Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

El Centro de Estudios Andaluces es una entidad de carácter científico y cultural, sin ánimo de lucro, adscrita a la Consejería de la Presidencia de la Junta de Andalucía.
El objetivo esencial de esta institución es fomentar cuantitativa y cualitativamente una línea de estudios e investigaciones científicas que contribuyan a un más preciso y detallado conocimiento de Andalucía, y difundir sus resultados a través de varias líneas estratégicas.

El Centro de Estudios Andaluces desea generar un marco estable de relaciones con la comunidad científica e intelectual y con movimientos culturales en Andalucía desde el que crear verdaderos canales de comunicación para dar cobertura a las inquietudes intelectuales y culturales.

Las opiniones publicadas por los autores en esta colección son de su exclusiva responsabilidad

Depósito Legal: SE-7350-08

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

E2008/11

R&D policy in Economies with Endogenous Growth and Non Renewable Resources

Betty Agnani *
UGR

Mª José Gutiérrez
UPV

Amaia Iza
UPV

RESUMEN

El objetivo de este artículo es analizar como las políticas activas de Investigación y Desarrollo directamente relacionadas con las tecnologías de la información afectan al crecimiento de la economía a través del aumento de la productividad en todos los sectores productivos en una economía que utilizan recursos no-renovables. En la literatura relacionada el resultado es que si el crecimiento es exógeno a través de cambios tecnológicos, la economía puede presentar un proceso de crecimiento a largo plazo. En este artículo se plantea un marco teórico distinto ya que consideramos un modelo de generaciones solapadas con crecimiento endógeno si dicho resultado sigue siendo válido. Se demuestra que existe dicho proceso si se acompaña de un proceso de cambio tecnológico (papel de los activos tecnológicos) y de una mayor participación del capital humano en el sector de I+D.

Clasificación JEL: O13, O40, Q32
Palabras Clave: Crecimiento Endógeno, I+D, recursos no renovables, sendas de crecimiento estable.

* Autor correspondencia: bagnani@ugr.es

ABSTRACT

The aim of this paper is to analyze how active R&D policies affect the growth rate of an economy with endogenous growth and non-renewable resources. We know from Scholz and Ziemens (1999) and Groth (2006) that in infinitely lived agents (ILA) economies, any active R&D policy increases the growth rate of the economy. To see if this result also appears in economies with finite lifetime agents, we developed an endogenous growth overlapping generations (OLG) economy à la Diamond which uses non-renewable resources as essential inputs in final good's production. We show analytically that any R&D policy that reduces the use of natural resources implies a raise in the growth rate of the economy. Numerically we show that in economies with low intertemporal elasticity of substitution (IES), active R&D policies lead the economy to increase the depletion of non-renewable resources. Nevertheless, we find that active R&D policies always imply increases in the endogenous growth rate, in both scenarios. Furthermore, when the IES coefficient is lower (greater) than one, active R&D policies affect the growth rate of the economy in the ILA more (less) than in OLG economies.

Key Words: endogenous growth, R&D, non-renewable resources, overlapping generations, infinitely lived agents, balanced growth path.
JEL classification: O13, O40, Q32

1 Introduction

One of the central analytical findings of the literature on growth is that worldwide economic growth is possible in spite of the finite supply of exhaustible resources if there is sufficient technological progress. The feasibility of positive long-run growth, despise nonrenewable natural resources being an essential input in the production sector, has been extensively explored in the neoclassical exogenous growth framework, among others by Stiglitz (1974), Solow (1974), Dasgupta and Heal (1974) and Agnani *et al.* (2005). In all these models, the feasibility of positive long-run growth of per capita consumption depends on the scope and extent of technological progress relative to the endogenous depletion rate of non-renewable resources. Furthermore, even though technological progress is exogenously given, long-run growth is endogenously determined since it depends on the endogenous depletion rate.

The relationship between the use of exhaustible resources and technological progress has also been analyzed in the endogenous growth literature developed in the 1990s. Studies such as Aghion and Howitt (1998), Barbier (1999), Scholz and Ziemens (1999) analyze the sustainability of positive long-run growth paths in economies with exhaustible resources and infinitely-lived agents (ILA), where the engine of growth is the creation of new intermediate inputs that are used as imperfect substitutes in the final-good sector.[1] This present paper follows this research line. In particular, our aim is to investigate how active R&D policies may affect the growth rate in endogenous growth economies that use exhaustible resources, which are essential inputs in the production sector.

We already know from Scholz and Ziemens (1999) and Groth (2006) that in ILA economies, any active R&D policy increases the growth rate of the economy. In this paper, we analyze the equivalent economy studied in Scholz and Ziemens (1999) with finite lifetime agents instead of considering infinitely-lived individuals. In particular, we develop an overlapping generations (OLG) model à la Romer (1990) where each generation consists of finite households that live for two periods and are not altruistic as in Diamond (1965). Authors such as Solow (1986) point out that OLG models appear to be "the natural habitat" for discussing on the impact of current resource extraction decisions on future generations. Other research such as Agnani *et al.* (2005) justifies the use of an OLG framework vs. that of the ILA models to analyze long-run growth with exhaustible resources,

[1] Aghion and Howitt (1998), Barbier (1999) and Nili (2001) solve the central planner's problem in this type of economy with constant elasticity of intertemporal substitution. Scholz and Ziemes (1999) extend this analysis by studying the market equilibrium in this kind of economy.

relying on the existence of empirical evidence against the altruism assumed in ILA models. Therefore, a comparison between the results in an OLG framework with respect to the ILA setup appears to be necessary. One of our main findings is that the policy implication is different in both scenarios.

From the theoretical point of view, we find that any active R&D policy affects the growth rate of the economy through two channels. First, the direct channel, which shows that the more productive the R&D sector is, the higher the growth rate of the stock of knowledge, regardless of the use of the exhaustible resources. This ceteris paribus result is quite intuitive, since this is the standard result in Romer's model, without exhaustible resources. Second, the indirect channel which comes through the use of the exhaustible resources in the final output sector. The sign of this indirect effect is ambiguous. We prove analytically that for both frameworks, ILA and OLG, any active R&D policy that leads the economy to deplete less exhaustible resources will increase the growth rate of the economy (this is the case in which direct and indirect effects work in the same direction).

For the ILA economy, we show that the indirect effect is positive whenever the intertemporal elasticity of substitution is greater than one and not too high. Contrariwise, the indirect effect is negative for values of the intertemporal elasticity of substitution lower than one. However, even for cases where the indirect effect goes in the opposite direction to the direct effect, we prove that the final effect of an active R&D policy on the growth rate is unambiguously positive.

For the OLG economy the determination of the stationary depletion rate is even more complex than in the ILA set up, so we are not able to characterize analytically the cases in which the indirect effect is positive or negative. Because of this complexity we numerically simulate the effects of active R&D policies in the economy under the two scenarios, ILA and OLG. First of all, the parameters of the model are selected such that the benchmark case for both scenarios represents the same economy, and mimics some empirical facts of the economy. Secondly, we compare the results under both scenarios when productivity in the R&D sector increases. Our main numerical findings are as follows: First, OLG and ILA economies are similar in terms of growth rates; however they are very different in the composition of the growth process. Whereas under the ILA scenario, economic growth relies more on a lower use of non-renewable resources, under the OLG economy the growth process depends on higher growth in the R&D sector. In this sense we could say that ILA economies are more exhaustible-conservationist. The intuition behind this result is clear. Since in ILA economies agents live up to infinity, they are able to wait until later to consume. Thus agents consume less today, depleting fewer resources, and devoting a high percentage of human capital to the R&D sector. Second, in both OLG and ILA economies, where agents are more willing to wait to consume in the future (i.e. with high IES coefficient), active R&D policies are more conservationist, depleting exhaustible resources less. And third, active R&D policies always increase the growth rate, under both scenarios. Furthermore, when current and future consumption are substitutes (complementaries), i.e. when the IES coefficient is lower (greater) than one, active R&D policies affect the growth rate more (less) in economies where agents live infinitely than those with finite lifetime agents.

The rest of the paper is organized as follows. Section 2 presents the OLG model. The market equilibrium in an OLG framework is defined in Subsection 2.1 and the balanced growth path is characterized in Subsection 2.2. In Section 3 we analyze the effect of an R&D policy on the two types of economies, ILA vs. OLG. Conclusions are presented in Section 4.

2 The Overlapping Generations (OLG) Model

We develop the basic two-period overlapping generations framework (Diamond (1965)) in an endogenous growth economy à la Romer (1990), with exhaustible resources which are essential inputs for production in the final good sector. From now on we refer to this set up as the OLG model. In order to analyze the role of the agents with finite lifetimes, we solve the equivalent model but with infinitely-lived agents. This is the model analyzed in Scholz and Ziemens (1999), but in continuous time rather than discrete time, and is developed in Appendix 2.

We assume that each generation consists of L new individual agents who live for two periods. There is no population growth. There are three production sectors: the final-good sector, the intermediate sector and the R&D sector.

Consumers/Households:

All individual agents have rational expectations and are identical except for their age. As usual in growth literature, since we are interested in economies for which balanced growth paths exist, we consider consumer preferences with constant elasticity of intertemporal substitution (King and Rebelo (1993))[2]. In particular the preferences of a representative agent born at period t are represented

[2]Constant elasticity of intertemporal substitution is a sufficient but not a necessary condition to guarantee the existence of balanced growth. See Stokey and Lucas (1984) for more details.

by

$$u\left(c_{1t}, c_{2,t+1}\right) = \frac{c_{1,t}^{1-\epsilon} - 1}{1-\epsilon} + \frac{1}{1+\theta}\left(\frac{c_{2,t+1}^{1-\epsilon} - 1}{1-\epsilon}\right),$$

where $c_{1,t}$ and $c_{2,t+1}$ represent consumption for young and old age, respectively; $\theta \geq 0$ is the subjective discount rate of the agent and $1/\epsilon > 0$ is the intertemporal elasticity of substitution (IES). The closer to (farther from) zero the parameter ϵ is, the more substitute (complementary) current and future consumptions are. In particular $\epsilon = 1$ represents the logarithmic preferences case.

Each agent born at period t, is endowed when young with a fixed quantity of human capital, h. Since all agents are identical, except for their age, the individual human capital of a young individual and the average level of human capital in the young population (which is assumed to be fixed in the economy) coincide. He/she receives the wage, w_{Ht}, per unit of labor, which can be used either to consume the final good, $c_{1,t}$, to buy the ownership rights to the resource stock, m_{t+1}, or to save, s_{t+1} (physical capital or bonds issued by the intermediate sector)[3]. The final consumption good is taken as a numerary and p_t is the price of the exhaustible resource in terms of final consumption good.

When the agent is old, at period $t+1$, his/her income comes from different sources. The return of his/her savings is $(1+r_{t+1})\, s_{t+1}$ which includes the rental from his/her physical capital stock and from the bonds issued by the intermediate firms. On the other hand, old agents receive income from selling resource property rights, m_{t+1}, to the young generation and to final-good firms.[4] The revenue from this sale is $p_{t+1} m_{t+1}$ (in per worker terms).

Therefore, the representative agent born at period t, maximizes his/her utility function with respect to young and old consumption taking prices as given. This problem can be set out in per worker terms as follows: $\forall t = 1, 2, ...$

$$\underset{\{c_{1,t}, c_{2,t+1}, s_{t+1}, m_{t+1}\}}{Max} \quad \frac{c_{1,t}^{1-\epsilon} - 1}{1-\epsilon} + \frac{1}{1+\theta}\left(\frac{c_{2,t+1}^{1-\epsilon} - 1}{1-\epsilon}\right),$$

[3] Consumers own the existing durable goods-producing firms, therefore the (net) intermediate sector's profits are paid to them. Alternatively, we could have assumed that consumers diversify their savings in the three forms, in physical capital, bonds (issued by intermediate firms) and exhaustible resource, but only in that amount of the exhaustible resource that is not used in the production process. (See Mourmouras (1993)).

[4] We are assuming that there exists a market for the exhaustible resource stock which is sold by older generations to younger generations, and a market for the exhaustible resource that is finally extracted and used in the production process (see, for example, Olson and Knapp (1997) or Agnani *et al.* (2005)).

$$
\begin{aligned}
s.t. \quad & c_{1,t} + p_t m_{t+1} + s_{t+1} = w_{H,t} h, & (1) \\
& c_{2,t+1} = (1 + r_{t+1}) s_{t+1} + p_{t+1} m_{t+1}, & (2) \\
& w_{H,t}, p_t \text{ and } r_{t+1} \text{ are given.}
\end{aligned}
$$

The first order conditions for this maximization problem can be expressed as

$$
\frac{c_{2,t+1}}{c_{1,t}} = \left(\frac{1+r_{t+1}}{1+\theta}\right)^{1/\epsilon}, \tag{3}
$$

$$
1 + r_{t+1} = \frac{p_{t+1}}{p_t}. \tag{4}
$$

Equation (3) indicates that each consumer equates the marginal rate of substitution between current and future consumption to their relative prices, or marginal rate of transformation given by $1 + r_{t+1}$. Equation (4) is the standard arbitrage condition that characterizes the optimal investment between the two forms of savings such that the marginal returns on both must be equal. In other words, the marginal rate of saving in the exhaustible resource, p_{t+1}/p_t, must be equal to the marginal rate of saving in physical capital or bonds issued by the intermediate firms, $1 + r_{t+1}$[5].

Combining first order conditions (3)-(4) and taking into account consumer budget constraints, the consumer saving function can be characterized as

$$
s_{t+1} + p_t m_{t+1} = \frac{w_{H,t} h}{1 + (1+\theta)^{1/\epsilon} (1 + r_{t+1})^{-\left(\frac{1-\epsilon}{\epsilon}\right)}}.
$$

Notice that given the arbitrage condition, (4), the consumer's income in the second period depends on $s_{t+1} + p_t m_{t+1}$. Therefore, from the consumer's point of view, any combination of physical capital, bonds and exhaustible resources satisfying this saving function maximizes his/her utility.

Production Sectors:

There are three production sectors: the final-good sector, the intermediate-goods sector and the R&D sector.

[5] This arbitrage condition satisfies the well-known Hotelling rule of optimal resource extraction for exhaustible resource in partial equilibrium models, under assumption of costless extraction (Hotelling, 1931).

a) The final-good sector:

This sector produces a homogeneous good, Y_t, that can be consumed or invested in the form of physical capital. All firms share the same production technology and use as inputs human capital, $H_{Y,t}$, a variety of intermediate goods, X_t^i with $i = 1, ...A_t$, and the exhaustible resource extracted, E_t. A_t indicates how large the variety of the intermediated goods is, and it also represents the stock of knowledge of the economy.

The aggregate production function for the final output is given by $Y_t = H_{Yt}^{\alpha_1}\left[\sum_{i=1}^{A_t}\left(X_t^i\right)^{\alpha_2}\right]E_t^{\alpha_3}$. Following Romer (1990), we assume the same technology for producing any intermediate good and, in consequence, their unit cost is the same. Therefore, since they enter in the final-good sector symmetrically, in equilibrium an identical amount of each intermediate good will be produced: $X_t^i = X_t, \quad \forall i = 1, ...A_t$. This implies that *in equilibrium* the total amount of intermediate-goods in the economy can be denoted by $\sum_{i=1}^{A_t}\left(X_t^i\right)^{\alpha_2} = A_t X_t^{\alpha_2}$ and the aggregate production function by

$$Y_t = A_t H_{Yt}^{\alpha_1} X_t^{\alpha_2} E_t^{\alpha_3}. \tag{5}$$

Constant returns to scale with respect to all private inputs are assumed, i.e., $\alpha_1 + \alpha_2 + \alpha_3 = 1$.

Final-good firms hire labor, intermediate goods and exhaustible resources to maximize profits taking prices and the stock of technology as given. Therefore, the representative firm's problem can be set down as follows in each period t,

$$\underset{\left\{H_{Yt},\{X_t^i\}_{i=1}^{A_t},E_t\right\}_{t=0}^{\infty}}{Max} \qquad Y_t - w_{H,t}H_{Y,t} - q_t\sum_{i=1}^{A_t}X_t^i - p_tE_t,$$

$$s.t. \quad Y_t = H_{Yt}^{\alpha_1}\sum_{i=1}^{A_t}\left(X_t^i\right)^{\alpha_2}E_t^{\alpha_3},$$

$$w_{H,t}, q_t, p_t, \text{and } A_t \text{ are given.}$$

where q_t is the price of the intermediate goods.

In the case of an interior solution, the first-order conditions for the firm's maximization problem are given by the following equations

$$\alpha_1 H_{Yt}^{(\alpha_1-1)}\left(A_t X_t^{\alpha_2}\right) E_t^{\alpha_3} = w_{H,t}, \quad (6)$$

$$\alpha_2 H_{Yt}^{\alpha_1} X_t^{(\alpha_2-1)} E_t^{\alpha_3} = q_t, \quad (7)$$

$$\alpha_3 H_{Yt}^{\alpha_1}\left(A_t X_t^{\alpha_2}\right) E_t^{\alpha_3-1} = p_t, \quad (8)$$

which indicate that firms hire labor, intermediate goods and exhaustible resources until their marginal products equal their factor prices.

b) The monopolistic intermediate-goods sector / design market:

The intermediate-goods sector uses the designs innovated by the R&D sector to produce the intermediate goods that are available in each period. This sector is composed of A_t firms indexed by "i". The only input used in the production of the intermediate good i is physical (man-made) capital, K_t, [6] and the production function is given by

$$X_t^i = K_t^i/\eta, \ \forall i \in [0, A_t],$$

where K_t^i is physical capital used in the production of intermediate good i, and η denotes the units of physical capital required to produce one unit of intermediate good, X_t^i.

Each firm indexed by "i" owns an infinite life-time patent that allows it to produce monopolistically its corresponding intermediate good. This patent is bought in a competitive market for new designs (patents) and it financed through a bond issued with an interest rate of r_{t+1}.

