Working papers series

WP ECON 09.09

Technological sources of productivity growth in Japan, the U.S. and Germany

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JEL Classification numbers: O3; O4

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October 19th 2009

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Abstract. 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: Japan, Germany and the U.S. 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. This decomposition analysis is done for both long term and short term growth. In the long run, neutral technological change is the main source of productivity growth in Japan and Germany. For the U.S., the main source of productivity growth arises from investment-specific technological change, mainly associated with ICT. Finally, impulse-response analysis reveals that deviations from the balanced growth path in the short run are mainly due to neutral shocks in the three countries.

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Acknowledgments: We are grateful to A. Bongers, J.C. Conesa, S. Danthine, G. Fernández de Córdoba, M. Lindquist, A. Moro, J.J. Pérez and participants at the Workshop on the New Economy, Málaga 2008, for their helpful comments and suggestions. We acknowledge financial support from Proyecto Excelencia Junta de Andalucía P07-SEJ-02479. Corresponding author: Jesús Rodríguez, Departamento de Economía, Universidad Pablo de Olavide, Carretera de Utrera, 1, 41003 Sevilla (Spain). e-mail: jrodlop@upo.es

1 Introduction

In this paper we investigate the contribution of different sources of technology to productivity growth in three leading economies, Japan, Germany and the United States, for the period 1977-2005 using a general equilibrium approach. We use a dynamic general equilibrium growth model calibrated with data from the EU-KLEMS database. Sources of technological change to productivity are decomposed into neutral and investment-specific change from different capital assets. Capital is disaggregated into three assets: structures, non-ICT equipment and ICT equipment.

According to the neoclassical growth model, long run productivity growth can only be driven by the state of technology. Here we adopt the view that the progress of technology can be due to two complementary sources: neutral progress and investment-specific progress. While the former is associated with multifactor productivity, the latter is the amount of technology that can be acquired by using one unit of a particular physical capital asset.

Investment-specific technology can widely vary from one asset to another. Indeed recent typologies recommend using disaggregated measures of capital, as for instance, structures and equipment. Equipment is in turn divided into information and communication technologies (ICT) equipment, i.e. hardware, software and communication networks, and non-ICT equipment, i.e. machinery, transport equipment. The amount of technology incorporated in a computer, for instance, is much higher than that in a non-ICT asset. As pointed out by Jorgenson (2002), this technological progress can be observed in improvements in performance, rather than a decline in the nominal price of the capital assets. In nominal terms, the price of a personal computer has changed very little in the last decade. But in real terms, when quality is also controlled for (in terms of processing units), the price has decreased by more than 25 percent by year.[1] The decay in the price in the rest of capital assets has been moderately smaller but also reflects an implicit technological progress. Thus both the acquisition prices and the rental prices of capital equipment have decreased in the last fifteen years.

Several recent studies have stressed the importance of the ICT as a key factor behind the upsurge in the U.S. productivity after 1995 (see among others, Collechia and Schreyer, 2001; Stiroh, 2002; Jorgenson, 2002). With regards to Europe, E.U. countries fall well below the United States in terms of ICT penetration (Timmer and van Ark, 2005). Whereas there exist a huge

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[1] Jorgenson (2002), for instance, pointed out that a 2005 typical personal computer is 140 times as fast compared with the typical personal computer in 1990.

literature for the case of the U.S. economy, the literature is relatively scarce for the cases of Japan and Germany. In the case of the European economies a relevant analysis is Inklaar, McGukin and van Ark (2005), which show that total factor productivity growth in Germany since the mid 1990s has been much slower than in the U.S., especially in market services.

Of particular interest is the case of Japan. Hayashi and Prescott (2002) calibrate a simple neoclassical growth model for the Japanese economy showing that the economic downturn during the 1990s can be explained by a slowdown in Total Factor Productivity (TFP). Braun and Shioji (2007) have extended this and found that economic growth in the *lost decade* was mainly due to investment-specific technological change. Additionally, Jorgenson and Motohashi (2005) study the role of ICT on 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 of the U.S. and that more than a half of Japanese output growth from the mid 1990s can be attributed to information technology. These authors conducted a simulation exercise on potential output growth in Japan and the U.S. until 2013, predicting that economic growth in Japan will continue to lag behind the U.S. but that labor productivity growth in both economies will be similar. More recently, Fueki and Kawamoto (2008) use a standard growth accounting approach to obtain that the TFP growth in Japan has been confined to the ICT production sector since 2000. Fukao and Miyagawa (2007), also using the EU-KLEMS database, make a comparison between Japan and the mayor E.U. countries and the U.S. As in the mayor European countries, Japan experienced a slowdown in TFP growth after 1995 of a similar magnitude.

The comparison of the technological progress in these economies 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, the economic performance has been different in each of these three countries, especially during the last decade. As we will see, while the Japanese economy has experienced a slowdown in the growth of its productivity during the nineties, the U.S. economy has seen an upsurge of productivity ever since, and German productivity growth has evolved within a more stable pattern. As shown by Fukao and Miyagawa (2007), real GDP growth in Japan during the period 1995-2004 did not exceed 1%, much lower than the 3.3% of output growth in the period 1973-1995. This sharply contrasts with the performance of the European economies and the U.S. economy. Third, it is expected that ICT plays a key role in the economic growth as in these economies the ratio of ICT capital to total capital is high. Therefore, it seems to be very important to quantify the size of this contribution.

Our results show some important differences in the performance among these economies. We find that neutral technological change is the driving source of productivity in Japan and Germany, accounting for about 70-75% of the growth in Japan and about 85% of the growth in Germany. For the U.S. economy, the main source of productivity derives from investment-specific technological change, mainly associated with ICT. The contribution to average productivity growth from investment-specific technological change is around 0.35 percentage points for Germany and around 0.65 percentage points for Japan whereas it is about 0.70 percentage points for the U.S. The main finding of the paper is that the importance of ICT technological progress in explaining productivity growth shows considerable differences across countries. ICT technological progress contribution to average productivity growth is only about 0.25 percentage points for Germany, around 0.45 percentage points for Japan and 0.65 percentage points for the U.S.

Finally, we study the effects of the three different technological change in the short-run. Whereas a neutral technological shocks has a positive impact on productivity growth, investment-specific technological shock to both ICT and non-ICT equipment have a negative, although small, impact on productivity growth. This is caused by the fact that an investment-specific technological shock has a higher impact on hours than on output. Additionally, specific technological shocks also have a negative impact on consumption growth and a positive impact on investment growth. We obtain that most of the variability of productivity in the short-run can be attributed to neutral shocks.

The structure of the paper is as follows. In Section 2 we present a theoretical dynamic general equilibrium growth model with embodied technological progress and the characterization of its balanced growth path. Section 3 presents a description of the data set and the calibration exercise. Section 4 presents the estimation of the contribution of each type of technological change to labor productivity growth in the long-run. Section 5 focuses on the effects of different technological shocks in the short-run. Finally, Section 6 presents some concluding remarks.

2 The model

Following Greenwood, Hercowitz and Krusell (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 technological change specific to the production of each type of capital. We use a simplification of the model developed in Martínez, Rodríguez and Torres (2008) which, in turn, is an extension of the Greenwood *et al.* (1997) model, but distinguish between non-ICT and ICT equipment capital assets. Thus, while Greenwood *et al.* (1997) disaggregate between structures and equipment, we distinguish among three different types of capital inputs. Output is therefore produced as a combination from four inputs: L is labor in hours worked; K_{str}, non residential structures; K_{nict}, non-ICT equipment and K_{ict}, ICT equipment.

Households. The economy is inhabited by an infinitely lived, representative agent of household who has time-separable preferences in terms of consumption of final goods and leisure. Preferences are represented by the following 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 on 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 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:

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

where 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 $\tau_c, \tau_\ell, \tau_k$, are the consumption tax, the labor income tax and the capital income tax, respectively.

Capital holdings evolve according to:

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

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

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

where δ_i is the depreciation rate. $Q_{i,t}$ determines the amount of asset of asset $i \in \{nict, ict\}$ 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. In our model $Q_{i,t}$ may increase or decrease over time depending on the type of capital we consider, 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. Notice that expression (5) implies the standard assumption where there is no investment-specific technological change in structures.[2]

The problem faced by the consumer is to choose a sequence C_t, O_t, and I_t 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 $i \in \{str, nict, ict\}$.

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 the services of three types of capital K_i, $i \in \{str, nict, ict\}$. 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,

$$Y_t = A_t L_t^{\alpha_L} K_{str,t}^{\alpha_{str}} K_{nict,t}^{\alpha_{nict}} K_{ict,t}^{\alpha_{ict}} \tag{6}$$

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

$$\begin{aligned} \alpha_{str} + \alpha_{nict} + \alpha_{ict} &< 1, \\ \alpha_L + \alpha_{str} + \alpha_{nict} + \alpha_{ict} &= 1. \end{aligned}$$

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

$$Y_t = C_t + I_{str,t} + I_{nict,t} + I_{ict,t} \tag{7}$$

Both output and investment are measured in units of consumption.

Technological progress. The forms of technological progress under consideration $\{A_t, Q_{nict,t}, Q_{nict,t}\}$ evolve according to the following motions:

$$Q_{i,t} = Q_{i,0}\eta_i^t \exp(u_{i,t}), \tag{8}$$

$$u_{i,t} = \rho_i u_{i,t-1} + \varepsilon_{i,t}, \tag{9}$$

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[2] Gort, Greenwood and Rupert (1999) estimate that the NIPA price for nonresidential structures should be quality adjusted by a 1% yearly.

for $i \in \{nict, ict\}$, and

$$A_t = A_0 g_A^t \exp\left(u_{A,t}\right), \tag{10}$$

$$u_{A,t} = \rho_A u_{A,t-1} + \varepsilon_{A,t}, \tag{11}$$

The fundamental shocks are governed by the following gaussian law

$$\left(\varepsilon_{nict,t}, \varepsilon_{ict,t}, \varepsilon_{a,t}\right)' \sim \mathcal{N}\left(\mathbf{0}_{(3\times1)}, \Lambda\right), \tag{12}$$

$$\Lambda = \begin{pmatrix} \sigma_{nict}^2 & 0 & 0 \\ 0 & \sigma_{ict}^2 & 0 \\ 0 & 0 & \sigma_A^2 \end{pmatrix}. \tag{13}$$

This means that these processes are the sum of a trend, with gross growth rates $\{\eta_{nict}, \eta_{ict}, g_A\}$, and a cycle around, represented by $u_{i,t}$. The fundamental shock $\varepsilon_{i,t}$ has a transitory impact on the level of the cyclical component $u_{i,t}$, whose persistency is given by $\{\rho_{nict}, \rho_{ict}, \rho_A\}$, all belonging to the unit circle.

