplification of the model developed in Martínez et al. (2008), which distinguishes between non-ICT and ICT equipment capital assets. Output is therefore produced as a combination of four inputs: L is labor in hours worked; K_{str}, nonresidential structures; K_{nict}, non-ICT equipment; and K_{ict}, ICT equipment.

ICT equipment refers to hardware, software, and communication networks, and non-ICT equipment refers to machinery and transport equipment. We assume that the investment-specific technology can be embedded within both forms of equipment but not in structures. The distinction between non-ICT and ICT equipment is justified by the fact that investment-specific technology can vary widely from one asset to another.

2.1. Households

The economy is inhabited by an infinitely lived representative household that has time-separable preferences in terms of consumption of final goods and leisure. Preferences are represented by the utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t C_t^{\gamma} O_t^{1-\gamma}, \tag{1}$$

where β is the discount factor, E_0 is the conditional expectation operator at time 0, and $\gamma \in (0, 1)$ is the participation of consumption in total income. 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, times population in the age taking labor–leisure decisions (N_t), minus the aggregate number of hours worked per 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:

$$\begin{aligned}
&(1+\tau_c)\, C_t + I_{\text{str},t} + I_{\text{nict},t} + I_{\text{ict},t} \\
&\quad = T_t + (1-\tau_\ell)\, W_t L_t \\
&\qquad + (1-\tau_k)\,(R_{\text{str},t} K_{\text{str},t} + R_{\text{nict},t} K_{\text{nict},t} + R_{\text{ict},t} K_{\text{ict},t}),
\end{aligned} \tag{2}$$

where T_t is the transfer received by the 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.

Capital holdings evolve according to

$$K_{\text{nict},t+1} = (1-\delta_{\text{nict}})\, K_{\text{nict},t} + Q_{\text{nict},t} I_{\text{nict},t}, \tag{3}$$

$$K_{\text{ict},t+1} = (1-\delta_{\text{ict}})\, K_{\text{ict},t} + Q_{\text{ict},t} I_{\text{ict},t}, \tag{4}$$

$$K_{\text{str},t+1} = (1-\delta_{\text{str}})\, K_{\text{str},t} + I_{\text{str},t}, \tag{5}$$

where δ_i is the depreciation rate. $Q_{i,t}$ determines the amount of asset $i \in \{\text{nict, ict}\}$ that can be purchased by one unit of the consumption good, 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. In our model, $Q_{i,t}$ may increase or decrease over time depending on the type of capital we consider, representing technical change specific to the production of each form of capital. In fact, an increase in $Q_{i,t}$ lowers the average cost of producing investment goods in units of the final good. Notice that expression (5) for structures implies the standard assumption where there is no investment-specific technical change in structures.[2]

The investment-specific technical change is assumed to evolve according to

$$Q_{i,t} = \eta_i Q_{i,t-1} \tag{6}$$

for $i \in \{\text{nict, ict}\}$, where $\eta_i > 1$ is the technical growth rate specific to asset i.

The problem faced by the consumer is to choose a sequence

$$\{C_t, O_t, I_{\text{nict},t}, I_{\text{ict},t}, I_{\text{str},t}\}_{t=0}^{\infty}$$

to maximize the utility (1), subject to the budget constraints (2) and the laws of motion (3)–(5), given taxes $\{\tau_c, \tau_k, \tau_\ell\}$ and the initial conditions $K_{i,0}$, for $i \in \{\text{str, nict, ict}\}$.

2.2. Firms

The problem of the firm 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 from labor L and the services from three types of capital K_i, $i \in \{\text{str, nict, ict}\}$. The firm rents capital and employs 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,

$$Y_t = A_t L_t^{\alpha_L} K_{\text{str},t}^{\alpha_{\text{str}}} K_{\text{nict},t}^{\alpha_{\text{nict}}} K_{\text{ict},t}^{\alpha_{\text{ict}}}, \tag{7}$$

where A_t is total factor productivity, $0 \leq \alpha_i < 1$, $i \in \{\text{str, nict, ict}\}$, and

$$\alpha_{\text{str}} + \alpha_{\text{nict}} + \alpha_{\text{ict}} < 1,$$

$$\alpha_L + \alpha_{\text{str}} + \alpha_{\text{nict}} + \alpha_{\text{ict}} = 1.$$