Since the patent has an infinite life-time, the equilibrium price of the patent will be equal to the present discount value of the infinite stream of profits it will generate. So, the price for the patent, P_t^A, is given by the following expression in each period t

$$P_t^A = \sum_{\tau=t+1}^{\infty} \frac{\pi_\tau}{\prod_{s=t+1}^{\tau}(1+r_s)}$$

or equivalently solving the above equation we can write,

[6] Capital goods are produced in a separate sector that has the same technology as the final-output sector, i.e. K_t can be accumulated as foregone output. We assume that physical capital stock, K_t, does not depreciate, $\delta = 0$.

$$P_t^A = \left(\frac{1}{1+r_{t+1}}\right)[P_{t+1}^A + \pi_{t+1}], \tag{9}$$

where π_t is the profit of a representative monopolist producing intermediate good i at period t.

Once the patent has been paid, each intermediate-good i is produced monopolistically by a single firm, which sells it to the final good sector at a price, q_t. Taking into account the demand function for intermediate good, (7), the monopoly problem for the intermediate firm producing a good i is given by,

$$\underset{\{X_t\}_{t=0}^{\infty}}{Max} \quad \pi_t = q_t X_t - r_t K_t^i,$$

$$s.t. \quad \begin{cases} q_t = \alpha_2 H_{Yt}^{\alpha_1} X_t^{(\alpha_2-1)} E_t^{\alpha_3}, \\ X_t = K_t^i/\eta, \\ H_{Y,t}, E_t \text{ and } r_t \text{ are given.} \end{cases}$$

The first-order condition for this maximization problem is

$$q_t = \frac{r_t \eta}{\alpha_2}. \tag{10}$$

The resulting monopoly price given by equation (10) is a markup over the marginal cost, and this markup is determined by the elasticity of the demand curve, $1/(\alpha_2 - 1)$. The flow of monopoly profit is positive and works out at

$$\pi_t = (1-\alpha_2) q_t X_t > 0. \tag{11}$$

c) The R&D sector:

This sector uses human capital and the existing stock of knowledge to produce new knowledge, which consists in designs for new intermediate goods. There are j competitive firms producing designs and sharing the same technology, $\sigma H_{A,t}^j A_t$, which depends upon a productivity parameter, σ, the amount of human capital devoted to R&D activities by the research firm j, $H_{A,t}^j$, and the stock of knowledge available (number of designs) in the economy, A_t.

The aggregate stock of designs evolves according to the following law of motion,

$$A_{t+1} - A_t = \sigma H_{A,t} A_t, \tag{12}$$

where we $H_{A,t} = \sum_j H^j_{A,t}$ is the aggregated amount of human capital used by the R&D firms.

The technological productivity parameter, σ, is an intrinsic parameter that characterizes the R&D process of the economy. It captures all those factors that affect productivity in the R&D sector, apart from the amount of human capital devoted to the R&D activities. Such factors might include property rights, corruption, R&D infrastructure, even the ability to imitate from outside. In fact, in some articles, such as Benhabib and Spiegel (1994) or Córdoba and Ripoll (2005), the R&D sector productivity depends on the distance of the technology in the country relative to the technology frontier, which is assumed to be exogenous to the country. In general, the higher the value of σ, the higher the growth rate of new knowledge, for a given amount of human capital devoted to the R&D sector. Therefore, if an economy wishes to accelerate the creation of new knowledge it should develop technological policies that increase this productivity parameter.

A representative research sector firm hires the stock of human capital to maximize its profits given the dynamics of the stock of technology and taking wages, patent price and initial stock of technology as given,

$$\underset{\{H_{A,t}\}_{t=0}^{\infty}}{Max} \qquad P_t^A\,(A_{t+1} - A_t) - w_{H,t} H_{A,t},$$

$$s.t. \qquad \begin{cases} A_{t+1} - A_t = H_{A,t}\sigma A_t, \\ H_{A,t} \geq 0, \\ w_{H,t},\, P_t^A \text{ and } A_0 \text{ are given.} \end{cases}$$

The first order condition for maximization of the R&D firm's problem is given by

$$P_t^A \sigma A_t \leq w_{H,t}, \tag{13}$$

with equality if $H_{A,t} > 0$. This condition indicates that R&D firms hire human capital until their marginal product equals its factor price. As in Romer (1990), if the stock of human capital in the economy is not high enough, the economy will allocate no resources to produce new designs.

Exhaustible Resources

The economy is initially endowed with a positive amount of exhaustible resources, M_0. The stock of exhaustible resources in the current period, M_t, is determined by the stock available in the previous period minus those resources extracted for the use of the final-good sector, i.e. $M_t = M_{t-1} - E_{t-1}$. If we define the depletion rate of exhaustible resources as

$$\tau_t = \frac{E_t}{M_t} \tag{14}$$

the equilibrium dynamics for exhaustible resources can be expressed as

$$M_{t+1} = (1 - \tau_t) M_t. \tag{15}$$

Human Capital

The human capital stock, $H = hL$, is fixed and is addressed either to the final good sector, H_Y, or to the R&D sector, H_A:

$$H = H_{Y,t} + H_{A,t}. \tag{16}$$

2.1 The Equilibrium Solution

In the endogenous growth model described above, a dynamic equilibrium is a sequence of quantities $\{c_{1,t}, c_{2,t}, s_{t+1}, K_{t+1}, Y_t, X_t, \tau_{t+1}, E_t, M_{t+1}, H_{Y,t}, H_{A,t}, A_{t+1}, \pi_t\}_{t=0}^{\infty}$ and prices $\{P_t^A, w_{H,t}, r_t, p_t, q_t\}_{t=0}^{\infty}$ such that: *i)* consumers maximize utility subject to their intertemporal budget constraint taking prices as given; *ii)* firms in the final-good sector maximize profits choosing labor and intermediate inputs taking their prices as given; *iii)* each design owner produces its corresponding intermediate good maximizing monopolistic profits, taking human capital and the demand they face as given; *iv)* producers of the new designs maximize profits choosing labor, taking wages, patent price and initial stock of technology as given; and *v)* all markets clear.

Market clearing

Market clearing conditions are given by the following:

i) Human capital allocates between the final-good sector and the R&D sector such that equations (6), (13) and (16) are satisfied.

ii) The resource market clears when non-renewable resources supplied by old agents are equal to the demand of firms and young agents. Therefore, the equilibrium evolution of the stock of exhaustible resources is given by equation (15)

iii) The designs market clears when the demand for each new design equals its supply, i.e. whenever equation (9) holds.

iv) The physical capital market clears when the stock of capital in the economy is equal to the demand for capital in the intermediate good sector. This means that

$$\eta A_t X_t = K_t. \tag{17}$$

v) The final good market clears when demand equals supply. The final good is devoted to consumption or to investment in physical capital, patents or non-renewable resources. Since we have used s_t to denote the savings per worker in physical capital and patents, the condition under which the final good market clears can be written in the standard way, i.e. the stock of physical capital per worker is given by

$$K_{t+1} + P_t^A A_{t+1} = s_{t+1} L. \tag{18}$$

The equilibrium characterization is summarized in the following definition.

Definition 1 *For any arbitrary initial value of τ_0, an equilibrium of this OLG economy is an infinite sequence of quantity allocations $\left\{c_{1,t}, c_{2,t+1}, s_{t+1}, K_{t+1}, Y_t, X_t, \tau_{t+1}, E_t, M_{t+1}, H_{Y,t}, H_{A,t}, A_{t+1}, \pi_t\right\}_{t=0}^{\infty}$ and prices $\left\{P_t^A, w_{H,t}, r_t, p_t, q_t\right\}_{t=0}^{\infty}$ such that consumers, final-goods producers and research firms maximize their objective functions taking prices as given, the intermediate firms maximize their monopolist profits and all markets clear, given the initial conditions $K_0, M_0, A_0 > 0$[7]. In other words, an equilibrium is a solution of the non-linear system (1)-(18).*

Note that the equilibrium is unable to determine the initial depletion rate. This problem has been solved in other related articles in different ways. Aghion and Howitt (1998) choose K_0 such that the economy starts on the balanced growth path and τ_0 is chosen under this assumption. Scholz and Ziemes (1999) choose τ_0 such that the steady state is a saddle path. Stiglitz (1974) takes the initial price for the exhaustible resource as given. Barbier (1999) takes the initial depletion rate of the exhaustible resource as given. Since we are interested only in the balanced growth equilibrium we do not address this issue.

[7]Since physical capital, exhaustible resources and technology are essential for production, K_0, M_0 and A_0 must be positive. Otherwise young consumers of the initial generation would have no income and consumption would remain zero forever.

2.2 The Balanced Growth Path

In general terms, balanced growth paths are those where all variables grow at a constant rate. As Groth (2006) notes, *compliance with Kaldor's styled facts is generally equivalent with the existence of balanced growth paths*. Furthermore, King *et. al.* (1988) point out that economies characterized by constant growth rates in the long-run provide clear evidence of industrialization. This is why in this section we focus on the equilibria paths where all variables grow at constant rates. In particular, we analyze balanced growth paths defined as follows :

Definition 2 *A balanced growth path is an equilibrium path where all variables grow at a constant rate and the depletion rate of exhaustible resources and stock of human capital allocations among the final-good and R&D sectors remain constant.*

Let us define γ_z as the ratio z_{t+1}/z_t, on the balanced growth path for all endogenous variables except for depletion rate and the stock of human capital in the final-good and R&D sectors. For the latter ones, we define $\tau = \tau_{t+1} = \tau_t, H_Y = H_{Y,t+1} = H_{Y,t}$ and $H_A = H_{A,t+1} = H_{A,t}$. With these definitions the balanced growth path will be determined by a zero growth rate for the depletion rate and human capital allocations and by constant growth rates $(\gamma_z - 1)$ for the rest of the endogenous variables. The following proposition states conditions that any balanced growth path of this OLG economy must satisfy.

Proposition 1 *Any balanced growth path of this OLG economy is given by a vector* $\left\{\gamma_Y, \gamma_K, \gamma_A, \gamma_M, \gamma_\pi, \gamma_s, \gamma_{c_1}, \gamma_{c_2}, \gamma_X, \gamma_E, \gamma_p, \gamma_q, \gamma_r, \gamma_{P^A}, \gamma_{\omega_H}, H_Y, H_A, \tau\right\}$ *satisfying the following system of equations*

$$\left.\begin{array}{c}
\frac{\alpha_2^2\gamma}{\gamma-(1-\tau)} = \frac{(1-\alpha_2)\alpha_2}{\gamma_A-(1-\tau)}\left(\frac{\sigma H}{1+(1+\theta)^{\frac{1}{\epsilon}}\left(\frac{\gamma}{1-\tau}\right)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}} - \gamma_A\right) - \frac{\alpha_3}{\tau}, \\
\gamma_A = \frac{(1-\tau)[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1]}{(1-\tau)(1-\alpha_2)\alpha_2+\alpha_1}, \\
H_Y = \frac{\alpha_1([\gamma_A-(1-\tau)]}{(1-\tau)\sigma(1-\alpha_2)\alpha_2}.
\end{array}\right\}, \; if \; H_A = H - H_Y > 0,$$

$$\left.\begin{array}{c}
\frac{(1-\tau)\alpha_2^2\gamma}{\gamma-(1-\tau)} = \frac{\alpha_1}{1+(1+\theta)^{\frac{1}{\epsilon}}\left(\frac{\gamma}{1-\tau}\right)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}} - \frac{\gamma_M(\alpha_3+(1-\alpha_2)\alpha_2)}{\tau}, \\
\gamma_A = 1, \\
H_Y = H.
\end{array}\right\}, \; if \; H_A = 0,$$

$$
\begin{aligned}
\gamma_M &= \gamma_E = 1-\tau, \\
\gamma_X &= \gamma_{P^A} = \gamma_\pi = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}, \\
\gamma_p &= \frac{\gamma}{1-\tau}, \\
\gamma_r &= \gamma_q = 1, \\
\gamma_K &= \gamma_Y = \gamma_{c_1} = \gamma_{c_2} = \gamma_s = \gamma_{w_H} = \gamma.
\end{aligned}
$$

where $\gamma = \gamma_A (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$.

Proof. See Appendix 1. ■

This proposition states that in this OLG framework the stationary depletion rate, τ, is obtained endogenously from a non-linear equation and is determined in the last instance for all the parameters of the economy.[8] This is not surprising since Agnani *et al.* (2005) obtain a similar result for OLG economies with exhaustible resources but with an exogenous engine of growth. Proposition 3, in Appendix 2, shows that in ILA economies, the stationary depletion rate also depends on all parameters of the model but in a different manner. But for the particular case of logarithmic consumer preferences ($\epsilon = 1$), the stationary depletion rate is given solely by the consumers' subjective discount rate, θ, in ILA economy (see Corollary 1 in Appendix 2) while it depends on all the parameters in the OLG setup.

There are two types of balanced growth paths: those with interior solutions for the stock of human capital devoted to the R&D sector and those with corner solutions characterized by a null allocation of human capital in the R&D sector.

The growth rate of the economy, both in OLG and ILA economies, is given by $\gamma - 1 = \gamma_A (1-\tau)^{\alpha_3/(1-\alpha_2)} - 1$, where γ_A also depends on the depletion rate, τ, in the case of an interior solution (i.e. when $H_A > 0$). Therefore, any change in the exogenous variables that affects the endogenous growth rate solely through their effect on the endogenous stationary depletion rate (such as θ and ϵ), will depend only on how the endogenous depletion rate τ affects the endogenous growth rate.[9] There are two effects, both of the same sign, such that any exogenous change (in θ or ϵ) that negatively affects the endogenous depletion rate will have

[8] It is not possible to characterize the uniqueness of the equilibrium of this economy. We have found numerical parametrizations for which there are multiple equilibria.

[9] This is not the case for the R&D parameter, σ. In this case this parameter affects γ directly through γ_A. See Proposition 1.

a positive effect on the endogenous growth rate[10]. The direct effect shows that the greater the endogenous depletion rate of the non-renewable resources, the lower the endogenous growth rate, regardless of the growth of the stock of knowledge, γ_A. That is $\partial\gamma/\partial\tau < 0$, taking γ_A as a constant. The indirect effect works through the allocation of the stock of human capital between R&D and the final output sector. Analyzing γ_A we can see that the higher the stationary depletion rate, the lower the growth of the stock of knowledge in the economy, and, consequently, the lower the growth rate.[11] Note that this indirect effect appears because the engine of growth in the economy is endogenous.[12]

From Propositions 1 and 3 in Appendix 2, the following remark shows necessary conditions that guarantee positive growth in ILA and OLG economies.

Remark 1 *A necessary (but not sufficient) condition for an ILA and OLG economy to exhibit positive growth is that part of the human capital has to be allocated to the R & D sector,* $H_A > 0$.

Note that equilibria with $H_A = 0$ imply that $\gamma_A = 1$ and $\gamma = (1-\tau)^{\alpha_3/(1-\alpha_2)} < 1$ whenever the exhaustible resource is an essential input in the final-good production, $\alpha_3 > 0$.

Propositions 1 and 3 also state that on the balanced growth path, income, physical capital, consumption, savings and wage rates grow at the same rate, $(\gamma - 1)$, which depends on all parameters of the economy. The price of non-renewable resources grows at a higher rate than income, indicating that these resources are exhaustible and consequently the supply decreases over time. Since

[10]This result is very similar to the one obtained in Groth (2006) under an endogenous growth model, with non-renewable resources, without technical progress. In particular, he finds that *along a BGP, policies that decrease (increase) the depletion rate (and only such policies) will increase (decrease) the per capita growth rate.*

[11]Note that from the definition of γ we have

$$\frac{\partial\gamma}{\partial\tau} = \frac{\partial\gamma_A}{\partial\tau}(1-\tau)^{\frac{\alpha_3}{1-\alpha_2}} - \frac{\alpha_3}{1-\alpha_2}(1-\tau)^{\frac{-\alpha_1}{1-\alpha_2}}\gamma_A.$$

The second sum of the left hand side expresses the direct effect. The indirect effect comes through γ_A, that is

$$\frac{\partial\gamma_A}{\partial\tau} = -\frac{\alpha_1[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1]}{[(1-\tau)(1-\alpha_2)\alpha_2+\alpha_1]^2} < 0.$$

Therefore $\partial\gamma/\partial\tau < 0$.

[12]When the engine of growth is exogenous, the indirect effect does not appear (see Agnani *et al*. (2005)).

the gross interest rate is the growth rate of the price of exhaustible resources (arbitrage condition (4)), the interest rate must be constant on the balanced growth path. Observe that the stock of non-renewable resources and the use of such resources in the production process, M_t and E_t, decline over time. Moreover, if the growth rate of the economy is positive, i.e. if $\gamma > 1$, then the price of exhaustible resources must increase.

Another interesting result from Proposition 1 and 3 is stated in the following remark.

Remark 2 *The patent price decreases along the balanced growth path.*

This result contrasts with Romer's growth model (1990) solution, where the patent price remains constant, because the wage per unit of labor must grow at the same rate in both sectors (final-good and R&D sector) (equations (6) and (13)), and income and physical capital grow at a lower rate than the number of designs (stock of knowledge) due to the use of the exhaustible resources in the final-good sector. In consequence, the patent price decreases, capturing the fact that on the balanced growth path the productivity of the stock of knowledge decreases with the use of non-renewable resources.

Although OLG and ILA economies show the same relationship between the endogenous growth rate and the endogenous stationary depletion rate, the relationships between the endogenous stationary depletion rate and the exogenous variables are different in both frameworks. In the following section we compare the balanced growth paths obtained in the ILA and OLG scenarios. In particular we focus on how the balanced growth varies when R&D policies are implemented in both scenarios.[13]

3 R&D Policy and the Finite Lifetimes

The aim of this paper is to analyze how an active R&D policy may affect the growth rate of the economy. In particular, we compare the results of an increase in the R&D productivity parameter, σ, in infinitely lived economies and in economies with finite lifetime agents.