Government. Finally, we consider the existence of a tax-levying government in order to take into account the effects of taxation on capital accumulation. 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:

$$\tau_c C_t + \tau_\ell W_t L_t + \tau_k \left(R_{str,t} K_{str,t} + R_{nict,t} K_{nict,t} + R_{ict,t} K_{ict,t}\right) = T_t. \tag{14}$$

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

$$\frac{1-\gamma}{\gamma} \frac{C_t}{N_t H - L_t} = \frac{1-\tau_\ell}{1+\tau_c} W_t, \tag{15}$$

$$E_t \left[\frac{C_t}{C_{t+1}} \frac{Q_{nict,t}}{Q_{nict,t+1}} \left(\left(1-\tau_k\right) Q_{nict,t+1} R_{nict,t+1} + \left(1-\delta_{nict}\right)\right)\right] = \frac{1}{\beta}, \tag{16}$$

$$E_t \left[\frac{C_t}{C_{t+1}} \frac{Q_{ict,t}}{Q_{ict,t+1}} \left(\left(1-\tau_k\right) Q_{ict,t+1} R_{ict,t+1} + \left(1-\delta_{ict}\right)\right)\right] = \frac{1}{\beta}, \tag{17}$$

$$E_t \left[\frac{C_t}{C_{t+1}} \left(\left(1-\tau_k\right) R_{str,t+1} + \left(1-\delta_{str}\right)\right)\right] = \frac{1}{\beta}, \tag{18}$$

$$\alpha_i \frac{Y_t}{K_{i,t}} = R_{i,t}, \tag{19}$$

$$\alpha_L \frac{Y_t}{L_t} = W_t, \tag{20}$$

for $i \in \{str, nict, ict\}$. The condition (15) equates the marginal rate of substitution between consumption and leisure to the opportunity cost of one additional unit of leisure. Conditions (16)-(18) mean that the intertemporal marginal rate of consumption equates the after-tax rates of return of the three investment assets. Finally, conditions (19) and (20) mean that the firm hires capital and labor so that the marginal contribution of these factors must equate their competitive rental prices.

Additionally, the economy must satisfy the feasibility constraint:

$$\begin{aligned} & C_t + I_{str,t} + I_{nict,t} + I_{ict,t} \\ = \; & R_{str,t}K_{str,t} + R_{nict,t}K_{nict,t} + R_{ict,t}K_{ict,t} + W_t L_t = Y_t \end{aligned} \tag{21}$$

First order conditions for the household (15) and (16), together with the first order conditions of the firm (19) and (20), the budget constraint of the government (14), and the feasibility constraint of the economy (21), characterize a competitive equilibrium for the economy.

The balanced growth path. The steady state is an equilibrium satisfying the above conditions such that all variables grow at a constant rate. Given the assumption of no unemployment, total hours worked grow by 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 (6) the balanced growth path implies that:

$$g = g_A g_{str}^{\alpha_{str}} g_{nict}^{\alpha_{nict}} g_{ict}^{\alpha_{ict}}, \tag{22}$$

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 $i \in \{str, nict, ict\}$. Then, from the laws of motion (3)-(5) we have that the growth of each capital input is given by:

$$g_i = \eta_i g, \tag{23}$$

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

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 (23) 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:

$$g = \underbrace{g_A^{1/\alpha_L}}_{\text{Neutral}} \times \underbrace{\eta_{nict}^{\alpha_{nict}/\alpha_L} \eta_{ict}^{\alpha_{ict}/\alpha_L}}_{\text{Investment-specific}}. \tag{24}$$

Expression (24) implies that the log of output growth can be decomposed as a linear combination of both progresses. Growth rate of each capital asset can be different, depending on the relative price of the new capital in terms of output.

The following ratios should be stationary along the balanced growth path

$$\frac{C}{Y}, \frac{I_{str}}{Y}, \frac{I_{nict}}{Y}, \frac{I_{ict}}{Y}, \frac{Y}{K_{str}}, \frac{Q_{nict}Y}{K_{nict}}, \frac{Q_{ict}Y}{K_{ict}}, \frac{L}{NH} \tag{25}$$

for $i \in \{str, nict, ict\}$, where the time subscript has been suppressed for simplicity.

Using these ratios, the balanced growth path can be characterized as

$$\frac{g}{\beta}\eta_i = (1-\tau_k)\,\alpha_i \frac{YQ_i}{K_i} + 1 - \delta_i, \tag{26}$$

$$\eta_i g = \left(\frac{YQ_i}{K_i}\right)\left(\frac{I_i}{Y}\right) + 1 - \delta_i, \tag{27}$$

for $i \in \{nict, ict\}$, and for structures:

$$\frac{g}{\beta} = (1-\tau_k)\,\alpha_{str} \frac{Y}{K_{str}} + 1 - \delta_{str},, \tag{28}$$

$$g = \left(\frac{Y}{K_{str}}\right)\left(\frac{I_{str}}{Y}\right) + 1 - \delta_{str}, \tag{29}$$

and

$$1 = \frac{C}{Y} + \frac{I_{str}}{Y} + \frac{I_{nict}}{Y} + \frac{I_{ict}}{Y}, \tag{30}$$

$$1 = \alpha_L + \alpha_{str} + \alpha_{nict} + \alpha_{ict}, \tag{31}$$

$$\frac{C}{Y} = \alpha_L \frac{\gamma}{1-\gamma} \frac{1-\tau_\ell}{1+\tau_c} \left(\left(\frac{L}{NH}\right)^{-1} - 1\right), \tag{32}$$

3 Data and parameters

From the EU-KLEMS Database[3] we retrieve (nominal and real) series of gross output, investment, compensation of inputs, capital assets and labor in hours worked for Japan, the U.S. and Germany.[4] We use observations from 1977 to 2005 for the three countries. Data are available from 1970 to 1990 only for West Germany, and from 1991 to 2005 for reunified Germany. We use data for West Germany to construct series of prices (implicit deflators) for investment assets and for 1977-1990. EU-KLEMS also provides complete series of gross output and total hours worked in Germany from 1970 to 2005. As regards series of capital, we calculate growth rates of the different assets from 1977 to 1990 using data from West Germany. These series are then linked to the growth rates from 1991 to 2005 using the data from reunified Germany.

We use a Törnqvist index to construct aggregate series for Non-ICT and ICT capital stock and investment that take account of the variation in relative prices of assets. For all the cases, the aggregated capital stock and their implicit deflators are computed. Non-ICT series are the aggregation of machinery and other equipment, transport equipment and other assets. ICT series are the aggregation of hardware, communication equipment and software. Structures only include non-residential constructions, that is, residential capital has been excluded.

Table 1 presents average labor productivity growth rates for several periods. Labor is measured in hours worked. On average for the period 1977-2005, according to EU-KLEMS data, the Japanese economy evinces the highest productivity growth rate with 2.90%. This is followed by Germany with 2.32% and the U.S. with 1.44%. The evolution of productivity over time has a different lecture: it is decreasing in Japan, increasing in the U.S. and (reasonably) stable in Germany. The Japanese growth rate during 2000-2005 is almost half as high as the growth rate during the nineties, while the U.S. growth rate in 2000-2005 is about double that of the nineties. However, average productivity growth in Japan during the period 2000-2005 is similar to average U.S. productivity growth and higher than in Germany for the same period. This upsurge in the U.S. productivity has been associated to the use of ICT assets (see, among others, Jorgenson and Stiroh, 2000, and Jorgenson, 2001). With regards to Japanese rates, a similar albeit more dramatic contraction in productivity growth is also documented in Hayashi

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[3] See `http://www.euklems.net/`

[4] Fukao and Miyagawa (2007) also use the EU-KLEMS Database to analyze the sources of productivity growth across Japan, the U.S. and the European countries.

and Prescott (2002), using growth per person aged 20-69, instead of hours worked.

In order to conduct the calibration of the model we need to assign values to the following set of parameters:

$$\Omega=\left\{g,\frac{L}{NH},\alpha_L,\left\{\delta_i,\frac{I_i}{Y},\eta_i\right\}_{i\in\{str,nict,ict\}},\tau_c,\tau_\ell,\tau_k\right\}. \tag{33}$$

Table 2 shows the selected values for this set of parameters. The first row presents figures for the gross productivity growth, g, for the three countries, and are backed by the results in table 1. Following is the fraction of hours worked over total hours, $L/\left(NH\right)$. This fraction goes from 29% in Germany to 36% in Japan and the U.S. In the case of Japan, this ratio has been decreasing from 42% in 1977, up to a stable value of 35% by the midle of the nineties (see Hayashi and Prescott, 2002). This decrease is related to institutional reforms in the labor market, that have limited the workweek since the late eighties. For the case of the U.S., this ratio is very stable using the EU-KLEMS data. Greenwood *et al.* (1997, 2000) instead use a value of $L/\left(NH\right)=0.24$ for the U.S. economy.

The EU-KLEMS data base provides estimated series of labor compensation and capital compensation that allow us to construct an estimate of the labor cost share parameter α_L, as the ratio of labor compensation over total costs. The compensation to the services from residential capital has been excluded. These cost shares α_L are between two thirds and three quarters. For the U.S. and Germany, these shares are consistent with those provided by Gollin (2002), who estimates that the income share 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], that catches our prior guess of $\alpha_L=0.7248$. This value is reasonably close to $\alpha_L=0.7$ as proposed by Greenwood et al. (1997, 2000) or Pakko (2005) in similar calibrations. However, for the case of Japan, Gollin's estimate is [0.692, 0.727], while we use a value of $\alpha_L=0.6387$, 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 exactly equal to the value we use.