Final output can be used for four purposes: consumption, or investment in three types of capital,

$$Y_t = C_t + I_{\text{str},t} + I_{\text{nict},t} + I_{\text{ict},t}. \tag{8}$$

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 the effects of taxation on capital accumulation into account. The government taxes consumption and income from labor and capital. 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:

$$\tau_c C_t + \tau_\ell W_t L_t + \tau_k (R_{\text{str},t} K_{\text{str},t} + R_{\text{nict},t} K_{\text{nict},t} + R_{\text{ict},t} K_{\text{ict},t}) = T_t. \tag{9}$$

2.4. Equilibrium

The following expressions summarize the first-order conditions for the consumer and the firm:

$$\frac{1-\gamma}{\gamma} \frac{C_t}{N_t H - L_t} = \frac{1-\tau_\ell}{1+\tau_c} W_t, \tag{10}$$

$$E_t \left[\frac{C_t}{C_{t+1}} \frac{Q_{\text{nict},t}}{Q_{\text{nict},t+1}} ((1-\tau_k)\, Q_{\text{nict},t+1} R_{\text{nict},t+1} + (1-\delta_{\text{nict}})) \right] = \frac{1}{\beta}, \tag{11}$$

$$E_t \left[\frac{C_t}{C_{t+1}} \frac{Q_{\text{ict},t}}{Q_{\text{ict},t+1}} ((1-\tau_k)\, Q_{\text{ict},t+1} R_{\text{ict},t+1} + (1-\delta_{\text{ict}})) \right] = \frac{1}{\beta}, \tag{12}$$

$$E_t \left[\frac{C_t}{C_{t+1}} ((1-\tau_k)\, R_{\text{str},t+1} + (1-\delta_{\text{str}})) \right] = \frac{1}{\beta}, \tag{13}$$

$$\alpha_i \frac{Y_t}{K_{i,t}} = R_{i,t}, \tag{14}$$

$$\alpha_L \frac{Y_t}{L_t} = W_t, \tag{15}$$

for $i \in \{\text{str}, \text{nict}, \text{ict}\}$. The condition (10) equates the marginal rate of substitution between consumption and leisure to the opportunity cost of one additional unit of leisure. The conditions (11)–(13) mean that the intertemporal marginal rate of consumption equates the after-tax rates of return of the three investment assets. Finally, conditions (14) and (15) mean that the firm hires capital and labor so that the marginal contribution of these factors equates their competitive rental prices.

Additionally, the economy satisfies the feasibility constraint

$$\begin{aligned} &C_t + I_{\text{str},t} + I_{\text{nict},t} + I_{\text{ict},t} \\ &\quad = R_{\text{str},t} K_{\text{str},t} + R_{\text{nict},t} K_{\text{nict},t} + R_{\text{ict},t} K_{\text{ict},t} + W_t L_t = Y_t. \end{aligned} \tag{16}$$

First-order conditions for the household, (10)–(13), together with first-order conditions for the firm, (14) and (15), the budget constraint of the government, (9), and the feasibility constraint of the economy, (16), characterize a competitive equilibrium for the economy.

2.5. The Balanced Growth Path

The steady state is an equilibrium satisfying the above conditions such that all variables grow at a constant rate. Assuming no unemployment, total hours worked grow at the population growth rate, which is assumed to be zero. 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 (7) the balanced growth path implies that

$$g = g_A g_{\mathrm{str}}^{\alpha_{\mathrm{str}}} g_{\mathrm{nict}}^{\alpha_{\mathrm{nict}}} g_{\mathrm{ict}}^{\alpha_{\mathrm{ict}}}, \tag{17}$$

where g_A is the steady state exogenous growth of A_t. Let us define g_i as the steady state growth rate of capital $i \in \{\mathrm{str}, \mathrm{nict}, \mathrm{ict}\}$. Then, from the laws of motion (3)–(5), we have that the growth of each capital input is given by

$$g_i = \eta_i g, \tag{18}$$

with $i \in \{\mathrm{nict}, \mathrm{ict}\}$ and $g_{\mathrm{str}} = g$, given the assumption of no specific technical progress for structures.

Therefore, the long-run growth rate of output can be accounted for by the neutral technical progress and by increases in the capital stock. In addition, expression (18) says that the capital stock growth also depends on the technology producing the capital goods. Therefore, it is possible to express output growth as a function of the exogenous growth rates of production technologies as

$$g = \underbrace{g_A^{1/\alpha_L}}_{\text{Neutral}} \times \underbrace{\eta_{\mathrm{nict}}^{\alpha_{\mathrm{nict}}/\alpha_L} \eta_{\mathrm{ict}}^{\alpha_{\mathrm{ict}}/\alpha_L}}_{\text{Investment-specific}}. \tag{19}$$

Expression (19) implies that output growth can be decomposed as a linear combination of the two progresses.