From Proposition 1 and 3 (last in Appendix 2), we know that the relationship between the endogenous growth rate of the economy and the technological

[13] Scholz and Ziemens (1999) focus on the determinacy and stability of the equilibrium for the ILA economy. They show that some technological prerequisites have to be met in order to guarantee the stability of the equilibrium. We do not focus on this aspect.

parameter of the R&D sector is not obvious. The next proposition shows that when increases in the R&D parameter lead an economy to reduce the extraction of resources, this implies an increase in the growth rate of the economy in question. However, the opposite may not occur.

Proposition 2 *In ILA and OLG economies, if $\partial\tau/\partial\sigma < 0$ then $\partial\gamma/\partial\sigma > 0$.*

Proof. Since the growth rate of the economy is given by $\gamma = \gamma_A(1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$, then

$$\frac{\partial\gamma}{\partial\sigma} = \frac{\partial\gamma_A}{\partial\sigma}(1-\tau)^{\frac{\alpha_3}{1-\alpha_2}} - \frac{\alpha_3}{1-\alpha_2}(1-\tau)^{\frac{-\alpha_1}{1-\alpha_2}}\gamma_A\frac{\partial\tau}{\partial\sigma}.$$

Since $\gamma_A = \frac{(1-\tau)[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1]}{(1-\tau)(1-\alpha_2)\alpha_2+\alpha_1}$, then

$$\frac{\partial\gamma_A}{\partial\sigma} = \frac{(1-\tau)H(1-\alpha_2)\alpha_2}{(1-\tau)(1-\alpha_2)\alpha_2+\alpha_1} + \frac{\partial\gamma_A}{\partial\tau}\frac{\partial\tau}{\partial\sigma}.$$

On the other hand, since

$$\frac{\partial\gamma_A}{\partial\tau} = -\frac{\alpha_1[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1]}{[(1-\tau)(1-\alpha_2)\alpha_2+\alpha_1]^2} < 0,$$

if $\frac{\partial\tau}{\partial\sigma} < 0$, then $\frac{\partial\gamma_A}{\partial\sigma} > 0$ and $\frac{\partial\gamma}{\partial\sigma} > 0$. ■

Groth (2006) shows that the condition imposed for the statement of this proposition is not only a sufficient but also a necessary condition in endogenous growth economies with non-renewable resources and without technical progress.

Note that the above proposition shows the best situation for the economy to stimulate its growth rate. Note also that $\gamma_A = \frac{(1-\tau)[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1]}{(1-\tau)(1-\alpha_2)\alpha_2+\alpha_1}$, where τ is endogenously determined by all parameters of the model. Therefore, any change in the technological parameter affects the growth rate of the stock of knowledge through two channels. First, the direct channel which shows that the greater the R&D productivity parameter, the higher the growth rate of the stock of knowledge, regardless of the stationary depletion rate, τ. This is so because the higher the productivity parameter of the R&D sector, the higher the amount of human capital allocated to the R&D sector. That is $\partial\gamma_A/\partial\sigma > 0$, taking τ as given. Second, the indirect channel which works through the use of the non-renewable resources in the final output sector. Analyzing γ_A we can see that any increase in the depletion rate leads to a reduction of technological growth; however, the relationship between the technological parameter and the stationary depletion rate is ambiguous. It is clear that if the relationship between the R&D

productivity parameter and the use of the non-renewable resources is negative, the direct and indirect channels work in the same direction and any stimulant R&D policy increases the growth rate of the stock of knowledge. However when an increase in the technological parameter leads to an increase in the depletion rate, the indirect effect goes in the opposite direction to the direct effect, and the final result of the R&D productivity parameter over the growth rate is ambiguous.

Corollaries 1 and 2 in Appendix 2 characterize the sign of the indirect effect for the ILA economy. In particular, the indirect effect is shown to be positive whenever $\frac{\alpha_3}{\alpha_1+2\alpha_3} \leq \epsilon \leq 1$ and negative for $\epsilon > 1$. Considering Proposition 2, it is straighforward that whenever $\frac{\alpha_3}{\alpha_1+2\alpha_3} \leq \epsilon \leq 1$, an active R&D policy will affect the growth rate of the economy positively. However, even for cases where the indirect effect goes in the opposite direction to the direct effect, i.e. when $\epsilon > 1$, Proposition 4 in Appendix 2 proves that the final effect of an active R&D policy over the growth rate is positively unambiguous.

To summarize, when the IES, $1/\epsilon$, is lower than $(\alpha_1 + 2\alpha_3)/\alpha_3$ an active R&D policy guarantees an increase in the growth rate of an ILA economy. However this result cannot be generalized for very large values of the IES in the ILA economy. This finding does not enter in conflict with Scholz and Ziemens (1999) who show that the growth rate of the economy always responds positively to active R&D policies.[14] In the case of the OLG economy the determination of the stationary depletion rate is even more complex than in the ILA set up, so, unlike the ILA model, we are not able to characterize cases in which $\partial\tau/\partial\sigma < 0$. Because of this analytical complexity, we present in the following subsections the calibration of the economy used to compare numerically, in both scenarios (ILA and OLG), the effects of an active R&D policy over the growth of the economy.

3.1 Parameterization

To compute the stationary equilibrium, we specify values for the parameters such that *i)* they are consistent with some empirical facts and *ii)* they are perfectly standard in the literature.

The subjective discount rate was chosen to make that the annual discount factor 0.98, which is standard in calibration literature. In the ILA framework it implies a value for θ equal to 0.02. If we assume that in the OLG economy, each period is 25 years long, an annual discount rate of 0.02 is equivalent to 0.65 for a

[14]Scholz and Ziemens (1999) develop their model in continous time. This allows them to find an explicit expression for the growth rate which is tractable to finding this effect.

25-year period.[15]

In the benchmark case, the IES is equal to 1 (i.e. $\epsilon = 1$) which represents consumer logarithmic preferences. Besides being studied in theoretical papers (see for instance Agnani *et al.* (2005), Hsuku (2007)), there is evidence that the IES is significantly different from zero and probably close to one (Beaudry and Wincoop (1996)). On the other hand, this value is in the interval that Gourinchas and Parker (2002) considered as plausible. They conclude that the IES coefficient varies between 0.7 and 2. Note that if the IES is equal to 1, we have already proved analytically that under the ILA economy, an active R&D policy never affects the depletion rate and, in consequence, we can assure that the growth rate of the economy increases. Since the value of the IES parameter substantially the endogenous variables, we also study the robustness of the results by analyzing how they might differ under different values for the IES (in the interval estimated by Gourinchas and Parker (2002)).

The values for capital and labor shares are standard. In particular, they were selected such that the labor share equals 60% ($\alpha_2 = 0.60$) and the capital share equals 35% ($\alpha_1 = 0.35$). The share of exhaustible resources in the final-good production function, α_3, was set at 0.05, as in Groth and Schou (2002).

Finally, the stock of human capital was normalized to one, and the productivity in the R&D sector selected to obtain an annual growth rate of 2% in the benchmark case of the two economies. This criterion meant selecting $\sigma = 14.80$ for the OLG economy and $\sigma = 0.086$ for the ILA set up.[16]

With this benchmark parametrization both the ILA and OLG economies have a unique balanced growth path with an annual growth rate of 2%. The human capital in the R&D sector, H_A, is positive at 26.34% in the ILA scenario and 6.86% within the OLG framework, implying an annual growth rate of the stock of knowledge, $\gamma_A - 1$, of 2.25 (ILA economy) and 4.51 (OLG economy). Moreover, the stationary depletion rates obtained, in annual terms, are such that the use of non-renewable resources is 1.98% and 6.37% in the ILA and OLG scenarios, respectively.

Table 1 summarizes the parameter values chosen to implement the numerical exercises for both scenarios, OLG and ILA.

[15] If each period covers 25 years, the parameter values for each period are such that $(1+\theta) = (1+\theta^*)^p$, $(1-\tau) = (1-\tau^*)^p$ and $\gamma = (\gamma^*)^p$, where variables with * are the annual parameter value and $p = 25$.

[16] An alternative way of choosing H is to take H for the ILA economy such that the growth rate of knowledge $(1+\sigma H)$ is equal, in annual terms, to that of the OLG economy.

Table 1: Parameter Values for OLG and ILA Benchmark Economies

Parameters	ILA	OLG	Data and annually targets
Preferences			
θ	0.02	0.65	Annual discount factor = 0.98
Final-good sector			Observed variables (values)
α_1	0.35	0.35	Standard
α_2	0.60	0.60	Standard
α_3	0.05	0.05	Groth and Schou (2001)
R&D sector			
σ	0.116	15.345	annual growth rate = 2%
H	1	1	

Table 2: Effects of Implementing Active R&D Policies

	(%)					
	τ		H_A		$\gamma - 1$	
$\sigma's$ % change	OLG	ILA	OLG	ILA	OLG	ILA
0%	6.37	1.98	6.86	26.34	2.00	2.00
30%	6.22	1.98	8.43	29.54	3.10	3.03
50%	6.16	1.98	9.12	30.96	3.70	3.71
100%	6.05	1.98	10.25	33.27	4.92	5.43
200%	5.95	1.98	11.26	35.58	6.42	8.87

3.2 Simulating changes in the productivity of the R&D sector

Once the benchmark ILA and OLG economies had been calibrated, a simulation exercise was implemented in order to check how much the results differ in the two scenarios when the R&D productivity parameter, σ, varies.

Table 2 illustrates the depletion rate, the percentage of the stock of human capital devoted to the R&D sector and the growth rate of both economies for different changes in σ. In particular, the first row of the table shows the value of the aforementioned endogenous variables in the benchmark economies.

Three important conclusions can be observed. First, in all the cases analyzed, OLG and ILA economies are clearly similar in terms of growth rates; however their make-up are radically different. Whereas in the ILA scenario, economic growth relies more on a lower use of non-renewable resources, in the OLG economy the growth process depends on higher growth in the R&D sector. In this sense we could say that ILA economies are more exhaustible-conservationist. The intuition behind this result is clear. Since in ILA economies agents live up to infinity, they are able to wait until later to consume. Agents thus consume less today, depleting fewer resources, and devoting a high percentage of human capital to the R&D sector.

Second, in the benchmark case, any increase in the R&D productivity parameter does not affect the stationary depletion rate in the ILA economy. This is consistent with the analytical result shown in Corollary 1 in Appendix 2, since the benchmark economy is assuming logarithmic preferences, and this implies that the depletion rate depends solely on the subjective discount rate. For the OLG economy we observe that any increase in the R&D productivity parameter reduces the use of non-renewable resources. This means that the two channels, through which the R&D productivity parameter affects the economic growth, move in the same direction, implying an increase in the growth rate (as we have analytically proved in Proposition 2). And third, although the growth rate increases in both scenarios, the increase in the ILA economy is higher than in the OLG economy. For instance, when the R&D parameter grows 100%, the growth rate increases 3.43 percentage points in the ILA economy while in the OLG set up it only increases 2.9 points.

We saw in Corollary 4 in Appendix 2 that the value of the IES parameter substantially affects the endogenous depletion rate. As a result, we carried out a sensitivity analysis of this parameter. Table 3 quantifies the changes, in percentage points, of the variables when the R&D parameter grows 100% for three different values of the IES coefficient, $\epsilon = 0.7$, $\epsilon = 1$ and $\epsilon = 2$. For instance the 3.08 in the first row of the last column means that for the case in which $1/\epsilon = 0.7$, if the R&D parameter grows 100%, the growth rate of the ILA economy increases by 3.08 percentage points.

Note that increases in the R&D parameter affect the use of the resources in equilibrium differently depending on the IES parameter. We already know from Corollary 2 in Appendix 2 that, in an ILA economy, if the IES coefficient belongs to the interval $\left[1, \frac{\alpha_1+2\alpha_3}{\alpha_3} = 9\right]$ then the depletion rate decreases when the R&D productivity parameter increases, and if the IES parameter is lower than 1, the use of non-renewable resources increases. We can see numerically that this is also true for the OLG economy if the IES parameter belongs to the above interval. In general, it is clear that for low (high) values of the IES coefficient, active

Table 3: Results of a 100% increase in the R&D productivity parameter for different values of the IES

	Changes in % points					
	τ		H_A		$\gamma - 1$	
IES parameter	OLG	ILA	OLG	ILA	OLG	ILA
$1/\epsilon = 0.7$	0.35	1.15	1.01	5.46	2.25	3.08
$1/\epsilon = 1$	-0.32	0.00	3.39	6.93	2.92	3.43
$1/\epsilon = 2$	-1.27	-1.00	9.63	9.14	3.62	3.35

R&D policies lead to increase (decrease) in the use of exhaustible resources. The intuition is clear. The larger the intertemporal elasticity substitution, the better substitutes current and future consumption are; in consequence, agents are willing to wait longer to consume in the future and, therefore, do not need to deplete exhaustible resources so much today.

We also can see that in all the simulated cases, R&D policy increases the growth rate of the economy. This result corroborates Scholz and Ziemens (1999) and Groth (2006)'s findings for the ILA economy. The numerical simulations also indicate that when current and future consumption are substitutes (complementaries), i.e. when the IES coefficient is lower (greater) than one, then the active R&D policy increases the growth rate in the ILA economy more (less) than in the OLG economy.

4 Conclusions

The aim of this paper was to analyze how an active R&D policy might affect the growth rate of an economy with endogenous growth and non-renewable resources. In particular, we compared the results of an increase in the R&D productivity parameter, in infinitely lived economies and in economies with finite lifetime agents.

From Scholz and Ziemens (1999) and Groth (2006) we know that in infinitely lived agents economies, any active R&D policy increases the growth rate of the economy. In order to see if this result also appears in economies with finite lifetime agents, we developed an endogenous growth overlapping generations (OLG) economy à la Diamond which uses non-renewable resources as essential inputs in the final-good production. Following Romer (1990), we considered there was an R&D sector which produces new designs to create new intermediate goods which are essential for the production of the final good. In particular, this innovation process creates new capital goods which do not substitute the exhaustible resources because all of them are essential in production.

From the theoretical point of view, we found that any change in the R&D productivity parameter affects the growth rate of the economy through two channels. First, the direct channel, which shows that the greater the R&D productivity parameter, the higher the growth rate of the stock of knowledge, regardless of the stationary depletion rate, τ. This ceteris paribus result is quite intuitive, since this is the standard result in Romer's model, with non-renewable resources. That is, the higher the R&D productivity parameter, the higher the endogenous amount of human capital allocated to the R&D sector, which implies higher growth in the stock of knowledge and higher growth in the economy, taking τ as given.

Second, the indirect channel which is opened through the use of non-renewable resources in the final output sector. We know that any variation in the use of non-renewable resources will affect endogenous growth in two ways. On the one hand, as in an exogenous growth model, i.e. without taking into account its effect on the endogenous amount of human capital allocated to the R&D sector, and therefore without taking into account its effect on the endogenous growth of the stock of knowledge. On the other hand, taking into account its effect on the endogenous amount of human capital allocated to the R&D sector and, in consequence, on the growth of the stock of knowledge. We show that both effects are unambiguously negative, that is the lower the depletion rate, the higher the growth rate of stock of knowledge and therefore the growth rate of the economy. However, we have not been able to obtain, algebraically, an unambiguous relationship between the R&D productivity parameter and the stationary depletion rate for the OLG economy. It is clear that if the relationship between the R&D productivity parameter and the use of exhaustible resources is negative, the direct and indirect channels work in the same direction and any stimulant R&D policy increases the growth rate of the stock of knowledge. However when an increase in the technological parameter leads to a rise in the use of resources, then the indirect effect works in the opposite direction to the direct effect, and the final result over the growth rate of the economy is ambiguous.

Finally, since it is not possible to characterize analytically the balanced growth path of an OLG economy and compare it with an ILA economy, we worked on a numerical simulation. First of all, we chose the parameters such that the benchmark case for those economies is the same, and mimics some empirical facts of the economy. Secondly, we compared the results under both scenarios when the R&D parameter increases. Our main numerical findings are as follows: First, OLG and ILA economies are similar in terms of growth rates; however they are very different in the composition of the growth process. Whereas in the ILA scenario, economic growth relies more on a lower use of non-renewable resources, in the OLG economy the growth process depends on higher growth in the R&D sector. In this sense we could say that ILA economies are more exhaustible-conservationist. Second, in both OLG and ILA economies where agents are more willing to wait longer to consume (i.e. with a large IES coefficient), active R&D policies are more conservationist, depleting the exhaustible resources less. And third, active R&D policies always increase the endogenous growth rate, in both scenarios. Furthermore, when current and future consumption are substitutes (complementaries), i.e. when the IES coefficient is lower (greater) than one, active R&D policies affect the growth rate more (less) in economies in which agents live infinitely than those in which agents have finite lifetimes.

Appendix 1

Proof of Proposition 1:

A market equilibrium for the OLG economy is an infinite sequence of quantity allocations $\left\{s_{t+1}, K_{t+1}, Y_t, X_t, c_{1,t}, c_{2,t+1}, \tau_{t+1}, E_t, M_{t+1}, H_{Y,t}, H_{A,t}, A_{t+1}\right\}_{t=0}^{\infty}$ and prices $\left\{P_t^A, w_{H,t}, r_t, p_t, q_t\right\}_{t=0}^{\infty}$ that solves the non-linear system, (1)-(18).

Proof of $\gamma_M = (1-\tau), \forall H_A \geqslant 0$:

Straightforward from valuation of resource market clearing equation (15) on the balanced growth path.

Proof of $\gamma_E = \gamma_M, \forall H_A \geqslant 0$:

Straightforward from evaluating the depletion rate definition, equation (14), on the balanced growth path.