Depreciation rates are estimated using the three aggregated series of capital. These estimates are similar but not identical across countries, as shown in table 2. Given that we are using aggregate series of capital, the weights within the portfolio of these physical assets differ from one to another country. This produces different estimates of the depreciation rate.[5] Structures depreciate by 2.8% a year on average. This rate contrasts with that assumed by Greenwood *et al.* (1997) of 5.6%. The rates of depreciation are much higher in the case of the of ICT equipment, [18%,22%], and the one of non-ICT assets, around 12%.

Table 2 also reports the investment weights as the ratio of nominal investment in asset i over total nominal investment expenditure that we label by ω_i. According to the notation in (25), note that $I_i/Y = (1 - C/Y)\,\omega_i$, and $\sum_i \omega_i = 1$. Non-ICT assets have the highest weight, specially in Japan and Germany, 47%. The U.S. economy has invested about a 25% from total nominal investment in ICT assets. This weight is sensibly higher than those of Japan and Germany, 15%.

Prices Q_{it} represent the amount of asset i that can be purchased by one unit of output at time t, $Q_{it} = P_t/q_{it}$, where P_t is the implicit deflator of gross output, and q_{it} is the implicit deflator of asset i calculated as the ratio of nominal to real investment. Table 2 reports the average gross price changes of the three assets for the three countries:

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

Price variations η_i are similar in the U.S. and Germany. The change in the price of non ICT equipment is 0.4% in the U.S. and Germany. In the case of Japan, this variation is 1%. The amount of ICT equipment that can be purchased by one unit of output has increased by 9% per year in the U.S. and Germany, and 6.3% per year in Japan. Investment-specific technological change, as measured by the evolution of the Q_i, is thereby stronger for ICT equipment.

A common practice in this type of exercises is to use the quality adjusted price series of the capital equipment estimated by Gordon (1990), later extended by Cummnis and Violante (2002), as a proxy for the investment specific technological change. For the U.S. data, the EU KLEMS base makes use of the NIPA prices. The equipment deflator could still be biased with respect to those of Gordon-Cummins-Violante. This problem was especially severe in the years prior to 1982, when the share of investment in quality-adjusted equipment was small. As long as we focus on the period

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[5] Depreciation rates provided by EU-KLEMS are the same for all countries but can vary depending on the sector. These are: [2.3%, 5.1%] for non residential structures; [9.2%, 22.9%] for transport equipment; [9.4%, 14.9%] for other machinery and other assets; 31.5% for hardware and software; and 11.5% for communication networks.

1977-2005, we consider that the NIPA prices correctly reflect the investment-specific technological change for equipment in the U.S. Accordingly, as long as Germany and Japan have also incorporated these hedonic techniques, we consider that these prices are valid measures that adjust their equipment assets for quality. The evolution of the levels of the $Q_{i,t}$'s are depicted in figure 1 (base year is 1995). As can be observed, the implicit change for non-ICT equipment shows a slightly upward trend. We also observe a significant upward trend in the case of the implicit change of ICT equipment, mainly due to implicit change associated to hardware equipment.

Finally, in order to take into account the distortionary effects of taxes, particularly on capital accumulation, realistic measures of tax rates are needed. In this paper we use the effective average tax rates, estimated by Boscá, García and Taguas (2008), who follow the methodology proposed by Mendoza, Razin and Tesar (1994). To that end, table 2 presents average values for the period 1980-2005. Tax structure is similar in Japan and the U.S., where labor income taxes are higher than capital income taxes. In Germany, the consumption tax rates doubles those of Japan and the U.S., but the labor income tax is higher than the capital income tax.

[**Tables 1 and 2 and figure 1 here**]

Model evaluation. In order to evaluate the empirical relevance of our model, simulated productivity growth are compared to the observed productivity growth year-by-year. Using a log-linear version of the model, figure 2 plots the observed productivity growth and the calibrated one derived from the model for the three countries. Series of $Q_{i,t}$ and A_t are taken as granted. As we can observe, the calibrated model does a good job of explaining movements in labor productivity growth. This means that our model is able to replicate not only the long-run behavior of productivity growth in the three countries, but also short-run fluctuations in labor productivity growth. The correlation coefficients of the observed productivity growths and those generated by the model are 0.8693 for Japan, 0.8722 for the U.S., and 0.8542 for Germany. For the U.S. economy we observe some differences in the period 1981-1985, with observed productivity growth larger than the predicted one. We conclude that the model can replicate productivity growth both in the short run and in the long run.

[**Figure 2 here**]

4 Long-run analysis

In this section we calibrate the contribution of investment-specific technological progress to long-run productivity growth. We follow the approach proposed by Greenwood *et al.* (1997), but incorporating the new element included in our model: investment-specific technological progress from the two equipment capital assets considered. Therefore, we can decompose long-run productivity growth into three different technological factors.

This calculation is given by expression (24), that relates the long run productivity growth to both neutral progress and investment specific technological progress. On the other hand, we exploit the system of nine steady state equations composed by (26) to (32) to solve for the following nine unknowns

$$\left\{\alpha_{str}, \alpha_{nict}, \alpha_{ict}, \frac{Y}{K_{str}}, \frac{Q_{nict}Y}{K_{nict}}, \frac{Q_{ict}Y}{K_{ict}}, \frac{C}{Y}, \beta, \gamma\right\}, \tag{34}$$

given the set of parameters Ω in (33) as reported in table 2. Once technological parameters α_i, $i \in \{str, nict, ict\}$, are calibrated, we use the series of output, capital and labor in hours worked to calculate residually the total factor productivity. This gives an estimation of the neutral change that, added to the specific change, produces a calibrated value of productivity growth according to (24).

Notice that table 2 proposes a vector of investment weights for the portfolio of physical assets, labeled as ω_i. The investment-saving rate on asset i would be given by $I_i/Y = (1 - C/Y)\,\omega_i$, and the total investment-saving rate is $(1 - C/Y)$. In order to calibrate the steady state value of this rate, we need an additional equation that fixes the after-tax return rate of capital to some value. This can be done by using equation (26). The right hand side of this expression is the real (after-tax) rate of return on asset $i \in \{str, nict, ict\}$, that in equilibrium should equal the stationary marginal rate of substitution between future and present consumption, as given by g/β. Expression (26) is therefore an arbitrage condition that imposes that the return of the different assets must be equal to g/β. For example, Greenwood *et al.* (1997, 2000) use a 7% rate, $g/\beta = 1.07$ for their long run analysis, and a 4% rate, $g/\beta = 1.04$, for their short run analysis. Pakko (2005) uses a rate of 6%. Hayashi and Prescott (2002) calculate that the after tax rate of return has decreased from 6.1% in the eighties until 4.2% at the end of the nineties. In this paper, in order to overcome the uncertainty associated to this rate, we will calibrate the parameters of the model in (34) for an interval of the after tax return rates going from 4% to 7%, and calibrate a stationary saving rate consistent with these values.

Tables 3, 4 and 5 summarize the results obtained from the calibrated decomposition exercise for the three countries.

Japan. Results are reported in table 3. The calibrated value of productivity growth is reasonably close to the observed one and seems to be robust to the assumed after tax return rate on capital. Neutral change produces increases in productivity between 1.63% and 1.72%, while implicit technological change produces changes from 0.70% to 0.61%. Therefore, neutral technological change accounts for around 70% of productivity growth. The remaining 30% is accounted for by the investment-specific technological change. ICT equipment provides most of this contribution, from 50% to 44%, whereas contribution from non-ICT equipment is around 18%. The calibrated saving rate moves within an interval from 16% to 20.0%. Estimated technological parameters are also provided in the subsequent lines of the table. Hayashi and Prescott (2002) estimate a discount factor for Japan of $\beta = 0.976$ and Hayashi and Nomura (2005) use a value of 0.964. Our benchmark model produces these same discount factors for an after-tax discount rate of 6-7%, with a stationary investment rate of 16-17%.

Miyagawa, Ito and Harada (2004) study the contribution of ICT investment to productivity growth in Japan at an industry level. These authors decompose labor productivity growth into intra-sectoral capital deepening, efficiency effects of capital deepening, efficiency effects of labor shifts, and intra-sectoral TFP growth, showing that the productivity slowdown in the 1990s was caused by the reduction in the efficiency effects of labor shifts. Shinjo and Zhang (2003), estimating the marginal Tobin's q-ratios of ICT capital, show the existence of an overinvestment in ICT capital relative to non-ICT capital in the U.S., but the opposite in the case of Japan. Tokui, Inui and Kim (2008) analyze embodied technological progress in the Japanese economy using firm-level data. These authors estimate a production function with several control variables accounting for technological progress, obtaining that the average rate of technological progress embodied in machinery and equipment is between 0.2 and 0.4 percent. Finally, Fueki and Kawamoto (2008), using EU-KLEMS industry-level database, find that the upsurge in productivity after the mid 1990s in Japan was specific to the ICT production sector.

[**Table 3 here**]

U.S. Results are reported in table 4. The calibrated value of productivity growth is close to the observed one and robust to the assumed after tax return rate on capital. Productivity growth is now dominated by the investment specific technological change, mainly due to the contribution of the technology embedded in the ICT assets, between 0.76% and 66%. This ICT contribution widely exceeds that of the neutral change and the estimated ICT contribution to productivity growth for the cases of Japan and Germany. Neutral technological change contribution to productivity growth is between 0.33% and 0.48%. Therefore, the investment-specific technological change account for a fraction between 70% and 58% of the total productivity growth. This is in line with the 58% result provided by Greenwood *et al.* (1997). The contribution to productivity growth from non-ICT equipment is very low, around 5%. The saving rate moves within an interval from 14% to 11%. Greenwood *et al.* (1997) propose a discount factor for the U.S. of $\beta = 0.97$, and an investment rate of 11.4%. Like in the case of Japan, our exercise produces these rates when the after tax discount rate is assumed to be 6-7%. Not surprisingly, the technological change decomposition replicates the 58% result given by Greenwood et al. (1997) for a different period.