The following ratios should be stationary along the balanced growth path:

$$\frac{C}{Y}, \frac{I_{\mathrm{str}}}{Y}, \frac{I_{\mathrm{nict}}}{Y}, \frac{I_{\mathrm{ict}}}{Y}, \frac{Y}{K_{\mathrm{str}}}, \frac{Q_{\mathrm{nict}} Y}{K_{\mathrm{nict}}}, \frac{Q_{\mathrm{ict}} Y}{K_{\mathrm{ict}}}, \frac{L}{NH}, \tag{20}$$

where the time subscript has been suppressed for simplicity.

The balanced growth path can be characterized, from the intertemporal Euler equation, as

$$\frac{g}{\beta} = (1 - \tau_k)\, \alpha_{\mathrm{str}} \frac{Y}{K_{\mathrm{str}}} + 1 - \delta_{\mathrm{str}}, \tag{21}$$

$$\frac{g}{\beta} = \frac{1}{\eta_{\text{nict}}}\left[(1-\tau_k)\,\alpha_{\text{nict}}\frac{YQ_{\text{nict}}}{K_{\text{nict}}} + 1 - \delta_{\text{nict}}\right], \tag{22}$$

$$\frac{g}{\beta} = \frac{1}{\eta_{\text{ict}}}\left[(1-\tau_k)\,\alpha_{\text{ict}}\frac{YQ_{\text{ict}}}{K_{\text{ict}}} + 1 - \delta_{\text{ict}}\right], \tag{23}$$

from the law of motion of capital,

$$g = \left(\frac{Y}{K_{\text{str}}}\right)\left(\frac{I_{\text{str}}}{Y}\right) + 1 - \delta_{\text{str}}, \tag{24}$$

$$\eta_{\text{nict}}\, g = \left(\frac{YQ_{\text{nict}}}{K_{\text{nict}}}\right)\left(\frac{I_{\text{nict}}}{Y}\right) + 1 - \delta_{\text{nict}}, \tag{25}$$

$$\eta_{\text{ict}}\, g = \left(\frac{YQ_{\text{ict}}}{K_{\text{ict}}}\right)\left(\frac{I_{\text{ict}}}{Y}\right) + 1 - \delta_{\text{ict}}, \tag{26}$$

and

$$1 = \frac{C}{Y} + \frac{I_{\text{str}}}{Y} + \frac{I_{\text{nict}}}{Y} + \frac{I_{\text{ict}}}{Y}, \tag{27}$$

$$1 = \alpha_L + \alpha_{\text{str}} + \alpha_{\text{nict}} + \alpha_{\text{ict}}, \tag{28}$$

$$\frac{C}{Y} = \alpha_L \frac{\gamma}{1-\gamma}\frac{1-\tau_\ell}{1+\tau_c}\left[\left(\frac{L}{NH}\right)^{-1} - 1\right]. \tag{29}$$

3. DATA AND PARAMETERS

We combine data from the EU KLEMS database with the GCV quality-adjusted price of equipment for the United States. From the EU-KLEMS database,[3] we retrieve series of nominal output, nominal investment, compensation of inputs, and hours worked for Germany, Japan, and the United States, for 1977–2006. EU KLEMS disaggregates assets into seven categories: (i) structures, (ii) hardware and office equipment, (iii) communication equipment, (iv) software, (v) transport equipment, (vi) machinery, and (vii) other equipment. Note that categories (ii) through (iv) are classed as ICT assets, whereas categories (v) through (vii) are classed as non-ICT assets. The investment in residential structures is also provided by the EU KLEMS database, although it is not considered in our analysis.

For unified Germany, data are available from 1991 to 2006, and from 1970 to 1990 for West Germany. We backward recover the series of investment assets of Germany for 1977–1990 from the West German data.

Using a Törnqvist index, weighted by the BEA nominal investment shares, the GCV series of quality-adjusted investment prices are used to build U.S. deflators for the nominal investment series labeled in previous categories (ii) through (vii), i.e., for ICT equipment and for non-ICT equipment. For Germany and Japan, we obtain harmonized deflators for the EU KLEMS investment series using Schreyer's

TABLE 1. Investment-specific technical change by asset, United States 1977–2006

	77–06	77–80	80–90	90–00	00–06
All equipment	5.8	2.6	5.5	7.0	5.7
Non-ICT equipment	3.5	0.0	3.5	4.0	4.3
(i) Transport equipment	3.8	2.6	3.3	4.6	4.1
(ii) Machinery equipment	3.1	2.0	2.2	3.7	4.5
(iii) Other equipment	2.2	0.1	2.0	2.5	2.9
ICT equipment	10.9	14.0	10.6	12.3	7.7
(iv) Hardware equipment	19.1	30.1	15.6	22.1	14.3
(v) Communication equipment	12.4	17.6	9.0	13.8	13.2
(vi) Software	4.2	5.2	4.9	4.1	2.6