Proof of $\gamma_X = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}, \forall H_A \geqslant 0$:

Combining equations (4), (7), (8) and (10) we obtain

$$\frac{\alpha_3 H_{Yt+1}^{\alpha_1}\left(A_{t+1}X_{t+1}^{\alpha_2}\right)E_{t+1}^{(\alpha_3-1)}}{\alpha_3 H_{Yt}^{\alpha_1}\left(A_t X_t^{\alpha_2}\right)E_t^{(\alpha_3-1)}} = 1+\frac{\alpha_2}{\eta}\alpha_2 H_{Yt+1}^{\alpha_1}X_{t+1}^{(\alpha_2-1)}E_{t+1}^{\alpha_3}.$$

Evaluating this expression on the balanced growth path and reordering,

$$\frac{\eta}{\alpha_2^2}H_Y^{-\alpha_1}\left[\gamma_A\left(\gamma_X\right)^{\alpha_2}\left(\gamma_E\right)^{(\alpha_3-1)}-1\right] = X_{t+1}^{(\alpha_2-1)}E_{t+1}^{\alpha_3}. \tag{A}$$

Taking the ratio of this expression in period $t+1$ and t, we have that $1 = \left(\gamma_X\right)^{(\alpha_2-1)}\left(\gamma_E\right)^{\alpha_3}$. Considering that $\gamma_E = (1-\tau)$, we obtain $\gamma_X = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$.

Proof of $\gamma_r = \gamma_q = 1, \forall H_A \geqslant 0$:

Taking the ratio of equation (10) en $t+1$ and t and evaluating on the balanced growth path we obtain that $\gamma_r = \gamma_q$. Doing the same with equation (7) we obtain

$$\gamma_q = \left(\gamma_X\right)^{(\alpha_2-1)}\left(\gamma_E\right)^{\alpha_3},$$

which, considering that $\gamma_E = (1-\tau)$ and $\gamma_X = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$, becomes $\gamma_q = 1$.

Proof of $\gamma_\pi = \gamma_X, \forall H_A \geqslant 0$:

Taking the ratio of monopoly profit equation in $t+1$ and t and evaluating on the balanced growth path we obtain that $\gamma_{\pi} = \gamma_{q}\gamma_{X}$. Since in the balanced growth path $\gamma_{q} = 1$ then $\gamma_{\pi} = \gamma_{X}$.

Proof of $\gamma_{Y} = \gamma_{w_H} = \gamma\,,\ \forall\ H_A \geqslant 0:$
Taking the ratio of equations (5) and (6) in $t+1$ and t and evaluating on the balanced growth path we obtain that $\gamma_{Y} = \gamma_{w_H} = \gamma_{A}\left(\gamma_{X}\right)^{\alpha_2}\left(\gamma_{E}\right)^{\alpha 3}$. Considering that $\gamma_{E} = (1-\tau)$, and $\gamma_{X} = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$, we obtain $\gamma_{Y} = \gamma_{w_H} = \gamma_{A}(1-\tau)^{\frac{\alpha_3}{1-\alpha_2}} \equiv \gamma$.

Proof of $\gamma_{p} \equiv \gamma/(1-\tau)\,,\ \forall\ H_A \geqslant 0:$
Taking the ratio of equation (8) in $t+1$ and t and evaluating on the balanced growth path we obtain that $\gamma_{p} = \gamma_{A}\left(\gamma_{X}\right)^{\alpha_2}\left(\gamma_{E}\right)^{(\alpha 3-1)}$. Considering that $\gamma_{E} = (1-\tau)$, and $\gamma_{X} = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$, we obtain $\gamma_{p} = \gamma_{A}(1-\tau)^{\frac{\alpha_3}{1-\alpha_2}-1} \equiv \gamma/(1-\tau)$.

Proof of $\gamma_{K} = \gamma\,,\ \forall\ H_A \geqslant 0:$
Taking the ratio of the physical capital clearing condition equation (17) in $t+1$ and t and evaluating on the balanced growth path we obtain that $\gamma_{K} = \gamma_{A}\gamma_{X}$. Considering that $\gamma_{X} = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$, we obtain $\gamma_{K} = \gamma_{A}(1-\tau)^{\frac{\alpha_3}{1-\alpha_2}} \equiv \gamma$.

Proof of $\gamma_{c_1} = \gamma_{c_2},\ \forall\ H_A \geqslant 0:$
Taking the ratio of the equation (3) in $t+1$ and t and evaluating on the balanced growth path we obtain that

$$\frac{\gamma_{c_2}}{\gamma_{c_1}} = \left(\frac{1+r_{t+1}}{1+r_t}\right)^{1/\epsilon}.$$

Considering that on the balanced growth path $\gamma_{r} = 1$, we have $r_{t+1} = r_t = r$. Therefore $\gamma_{c_1} = \gamma_{c_2}$.

Proof of $\gamma_{c_1} = \gamma\,,\ \forall\ H_A \geqslant 0:$
Substituting the saving function in the first consumer restriction (1), we obtain

$$c_{1t} = \left(w_{H,t}h\right)\left(1 - \frac{1}{1+(1+\theta)^{\frac{1}{\epsilon}}\,(1+r_{t+1})^{-\left(\frac{1-\epsilon}{\epsilon}\right)}}\right).$$

Taking the ratio of this expression in $t+1$ and t and evaluating on the balanced growth path we obtain that $\gamma_{c_1} = \gamma_A (\gamma_X)^{\alpha_2} (\gamma_E)^{\alpha 3}$. Considering that $\gamma_E = (1-\tau)$ and $\gamma_X = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$, we obtain $\gamma_{c_1} = \gamma_A (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}} \equiv \gamma$.

Proof of $\gamma_s = \gamma$, $\forall\ H_A \geqslant 0$:

Substituting (6) and (8) in the saving function and evaluating on the balanced growth path we obtain

$$s_{t+1} = H_Y^{\alpha_1} A_t X_t^{\alpha_2} E_t^{\alpha_3} \left[\frac{\alpha_1 H}{\left(1+(1+\theta)^{\frac{1}{\epsilon}}(1+r)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}\right) H_Y} - \frac{\alpha_3 \gamma_E}{\tau} \right]. \qquad \text{(B)}$$

Taking the ratio of this expression in periods $t+1$ and t, we obtain that $\gamma_s = \gamma_A (\gamma_X)^{\alpha_2} (\gamma_E)^{\alpha 3}$. Since $\gamma_E = (1-\tau)$, and $\gamma_X = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$, we obtain $\gamma_s = \gamma_A (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}} \equiv \gamma$.

Proof of $\gamma_{P^A} = \gamma_X$, $\forall\ H_A > 0$:

Equalizing human capital wage in equations (13) and (6), we obtain the following expression

$$P_t^A \sigma = \alpha_1 H_{Yt}^{\alpha_1 - 1} X_t^{\alpha_2} E_t^{\alpha_3}.$$

Taking the ratio of this expression in $t+1$ and t, and evaluating on the balanced growth path, we arrive at $\gamma_{P^A} = (\gamma_X)^{\alpha_2} (\gamma_E)^{\alpha_3}$. Considering that $\gamma_E = (1-\tau)$ and $\gamma_X = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$, we obtain $\gamma_{P^A} = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$.

Proof of $H_y = \frac{\alpha_1(\gamma_A - \gamma_M)}{\gamma_M \sigma (1-\alpha_2)\alpha_2}$, $\forall\ H_A > 0$:

First, by solving the patent price difference equation (9) we obtain the following expression

$$P_t^A = \sum_{i=0}^{\infty} \pi_{t+1+i} \prod_{\omega=0}^{t+1+i} \left(\frac{1}{1+r_{t+1+i}} \right)^{i+1}.$$

On the balanced growth path, $\pi_{t+1+i} = \gamma_\pi^{i+1} \pi_t$ and $r_{t+1+i} = r^{i+1} r_t = r_t$. Therefore, the patent price on the balanced growth path can be written

$$P_t^A = \sum_{i=0}^{\infty} \gamma_\pi^{i+1} \pi_t \frac{1}{(1+r_t)^{i+1}} = \frac{\gamma_\pi \pi_t}{1+r_t} \sum_{i=0}^{\infty} \left(\frac{\gamma_\pi}{1+r_t} \right)^i = \frac{\pi_{t+1}}{1+r_t-\gamma_\pi}.$$

Substituting intermediate sector profits and intermediate good prices (7) and considering the final good production function (5),

$$P_t^A = \frac{(1-\alpha_2)\,\alpha_2 q_{t+1} X_{t+1}}{1+r_t-\gamma_\pi} = \frac{(1-\alpha_2)\,\alpha_2 \frac{Y_t}{A_t}\frac{\gamma_Y}{\gamma_A}}{1+r_t-\gamma_\pi}. \tag{C1}$$

On the other hand, substituting conditions (6) and (5) in (13) we obtain the following expression for the patent price,

$$P_t^A = \frac{w_{H,t}}{\sigma A_t} = \frac{\alpha_1 \frac{Y_t}{A_t}}{\sigma H_{Y,t}}. \tag{C2}$$

Taking into account $\gamma_\pi = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}} = \frac{\gamma_Y}{\gamma_A}$ and $1+r_t = \frac{\gamma_Y}{\gamma_M}$, equalizing patent prices in (C1) and (C2) and reordering we obtain

$$H_Y = \frac{\alpha_1 (\frac{\gamma_A}{\gamma_M}-1)}{\sigma(1-\alpha_2)\alpha_2}.$$

Proof of $\gamma_A = \frac{\gamma_M(1+\sigma h)(1-\alpha_2)\alpha_2+\gamma_M\alpha_1}{\gamma_M(1-\alpha_2)\alpha_2+\alpha_1}, \forall\, H_A > 0:$

Evaluating the knowledge dynamics equation (12) on the balanced growth path and considering the human capital clearing condition (16), we obtain the following condition

$$\gamma_A = 1+\sigma\,(H-H_Y).$$

Substituting the value that human capital attributes to the final goods sector, H_Y, and reordering, we obtain the value

$$\gamma_A = \frac{(1+\sigma H)\,(1-\alpha_2)\,\alpha_2+\alpha_1}{(1-\alpha_2)\,\alpha_2+\alpha_1\left(\gamma_M\right)^{-1}}.$$

Proof of $\frac{\alpha_2^2\gamma}{\gamma-\gamma_M} = \frac{(1-\alpha_2)\alpha_2}{(\gamma_A-\gamma_M)}\left(\frac{\sigma H}{1+(1+\theta)^{\frac{1}{\epsilon}}\left(\frac{\gamma}{\gamma_M}\right)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}}-\gamma_A\right)-\frac{\alpha_3}{\tau}, \forall\, H_A > 0:$

Reordering terms in equation (A) :

$$\frac{\gamma_A\left(\gamma_X\right)^{\alpha_2}\left(\gamma_E\right)^{(\alpha_3-1)}-1}{\alpha_2^2} = \frac{H_Y^{\alpha_1}A_{t+1}X_{t+1}^{\alpha_2}E_{t+1}^{\alpha_3}}{\eta A_{t+1}X_{t+1}}.$$

And taking into account equation (17) and $\gamma_A (\gamma_X)^{\alpha_2} (\gamma_E)^{(\alpha_3-1)} = \frac{\gamma_Y}{\gamma_M} = \gamma_p$:

$$\frac{Y_{t+1}}{K_{t+1}} = \frac{\gamma_Y - \gamma_M}{\alpha_2^2 \gamma_M}. \tag{D1}$$

On the other hand, substituting (B), (C2), H_Y and γ_A with $H_A > 0$ into equation (18), we obtain the following expression:

$$\frac{Y_t}{K_t} = \gamma_K \left(\frac{\alpha_1 H}{\left(1+(1+\theta)^{\frac{1}{\epsilon}} (1+r)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}\right) H_Y} - \frac{\alpha_3 \gamma_M}{\tau} - \frac{\alpha_1 \gamma_A}{\sigma H_Y} \right)^{-1}. \tag{D2}$$

On the balanced growth path, equation (D1) must be equal to equation (D2):

$$\frac{\gamma_Y - \gamma_M}{\alpha_2^2 \gamma_M} = \gamma_K \left(\frac{\alpha_1 H}{\left(1+(1+\theta)^{\frac{1}{\epsilon}} (1+r)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}\right) H_Y} - \frac{\alpha_3 \gamma_M}{\tau} - \frac{\alpha_1 \gamma_A}{\sigma H_Y} \right)^{-1}.$$

Taking into account that $\gamma_K = \gamma_Y = \gamma$, $1+r = \frac{\gamma}{\gamma_M}$ and substituting H_y:

$$\frac{\alpha_2^2 \gamma}{\gamma - \gamma_M} = \frac{(1-\alpha_2)\alpha_2}{(\gamma_A - \gamma_M)} \left(\frac{\sigma H}{1+(1+\theta)^{\frac{1}{\epsilon}} \left(\frac{\gamma}{\gamma_M}\right)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}} - \gamma_A \right) - \frac{\alpha_3}{\tau}.$$

Proof of $H_y = H$, if $H_A = 0$:

Straightforward from evaluation of the human capital clearing condition (16) with $H_A = 0$.

Proof of $\gamma_A = 1$, if $H_A = 0$:

Evaluating the knowledge dynamics equation (12) on the balanced growth path, we obtain $\gamma_A = 1$.

Proof of $\gamma_{P^A} = \gamma_Y$, if $H_A = 0$:

On the one hand, from equations (5), (6) and (17), we obtain $\pi_{t+1} = (1-\alpha_2)\alpha_2 \frac{Y_{t+1}}{A_{t+1}}$. On the other hand, from (5), (7) (10) and (17), we obtain the expression $r_{t+1} = \alpha_2 \frac{Y_{t+1}}{K_{t+1}}$. Substituting both expressions in the equilibrium price for the patent (9), after some manipulations we obtain

$$\gamma_{P^A} = 1 + \alpha_2^2 \left(\frac{Y_{t+1}}{K_{t+1}} \right) - \frac{(1-\alpha_2)\alpha_2}{A} \left(\frac{Y_{t+1}}{P_t^A} \right). \tag{E}$$

Since $\frac{Y_{t+1}}{K_{t+1}}$ is a constant by (D1), then on the balanced growth path $\frac{Y_{t+1}}{P_t^A}$ must be a constant. Therefore, $\gamma_{P^A} = \gamma_Y$. Since $H_A = 0$, $\gamma_A = 1$, we obtain $\gamma_{P^A} = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}}$.

Proof of $\frac{\gamma_M \alpha_2^2 \gamma}{\gamma - \gamma_M} = \frac{\alpha_1}{\left(1+(1+\theta)^{\frac{1}{\epsilon}} \left(\frac{\gamma}{\gamma_M}\right)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}\right)} - \frac{\gamma_M(\alpha_3+(1-\alpha_2)\alpha_2)}{\tau}$, if $H_A = 0$:

Substituting (1) - (6) and (8) in the final good market clearing condition (18) we obtain

$$K_{t+1} = \frac{\alpha_1 Y_t}{\left(1 + (1+\theta)^{\frac{1}{\epsilon}} (1+r_{t+1})^{-\left(\frac{1-\epsilon}{\epsilon}\right)}\right)} - \frac{\alpha_3 \gamma_M Y_t}{\tau} - P_t^A A.$$

Reordering and taking into account (D1), this expression can be rewritten as

$$\gamma_Y \left(\frac{\alpha_2^2 \gamma_M}{\gamma_Y - \gamma_M} \right) = \frac{\alpha_1}{\left(1 + (1+\theta)^{\frac{1}{\epsilon}} (1+r_{t+1})^{-\left(\frac{1-\epsilon}{\epsilon}\right)}\right)} - \frac{\alpha_3 \gamma_M}{\tau} - \frac{P_t^A A}{Y_t}.$$

Given that $\gamma_{P^A} = (1-\tau)^{\frac{\alpha_3}{1-\alpha_2}} = \gamma_Y$ when $H_A = 0$ from expression (E), after some manipulations we obtain

$$\frac{P_t^A A}{Y_t} = \frac{(1-\alpha_2)\alpha_2 \gamma_M}{\tau}.$$

Substituting this in the former equation taking into account that $1 + r = \frac{\gamma}{\gamma_M}$ and reordering

$$\frac{\gamma_M \alpha_2^2 \gamma}{\gamma - \gamma_M} = \frac{\alpha_1}{\left(1 + (1+\theta)^{\frac{1}{\epsilon}} \left(\frac{\gamma}{\gamma_M}\right)^{-\left(\frac{1-\epsilon}{\epsilon}\right)}\right)} - \frac{\gamma_M (\alpha_3 + (1-\alpha_2)\alpha_2)}{\tau}.$$

Appendix 2

Infinitely-lived agents model

Scholz and Ziemens (1999) analyze an economy similar to the one developed in Section 2, but with infinitely-lived agents (ILA) and in a continuous set up. In this appendix, we solve their model in a discrete time, in order to compare the results in both frameworks, OLG and ILA.

Since the only difference between the equilibrium characterization of the ILA model and the OLG model is the consumers's life-span, we only illustrate the consumers' problem and the characterization of the balanced growth path of the ILA set up.

Consumers own the stock of exhaustible resources, designs and physical capital. So the problem of an infinitely lived representative agent consumer, in per worker terms, can be written as[17],

$$\underset{\{c_t,k_{t+1},m_{t+1},s_{t+1}\}_{t=0}^{\infty}}{Max} \qquad \sum_{t=0}^{\infty}\left(\frac{1}{1+\theta}\right)^t \frac{c_{1,t}^{1-\epsilon}-1}{1-\epsilon},$$

$$s.t. \begin{cases} c_t + s_{t+1} + p_t m_{t+1} = w_{H_t} h + (1+r_t) s_t + p_t m_t, \\ m_0 > 0 \text{ given.} \end{cases} \tag{19}$$

The FOC of this maximization problem can be written as

$$\frac{c_{t+1}}{c_t} = \left(\frac{1+r_{t+1}}{1+\theta}\right)^{1/\epsilon}, \tag{20}$$

$$\frac{p_{t+1}}{p_t} = 1 + r_{t+1}. \tag{21}$$

Note that these first order conditions are the same as those obtained in OLG model (equations 3 and 4, respectively). The first equation indicates that consumers equate the marginal rate of substitution between consumption today and consumption tomorrow to their relative prices $1+r_{t+1}$. The second equation states that the marginal rate of saving in exhaustible resources must be equal to the marginal rate of saving in physical capital or bonds issued by the intermediate firms.

The equilibrium characterization for the ILA model is summarized in the following definition.