[**Table 4 here**]

Germany. Results are finally reported in table 5. The calibrated value of productivity growth accurately fits the observed one. Productivity growth is now dominated by the neutral technological change as in the case of Japan but in a more dramatic way. Neutral technological change produces increases in productivity of around 2%. Therefore, the neutral technical change account for a fraction of 85% of productivity growth with investment-specific technical change accounting for the rest 15%. The contribution of ICT equipment is between 0.25% and 0.28%, whereas contribution from non-ICT equipment is about 0.08%. The saving rate moves within an interval from 13.3% to 16.7%. Bems and Hartelius (2006) estimate values for the German discount factor of 0.95-0.96. Again, our exercise produces this rates when the after tax discount rate is assumed to be between 6% and 7%.

[**Table 5 here**]

In light of these tables, there are four results that we would like to emphasize. *First*, neutral technological change dominates productivity growth in Japan (70%) and Germany (85%) while investment specific technological change accounts for a fraction of 60%-70% of the U.S. productivity growth. This implies that the sources of long run productivity growth are very different in the U.S. economy as compared with the Japanese and the German economies. It is important to note the differences in the average productivity growth across countries during the sample period (see table 1). Average productivity growth is higher in Japan and Germany than in the U.S. The contribution to productivity growth from investment specific technological change is around 0.32%-0.36% for Germany, 0.61%-0.70% for Japan and 0.66%-0.76% for the U.S. Another difference is found in the contribution from neutral technological change. In this case we obtain a value of around 1.7% for Japan, 2.0% for Germany and only a value of about 0.4% for the U.S. This factor accounts for an important fraction of productivity growth performance in Japan and Germany with respect to the U.S. economy during the sample period.

Second, technology embedded in the ICT assets are the main source of the investment-specific change for all three economies but with significant quantitative differences across them. With only ICT investment-specific technological change, productivity growth would have increased by 0.25%-0.28% in Germany, 0.44%-0.50% in Japan and 0.61%-0.70% in the U.S. Table 1 reported that productivity growth is declining in Japan, increasing in the U.S. and stable in Germany, and table 2 reported that the U.S. has invested in ICT assets more than Japan and Germany have done, while the amount of technology embedded in the ICT assets is the highest one among the three U.S. investment assets, as measured by the $\eta_i' s$, $i \in \{str, nict, ict\}$. This supports other results that make the ICT responsible in the upsurge in the U.S. productivity growth during the nineties.

Third, the contribution to productivity growth from "traditional" non-ICT equipment shows dramatic differences across countries. Whereas this contribution is about 0.06 percentage points for the U.S. and 0.08 percentage points for Germany, in the case of Japan this figure is around 0.18 percentage points. This implies that technological change associates with non-ICT equipment is much larger in the Japanese economy than in the other two countries. This is an important factor in explaining the larger productivity growth in Japan as compared with Germany and the U.S.

Finally, when we compare our exercise with other calibrations, we see that the model demands an after tax return rate of about 6-7% for all countries, a result consistent with a non-arbitrage condition under international free capital mobility.

A conclusion derived from the previous results seems to indicate that the U.S. was the leading economy in the new information and communication era, followed by Japan. Yet, in order to study how specific technological change has evolved over time, we repeat the previous analysis by splitting the sample period into two periods, 1977-1990 and 1991-2005, using an after-tax rate of return of 6.5% for the three countries. Results are summarized in table 6. If we pay attention to the contribution from total (ICT and non-ICT) investment-specific technological change, during the period 1977-2005, Japan was the leading country. For that period, average contribution to productivity growth from investment specific technological change was about 0.66% for Japan, 0.65% for the U.S. and 0.29% for Germany. On the other hand, Japan has been the country with the larger average productivity growth during the period. However, for the second period, 1995-2005, the contribution from investment-specific technological change increases in the U.S. and in Germany, but decreases in Japan with respect to the first period.

Our results are consistent with the ones presented by Fukao and Miyagawa (2007) for the three countries. These authors show that the U.S. has experienced a very rapid increase in ICT capital after 1995. On the contrary, ICT capital in Japan in 2004 was less than twice as high as in 1995. Jorgenson and Motohashi (2005) show that the contribution of ICT capital in Japan declined during the first half of the 1990s, but rebounded strongly after 1995. In our case, ICT contribution to productivity growth remains constant, on average, between the periods 1977-1995 and 1995-2005 for the U.S. economy, whereas it increased for the Japan and Germany economies. In the U.S. we obtain that ICT contribution to productivity growth is similar in both sub-periods, about 0.62%. Jorgenson and Motohashi (2005) using a traditional growth accounting obtained that the contribution from ICT to output growth is larger in the second subperiod compared with the first one. Non-ICT contribution increases, from a 0.01 to 0.13 percentage points.

Neutral technological change is the main source of productivity growth for the three countries and accounting for about 70-80% of total productivity growth during 1995-2005. Comparing both subperiods of time, we obtain that the contribution of neutral technological change to productivity growth decreases in Japan, increases in the U.S. and remains almost constant in Germany. 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 the reduction in total factor productivity growth. Average neutral technological change contribution is negative in the U.S. economy during the period 1977-1995. This result is produced by the first years of the sample period, in which TFP growth was negative. However, recovery of TFP growth has been very remarkable during the period 1995-2005.

[**Tables 6 here**]

5 Short-run analysis

In this section we analyze the quantitative effects of fluctuations from neutral shocks and investment-specific shocks. The model developed in the previous sections allows us to study the effect of two additional types of investment-specific technological shocks, associated to non-ICT equipment and ICT equipment.

The three processes representing the motion of technology expressed in (8) and (10) can be filtered and written as

$$\begin{aligned} \ln Q_{i,t} &= \gamma_{i,0} + \gamma_{i,1} t + \rho_i \ln Q_{i,t-1} + \varepsilon_{i,t}, \\ \text{with } \gamma_{i,0} &= (1-\rho_i)\, a_i + \rho_i \ln(\eta_i), \\ \gamma_{i,1} &= (1-\rho_i) \ln(\eta_i), \end{aligned} \tag{35}$$

given $\ln(\eta_i)$. The process for the neutral technological change has an analogous obvious representation. A value for $\{\rho_i, \sigma_i\}$ is obtained using a maximum likelihood estimator. Results are shown in table 7.

[**Table 7 here**]

We next study how these shocks affect the economy around the balanced growth path, using the impulse response functions from a log-linear version of previous model. The neutral shock, $\varepsilon_{A,t}$, has an immediate impact on output by raising the total factor productivity, A_t. Its short-run effect on consumption is always positive due to the income effect. A non neutral shock affects the after-tax real rate of return that implies an intertemporal substitution in consumption from (16), and a substitution between consumption and leisure. Output is therefore affected in the current period through the impact on labor supply and on investment decisions.

Instead, a non-neutral shock in asset $i \in \{nict, ict\}$ only affects the marginal product of i. This induces a substitution in the portfolio of assets: a higher investment in asset i and a disinvestment in the remaining ones. The net effect on total savings depends on the substitution effect and the portfolio composition. Total savings also increase due to the rise in returns to labor and the increases in labor supply (or a reduction in leisure). In the following and subsequent periods, a positive non-neutral shock in asset $i \in \{nict, ict\}$ impulses the marginal product of own and the remaining factors in the production function, which implies the existence of a complementary effect.

Labor productivity increases in response to a neutral shock (output increases more than hours worked). But a non-neutral shock can have a negative immediate impact on productivity. In response to a non neutral shock in $i \in \{nict, ict\}$, there is an increase in investment in asset i and in total investment that produces a decrease in consumption. Given the wage, leisure must also decrease. This produces a rise in hours worked. Note that $\alpha_L < 1$ is the elasticity of output with respect to labor. A one percent increase in the amount of hours worked produces a less than proportional increase on output of α_L percent.[6]

Figures 3 to 5 plot the response of productivity growth, consumption growth and investment growth, respectively, to a one standard deviation impulse in the three shocks. For each country we compute four impulse-response functions, corresponding to (the growth rates of) non-ICT equipment, ICT equipment and total investment, in terms of the three technological shocks. The impulse response figures show deviations with respect to the balanced growth rates of the variables.

In the three economies, labor productivity increases in response to a positive neutral technological shock. The highest impact occurs in the first period and declines thereafter. The immediate response is similar in the three countries: labor productivity growth increases by 0.75 percentage points in response to a neutral shock of one standard deviation. Interestingly, specific technological shocks have a negative impact effect on productivity growth, showing a hump-shaped impulse response (Figure 3). A technological shock to ICT and non-ICT equipment has a negative impact on productivity but it is negligible and it becomes positive thereafter. Concerning the persistency of these shocks, all shocks have a cumulative positive effect on productivity in the medium and the long term. In quantitative terms, the largest effect is observed for the Japanese economy.

Figure 4 presents the impulse-response for consumption growth. Consumption growth increases in response to a positive neutral shock. However, non-neutral shocks induce a suddenly decrease in consumption growth, provoked by the positive impact on investment growth but the effect turns out positive afterwards, showing also a hump-shaped impulse-response. Figure 5 shows the impulse-responses for investment growth. Neutral technological shock provokes an immediate positive response of total investment growth above the steady state growth rate but thereafter the effect turns out negative for some periods with a total investment growth rate below the steady state value. A non-ICT technological shock has a negative impact effect on structures investment growth

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[6] Miyagawa, Sakuragawa and Takizawa (2006) using a VAR approach with Japanese firm-level data find that a positive technology shock results in a reduction of labor input on impact indicating the existence of an adjustment cost to investment.