(2002) methodology.[4] A detailed explanation on how the different series have been aggregated can be found in the Technical Appendix of this paper. Structures are deflated using a price index for the consumption of nondurables and services less housing. This strategy is justified given that the EU KLEMS database *only* quality-adjusts series for the ICT assets using the corresponding NIPA prices and the Schreyer's harmonized deflator. Non-ICT series *are not* quality adjusted in the EU KLEMS database, so that their deflators cannot be used to measure the investment-specific technical change for those assets.

Using the GCV quality-adjusted investment prices, $q_{i,t}$, $i \in \{\text{nict}, \text{ict}\}$, the investment-specific technical change is proxied as $Q_{i,t} = PC_t/q_{i,t}$, where PC_t is the price index for the consumption of nondurables and services less housing. No investment-specific technological change is assumed for structures. Table 1 presents the average percentage change in the $Q'_{i,t}s$, for the United States using the GCV data set, i.e., the investment-specific technical change. The first row aggregates over all equipment (TIC and no-TIC). Across 1970–2006, the investment-specific change has been growing by 5% in the United States. This rate is decomposed into progress due to the non-ICT, 3%, and to the ICT equipment, 10.5%. The ICT assets are, by far, the most important contributors to this progress. However, an additional non-negligible source of the investment-specific change is also due to the non-ICT assets, using as measures quality-adjusted prices. In fact, the three considered assets of non-ICT equipment show an increasing role.[5]

The evolution of the levels of the $Q_{i,t}$'s is depicted in Figure 1 (base year 1995). The investment-specific technical change aggregated over the two types of equipment is also represented. The three lines show an upward trend, although the slope for the ICT is higher, according to the estimates of Table 1.

In Table 2 we calculate productivity according to our definition of output, which measures it in terms of the unit of consumption, which does not coincide with the measure provided by the EU KLEMS database due to the fall in the price for investment [see Whelan (2002)].[6] Table 2 presents average labor productivity growth rates for several periods. Labor is measured in hours worked. On average