[17] Alternatively, we could solve the individual problem, denoting the total saving allocated to buy physical capital and bonds issued by the intermediate firms as $s_{t+1} = k_{t+1} + P_t^A a_{t+1}$.

Definition 3 *For any arbitrary initial value of τ_0, an equilibrium of this ILA economy is an infinite sequence of quantity allocations $\left\{K_{t+1}, Y_t, X_t, s_{t+1}, c_t, \tau_t, E_t, M_{t+1}, H_{Y,t}, H_{A,t}, A_{t+1}, \pi_t\right\}_{t=0}^{\infty}$ and prices $\left\{P_t^A, w_{H,t}, r_t, p_t, q_t\right\}_{t=0}^{\infty}$ such that consumers, final-goods producers and research firms maximize their objective functions taking prices as given, the intermediate firms maximize their monopolist profits and all markets clear, given the initial conditions $K_0, M_0, A_0 > 0$. In other words, an equilibrium is a solution of the non-linear system (5) -(21) and the transversality condition*[18].

Balanced Growth Path

The balanced growth path is defined as in the OLG framework (definition 2). From now on, the superscript *ILA* stands for solutions of the infinitely-lived representative agent's economy.

Proposition 3 *Any balanced growth path of the ILA economy is given by a vector $\left\{\gamma_Y^{ILA}, \gamma_K^{ILA}, \gamma_A^{ILA}, \gamma_M^{ILA}, \gamma_c^{ILA}, \gamma_X^{ILA}, \gamma_E^{ILA}, \gamma_p^{ILA}, \gamma_q^{ILA}, \gamma_r^{ILA}, \gamma_{P^A}^{ILA}, \gamma_{w_H}^{ILA},\right.$ $\left.H_Y^{ILA}, H_A^{ILA}, \tau^{ILA}\right\}$ satisfying the following system,*

$$\left.\begin{array}{r}\gamma_A^{ILA} = \frac{[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1]\left(1-\tau^{ILA}\right)}{\left(1-\tau^{ILA}\right)(1-\alpha_2)\alpha_2+\alpha_1}, \\ H_Y^{ILA} = \frac{\alpha_1\left[\gamma_A^{ILA}-(1-\tau)\right]}{\left(1-\tau^{ILA}\right)\sigma(1-\alpha_2)\alpha_2},\end{array}\right\}, \ \text{if } H_A^{ILA} = H - H_Y^{ILA} > 0,$$

$$\left.\begin{array}{r}\gamma_A^{ILA} = 1, \\ H_Y^{ILA} = H.\end{array}\right\}, \ \text{if } H_A = 0,$$

$$\begin{aligned}
\tau^{ILA} &= 1 - \frac{1}{\left(\gamma^{ILA}\right)^{\epsilon-1}(1+\theta)}, \\
\gamma_M^{ILA} &= \gamma_E^{ILA} = 1-\tau^{ILA}, \\
\gamma_X^{ILA} &= \gamma_{P^A}^{ILA} = \gamma_\pi^{ILA} = \left(1-\tau^{ILA}\right)^{\frac{\alpha_3}{1-\alpha_2}}, \\
\gamma_r^{ILA} &= \gamma_q^{ILA} = 1, \\
\gamma_p^{ILA} &= \frac{\gamma^{ILA}}{1-\tau^{ILA}}, \\
\gamma_K^{ILA} &= \gamma_Y^{ILA} = \gamma_c^{ILA} = \gamma_{w_H}^{ILA} = \gamma^{ILA},
\end{aligned}$$

[18]In this model the transversality condition implies that the following condition must be satisfied: $\gamma^{(1-\varepsilon)} < (1+\theta)$, which implies that $(1-\tau) < 1$. This condition is analogous to the condition provided by Groth (2006) when solving a model similar to ours in continuous time.

where $\gamma^{ILA} = \gamma_A^{ILA}\left(1-\tau^{ILA}\right)^{\frac{\alpha_3}{1-\alpha_2}}$.

Proof of Proposition 3

Following proof of Proposition 1, it is clear that in this context the balanced growth path is such that

$$\begin{aligned}
\gamma^{ILA} &= \gamma_k^{ILA} = \gamma_y^{ILA} = \gamma_{w_H}^{ILA} = \gamma_A^{ILA}\left(1-\tau^{ILA}\right)^{\frac{\alpha_3}{1-\alpha_2}}, \\
\gamma_M^{ILA} &= \gamma_E^{ILA} = 1-\tau^{ILA}, \\
\gamma_A^{ILA} &= \frac{\left((1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1\right)\left(1-\tau^{ILA}\right)}{\left(1-\tau^{ILA}\right)(1-\alpha_2)\alpha_2+\alpha_1}, \text{ if } H_A^{ILA} > 0, \\
H_A &= H - H_Y, \text{ if } H_A^{ILA} > 0, \\
H_Y &= \frac{\alpha_1\left[\gamma_A^{ILA} - \gamma_M^{ILA}\right]}{\gamma_M^{ILA}\sigma(1-\alpha_2)\alpha_2}, \text{ if } H_A^{ILA} > 0, \\
\gamma_A^{ILA} &= 1, \text{if } H_A^{ILA} = 0, \\
H_Y &= H, \text{ if } H_A^{ILA} = 0, \\
\gamma_r^{ILA} &= \gamma_q^{ILA} = 1, \\
\gamma_p^{ILA} &= \frac{\gamma^{ILA}}{\gamma_M^{ILA}}, \\
\gamma_X^{ILA} &= \gamma_{P^A}^{ILA} = \gamma_\pi^{ILA} = \left(1-\tau^{ILA}\right)^{\frac{\alpha_3}{1-\alpha_2}}.
\end{aligned}$$

Proof of $\gamma_c^{ILA} = \gamma_y^{ILA} = \gamma^{ILA}$:

Taking into account the restriction in the representative agent problem (19) and substituting, in per worker terms, the final good production function (5) and firms' optimization conditions (6), (7), (8) and (10), we obtain

$$c_t + s_{t+1} = \frac{\alpha_1 h}{h_{Y_t}} y_t + \left(1 + \frac{\alpha_2^2 y_t}{\eta A_t x_t}\right) s_t + \alpha_3 \frac{y_t}{e_t}\left(m_t - m_{t+1}\right).$$

Considering the depletion rate (14), market clearing conditions (15) and (17), this expression can be written

$$c_t + s_{t+1} - s_t = y_t\left(\frac{\alpha_1 h}{h_{Y_t}} + \alpha_2^2 \frac{s_t}{k_t} + \alpha_3\right).$$

Substituting the final-good market clearing condition (18) and the R&D optimization condition (13), the above expression can be rewritten as

$$c_t + k_{t+1} - k_t = y_{t-1}\left[\gamma_y^{ILA}\left(\frac{\alpha_1 h}{h_{Y_t}} + \alpha_2^2 + \alpha_3\right) + \frac{\alpha_1 \gamma_A^{ILA}}{\sigma h_{Y_{t-1}}} + \frac{\alpha_2^2 \alpha_1 \gamma_A^{ILA}}{\sigma h_{Y_{t-1}}}\frac{y_t}{k_t}\right].$$

Taking the ratio of the above equation in t and $t-1$ and evaluating on the balanced growth path, we obtain that

$$\frac{\gamma_c^{ILA} c_{t-1} + \gamma_k^{ILA}(k_t - k_{t-1})}{c_{t-1} + k_t - k_{t-1}} = \frac{y_{t-1}}{y_{t-2}} = \gamma_y^{ILA}.$$

Since $\gamma_k^{ILA} = \gamma_y^{ILA}$, we have

$$\frac{\gamma_c^{ILA}}{\gamma_y^{ILA}} c_{t-1} + k_t - k_{t-1} = c_{t-1} + k_t - k_{t-1},$$

which implies that $\gamma_c^{ILA} = \gamma_y^{ILA} = \gamma^{ILA}$.

From valuation of conditions (20) and (21) on the balanced growth path, we obtain straightforwardly that $\gamma_c^{ILA} = \left(\frac{\gamma_p^{ILA}}{1+\theta}\right)^{1/\epsilon}$. Since we have proved that $\gamma_c^{ILA} = \gamma^{ILA}$ and $\gamma_p^{ILA} = \frac{\gamma}{1-\tau^{ILA}}$, it must be true that $1 - \tau^{ILA} = \frac{1}{(\gamma^{ILA})^{\epsilon-1}(1+\theta)}$ ■

Note that for the case of logarithmic consumer preferences ($\epsilon = 1$), the results coincide with Aghion and Howitt (1998), Barbier (1999) and Scholz and Ziemes (1999). In particular, the stationary depletion rate depends solely on the consumer discount rate.

Corollary 1 *With elasticity of intertemporal substitution equal to one, the stationary depletion rate for the ILA economy is given by* $\tau = \theta/(1+\theta)$.

Proof. Straightforward from the first equation on Proposition 3. ■

Corollary 2

$$\textit{If}\ \left\{\begin{array}{ccc} \frac{\alpha_3}{\alpha_1+2\alpha_3} \leq \epsilon < & \Longrightarrow & \partial\tau^{ILA}/\partial\sigma < 0, \\ \epsilon = 1 & \Longrightarrow & \partial\tau^{ILA}/\partial\sigma = 0, \\ 1 < \epsilon & \Longrightarrow & \partial\tau^{ILA}/\partial\sigma > 0. \end{array}\right.$$

Proof. Substituting γ^{ILA} in τ^{ILA} on Proposition 3 and after some manipulation, we can write the following expression,

$$\left(1-\tau^{ILA}\right)^{\frac{(1-\alpha_2)\epsilon+\alpha_3(\epsilon-1)}{(1-\alpha_2)}}\left[\left(1-\tau^{ILA}\right)(1-\alpha_2)\alpha_2+\alpha_1\right]^{1-\epsilon}=\left[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1\right]^{1-\epsilon}(1+\theta)^{-1}.$$

Differentiating with respect to τ^{ILA} and σ, we obtain

$$\frac{\partial\tau^{ILA}}{\partial\sigma}=\frac{N}{D},$$

where

$$\begin{aligned}N &= (1-\epsilon)\left[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1\right]^{-\epsilon}H(1-\alpha_2)\alpha_2(1+\theta)^{-1},\\ D &= -\frac{(1-\alpha_2)\epsilon+\alpha_3(\epsilon-1)}{(1-\alpha_2)}\left(1-\tau^{ILA}\right)^{\frac{(\alpha_1+2\alpha_3)(\epsilon-1)}{(1-\alpha_2)}}\left[\left(1-\tau^{ILA}\right)(1-\alpha_2)\alpha_2+\alpha_1\right]^{1-\epsilon}+\\ &\quad(\epsilon-1)\left[\left(1-\tau^{ILA}\right)(1-\alpha_2)\alpha_2+\alpha_1\right]^{-\epsilon}\left(1-\tau^{ILA}\right)^{\frac{\alpha_3(1-2\epsilon)-\epsilon\alpha_1}{(1-\alpha_2)}}(1-\alpha_2)\alpha_2.\end{aligned}$$

After some mathematical work, D can be expressed as

$$\begin{aligned}D &= -\left(1-\tau^{ILA}\right)^{\frac{(\alpha_1+2\alpha_3)(\epsilon-1)}{(1-\alpha_2)}}\left[\left(1-\tau^{ILA}\right)(1-\alpha_2)\alpha_2+\alpha_1\right]^{1-\epsilon}\\ &\quad\times\left\{\left(1-\tau^{ILA}\right)(1-\alpha_2)\alpha_2(\alpha_3\epsilon+\alpha_1)+\alpha_1\left[\epsilon(\alpha_1+2\alpha_3)-\alpha_3\right]\right\}.\end{aligned}$$

For the case in which $\frac{\alpha_3}{\alpha_1+2\alpha_3}\leq\epsilon<1$, $N>0$ and $D<0$. This implies that $\partial\tau^{ILA}/\partial\sigma<0$. When $\epsilon=1$, $N=0$ and $\partial\tau^{ILA}/\partial\sigma=0$. For $\epsilon>1$, $N<0$ and $D<0$. Therefore $\partial\tau^{ILA}/\partial\sigma>0$. ■

Proposition 4 *In an ILA economy,* $\partial\gamma^{ILA}/\partial\sigma>0$ *if* $\frac{\alpha_3}{\alpha_1+2\alpha_3}\leq\epsilon$.

Proof. Substituting τ^{ILA} in the γ^{ILA} expression on Proposition 3 in Appendix 2 and after some manipulation, we can write the following expression for γ^{ILA}

$$\left(\gamma^{ILA}\right)^{1-(1-\epsilon)\frac{\alpha_1+2\alpha_3}{(1-\alpha_2)}}\left[\left(\gamma^{ILA}\right)^{1-\epsilon}(1-\alpha_2)\alpha_2+\alpha_1(1+\theta)\right]=\left[(1+\sigma H)(1-\alpha_2)\alpha_2+\alpha_1\right](1+\theta)^{-\frac{\alpha_3}{(1-\alpha_2)}}.$$

Differentiating with respect to γ^{ILA} and σ, and after some work we obtain

$$\frac{\partial\gamma^{ILA}}{\partial\sigma}=\frac{H(1-\alpha_2)\alpha_2(1+\theta)^{-\frac{\alpha_3}{(1-\alpha_2)}}}{(\alpha_1+\epsilon\alpha_3)\alpha_2\left(\gamma^{ILA}\right)^{-\frac{(1-\epsilon)\alpha_3}{(1-\alpha_2)}}+\left[\epsilon(\alpha_1+2\alpha_3)-\alpha_3\right]\alpha_1(1+\theta)\left(\gamma^{ILA}\right)^{-(1-\epsilon)\frac{\alpha_1+2\alpha_3}{(1-\alpha_2)}}},$$

which is positive whenever $\frac{\alpha_3}{\alpha_1+2\alpha_3}\leq\epsilon$. ■

References

[1] Aghion, P. and P. Howitt, (1998), "*Endogenous Growth Theory*". MIT Press, Massachusetts.

[2] Agnani, B. *et al.*, (2005), "Growth in Overlapping Generations Economies with Non-Renewable Resources". *Journal of Environmental Economics and Management,* Vol 50/2 pp 387-407.

[3] Barbier, E.B., (1999), "Endogenous Growth and Natural Resource Scarcity", *Environmental and Resource Economics*, 14, 51-54.

[4] Beaudry, P. and E. Wincoop (1996). "The Intertemporal Elasticity of Substitution: An Exploration using a US Panel of State Data", *Economica,* 63, 495-512.

[5] Benhabib, J. and M. Spiegel (1994), "The role of Human Capital in Economic Development: Evidence from Aggregate Cross-Country Data", *Journal of Monetary Economics*, 34 (2), 143–173.

[6] Córdoba, J. and M. Ripoll (2005), "Endogenous TFP and Cross-Country Income Differences", *mimeo*.

[7] Dasgupta, P. and G.M. Heal (1974), "The Optimal Depletion of Exhaustible Resources", *Review of Economic Study. Symposium* 41, 3-28.

[8] Diamond, P.A., (1965). "National Debt in a Neoclassical Growth Model", *American Economic Review,* 55, 1126-1150.

[9] Gourinchas P. and J.A. Parker (2002), "Consumption over the Life Cycle" *Econometrica* 70(1), 47-89.

[10] Groth, C. (2006), "A new-Growth Perspective on Non-Renewable Resources", Discussion Papers. Department of Economics, University of Copenhagen.

[11] Groth, C. and P. Schou, (2002). "Can Non-renewable Resources Alleviate the Knife-Edge Character of Endogenous Growth?", *Oxford-Economic-Papers.* July; 54(3): 386-411

[12] Hotelling, H., (1931), "The Economics of Exhaustible Resources", *Journal of Political Economy,* 39, 137-175.

[13] Hsuku, Y. (2007), "Dynamic Consumption and Asset Allocation with Derivate Securities",.*Quantitative Finance*, 7 (2), 137- 149.

[14] King, R. *et. al.* (1988), Production, Growth and Business Cycles: 1. The Basic Neoclassical Model", *Journal of Monetary Economics,* 21, 195-232.

[15] King, R. and S. Rebelo, (1993), "Transitional Dynamics and Economic Growth in the Neoclassical Model", *American Economic Review*, 83, 4, 908-931.

[16] Mourmouras, A. (1993), "Conservationist Government Policies and Intergenerational Equity in an Overlapping Generations Model with Renewable Resources", *Journal of Public Economics*, 51, 249-268.

[17] Nili, F. (2001), "Nonrenewable Natural Resources and Innovation-based Growth", *mimeo*. Presented at the Summer School on Economics, Innovation, Technological Progress and Environmental Police, Seeon (Germany), September.

[18] Olson, L.J. and K. Knapp, (1997), "Exhaustible Resource Allocation in an Overlapping Generations Economy", *Journal of Environmental Economics and Management*, 32(3), 277-92.

[19] Romer, P. (1990), "Endogenous Technological Change", *Journal of Political Economy,* 98, 5, S71-S102.

[20] Scholz, C.M. and G. Ziemes, (1999), "Exhaustible Resources, Monopolistic Competition, and Endogenous Growth", *Environmental and Resource Economics,* 13, 169-189.

[21] Solow, R. M. (1974), "Intergenerational Equity and Exhaustible Resources", *Review of Economic Study. Symposium* 41, 29-45.

[22] Solow, R.M., (1986), "On the Intergenerational Allocation of Natural Resources", *Scandinavian Journal of Economics,* 88(1), 141-149.

[23] Stiglitz, J.E., (1974), "Growth with Exhaustible Natural Resources: The Competitive Economy", *Review of Economic Studies. Symposium,* 41, 139-152.

[24] Stokey, N and R. Lucas, (1984), "Optimal Growth with Many Consumers", *Journal of Economic Theory,* 32 (1), 139-171.

El Centro de Estudios Andaluces es
una entidad de carácter científico y
cultural, sin ánimo de lucro, adscrita
a la Consejería de la Presidencia
de la Junta de Andalucía.
El objetivo esencial de esta institución
es fomentar cuantitativa y cualitativamente
una línea de estudios e investigaciones
científicas que contribuyan a un más
preciso y detallado conocimiento de
Andalucía, y difundir sus resultados
a través de varias líneas estratégicas.