The most interesting result is the response of ICT equipment investment growth and non-ICT equipment investment growth. On the one hand, the immediate impact of a shock on asset i moves decisions to invest in this asset: the weight in the portfolio of asset i increases and decreases the weight of the remaining ones. However, this effect reverts in the next period, indicating that the different capital assets are complementary in the short-run, in spite of the rivalry existing among different capital assets in the investment process. On the other hand, the effect of a non-ICT technological shock on ICT equipment investment growth and the effect of a ICT technological shock on non-ICT equipment investment growth, are in both cases negligible. This implies that there is no substitution effect between the two types of capital equipment given a specific shock to each one. Finally, a neutral technological shock has a very small effect on ICT and non-ICT equipment investment growth.

Table 8 reports the variance decomposition of productivity, consumption and investment. It is worth mentioning that most of the variability of productivity, around 90% for the three countries, is accounted for by the neutral shock in the short run. In the medium and long run, neutral shocks is responsible of about 80% of productivity variability in the U.S. and about 75% in Germany. In Japan, the non neutral shocks account for a fraction of 40% of this variance in the medium and the long term.[7] With regards to consumption decisions, most of this variability is due to the neutral shock. However, investment decisions on structures are mainly explained by a shock to non-ICT equipment. The variability of ICT investment is mainly explained by shocks to the ICT, whereas variability of non-ICT investment is explained by a shock to both structures and non-ICT technical change. Total investment variability is mainly explained by neutral technological shocks and shocks to structures.

Our results contrast with those found for the U.S. economy in two recent articles, Fisher (2006) and Justiniano and Primiceri (2008). Fisher (2006) proposes a set of identifying conditions for the two technology shocks. The investment-specific shock is found to have a crucial role in accounting for the fluctuations of both hours and output. Fischer (2006) assumes that both forms of technical progress follow a random walk with a drift. This assumption is crucial for his identifying conditions and makes his findings differ from ours. Indeed, when we assume a trend stationary process the effects

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[7] Braun and Shioji (2007) estimate a SVAR model showing that investment-specific technological shocks are at least as important as neutral technology shocks in Japan's business cycles.

of a shock on technology tend to die out over time. Justiniano and Primiceri (2008) estimate a DSGE model to analyze the different sources of U.S. fluctuations: shocks to technology, shocks to preferences, fiscal shocks and nominal shocks. They do not use quality adjusted investment prices to construct a proxy measure of investment-specific technological shock. Instead, the model is estimated taking all these shocks as unobservable. Their main finding is that the investment-specific technological shock can account for most of the bulk of U.S. output fluctuations. While their approach is econometric where the structural shocks are subject to time varying volatility, ours is a calibration exercise.

[**Tables 7 and 8 and figures 3-5 about here**]

6 Concluding remarks

This paper investigates the contribution of different sources of technological progress to productivity growth in three leading world economies, i.e., Japan, Germany and the United States. We use a dynamic general equilibrium growth model with investment-specific technological progress, which allows us to decompose productivity growth into three different sources of technological progress: neutral technological change and two different investment-specific technological change. This distinction is crucial as we want to focus on quantifying the importance of ICT in explaining differences in productivity growth across the three economies. We find that the ICT equipment, in spite of the fact that it represents a small fraction of total capital used by the economy, explain a large fraction of productivity growth.

The results obtained from the calibration of the model suggest that, in the long-run, the sources of productivity growth are different across the three countries. Investment-specific technological change is more important in the U.S. than in Japan or Germany. As long as the U.S. economy is an intensive user of the ICT, these differences are mainly due to the technological progress embedded in these capital assets. On the other hand, the contribution from neutral technological change is much more important in Japan and Germany than in the U.S. This source accounts for a large fraction of productivity growth in the Japanese and the German economies. This implies that differences in long swings of productivity growth can be attributed to the relative importance of both type of fluctuations. Additionally, we obtain that "traditional" non-ICT equipment technological progress plays an important role in the Japanese productivity growth, whereas its contribution in Germany and in the U.S. is more modest.

Our results indicate that the U.S. is the leading economy in terms of productivity growth derived from ICT equipment and also seems to provide an "optimistic" rather than a "pessimistic" view of the Japanese economy, showing a better performance compared to the German economy. Those results are consistent with the projections of Jorgenson and Motohashi (2005) in which labor productivity growth will be similar for Japan and the U.S., but with output growth larger in the U.S., due to the slower growth of the labor input in the Japanese economy.

Finally, when we have explored the short run implications of the different shocks to productivity growth, we find that most of the deviations from the balanced growth path are caused by the neutral shock in the three countries. Hence, there are not important differences among these three economies when we move our focus from the long term to the short term analysis. Having a look at the variance decomposition analysis suggests that a transitory shock to investment-specific technological progress causes a minor impact on the growth of productivity from its balanced growth path, provided that the bulk of these short run swings are motivated by the neutral progress.

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A Tables and figures

Table 1: Average productivity growth rates 1977-2005

	Japan	U.S.A.	Germany
1977-1980	4.09	-0.26	2.91
1980-1990	3.79	0.95	2.17
1990-2000	2.24	2.07	2.88
2000-2005	2.08	2.10	1.44
1977-2005	2.90	1.44	2.37

Table 2: Parameters values

	Japan	U.S.A.	Germany
g	1.0302	1.0144	1.0237
$L/(NH)$	0.3530	0.3660	0.2998
α_L	0.6387	0.7248	0.7412
δ_{str}	0.0286	0.0277	0.0310
δ_{nict}	0.1261	0.1284	0.1259
δ_{ict}	0.2209	0.1933	0.1813
ω_{str}	0.3747	0.3545	0.3783
ω_{nict}	0.4795	0.3930	0.4717
ω_{ict}	0.1458	0.2525	0.1500
η_{nict}	1.0055	1.0043	1.0046
η_{ict}	1.0613	1.0916	1.0914
τ_c	0.0510	0.0470	0.1130
τ_ℓ	0.2510	0.2300	0.3390
τ_k	0.3850	0.3300	0.2420

Table 3: Japan, 1977-2005

After tax return rate, $(g/\beta - 1) \times 100$	4%	5%	6%	7%
Observed productivity, g	2.97	2.97	2.97	2.97
Calibrated productivity, (a)+(b)	2.32	2.33	2.33	2.34
Neutral change (a)	1.63	1.66	1.70	1.72
Specific change (b)=(b1)+(b2)	0.70	0.66	0.64	0.61
NICT equipment (b1)	0.19	0.18	0.18	0.18
ICT equipment (b2)	0.50	0.48	0.46	0.44
Discount factor, β	0.9906	0.9811	0.9719	0.9628
Investment rate, $(1 - C/Y) \times 100$	20.26	18.60	17.19	15.98
Cost shares				
Structures, α_{str}	0.1441	0.1516	0.1579	0.1633
NICT equipment, α_{nict}	0.1676	0.1627	0.1586	0.1551
ICT equipment, α_{ict}	0.0496	0.0470	0.0448	0.0429
Decomposition of technological change				
Neutral	69.98	71.44	72.68	73.74
Investment-specific	30.02	28.55	27.31	26.26

Table 4: U.S.A., 1977-2005

After tax return rate, $(g/\beta - 1) \times 100$	4%	5%	6%	7%
Observed productivity, g	1.43	1.43	1.43	1.43
Calibrated productivity, (a)+(b)	1.09	1.11	1.12	1.14
Neutral change (a)	0.33	0.39	0.43	0.48
Specific change (b)=(b1)+(b2)	0.76	0.72	0.68	0.66
NICT equipment (b1)	0.06	0.05	0.05	0.05
ICT equipment (b2)	0.70	0.66	0.63	0.61
Discount factor, β	0.9754	0.9661	0.9570	0.9481
Investment rate, $(1 - C/Y) \times 100$	14.10	12.91	11.91	11.05
Cost shares				
Structures, α_{str}	0.1199	0.1261	0.1312	0.1357
NICT equipment, α_{nict}	0.0972	0.0942	0.0916	0.0894
ICT equipment, α_{ict}	0.0581	0.0550	0.0523	0.0501
Decomposition of technological change				
Neutral	30.24	34.98	38.85	42.09
Investment-specific	69.75	65.01	61.14	57.90

Table 5: Germany, 1977-2005

After tax return rate, $(g/\beta - 1) \times 100$	**4%**	**5%**	**6%**	**7%**
Observed productivity, g	2.38	2.38	2.38	2.38
Calibrated productivity, (a)+(b)	2.37	2.37	2.37	2.38
Neutral change (a)	2.00	2.02	2.04	2.05
Specific change (b)=(b1)+(b2)	0.36	0.35	0.33	0.32
NICT equipment (b1)	0.08	0.08	0.08	0.07
ICT equipment (b2)	0.28	0.27	0.25	0.25
Discount factor, β	0.9847	0.9753	0.9661	0.9571
Investment rate, $(1 - C/Y) \times 100$	16.70	15.39	14.27	13.30
Cost shares				
Structures, α_{str}	0.1059	0.1106	0.1146	0.1181
NICT equipment, α_{nict}	0.1141	0.1110	0.1084	0.1061
ICT equipment, α_{ict}	0.0350	0.0334	0.0320	0.0308
Decomposition of technological change				
Neutral	84.65	85.32	85.89	86.38
Investment-specific	15.34	14.67	14.11	13.32

Table 6: Contribution to growth, 1977-1995 versus 1995-2005

	Japan		USA		Germany	
	77-95	95-05	77-95	95-05	77-95	95-05
Observed productivity, g	3.41	2.19	0.92	2.28	2.50	2.28
Calibrated productivity, (a+b)	2.70	1.68	0.36	2.42	2.47	2.35
Neutral change (a)	2.04	1.15	-0.27	1.67	2.18	1.93
Specific change (b=b1+b2)	0.66	0.53	0.63	0.74	0.29	0.42
NICT equipment (b1)	0.21	0.10	0.01	0.13	0.11	0.04
ICT equipment (b2)	0.45	0.43	0.62	0.62	0.18	0.38
Percentage						
Neutral	0.76	0.69	-	0.69	0.88	0.82
Investment-specific	0.24	0.31	-	0.31	0.12	0.18