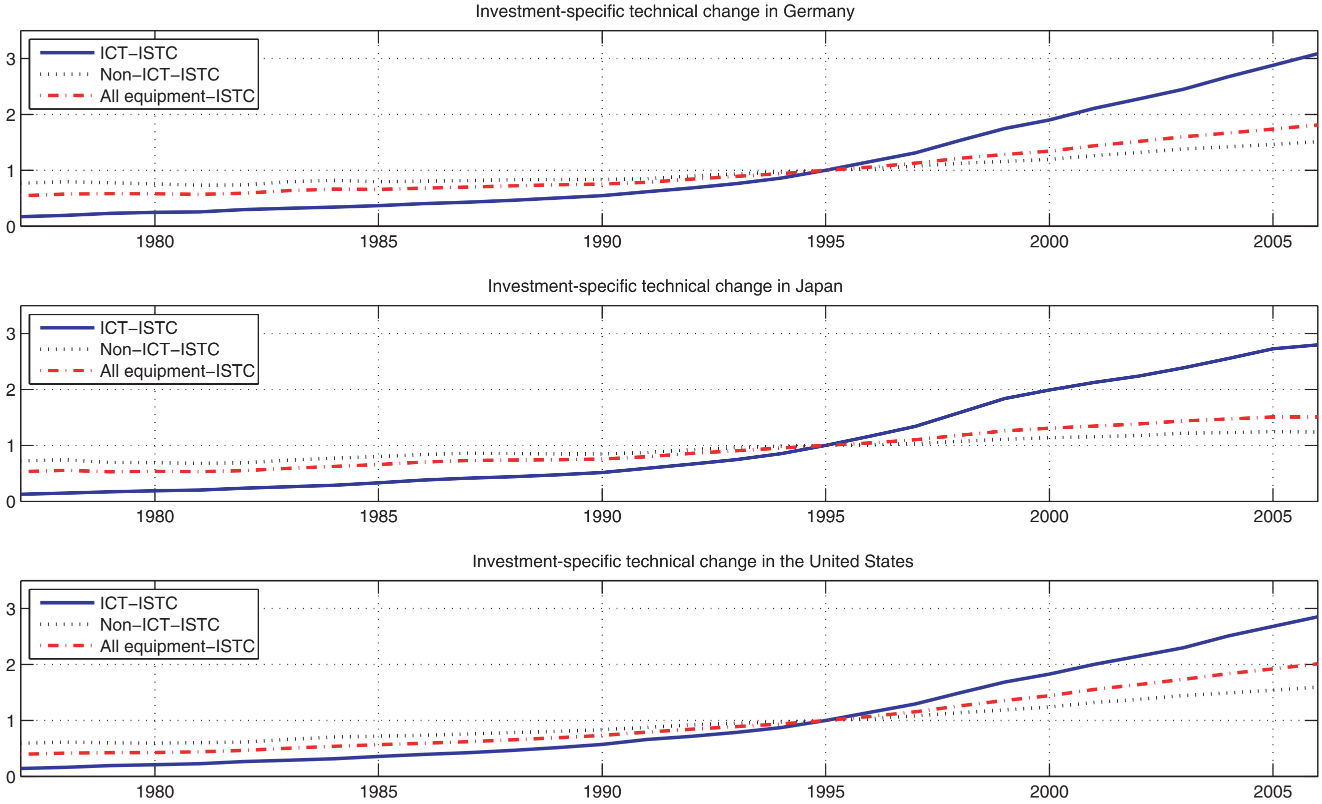

FIGURE 1. Investment-specific technological change, 1977–2006.

TABLE 2. Average productivity growth rates 1977–2006

	Germany	Japan	U.S.
1977–1980	3.54	4.46	−0.74
1980–1990	3.40	4.37	1.03
1990–2000	2.36	2.66	1.18
2000–2006	1.72	3.40	1.74
1977–2006	2.71	3.59	1.05

for the period 1977–2005, the Japanese economy evinces the highest productivity growth rate with 3.59%. This is followed by Germany with 2.71% and by the United States with 1.05%. The evolution of productivity over time has a different results: whereas it is (reasonably) stable for Japan, it is decreasing in Germany and increasing in the United States. The German growth rate during 2000–2006 is almost half as high as the growth rate during the eighties. The upsurge in U.S. productivity has been associated with the use of ICT assets [see Jorgenson and Stiroh (2000); or Jorgenson (2001)].

The calibration requires assigning values to the following set of parameters:

$$\left\{ g, \frac{L}{NH}, \alpha_L, \left\{ \delta_i, \frac{I_i}{Y}, \eta_i \right\}_{i\in\{\text{str},\text{nict},\text{ict}\}}, \tau_c, \tau_\ell, \tau_k \right\}. \tag{30}$$

Table 3 shows the selected values for these parameters. The first row presents figures for the gross productivity growth, g, backed by the results in Table 1. The

TABLE 3. Parameter values

	Germany	Japan	U.S.
g	1.0271	1.0359	1.0105
$L/(NH)$	0.2998	0.3530	0.3660
α_L	0.7848	0.6335	0.7003
δ_{str}	0.0240	0.0240	0.0240
δ_{nict}	0.1183	0.1116	0.1176
δ_{ict}	0.1448	0.1475	0.1566
s_{str}	0.0533	0.0673	0.0495
s_{nict}	0.0656	0.1016	0.0549
s_{ict}	0.0205	0.0309	0.0374
η_{nict}	1.0239	1.0191	1.0349
η_{ict}	1.1060	1.1140	1.1096
τ_c	0.1130	0.0510	0.0470
τ_ℓ	0.3390	0.2510	0.2300
τ_k	0.2420	0.3850	0.3300

model will be calibrated to ensure that labor productivity growth exactly matches our estimates in Table 1.

Following is the fraction of hours worked over total hours, $L/(NH)$. Hours worked steady shares (L/NH) have been calculated as the average of hours worked taken from the EU-KLEMS database over total hours, calculated assuming that each worker has a time endowment of 96 hours (16 nonsleeping hours by 6 days) a week (therefore, $H = 96 \times 52 = 4{,}992$) and where N is the total number of workers. This fraction goes from 29% in Germany to 36% in Japan and the United States. In the case of Japan, this ratio has been decreasing from 42% in 1977, up to a stable value of 35% by the middle of the nineties [see Hayashi and Prescott (2002)]. This decrease is related to institutional reforms in the labor market, which have limited the workweek since the late eighties. For the case of the United States, this ratio is very stable using the EU-KLEMS data. Greenwood et al. (1997) instead use a value of $L/(NH) = 0.24$ for the U.S. economy.