El Centro de Estudios Andaluces desea
generar un marco estable de relaciones
con la comunidad científica e intelectual
y con movimientos culturales en
Andalucía desde el que crear verdaderos
canales de comunicación para dar
cobertura a las inquietudes intelectuales y culturales.

Las opiniones publicadas por los autores en
esta colección son de su exclusiva responsabilidad

Depósito Legal: SE-7352-08

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

E2008/12

PRODUCTIVITY GROWTH AND TECHNOLOGICAL CHANGE IN EUROPE AND US

Diego Martínez
UPO
Jesús Rodríguez-López
UPO
José L. Torres
UMA

RESUMEN

En este trabajo se presenta una evaluación de las causas tecnológicas que afectan al crecimiento de la productividad en los países europeos y en Estados Unidos en el período 1980-2004. El progreso tecnológico se clasifica entre cambios neutrales y cambios específicos de la inversión. La contribución al crecimiento de la productividad de cada uno de los cambios tecnológicos se calcula con el enfoque de contabilidad del crecimiento y con un enfoque de equilibrio general. En cuanto a la contribución del cambio tecnológico neutral, se observa que las tecnologías de la información y de la comunicación son las que más contribuyen a través de los cambios tecnológicos implícitos que producen. Además, producen más efecto en las tasas de crecimiento de la productividad. En particular la mayor contribución proviene del equipamiento informático.

Clasificación JEL: O41, O47.
Palabras Clave: Crecimiento de la productividad, Cambio tecnológico específico de la inversión, Cambio tecnológico neutral.

* Autor correspondencia: dmarlop@upo.es

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

ABSTRACT

This paper presents an evaluation on the technological sources of productivity growth across European countries and the U.S. for the period 1980-2004. Technological progress is divided into neutral change and investment specific change. Contribution to productivity growth from each type of technological progress is computed using a growth accounting approach and a general equilibrium approach. Concerning the growth accounting view, the neutral change dominates the effect from the implicit change, and the ICT assets provide most of the implicit technological change. Regarding the general equilibrium approach, ICT assets (specially the hardware equipment) also respond for most of the implicit change affecting productivity growth.

JEL Classification: O41, O47.
Keywords: Productivity growth, Investment-specific technological change, Neutral technological change

1 Introduction

Technological improvements in equipment have been impressive in the last two decades. Whereas there were some doubts at the beginning of the 1990s, now there is a wide consensus about the positive and significant effects of these improvements on growth and productivity. Neoclassical models predict that long-run productivity growth can only be driven by technological progress. Technology in turn can be differentiated into neutral progress and investment-specific progress. While the first of them is associated to the multifactor productivity, the second one is the amount of technology that can be acquired by using one unit of output. In this sense, the amount of technology that can be transferred to productivity widely differs among the different capital assets.

To this end, recent typologies and data bases recommend the use of disaggregated measures of capital, in order to disentangle the marginal effect of each investment asset. In these new data bases, special focus has been given to the distinction of capital assets among those related to the information and communication technologies (ICT), like computers, the internet, or software licenses, and non-ICT assets, like machinery, transport equipment or structures. As mentioned before, the quality improvements widely differ among these assets. ICT, which have spread more rapidly and bolstered productivity more effectively than earlier technologies, have had a definite impact on the economy. Numerous studies have pointed out the special role played by these technologies in the recovery of productivity growth since the mid-1990s in the United States and some European countries (see among others Colecchia and Schreyer, 2001; and Stiroh, 2002; Daveri, 2002; and Timmer, Ypma and van Ark, 2003).

This paper studies the importance of the different sources of technological progress on labor productivity growth across the U.S. and some European countries during 1980-2004. For this purpose, we use the "Total Economy Growth Accounting" Data Base from the Groningen Growth & Development Center (GGDC), that contains information on the EU-15 and the U.S.[1] Two different approaches are used to identify the *neutral progress* from the *investment-specific progress*: (i) the standard growth accounting decomposition and (ii) the calibration of a general equilibrium model. This refers to the controversy held by Solow and Jorgenson during the sixties regarding the best approach to measure the contribution of production factors to growth. This debate was retaken by the criticism of Greenwood, Hercowitz and Krusell (1997) to Hulten (1992), with extensions until today (see, for instance, Oulton, 2007 *versus* Greenwood and Krusell, 2007).

As regards the *growth accounting approach*, we implement in turn three

[1] For comparisons between the European Union and the US of productivity growth, see for instance, van Ark, Melka, Mulder, Timmer and Ypma (2002), van Ark, Inklaar and McGuckin (2003) van Ark (2005) and Timmer and van Ark (2005).

different measures: the traditional one proposed by Solow (1956) plus two other approaches that take into account the existence of investment-specific technological progress, one proposed by Jorgenson (1966) and the other proposed by Hulten (1992). Concerning the *general equilibrium approach*, we use an extension of the Greenwood, Hercowitz and Krusell (1997) model, developed in Martínez, Rodríguez and Torres (2008). We first consider six different types of capital assets, three of them corresponding to ICT (hardware, software and communications) and three non-ICT (constructions and structures, machinery and transport equipment); and second, we take into account the existence of investment-specific technological change to all the capital assets.

The controversy between the *growth accounting approach* and the *general equilibrium approach* can be interpreted as complement views of the same issue. In fact, the traditional growth accounting can be seen as a good approximation to the fluctuations of technical progress in the short-run whereas the general equilibrium approach fits better the determinants of productivity growth in the long-run.

Regardless the approach, we find that the contribution of neutral technological progress to the productivity growth overcomes that of implicit change. Using the growth accounting view, the neutral change dominates the effect from the implicit change. Capital deepening also accounts for an important fraction of productivity growth, with the exceptions of Finland, Germany and Ireland. Both according to Hulten's view and Jorgenson's view, the ICT assets provide most of the implicit technological change in these economies. The contribution from non-ICT capital assets to productivity growth is negative or negligible for the majority of countries. Regarding the general equilibrium approach, ICT assets, specially the hardware equipment, respond for most of the implicit change. ICT-technological progress contribution to productivity growth is very large in Belgium (0.56 percentage points), Denmark (0.55 percentage points) and the U.S. (0.59 percentage points), explaining over one quarter of their productivity growth. These are three intensive users of the ICT assets. The lowest contributions correspond to Spain and Greece, where ICT-technological progress only contributes to productivity growth 0.18 and 0.12 percentage points, respectively.

The structure of the paper is as follows. Section 2 presents the growth model in which it is included six types of capital assets and the technological progress corresponding to each capital asset. Section 3 calculates the decomposition of productivity growth using the two alternative approaches. Finally, Section 4 presents some conclusions.

2 The model

Following Greenwood *et al.* (1997) we use a neoclassical growth model in which two key elements are present: the existence of different types of capital and the presence of technological change specific to the production of capital. We use the model developed in Martínez *et al.* (2008) that extends the model of the Greenwood *et al.* (1997) model in two directions. *First*, while Greenwood *et al.* (1997) disaggregate between structures and equipment capital assets, we distinguish among six different types of capital inputs. Our production function relates output with seven inputs: L is labor in hours worked; K_1 constructions and structures; K_2 transport equipment; K_3 machinery and other equipment; K_4 communication equipment; K_5 hardware; and K_6 is software. The first three types of capital are grouped into non-ICT capital inputs, whereas the remaining three ones are ICT inputs. *Second*, denote Q_i as the price of asset i in terms of the amount of which that can be purchased by one unit of output. This price reflects the current state of technology for producing each asset. Greenwood *et al.* (1997), by contrast, consider that this price is constant for structures, but is allowed to vary for equipment assets. Note that, according to their definition, equipment include both ICT and non-ICT inputs.

In order to take into account the effect of taxation on capital accumulation we introduce the role of government. The government levies private consumption goods, capital income and labor income, to finance an exogenous sequence of lump-sum transfers, $\{T_t\}_{t=0}^{\infty}$. For simplicity, the government balances its budget in each period.

2.1 Households

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

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

where β is the discount factor and $\phi \in (0,1)$ 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 ($H = 96 \times 52 = 4992$), times population in the age of taking labor-leisure decisions (N_t), minus the aggregated number of hours worked a year ($L_t = N_t h_t$, with h_t representing annual hours worked per worker).

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

$$(1+\tau_c)\,C_t + \sum_{i=1}^{6} I_{i,t} = (1-\tau_l)\,W_t L_t + (1-\tau_k)\sum_{i=1}^{6} R_{i,t}K_{i,t} + T_t, \qquad (2)$$

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 τ^c, τ^l, τ^k, are the consumption tax, the labor income tax and the capital income tax, respectively.

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

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

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

The problem faced by the consumer is to choose C_t, L_t, and I_t to maximize the utility (1):

$$\max_{(C_t,I_t,O_t)} \sum_{t=0}^{\infty} \beta^t \left[\phi \log C_t + (1-\phi)\log(N_t\overline{H} - L_t)\right], \qquad (4)$$

subject to the budget constraint (2) and the law of motion (3), given taxes (τ_c, τ_k, τ_l) and the initial conditions $\{K_{i,0}\}_{i=1}^{6}$.

2.2 Firms

The problem of firms is to find optimal values for the utilization of labor and the different types of capital. The production of final output Y requires the services of labor L and six types of capital K_i, $i = 1, ...6$. The 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,

$$Y_t = A_t L_t^{\alpha_L} \prod_{i=1}^{6} K_{i,t}^{\alpha_i}, \qquad (5)$$

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

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

Both output and investment are therefore measured in units of consumption.

2.3 Government

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

$$\tau^c C_t + \tau^l W_t L_t + \tau^k \sum_{i=1}^{6} R_{i,t} K_{i,t} = T_t. \tag{7}$$

2.4 Equilibrium

The first order conditions for the consumer are:

$$\begin{aligned} \phi C_t^{-1} &= \lambda_t \left(1 + \tau_c\right), & (8) \\ \left(1 - \phi\right) O_t^{-1} &= \lambda_t \left(1 - \tau_l\right) W_t, & (9) \\ \beta \frac{Q_{i,t}}{Q_{i,t+1}} \left[\left(1 - \tau_k\right) Q_{i,t+1} R_{i,t+1} + 1 - \delta_i\right] &= \frac{\lambda_t}{\lambda_{t+1}}, & (10) \end{aligned}$$

for each $i = 1, ...6$. λ_t is the Lagrange multiplier assigned to date's t constraint.

Combining (8) and (9) we obtain the condition that equates the marginal rate of substitution between consumption and leisure to the opportunity cost of one additional unit of leisure:

$$\frac{1-\phi}{\phi} \frac{C_t}{O_t} = \frac{1-\tau_l}{1+\tau_c} W_t. \tag{11}$$

Combining (10) and (8) gives

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

for $i = 1, ...6$. Hence, the (inter-temporal) marginal rate of consumption equates the rates of return of the six investment assets.

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

$$\left\{ R_{i,t} = \alpha_i \frac{Y_t}{K_{i,t}} \right\}_{i=1}^{6}, \tag{13}$$

and

$$W_t = \alpha_L \frac{Y_t}{L_t}, \tag{14}$$

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

Additionally, the economy must satisfy the feasibility constraint:

$$C_t + \sum_{i=1}^{6} I_{i,t} = \sum_{i=1}^{6} R_{i,t} K_{i,t} + W_t L_t = Y_t. \tag{15}$$

First order conditions for the household (8), (9) and (10), together with the first order conditions of the firm (13) and (14), the budget constraint of the government (7), and the feasibility constraint of the economy (15), characterize a competitive equilibrium for the economy.

2.5 The balanced growth path

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

According to a balanced growth path, output, consumption and investment must all grow at the same rate, which is denoted by g. However, the different types of capital would grow at a different rate depending on the evolution of their relative prices. From the production function (5) the balanced growth path implies that:

$$g = g_A \prod_{i=1}^{6} g_i^{\alpha_i}, \tag{16}$$

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

$$\{g_i = \eta_i g\}_{i=1}^{6}, \tag{17}$$

with η_i being the exogenous growth rate of $Q_{i,t}$. 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 (17) says that the capital stock growth also depends on technological progress in the process producing the different capital goods. Therefore, it is possible to express output growth as a function of the exogenous growth rates of production technologies as:

$$g = g_A^{1/\alpha_L} \prod_{i=1}^{6} \eta_i^{\alpha_i/\alpha_L}. \tag{18}$$

Expression (18) implies that output growth can be decomposed as the weighted sum of the neutral technological progress growth and embedded technological progress, as given by $\{\eta_i\}_{i=1}^{6}$. Growth rate of each capital asset can be different, depending on the relative price of the new capital in terms of output.

Denote as $\left\{\{\rho_i, s_i\}_{i=1}^{6}, c, \psi\right\}$ the following steady state ratios

$$\begin{aligned}
\rho_i &\equiv \left(Q_i \frac{Y}{K_i}\right)_{ss} > 0, & (19)\\
c &\equiv \left(\frac{C}{Y}\right)_{ss} \in (0,1), & (20)\\
s_i &= (1-c)\,\omega_i \equiv \left(\frac{I_i}{Y}\right)_{ss} \in (0,1), & (21)\\
\psi &\equiv \left(\frac{L}{NH} = \frac{h}{4992}\right)_{ss} \in (0,1), & (22)
\end{aligned}$$

where the subscript ss denotes its steady-state reference. Notice that s_i in (21) refers to the investment rate of asset i, while ω_i is its portfolio weight, such that $\sum_{i=1}^{6} \omega_i = 1$. The total investment-saving rate is given by $(1-c)$.

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

$$\begin{aligned}
&\left\{g\beta^{-1} = \eta_i^{-1}\left[(1-\tau_k)\,\alpha_i\rho_i + 1 - \delta_i\right]\right\}_{i=1}^{6}, & (23)\\
&\left\{\eta_i g = \rho_i s_i + 1 - \delta_i\right\}_{i=1}^{6}, & (24)
\end{aligned}$$

and

$$\begin{aligned}
1 &= \alpha_L + \sum_{i=1}^{6} \alpha_i. & (25)\\
c &= \alpha_L \frac{\phi}{1-\phi} \frac{1-\tau_l}{1+\tau_c}\left(\psi^{-1} - 1\right), & (26)
\end{aligned}$$

For calibrating the model, we need an additional equation that fixes the after-tax return rate of capital to some value. The right hand side of expression (23) is the real (after-tax) rate of return on asset i, that in equilibrium should equal the intertemporal marginal rate of substitution of consumption, as given by g/β. Expressions (23), as well as its corresponding first order condition (12), implies an arbitrage condition that imposes that the return of the different assets must be equal to g/β. Following Greenwood *et al.* (1997) we will use an after tax rate of return of 7% rate for all countries,

$$g\beta^{-1} = 1.07. \tag{27}$$

In similar calibrations, Pakko (2005) uses a rate of 6% for the U.S. and Bakhshi and Larsen (2005) use a rate of return of 5.3% for the U.K. economy. Expression (27) is also a non arbitrage condition under international free capital mobility.

2.6 Data and Parameters

Expressions from (23) to (27) define a system of fifteen equations. As usual, we will estimate part of the parameters in the model in order to have a complete system of equations. First, using a data set, the following set of parameters will be estimated

$$\left\{g, \psi, \alpha_L, \tau^c, \tau^k, \tau^l, \{\eta_i, \delta_i, \omega_i\}_{i=1}^{6}\right\}. \tag{28}$$

Second, using the nonlinear system of fifteen equations from (23) to (27), we will solve for the following fifteen unknowns

$$\left\{\{\alpha_i, \rho_i\}_{i=1}^{6}, c, \beta, \phi\right\}. \tag{29}$$

From the Groningen Growth & Development Center (GGDC) "Total Economy Growth Accounting" Data Base[2] we retrieve data on GDP, (nominal and real) investment, cost shares, capital assets and labor in hours worked from 1980 to 2004 for the EU-15 countries and for the U.S. economy. Luxemburg is excluded in our analysis. Capital and investment series are disaggregated into 6 assets. Non-ICT series have been grouped into three assets: machinery and other equipment, transport equipment and constructions and structures; whereas ICT series have been aggregated into three assets: hardware, communication equipment and software. This data base suffices to calculate most of the parameters in (28).

The estimated values of (28) are reported in table 1, divided into four panels. Productivity growth is collected in the first row of this table and is calculated as $g = T^{-1}\sum_t y_t/y_{t-1}$, where y_t is the GDP per hour worked. With the exception of Ireland, that according to the GGDC evinces an impressively high rate of productivity growth, 4.3%, for the rest of the countries this rate is limited to the interval $0.014 \leq \ln(g) \leq 0.024$.

[2] See Timmer, Ypma and van Ark (2003): `http://www.ggdc.net/dseries/totecon.html`

The following row collects the fraction of hours worked, ψ. The highest fractions are found for the Greece, Ireland, Spain and the U.S., while the lowest ones are for Denmark, France and the Netherlands. This fraction in the major European economies are well below that of the U.S. This fact is also illustrated in Blanchard (2004) and Prescott (2004).

The average labor cost shares provided by the GGDC data base is used as an estimator of α_L, presented in the third row of table 1. 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.

In order to calculate the tax rates, not provided in the GGDC data base, a complementary set of data has been used. In this paper we borrow from Boscá, García and Taguas (2005) their estimates of effective average tax rates, who follow the methodology of Mendoza, Razin and Tesar (1994), for OECD countries for the period 1964-2001. To compute tax rates averages, we select the period 1980-2001. With the exceptions of Denmark, the U.K. and the U.S., the respective governments levy higher taxes on the labor income than on the capital income.