Table 7: Estimation of parameters[8]

	Japan	**U.S.A.**	**Germany**
ρ_{nict}	0.8852	0.9221	0.8064
	(0.0958)	(0.0964)	(0.1585)
σ_{nict}	0.0143	0.0104	0.0090
	(0.0006)	(0.0002)	(0.0001)
ρ_{ict}	0.9595	0.8472	0.9698
	(0.0602)	(0.1144)	(0.0547)
σ_{ict}	0.0487	0.0274	0.0337
	(0.0045)	(0.0010)	(0.0011)
ρ_A	0.8313	0.9478	0.7206
	(0.1080)	(0.0725)	(0.1388)
σ_A	0.0134	0.0142	0.0143
	(0.0002)	(0.0003)	(0.0004)

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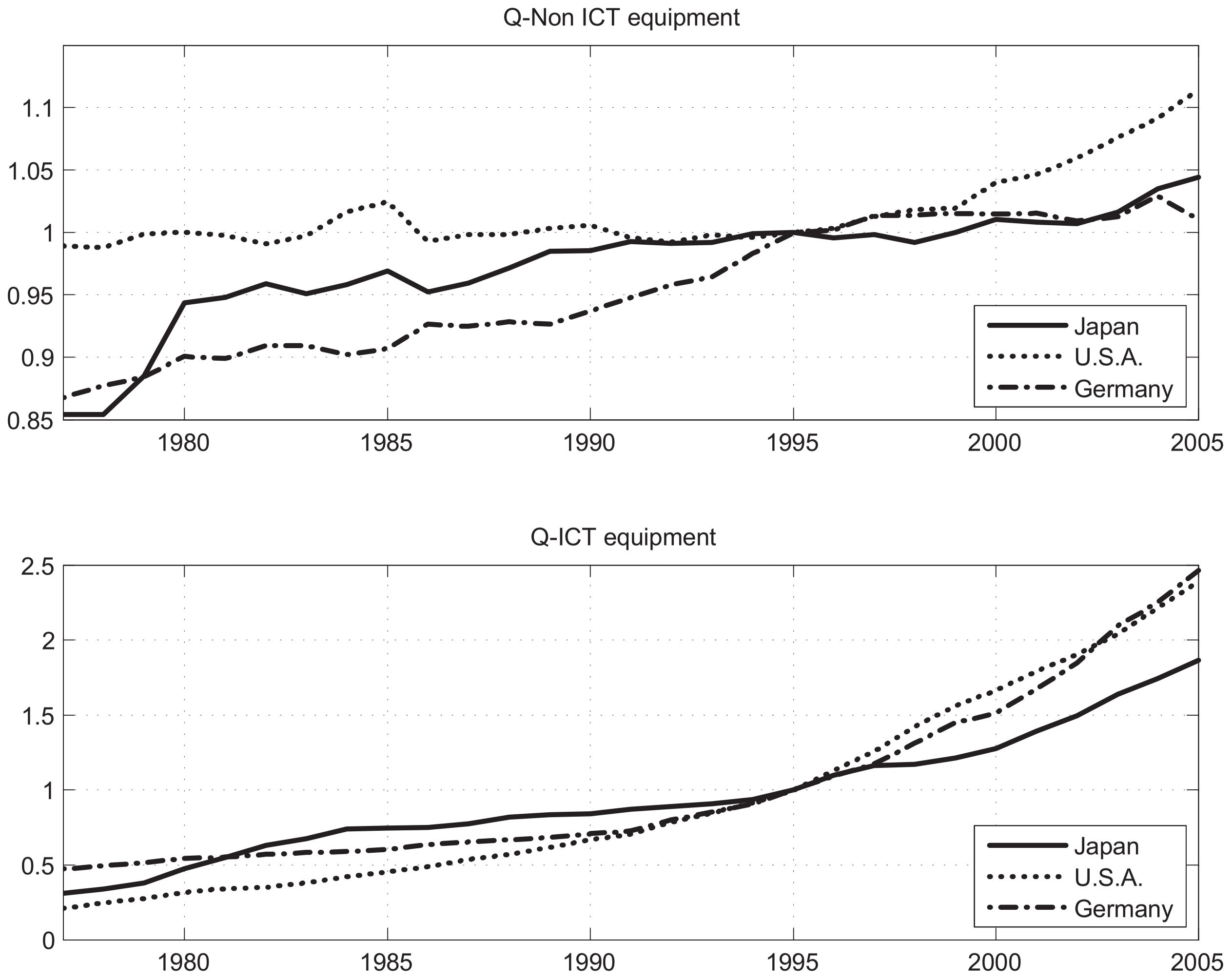
[8] Note: We estimate expresions (35) using maximum likelihood. Numbers into brackets below the $\rho_i^{\prime}s$ parameters represent the standard deviations. Greenwood *et al.* (2000) for the U.S. economy estimate a parameter of 0.64 for equipment technological change. Pakko (2005), using a similar model for the US, estimates a parameter of 0.945 for the neutral technological change and a value of 0.941 for the equipment technological change. These estimates are similar to our estimates of ρ_A and ρ_{nict} for the U.S.

Table 8: Variance decomposition of growth rates

	Japan			USA			Germany		
	ε_{nict}	ε_{ict}	ε_{A}	ε_{nict}	ε_{ict}	ε_{A}	ε_{nict}	ε_{ict}	ε_{A}
Time				**Productivity growth**					
1	0.30	0.00	99.69	0.03	0.00	99.96	0.09	0.00	99.90
5	19.95	10.73	69.31	3.66	5.25	91.08	4.56	3.29	92.14
Time				**Consumption growth**					
1	9.66	0.03	90.30	1.61	0.04	98.34	2.98	0.16	96.85
5	27.53	10.20	62.26	4.55	3.67	91.78	10.06	4.57	85.36
Time				**Investment growth of Structures**					
1	79.17	7.31	13.51	45.16	12.01	42.81	43.82	7.03	49.14
5	83.93	9.24	6.82	56.43	18.85	24.71	57.31	10.22	32.46
Time				**Investment growth of Non-ICT**					
1	99.36	0.00	0.63	98.04	0.02	1.93	97.54	0.09	2.36
5	99.55	0.06	0.38	98.75	0.11	1.13	98.23	0.21	1.55
Time				**Investment growth of ICT**					
1	0.01	99.93	0.05	0.02	99.65	0.32	0.08	99.83	0.09
5	0.05	99.91	0.03	0.04	99.75	0.19	0.11	99.81	0.06

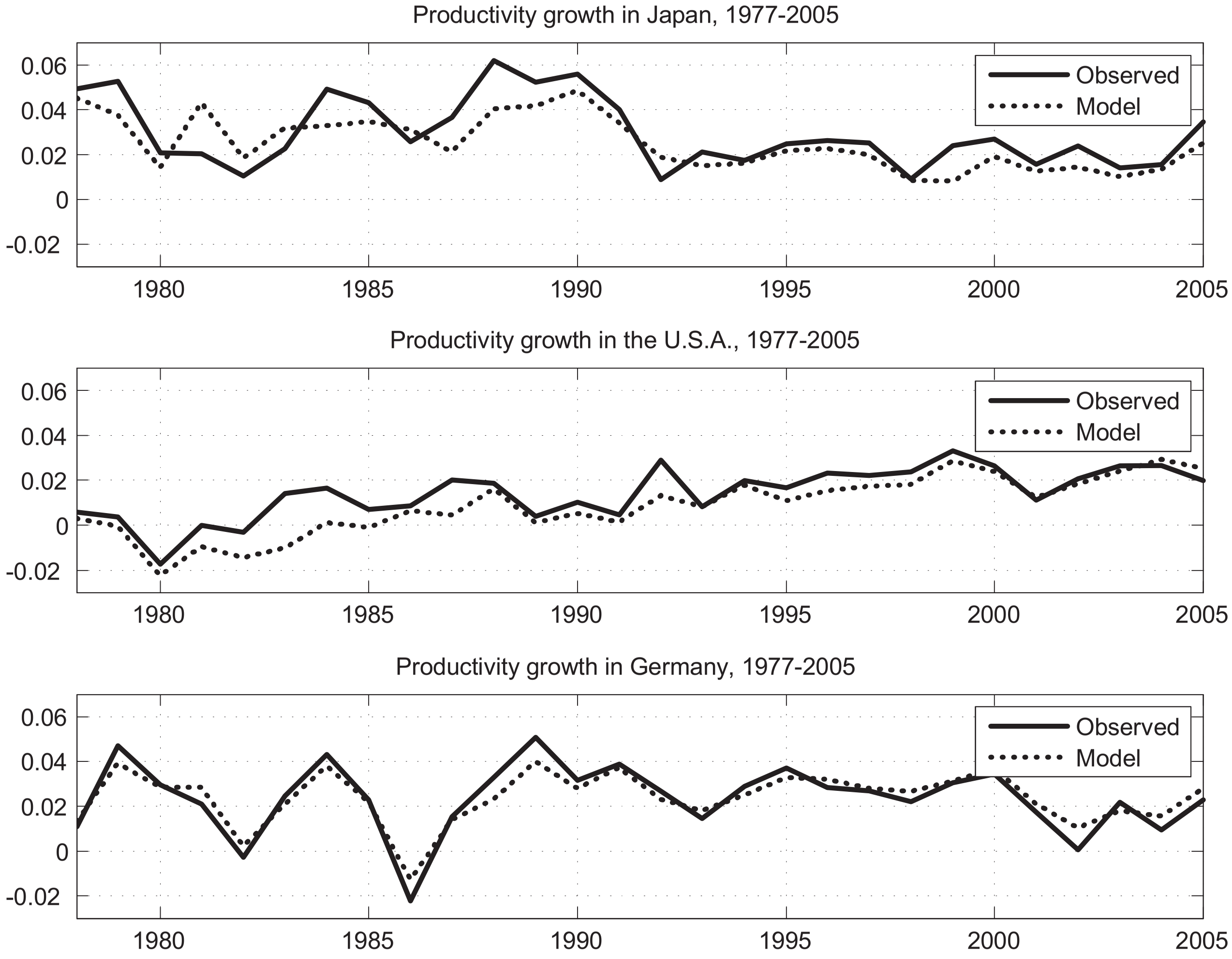
Figure 1: **Implicit progress of investment**