We estimate the labor cost share parameter α_L as the ratio of labor compensation over total compensation (all these series are provided by the EU-KLEMS database). Compensation for services from residential capital has been excluded. For the United States and Germany, these shares are consistent with those provided by Gollin (2002), who estimates that it should be within the [0.65, 0.80] interval in a wide set of countries under consideration. Particularly, for the U.S. economy, Gollin estimates a band of [0.664, 0.773], which catches our prior guess of $\alpha_L = 0.7003$. This value is the one used by Pakko (2005) or Greenwood et al. (1997) in similar calibrations. However, for the case of Japan, Gollin's estimate is [0.692, 0.727], whereas we use a value of $\alpha_L = 0.6335$, using the EU-KLEMS data set. Hayashi and Prescott (2002) estimate a value $\alpha_L = 0.638$, using data from national accounts and input–output matrices, which is close to the one we use.

The depreciation rates, $\{\delta_{\text{str}}, \delta_{\text{nict}}, \delta_{\text{ict}}\}$, are estimated using the three aggregated series of capital. As shown in Table 3, these estimates are similar but not identical across countries, given that the weights within the portfolio of assets differ from one to another country. Further explanations on how we calculate this rate can be found in the Online Technical Appendix of this paper.[7]

The following rows of Table 3 report the ratio of investment in asset i to output, I_i/Y. In *relative* terms, the portfolio structure is similar in Germany and Japan but not in the United States. Non-ICT equipment represents about half of total investment in Germany and Japan. The U.S. economy has invested 26% in ICT assets. This weight is sensibly higher than those of Germany and Japan, of about 15%.

The average gross price changes of the three assets for the three countries are reported in the following rows of Table 3, 1977–2006:

$$\eta_i = T^{-1} \sum_t Q_{it}/Q_{it-1}.$$

Price variations η_i are similar in Germany and the United States. The change in the price of non-ICT equipment is 2.4% and 3.5% in the United States and Germany, respectively. In the case of Japan, this variation is 1.9%. The investment-specific technical change, measured by the evolution of the Q_i, is thereby stronger for the ICT equipment (about 11% in the three countries).

Finally, in order to take into account the distortionary effects of taxes, particularly on capital accumulation, realistic measures of tax rates are needed. We use the tax rates estimated by Boscá et al. (2008), who follow the methodology proposed by Mendoza et al. (1994). To that end, Table 3 presents average values for the period 1980–2005. Tax structure is similar in Japan and the United States, where labor income taxes are higher than capital income taxes. In Germany, the consumption tax rates double those of Japan and the United States, but the labor income tax is higher than the capital income tax.

4. PRODUCTIVITY GROWTH DECOMPOSITION

According to the neoclassical growth model, long-run productivity growth can only be driven by the state of technology. In our framework, we can decompose long-run labor productivity growth into three different technological factors: neutral change, non-ICT equipment investment, and ICT equipment investment.

In this section, we calibrate the contribution of investment-specific technological progress to long-run labor productivity growth. This calculation is driven by expression (19), which relates long-run productivity growth to both neutral progress and investment-specific technical progress. Additionally, we exploit the system of nine steady state equations (21)–(29) to solve for the following nine unknowns:

$$\left\{\alpha_{\text{str}}, \alpha_{\text{nict}}, \alpha_{\text{ict}}, \frac{Y}{K_{\text{str}}}, \frac{Q_{\text{nict}}Y}{K_{\text{nict}}}, \frac{Q_{\text{ict}}Y}{K_{\text{ict}}}, \frac{C}{Y}, \beta, \gamma\right\}, \tag{31}$$

given the parameters in (30), reported in Table 3. The right-hand sides of expressions (21), (22), and (23) are the real (after-tax) rate of return on each asset, which in equilibrium should equal the stationary marginal rate of substitution between future and present consumption, given by g/β. Table 4 summarizes the results obtained from the calibrated decomposition exercise for the three countries using an after-tax rate of return of 4%, $g/\beta = 1.04$. These are the results.

Germany. Labor productivity growth is dominated by neutral technical change. Neutral change produces increases in total labor productivity of 2.02%; this represents 74.5% of productivity growth. Investment-specific technical change accounts for the remaining fraction, 25.5%. The contribution of the ICT equipment is 0.39 percentage points (14% of productivity growth), whereas the contribution from the non-ICT equipment is about 0.30 percentage points (explaining about 11% of productivity growth).

Japan. Neutral change produces increases in productivity of 2.06%, whereas specific technological progress produces increases of 1.53%. Therefore, neutral technological change accounts for around 57% of productivity growth. The remaining 43% is accounted for by investment-specific technological change.