As regards the *relative price changes* $\{\eta_i\}_{i=1}^{6}$, prices Q_{it} represent the amount of asset i that can be purchased by one unit of output at time t. We consider the following series as proxy for Q_{it}

$$Q_{it} = \frac{P_t}{q_{it}}, \tag{30}$$

where P_t is the consumption price index (taken from IMF-IFS, line 64, 2000 base year), and q_{it} is the implicit deflator of asset i, which is calculated as the ratio of nominal to real investment in asset i. The second panel of table 1 reports the average price changes of the six assets through 1980-2004, $\eta_i = T^{-1} \sum_t Q_{i,t}/Q_{i,t-1}$. Price variations η_i are similar across countries. For transport equipment, however, there are five countries whose price evolution exhibits a differentiated pattern (Spain, Ireland, Italy, Portugal and Sweden): the change in this price exceeds 1 per cent. The change in the price of non-ICT equipment is almost 0 per cent on average. Importantly, the implicit technological change, as measured by the evolution of the Q_i, is stronger in the ICT equipment: for hardware is 16.25%, and for communication and software it is about 3.5 per cent per year. As an illustration, figure 1 depicts the series of the levels of $Q_{i,t}$ for the U.S. economy, 1980-2004. There are moderately long swings in the implicit change for structures that tend to revert to 1. There is an upward continuous trend for the $Q_{i,t}$ of transport equipment and machinery. The series for the three ICT assets are also positively sloped, mainly the one of hardware equipment.

For the rates of depreciation, we take the estimation given in van Ark, Inklaar and McGukin (2003, p. 23-24) as a central moment, and adjust it using the GGDC data base series on the stock of capital i and gross formation of fixed capital. These estimates are stable across years and very similar across countries, as shown in table 3. Structures depreciate by 2.8 per cent a year, which contrasts with that assumed by Greenwood *et al.* (1997) of 5.6%. The rates of depreciation of ICT equipment are high, specially the software, 42%.

The last panel of table 1 finally reports the investment weights averaged over 1980-2004, ω_i. Using the GGDC data base, these weights represent the ratio of nominal investment in asset i to nominal GDP. In all countries, structures receive the highest weight, going from a minimum of 36 per cent in Italy and the U.S. up to a 57 per cent in Spain. Note that the implicit technological change in structures is nearly zero. The assets of the new economy have had a minor relevance on the composition of this physical portfolio. However, there are six countries that could be considered as intensive users of ICT assets: the U.S. invests a 23% of its portfolio on these assets; this is followed by Sweden, Denmark, Belgium and the U.K. The sum of these weights is only 14% for Germany.

[**Table 1 and figure 1 here**]

3 Technological sources of productivity growth

In this section we estimate the sources of productivity growth using two methodologies adopted in the literature: the growth accounting view and the general equilibrium view. In turn, we consider three alternative growth accounting approaches: the standard growth accounting decomposition, due to Solow (1956) plus two decompositions that take explicit account of the quality improvement in the capital assets, one proposed by Jorgenson (1966) and the other by Hulten (1992). The general equilibrium view uses the model developed in Section 2 of this paper. We follow the terminology of Cummins and Violante (2002) which define the first approach as the *traditional growth accounting* and the second one as *equilibrium growth accounting*.

The debate about the correct approach to quantify the contribution of technological progress for growth was initiated by Solow (1960) versus Jorgenson (1966). Both authors introduce the concept of *embodied* technological change using different frameworks. The difference is that while Solow (1960) assumes *embodied* technological change only in the production of investment goods, Jorgenson (1966) assumes that it also affects output. A review of the Solow-Jorgenson controversy can be found in Hercowitz (1998).

The recent revival of the Solow-Jorgenson controversy had been hosted by Hulten (1992) versus Greenwood *et al.* (1997). This debate has its continuity in Oulton (2007) versus Greenwood and Krusell (2007). 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, being the second approach preferred to the first one. The reason is that whereas the use of a general equilibrium model can isolate the technological progress from other sources of output growth as capital accumulation, the traditional growth accounting cannot. Output growth derives from both technological progress and capital accumulation. Traditional growth accounting quantify the importance of both components in growth as though they were independent from each other. The problem is that capital accumulation is affected by technological progress. Hence, traditional growth accounting is not able to quantify the importance of technological change given that it is not possible to verify the proportion of capital accumulation due to technological progress. Only a fully articulated general equilibrium model can do that. As pointed out by Hercowitz (1998), if technological change is *disembodied*, it affects output independently from capital accumulation. On the opposite site, Oulton (2007) claims that the general equilibrium growth model with embodied technological change is a particular case of the Jorgenson's approach, where the concept of investment-specific technological change is closely related to the concept of total factor productivity. Within the lines proposed by Greenwood and Krusell (2007), Cummins and Violante (2002) pointed out that the main drawback of the traditional growth accounting view is that is does not isolate the underlying sources of capital accumulation. By contrast, a general equilibrium model can solve the optimal investment behavior as a function of the underlying sources of growth.

3.1 Three growth accounting approaches

In this subsection, we report the results obtained from carrying out three versions of the traditional growth accounting. The first approach is the growth accounting approach, which obtains the contribution of (neutral) technical progress residually after controlling for the growth rates and output shares of production factors (Solow, 1956 and 1957). This simple methodology, widely used, is flexible enough to take account not only the contribution of the traditional inputs but also for distinguishing between neutral and investment-specific technological change. This approach, however, does not control for changes in the prices of the capital assets and assumes constant returns to scale. Given this view, productivity growth can be decomposed as:

$$\ln(g) = \underbrace{\gamma_{A,S}}_{\text{Neutral}} + \sum_{i=1}^{6} \underbrace{v_i \left(\gamma_{K_i} - \gamma_L\right)}_{\text{Accumulation}}, \tag{31}$$

where γ_χ is the growth rate of χ and $\gamma_{A,S}$ is the change in neutral technological progress (total factor productivity, TFP, or Solow residual). In our exercises, as a measure of productivity growth we use that reported in table 2 as $\gamma_Y - \gamma_L = \ln(g)$. Productivity growth is decomposed in two different elements: total factor productivity growth and the contribution from the growth in the capital to labor ratio. v_i is the elasticity of output with respect to capital asset i, that can be measured as the ratio of the marginal product to average product. This ratio can be computed as the share of compensation of asset i over total compensation, including the labor costs. Note that the elasticity of substitution between the factors employed to produce output is not assumed to be one. The Cobb-Douglas production function of previous section does assume it.

Particularly, the GGDC data base follows the recommendations of OECD (2001) for constructing the series of capital assets, which are based on the concept of *capital services*. The idea is to capture the productive services embedded into the stock of capital. This concept of productive capital can be seen as a volume index of capital services. The expression driving the concept of capital services for the asset i is as follows:

$$VCS_{it} = \mu_{it} K_{it}, \tag{32}$$

where μ_{it} is, in turn, the nominal usage cost of capital. Call RE_t the remuneration of employees. The cost shares are given by the following expressions:

$$v_{L,t} = \frac{RE_t}{RE_t + \sum_{i=1}^{6} VCS_{it}}, \tag{33}$$

$$v_{i,t} = \frac{VCS_{it}}{RE_t + \sum_{i=1}^{6} VCS_{it}}. \tag{34}$$

These cost shares are used in growth accounting decompositions for weighting the contribution of the different inputs to output growth and productivity growth, as guided by theoretical foundations. Note that our measure of the labor cost share is equivalent to $\alpha_L = T^{-1} \sum_t v_{L,t}$. However, while the cost ratios v_i are computed using the series of inputs compensation, the values of technological parameters $\{\alpha_i\}_{i=1}^{6}$ are calibrated using the balanced growth equilibrium expressions from (23) to (27). Also note that

$$\alpha_L = 1 - \sum_{i=1}^{6} v_i = 1 - \sum_{i=1}^{6} \alpha_i.$$

The other two approaches take into account the existence of investment-specific technological change. The second one is due to Jorgenson (1966), where productivity growth is decomposed as:

$$\ln(g) = \underbrace{\gamma_{A,J}}_{\text{Neutral}} + \sum_{i=1}^{6} \underbrace{v_i \left(\gamma_{K_i} - \gamma_L\right)}_{\text{Accumulation}} + \sum_{i=1}^{6} \underbrace{z_i \ln(\eta_i)}_{\text{Implicit}}, \tag{35}$$

where $\gamma_{A,J}$ is the change in neutral technological progress as defined by Jorgenson (1966) and z_i is the ratio of nominal investment in asset i to nominal GDP. Note that portfolio weights ω_i in table 1 are related to the investment rates as $\omega_i = z_i / \sum_i z_i$.The last term of (35) is a measure of the contribution from implicit technical change. In our case, we take the values of η_i reported in table 1.

The third decomposition approach is due to Hulten (1992):

$$\ln(g) = \underbrace{\gamma_{A,H}}_{\text{Neutral}} + \sum_{i=1}^{6} \underbrace{v_i \left(\gamma_{K_i} - \gamma_L\right)}_{\text{Accumulation}} + \sum_{i=1}^{6} \underbrace{v_i \ln(\eta_i)}_{\text{Implicit}}, \tag{36}$$

where $\gamma_{A,H}$ is the change in neutral technological progress as defined by Hulten (1992). As in the Jorgenson's decomposition, it is considered a measure of implicit technical change. The last terms of (36) and (35) can be interpreted as measures of implicit technological change. Note that the difference between both of them lies in using the output share of capital assets, v_i, or the investment ratio, z_i, as a way of weighting the growth of capital input prices Q_i. Note finally that the central term that collects the effect of capital-to-labor ratio accumulation, is common in the three expressions (31), (35) and (36), and must render an identical value.

The contributions of both types of technical progress and capital deepening to the productivity growth in the EU-15 and U.S. are reported in table 2 according to these three approaches. The first panel in this table reports observed productivity, $\ln(g)$, and the three measures of total factor productivity, the Solow-traditional approach $\gamma_{A,S}$, the extended Jorgenson's approach $\gamma_{A,J}$, and that proposed by Hulten, $\gamma_{A,H}$. The second panel reports calculation of the effect of capital deepening on productivity, a measure that is common to the three approaches. Next , the following two panels report the contribution on implicit technological change to productivity growth according to Jorgenson's and Hulten's views. Finally, in the last panel of the table, we calculate the weights of the different contributions to productivity growth, v_i, and the investment rates, z_i. For the sake of brevity, we present the contribution of the capital inputs aggregated into three assets: constructions, non-ICT equipment and ICT equipment.

The contribution of technical progress is quite sensitive to the approach followed. Obviously, the impact of neutral change is higher under the Solow's (1956) method as long as total factor productivity is computed as a residual that neglects the effects from the implicit technological progress. When the prices of the capital inputs are taken into consideration, neutral technical change is higher under Jorgenson's view, where the investment ratio is used as weighting factor of capital assets prices. This is quite reasonable as long as the this approach only recognizes the existence of embedded technological progress in the new capital assets through investment, while the later considers the investment-specific technical change through the output share of capital inputs over final output.

The growth of neutral technical change is distributed across countries without following a well-defined pattern with respect to the intensity in the use of ICT. Regardless the differences coming from the approach, it seems to be clear that the relative contribution of neutral technical change does not depend on whether the country is an intensive user of the ICT or not. Relatively similar countries in terms of ICT development such as the U.K. and the US show significant differences by comparing the effects of neutral technological progress on productivity growth using the two approaches which control for the prices of capital assets, Hulten's view and Jorgenson's view. Indeed, the percentage of productivity growth explained by neutral change is 13 points higher (taking Jorgenson's view) and over 17 points (on the basis of Hulten's approach) in the U.K. than in the U.S. By contrast, quite different economies such as Sweden and Spain have a similar effect of neutral technical change on productivity growth (in any case less different than the comparison between the U.K. and the U.S.), both measured according to the traditional approach by Solow and the more elaborated contribution of Hulten.

The differences between countries with heterogenous levels of ICT penetration rather come from the comparison between subperiods. Our results (not reported here but available upon request) show how, in general, the countries with a higher development of the "new economy" (the U.S., Sweden, the U.K. and Finland) usually experienced a poor contribution of neutral technological growth to the dynamics of productivity at the beginning of the sample, specially when they are compared to the economies where the new technologies are not widely extended (Spain, Italy, Portugal and, in a sense, the Netherlands). Obviously, many factors could be behind this fact but it is reasonable to think that the introduction of ICT generates adjustment costs (Samaniego, 2006). Indeed, the magnitude of the technological revolution related to ICT is huge enough to suffer organizational costs at level plant. This issue does not matter when the use of ICT is quite smaller. As time goes by, these negative effects of ICT on efficiency are assimilated and the new equipment start developing their productive potential. That may be one of the reason why ICT-intensive countries experience a significant contribution of neutral technical change to productivity growth over the last years of the sample (1995-2004).

[**Table 2 here**]

3.2 The equilibrium growth accounting approach

Next, the different sources of long-run productivity growth is calibrated using the general equilibrium approach of section 2, following Greenwood *et* *al.* (1997) approach. In order to compare the approaches expressed in (31), (35) and (36), we use a log-linear version of expression (18)

$$\ln(g_{GE}) = \underbrace{\frac{\ln(g_A)}{\alpha_L}}_{\text{Neutral}} + \sum_{i=1}^{6} \underbrace{\frac{\alpha_i}{\alpha_L}\ln(\eta_i)}_{\text{Implicit}}, \tag{37}$$

with

$$\ln(g_A) = \ln(g) - \sum_{i=1}^{6} \alpha_i \left(\gamma_{K_i} - \gamma_L\right),$$

where $\ln(g_{GE})$ is the productivity growth rate calibrated by the model that needs not coincide with the observed rate $\ln(g)$. Therefore, $\ln(g_A)$ is now the growth rate of total factor productivity, which is proportional to the neutral change by α_L, the elasticity of output with respect to labor.

Table 3 summarizes the results. The first panel of it, presents observed and calibrated productivity as well as the neutral technological change. The second panel reports the technological change implicit in the six capital assets under consideration. The following panel calculates how much the neutral change and the implicit change account to explain the productivity growth. In the following panels we report the calibration of some relevant parameters (β, $1-c$, and $\{\alpha_i\}_{i=1}^{6}$). Note that these calibrated technological parameters $\{\alpha_i\}_{i=1}^{6}$ are similar to the cost shares $\{v_i\}_{i=1}^{6}$ in table 2. For the U.S., those shares corresponding to the ICT capital are higher than the remaining countries, which reflects higher investment effort in these assets. Using a log-linear version of the model, the last panel of table 3 presents some statistical moments of productivity growth to check how the model fits the observations: standard deviations and the correlation coefficient between observed growth and the growth rate predicted by the model. We take the series A_t, and $\{Q_i\}_{i=1}^{6}$ as exogenous from 1980 to 2004. In general, the model produces slightly smoother series of productivity growth, as standard deviations of the observed series are higher than those motivated by the model (due probably to the log-linearization). Yet the correlation coefficients, with the exception of the U.K., are between 0.70 and 0.95. We thereby conclude that the approximation given by the model is accurate. As an illustration, figure 2 plots the series of productivity growth for the U.S. economy (the correlation coefficient is 0.75). Note that the model reproduces and leads the recovery of productivity growth after 1995. This fact is well documented in other works like Timmer and van Ark (2005). The main peaks of the observed series are replicated by the model.

In view of this table, we remark the following results. The contribution of neutral technological progress dominates that of the implicit technological progress. The lowest contribution of neutral technological change corresponds to Italy (48% of total growth). This contribution is 65% in the U.S.;

this result contrasts with that obtained by Greenwood *et al.* (1997) where the neutral change accounts for a 42%, thereby dominated by the implicit change, and a 58% of productivity growth can be attributed to implicit technological change during the period 1954-1990. However, our exercise should be compared with caution with the one by Greenwood *et al.* (1997), as the sample period, the disaggregation of capital, and the data set are different. For the rest of countries, contribution from neutral technological change appears very large (above 70%). Therefore, for most of the countries, we find that neutral technological progress explain a very large fraction of productivity growth during this subperiod.

Average productivity growth during the period 1980-2004 ranges from the 4.22% of Ireland to the 1.3% of the Netherlands. However, most of the countries show an average productivity growth during the period of around 2%. Our calibrated growth rates are slightly different than the actual one. Calibrated average productivity growth varies from 4.84% of Ireland, to the 0.92% of Greece. Differences between the productivity growth from the data and the steady state approximation are negligible (the highest discrepancy is for Ireland, where observed and calibrated productivity differ by 0.62%).

During the period 1980-2004 no important differences are observed between the behavior of the U.S. economy versus the European economies in terms of labor productivity growth. The U.S. average productivity growth were 1.83%, while the average of productivity growth in Europe was 2.12%. The data evince, however, that some European countries as the Netherlands, Italy and Spain, have a relatively low productivity growth since the mid of the nineties.

The largest contributions from investment-specific technological change correspond to the U.K., the U.S. and Denmark, 0.80%, 0.73%, 0.61%, respectively. For the remaining countries, contributions fall between the 0.08 percentage points of Finland to the 0.58 percentage points of Italy. ICT-technological progress contribution to productivity growth is very large in Belgium (0.56 percentage points), Denmark (0.55 percentage points) and the U.S. (0.59 percentage points), explaining around a quarter of total productivity growth. In the case of the U.S., we obtain that the contribution of only ICT-specific technological change is 28% of labor productivity growth for all the period. The lowest contribution from the ICT corresponds to Ireland, where it only accounts for a fraction of 6% of productivity growth (6% = 0.29/4.84). Also Greece, Spain and France show relative low contribution from ICT (0.12%, 0.18% and 0.24% respectively). Contribution from ICT-specific technological change in U.K. is around 32% of total labor productivity growth. Bakhshi and Larsen (2005) in a similar analysis for the U.K. for the period 1976-1998 obtained that ICT-specific technological was around 20-30% of total labor productivity growth.

The main difference in our results with respect to previous literature relays on the contribution of non-ICT technological change to productivity growth. It is important to note that structures are included in our specification of non-ICT capital. By assumption, the contribution from non-ICT technological change to productivity growth is zero in previous work (see Greenwood *et al.* (1997), Bakhshi and Larsen (2005), among others). However, as Fisher (2003) shows, the relative price of non residential structures changes through time. Therefore, implicit technological change associated to structures is included in total implicit technological change from non-ICT capital. As a result, contribution to growth for non-ICT specific technological change is negative for Belgium, Finland, Germany, Ireland, the Netherlands and Sweden.