Q-Non ICT equipment

Q-ICT equipment

Figure 2: Observed and simulated productivity growth


Productivity growth in Japan, 1977-2005

Productivity growth in the U.S.A., 1977-2005

Productivity growth in Germany, 1977-2005

Figure 3: **Impulse responses of productivity growth**

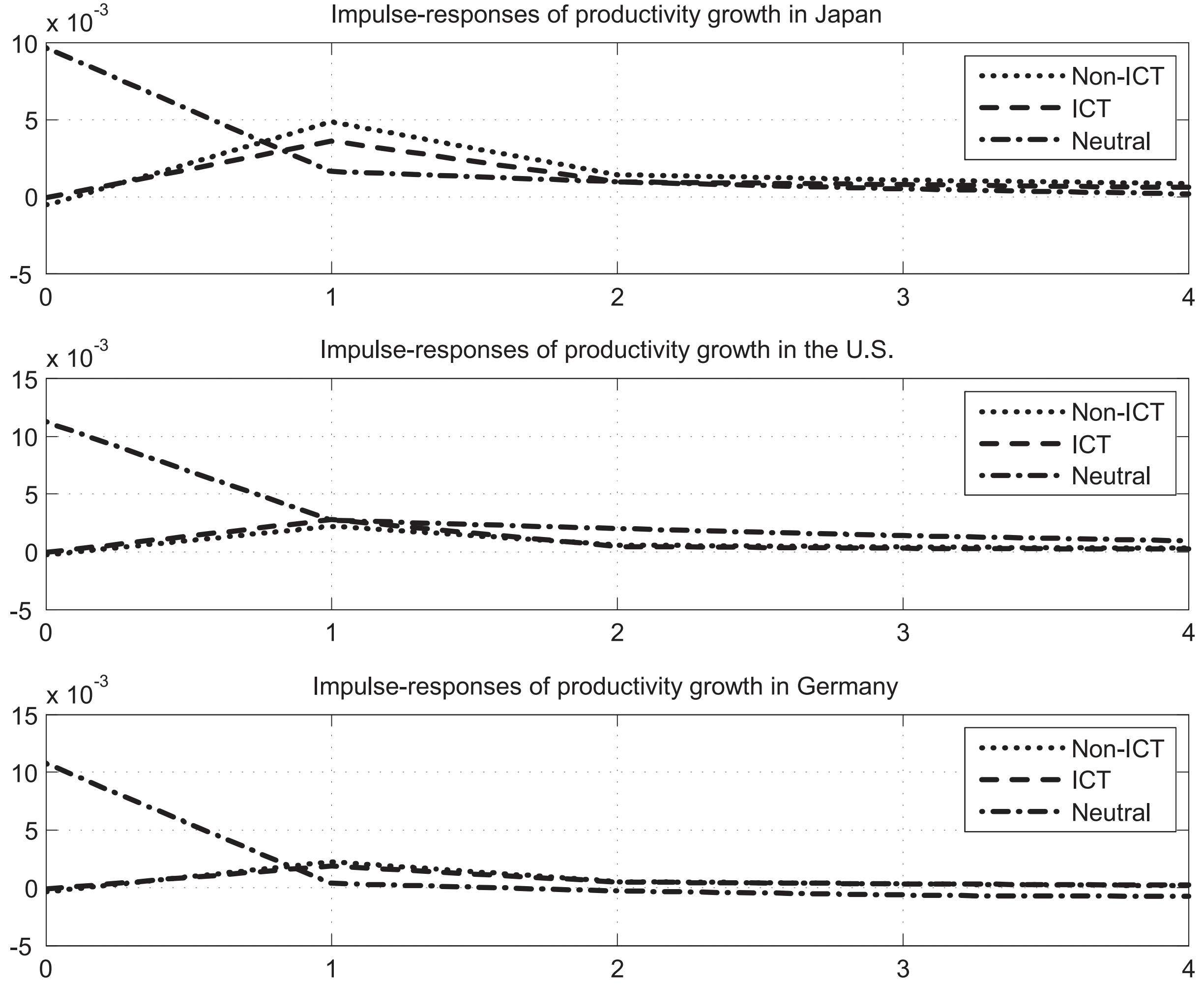


Figure 4: **Impulse responses of consumption growth**

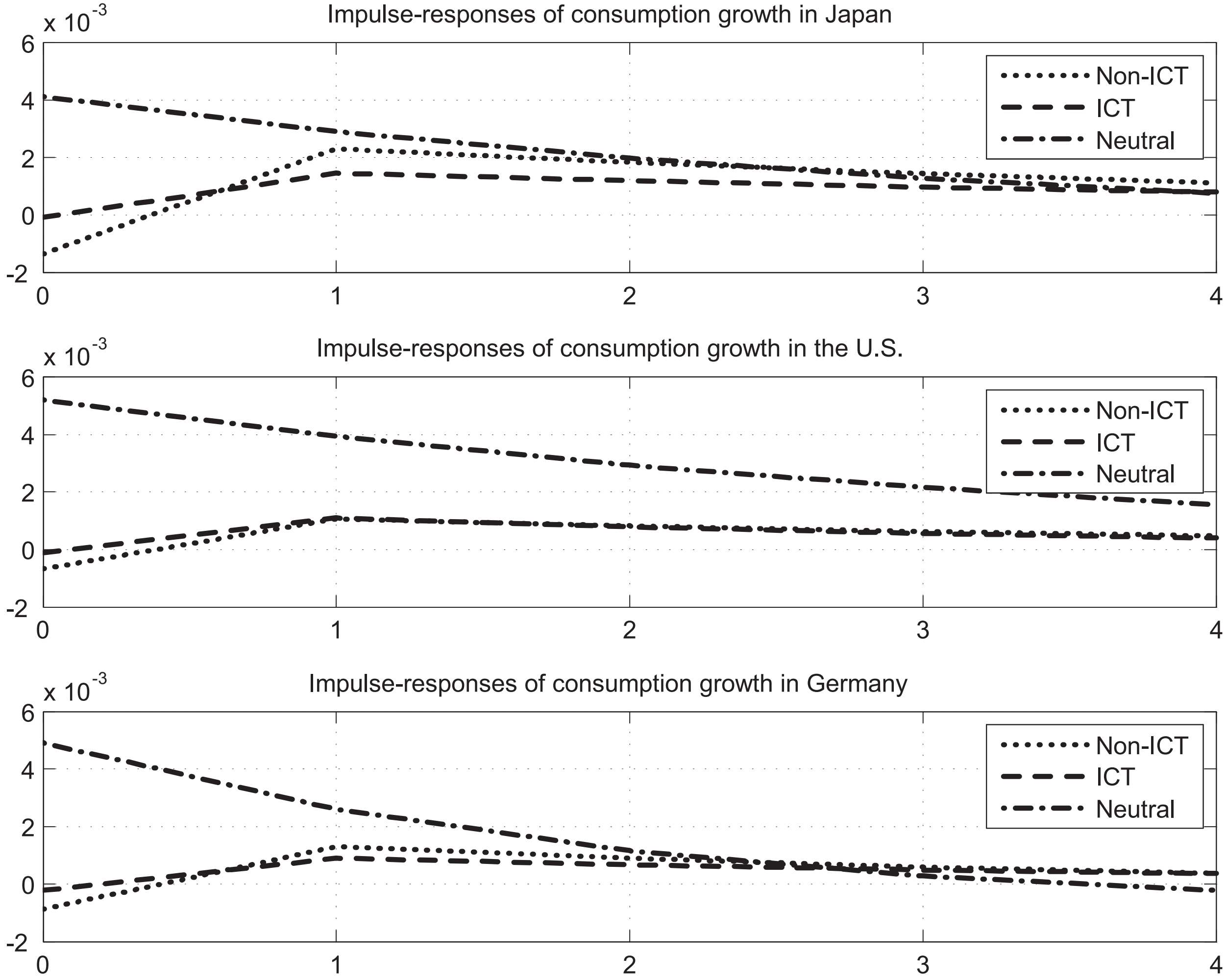


Figure 5.1: Impulse responses of investment growth in Japan