TABLE 4. Sources of productivity growth, 1977–2006

	Germany	Japan	U.S.
Productivity g, (a) + (b)	2.71	3.59	1.05
Neutral change (a)	2.02	2.06	−0.29
Specific change (b) = (b1) + (b2)	0.69	1.53	1.34
Non-ICT equipment (b1)	0.30	0.57	0.46
ICT equipment (b2)	0.39	0.96	0.88
Elasticities			
Structures, α_{str}	0.0904	0.1272	0.1469
Non-ICT equipment, α_{nict}	0.0958	0.1839	0.0938
ICT equipment, α_{ict}	0.0290	0.0553	0.0590
Decomposition of technical change			
Neutral	74.5	57.4	—
Investment-specific	25.5	42.6	—
Non-ICT	11.1	15.9	—
ICT	14.4	26.7	—

Contribution from ICT equipment and non-ICT equipment are 16% and 27%, respectively.

United States. Labor productivity growth is totally dominated by investment-specific technical change, due mainly to ICT assets, whereas the contribution from neutral technological change is negative. This finding is much larger than the 60% fraction calculated by Greenwood et al. (1997) for the period 1954–1990, or by Cummins and Violante (2002) for 1947–2000. The contribution of the ICT equipment is 0.88 percentage points, whereas the contribution of non-ICT equipment is 0.46 percentage points. Neutral change has an overall negative contribution on the U.S. productivity growth (-0.29 percentage points).

In view of these results, we highlight the following facts. *First*, the technological nature of long-run productivity growth are very different in the Japanese and the German economies than in the U.S. economy. Neutral technological change dominates productivity growth in Germany (74.5%) and Japan (57.4%). By contrast, investment-specific technological change is the main source of productivity growth in the U.S. The contribution to productivity growth from investment-specific technological change is around 0.7 percentage points for Germany, compared to a contribution of 1.53 percentage points for Japan and 1.34 percentage points for the United States.

Second, technology embedded in the ICT assets is a very important source of investment-specific change in these economies but with significant quantitative differences across them. This is a standard result also found in other papers such as Jorgenson and Stiroh (2000) or Collechia and Schreyer (2001), which make the ICT responsible in the upsurge in the U.S. productivity growth during the nineties. We find that with only ICT investment-specific technological change, productivity

TABLE 5. Contribution to growth, 1977–1995 versus 1995–2006

	Germany		Japan		U.S.	
	77–95	95–06	77–95	95–06	77–95	95–06
Productivity, *g* (a + b)	3.35	1.66	3.96	2.99	0.73	1.56
Neutral change (a)	2.74	0.86	2.33	1.60	−0.53	0.08
Specific change (b = b1 + b2)	0.61	0.80	1.63	1.39	1.26	1.48
Non-ICT equipment (b1)	0.21	0.44	0.57	0.58	0.38	0.61
ICT equipment (b2)	0.40	0.36	1.06	0.81	0.88	0.87
		Percentage				
Neutral	81.8	51.8	58.8	53.5	—	5.1
Investment-specific	18.2	48.2	41.2	46.5	—	94.9
Non-ICT-equipment	6.3	26.5	14.4	19.4	—	39.1
ICT equipment	11.9	21.7	26.8	27.1	—	55.8

growth would have increased by 0.39% in Germany, 0.96% in Japan, and 0.88% in the United States.

Third, the “traditional” non-ICT equipment also make a non-negligible contribution to economic growth, with some differences across countries. In Japan and the United States, the investment-specific change associated with the ICT equipment doubles that of the non-ICT equipment. By contrast, contribution to productivity growth from non-ICT and ICT are fairly similar in Germany. This contribution is about 0.3 percentage points in Germany and around 0.5 percentage points for Japan and the United States. Therefore, not only is ICT-specific change larger in the Japanese and U.S. economies than in the German economy, but the same is also true for non-ICT investment-specific technical change.

This finding indicates that investment-specific technological changes contributions to labor productivity growth are similar in Japan and the United States, being the main source of long-run labor productivity growth for both economies, but the same is not true for Germany. This difference is mainly explained by the role of technical change associated with ICT equipment. Jorgenson and Motohashi (2005) study the role of ICT in economic growth in Japan and the United States. They show that the contribution of ICT to economic growth in Japan after 1995 was similar to that in the United States and that more than half of Japanese output growth from the mid-1990s can be attributed to information technology.