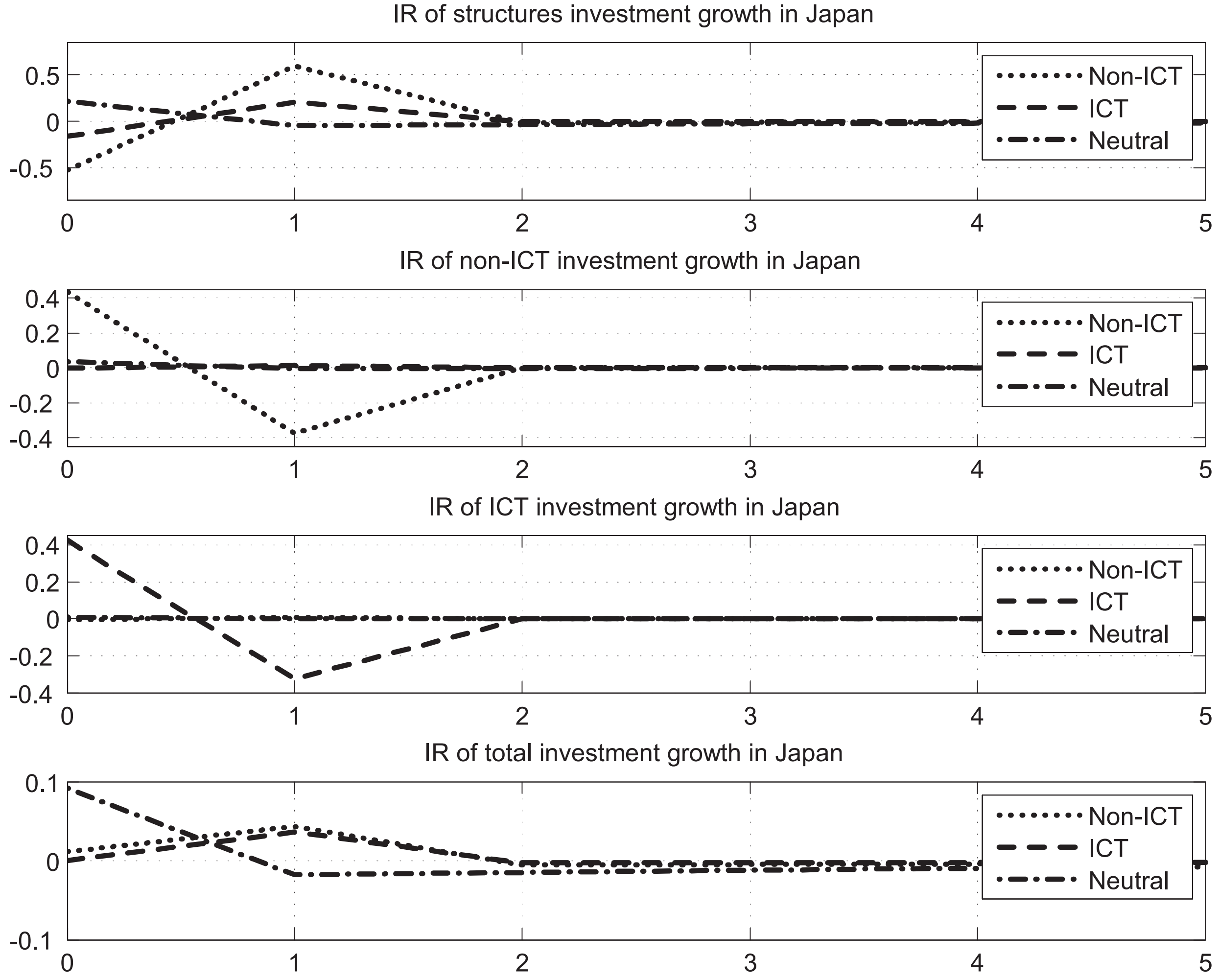


Figure 5.2: Impulse responses of investment growth in the U.S.A.

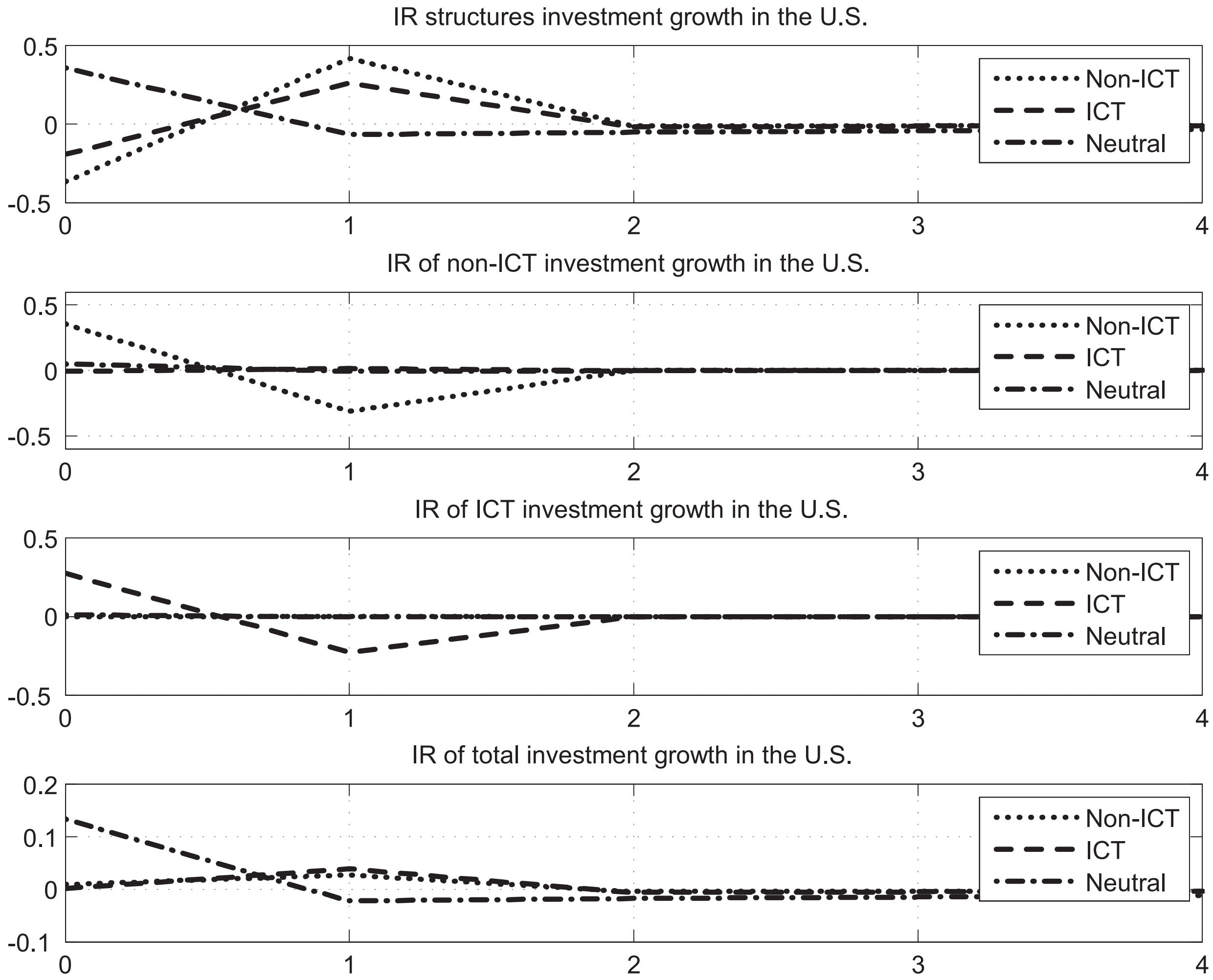
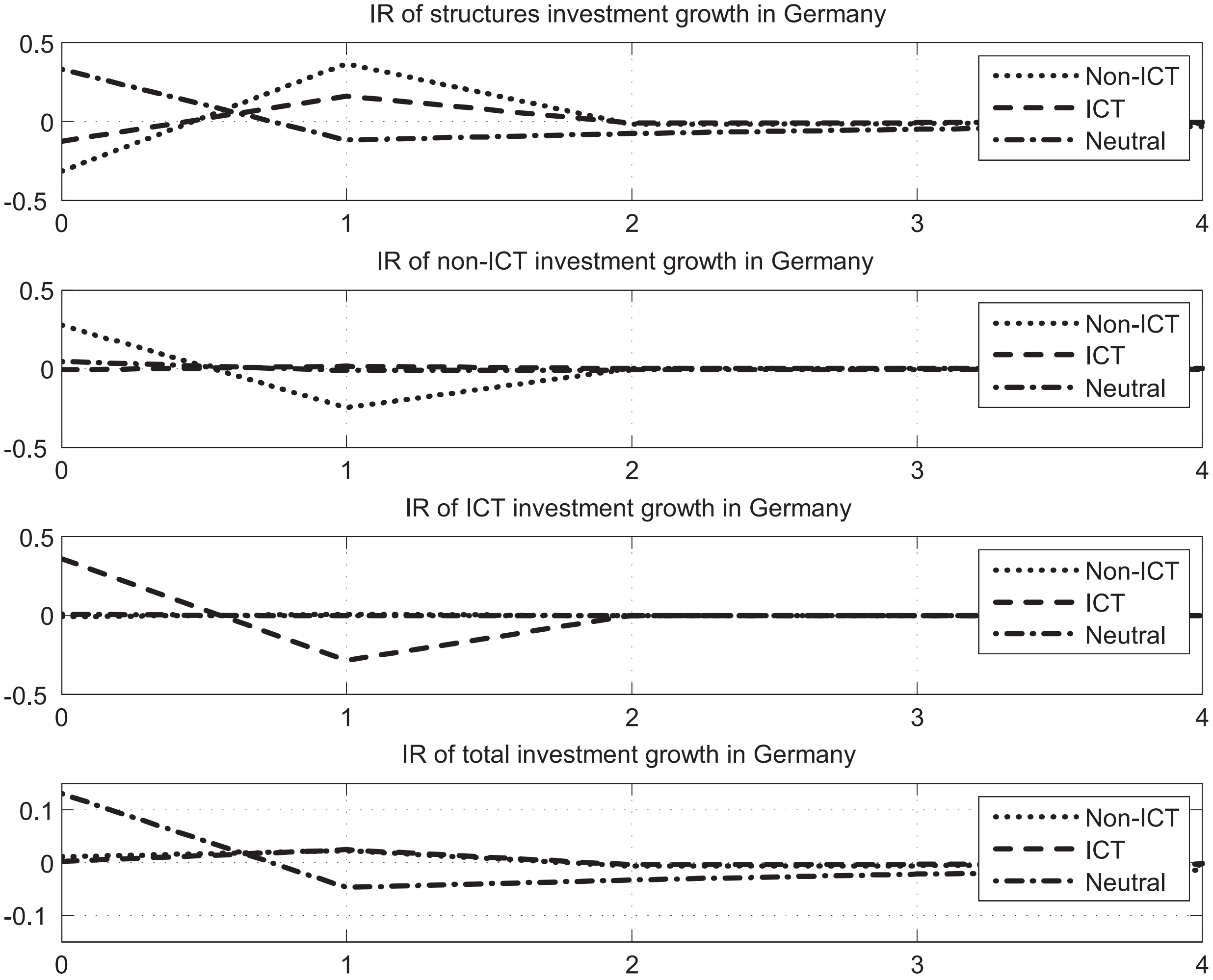


Figure 5.3: Impulse responses of investment growth in Germany


IR of structures investment growth in Germany

IR of non-ICT investment growth in Germany

IR of ICT investment growth in Germany

IR of total investment growth in Germany