In order to study how specific technical change has evolved over time, we repeat the previous analysis by splitting the sample period into two periods, 1977–1995 and 1995–2006. Results are summarized in Table 5. In both subperiods, productivity growth is led by the neutral change in Germany. However, the specific contribution of technical change to productivity growth is 0.61 percentage points in the first subperiod and 0.80 percentage points in the second. Japan reflects a deceleration in the “lost decade” due to contraction in both neutral change and specific technical change. For the second subperiod, average contribution to total labor productivity growth from investment-specific technological change was about 1.4 percentage points, mainly due to ICT equipment (0.81 percentage points). This is consistent with the results obtained by Hayashi and Prescott (2002), in which low productivity growth in Japan in the 1990s is associated with reduction in total factor productivity growth. Braun and Shioji (2007) have extended this exercise and found that economic growth in the *lost decade* was due mainly to investment-specific technological change. Also, Fueki and Kawamoto (2009), using the EU-KLEMS industry-level database, find that the upsurge in productivity after the mid-1990s in Japan was specific to the ICT production sector. The evolution of the U.S. economy presents an improvement in neutral change (positive in the second subperiod), whereas the contribution from investment-specific technical change also increases, mainly associated with non-ICT equipment. In the first period, neutral change even has a negative evolution, reflecting the change in pattern that occurred after the 1974 slowdown. However, the recovery of TFP growth has been remarkable during the period 1995–2006.

5. CONCLUDING REMARKS

This paper investigates the contribution of different sources of technological progress to productivity growth in three leading world economies, Germany, Japan, and the United States. We use a dynamic general equilibrium growth model, which allows us to decompose productivity growth into three different sources of technical progress: neutral technological change and two different forms of investment-specific technical change. This distinction is crucial, as we want to focus on quantifying the importance of both ICT and non-ICT equipment in explaining differences in productivity growth across the three economies.

The results obtained from the calibration of the model economy show that the sources of productivity growth are different among these three countries. Differences in long swings of productivity growth can be attributed to the relative importance of both type of progresses. In Germany, the high productivity growth before the nineties can be explained on the basis of high growth rates in its TFP. Indeed, the contraction in its productivity growth can be associated to a drastic decline in the growth of its neutral progress. In Japan, neutral change has accounted for a large fraction of total productivity growth, and declined during the nineties. The absolute role of investment-specific technical change has remained relatively constant. Finally, in the United States, investment-specific technical change has overwhelmingly led productivity growth after the slowdown of the seventies. We also conclude that the recovery of productivity after the mid-nineties in this country was due to a mild improvement in neutral change. Therefore, the higher observed labor productivity growth of Germany and Japan in comparison with the United States during the sample period can be explained by differences in the contribution from neutral change.

We find that the advances and technical improvements of ICT equipment can help explain a considerable fraction of productivity growth, mainly in the United

States and Japan and secondarily in Germany. Notwithstanding, the contribution from non-ICT equipment (i.e., technical progress therein) is shown to be very relevant.

Our results also stress the importance of using quality-adjusted investment prices for all type of assets, not only for ICT assets. Technical progress embedded within non-ICT equipment has increased its role as a productivity contributor after 1995, especially in Germany and the United States, which, together with the evolution of neutral change, may help explain the differences in these growth rates.

NOTES

1. The debate about the correct approach to quantifying the contribution of technological progress for growth was initiated by Solow (1960) versus Jorgenson (1966). Both authors introduce the concept of "embodied" technological change but using different frameworks. The difference is that Solow (1960) assumes "embodied" technological change but only in the production of investment goods, whereas Jorgenson (1966) assumes that it also affects output. A review of the Solow–Jorgenson controversy can be found in Hercowitz (1998). This debate has been recently updated by the criticism of Greenwood et al. (1997) of Hulten (1992), with extensions upto today [see, for instance, Greenwood and Krusell (2007) and Oulton (2007)].
2. Gort et al. (1999) estimate that the NIPA price for nonresidential structures should be quality-adjusted by 1% yearly.
3. See http://www.euklems.net/.
4. An application of Schreyer's harmonized deflator can be seen in Basu et al. (2003), which compares the productivity evolution in the United Kingdom and the United States.
5. A similar table can be found in Cummins and Violante (2002).
6. As is pointed out by Whelan (2002), national accounts methodology implies that real GDP will generally not be the arithmetic sum of the real components of GDP, as the model states (both measures will be only equal in the base year). This is particularly important when there is change in relative prices, given that, in general, chain-aggregated output will grow slower its their fixed-weighted counterpart after the base year and faster prior to the base year.
7. When quality improvements exist, the economic depreciation rate is different from the physical depreciation rate due to obsolenscence. Cummins and Violante (2002) and Whelan (2002) recommend the use of physical depreciation rather than economic depreciation when capital is measured in efficiency units, as in our case (the rates in Table 2 are physical). The calibration has been done using both rates of depreciation (i.e., physical and economic), but the results do not hinge on it.

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