How different are these results in comparison with those corresponding to the traditional growth accounting approaches? Certainly, a major difference arises when the two approaches are compared: both types of technical progress have higher contributions to productivity growth with the general equilibrium approach than under the standard growth accounting exercises. The reason of this is related to the different dimensions of economic growth on which both approaches focus. The traditional growth accounting methods can be interpreted as a good approximation for explaining the short-term fluctuations of technical progress and output. In fact, they consider capital deepening as one of the forces driving the productivity growth. In the case of the general equilibrium approach, the analysis pays attention upon the long-term view, with the economy placed on its balanced growth path. In the steady-state, the only reason for capital accumulation is the presence of (neutral or embedded) technical progress. This is the only condition for increasing the marginal productivity of capital endlessly. Consequently, under a long-term perspective, only controlling for the growth of technical change is enough for having a complete description of the sources of productivity growth.

[**Table 3 and figure 2 here**]

4 Concluding remarks

The recent experiences of the U.S. and some European countries show that ICT investment encourages economic growth and labor productivity. However, the European Union as a whole are considerably lagged with respect to the U.S. economy in the use of ICT at all economic levels. Since the early eighties, the U.S. economy has doubled European investment in ICT. As a way to fill this gap, the Lisbon Strategy and the initiative *i2010* collected a number of policy recommendations in order to make significant advances on this issue. Therefore, the use of new technologies should be viewed as an instrument for reversing productivity slowdown but properly combined with other policy tools.

This paper investigates the importance of different sources of technological progress in explaining productivity growth in Europe and the U.S.. Two different approaches had been used to quantify the contribution of technological change to productivity growth: a traditional growth accounting and a general equilibrium method. Whereas the first approach is a good approximation to the fluctuation of technological progress in the short-run, the second approach can isolate the underlying sources for capital accumulation and it is a better approximation for the determinants of productivity growth in the long-run.

Regarding the traditional growth accounting methodology, we have seen that the contribution of neutral technical change on productivity growth is not distributed across countries following a clear pattern. Particularly, we have shown that the relative magnitude of this source of growth does not depend on whether the country is an intensive user of ICT assets or not. If subperiods were considered, things would be different and a significant correlation between neutral technological progress and intensity in the use of ICT would be found. Moreover, regardless the approach followed within this growth accounting exercise (Hulten versus Jorgenson), it happens that the relative importance of neutral technical change is higher than the implicit technical change.

Under the equilibrium growth accounting approach, the contribution of neutral technical change also dominates that of the implicit technological progress. As can be expected, the implicit technological change linked to ICT assets is more powerful than that coming from non-ICT inputs, with the exceptions of France and Greece. Even for some countries (Belgium, Finland, Germany, Ireland, Netherlands and Sweden) the implicit technical progress of non-ICT assets appears as a negative contributor to productivity growth.

The main conclusion that we obtain is that the E.U. member countries fall well behind the U.S. with respect to the effects from ICT technological change. Only two rather small economies, Denmark and Belgium, show important contributions to productivity growth from ICT technological revolution. Therefore, it seems that the goal of the so-called Lisbon Strategy, i.e., the European Union to become by 2010 the most dynamic and competitive knowledge-based economy in the world, is far away from reality.

References

[1] Ark, B. van, Inklaar, R., and McGukin, R. (2003): ICT and productivity in Europe and the United States. Where do the differences came from? *The Conference Board, EPWP*, 03-05.

[2] Ark, B. van, Melka, J., Mulder, N., Timmer, M. and Ypma, G. (2002): ICT investments and growth accounts for the European Union 1980-2000. *Research Memorandum* GD-56, Groningen Growth and Development Centre.

[3] Ark, B. van (2005): Does the European Union need to revive productivity growth, *Research Memorandum* GD-75, Groningen Growth and Development Centre.

[4] Bakhshi, H. and Larsen, J. (2005): ICT-specific technological progress in the United Kingdom. *Journal of Macroeconomics* 27(2), 648-669.

[5] Blanchard, O. (2004): The economic future of Europe. *Journal of Economic Perspectives*, 18(4), pp. 3-26.

[6] Boscá, J., García, J. and Taguas, D. (2005): Taxation in the OECD: 1965-2001, *Working Paper Ministerio de Economía y Hacienda*, D-2005-06.

[7] Colecchia, A. and P. Schreyer (2002): ICT investment and economic growth in the 1990's: Is the United States a unique case? A comparative study of nine OECD countries. *Review of Economic Dynamics*, 5(2): 408-442.

[8] Cummins, J.G. and Violante, G. L. (2002): Investment-specific technical change in the U.S. (1947-2000): Measurement and macroeconomic consequences. *Review of Economic Dynamics*, 5, 243-284.

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

[10] Fisher, J. (2003): The new view of growth and business cycles. *Federal Reserve Bank of Chicago Economics Perspectives*, 35-56.

[11] Gollin, D. (2002): Getting Income Shares Right. *Journal of Political Economy*, 110(2), 458-474.

[12] Greenwood, J., and Krusell, P. (2007): Growth accounting with investment-specific technological progress: A discussion of two approaches. *Journal of Monetary Economics*, 54(4), 1300-1310.

[13] Greenwood, J., Hercowitz, Z. and Krusell, P. (1997): Long-run implication of investment-specific technological change, *American Economic Review* 87(2), 342-362.

[14] Hercowitz, Z. (1998): The 'embodiment' controversy: a review essay, *Journal of Monetary Economics*, 41(1), 217-224.

[15] Hulten, C. (1992): Growth accounting when technical change is embodied in capital. *American Economic Review*, 82(4), 964-980.

[16] Jorgenson, D. W. (1966): The embodiment hypothesis. *The Journal of Political Economy* vol. 74(1), 1-17.

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

[18] Martínez, D., J. Rodríguez and Torres, J.L. (2008): The productivity paradox and the new economy: The Spanish case, *Journal of Macroeconomics*, 30(4), 1569-1586.

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

[20] OECD (2001): "Measuring capital. A manual on the measurement of capital stocks, consumption of fixed capital and capital services", Paris, OECD.

[21] Oulton, N. (2007): Investment-specific technological change and growth accounting, *Journal of Monetary Economics*, 54(4), 1290-1299.

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

[23] Prescott, E.C. (2004): Why do Americans work so much more than Europeans? *Federal Reserve Bank of Minneapolis Quarterly Review*, 28(1), 2-13.

[24] Samaniego, R. M. (2006): Organizational capital, technology adoption and the productivity slowdown, *Journal of Monetary Economics* 53(7), 1555-1569.

[25] Solow, R. (1956): A contribution to the theory of economic growth, *Quarterly Journal of Economics*, 70(1), 65-94.

[26] Solow, R. (1957): Technical change and the aggregate production function, *Review of Economics and Statistics*, 39(3), 312-320.

[27] Solow, R. (1960): Investment and technological progres, in K. Arrow, S. Karlin and P. Suppes (eds.), *Mathematical Methods in the Social Sciences*. Stanford: Stanford University Press.

[28] Stiroh, K: (2002): Information technology and U.S. productivity revival: What do the industry data say?, *American Economic Review* 92(5), 1559-1576.

[29] Timmer, M. P., G. Ypma and van Ark, B. (2003), IT in the European Union: Driving Productivity Divergence?, GGDC Research Memorandum GD-67 (October 2003), University of Groningen.

[30] Timmer, M. and van Ark, B. (2005): Does information and communication technology drive EU-U.S. productivity growth differentials?, *Oxford Economic Papers* 57(4), 693-716.

Figure 1: **Evolution of the Q –prices in the U.S.A., 1980-2004**

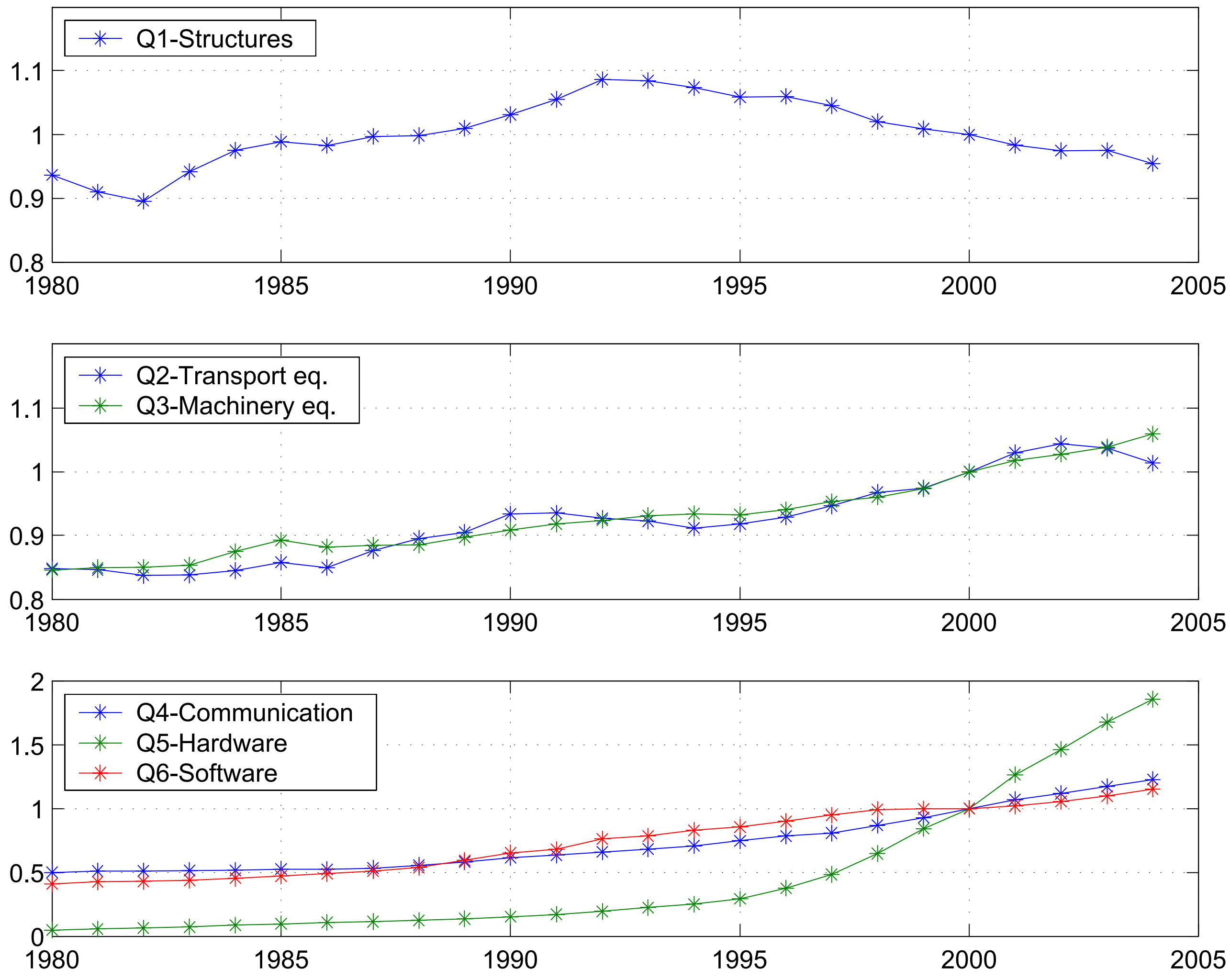


Figure 2: Productivity growth in the U.S.A., 1980-2004

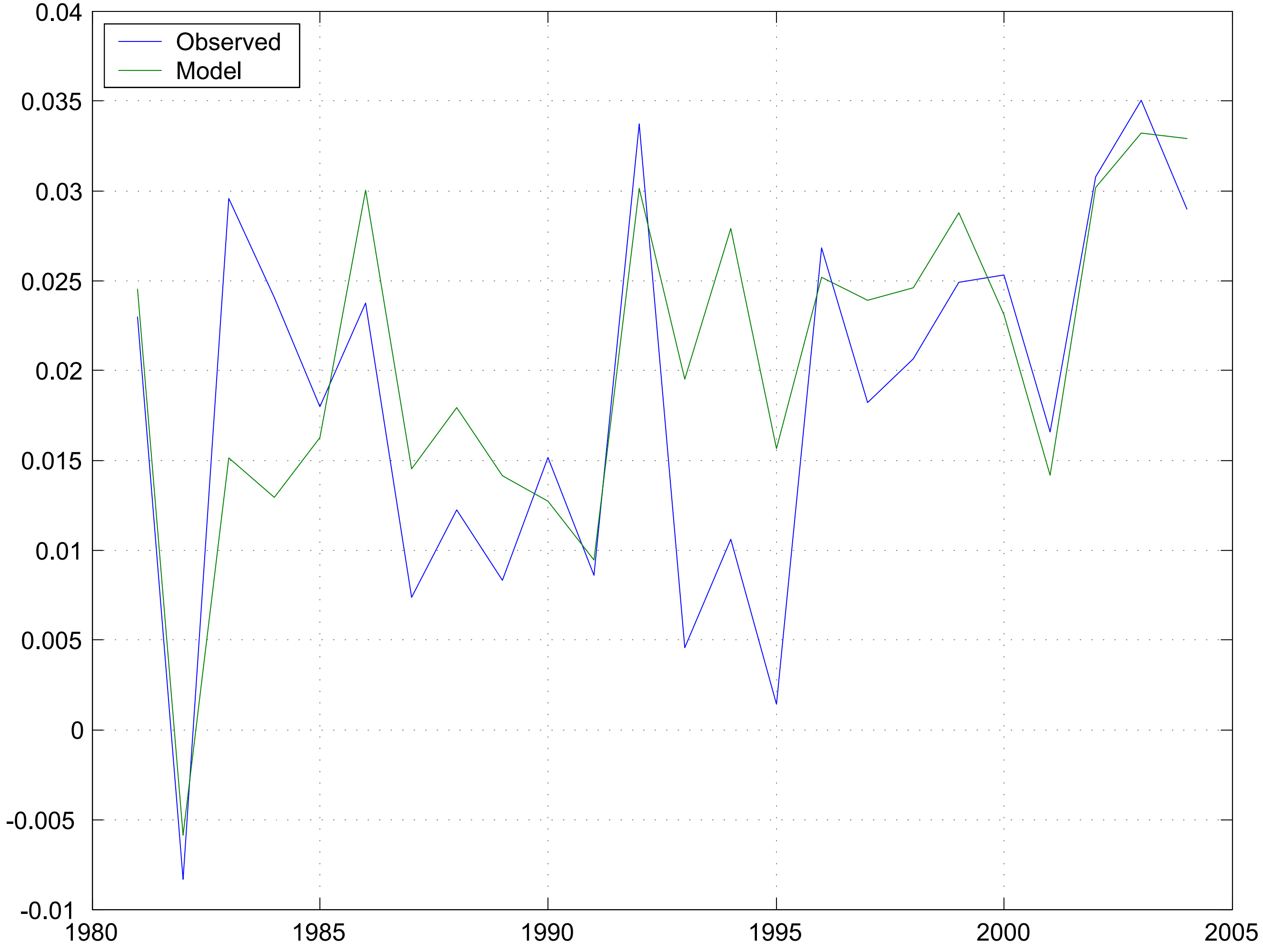


Table 1: Parameters, period 1980-2004

	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherl.	Portugal	Spain	Sweden	U.K.	U.S.A.
Productivity growth, g	1,019	1,020	1,022	1,028	1,023	1,024	1,012	1,043	1,015	1,014	1,021	1,018	1,020	1,024	1,019
Fraction of hours worked, ψ	0,327	0,331	0,307	0,337	0,308	0,308	0,388	0,366	0,330	0,283	0,365	0,370	0,313	0,338	0,370
Labor income share, α_L	0,651	0,709	0,676	0,684	0,671	0,697	0,766	0,644	0,661	0,698	0,698	0,734	0,706	0,688	0,706
Consumption tax rate, τ_C	0,151	0,127	0,198	0,177	0,139	0,113	0,133	0,173	0,107	0,135	0,137	0,096	0,143	0,126	0,047
Capital income tax rate, τ_K	0,206	0,276	0,435	0,299	0,270	0,242	0,100	0,116	0,281	0,236	0,184	0,190	0,363	0,322	0,330
Labor income tax rate, τ_L	0,426	0,443	0,379	0,418	0,428	0,359	0,348	0,323	0,389	0,447	0,243	0,321	0,513	0,244	0,230
Price changes across $\{\eta_i\}$															
Constructions, η_1	1,004	1,009	1,002	0,997	1,006	1,008	1,003	0,993	0,997	1,002	1,004	0,999	0,998	1,016	1,001
Transport equipment, η_2	1,001	1,006	0,992	1,001	1,013	0,995	1,011	1,014	1,005	1,006	1,017	1,013	1,015	1,004	1,008
Machinery equipment, η_3	0,992	0,968	1,005	0,985	1,016	0,986	1,011	1,004	1,017	0,983	0,995	1,006	0,999	1,003	1,009
Communication equip., η_4	1,035	1,034	1,037	1,030	1,044	1,034	1,030	1,027	1,047	1,035	1,029	1,036	1,032	1,033	1,038
Hardware, η_5	1,163	1,162	1,165	1,158	1,173	1,162	1,157	1,150	1,177	1,164	1,156	1,164	1,160	1,160	1,167
Software, η_6	1,041	1,040	1,037	1,036	1,040	1,040	1,036	1,030	1,033	1,042	1,034	1,035	1,038	1,039	1,044
Depreciation rates $\{\delta_i\}$															
Constructions, δ_1	0,027	0,028	0,028	0,028	0,028	0,028	0,027	0,027	0,028	0,028	0,026	0,027	0,028	0,027	0,028
Transport equipment, δ_2	0,188	0,188	0,188	0,191	0,186	0,190	0,182	0,182	0,187	0,187	0,185	0,187	0,184	0,189	0,188
Machinery equipment, δ_3	0,132	0,132	0,130	0,133	0,130	0,133	0,129	0,132	0,130	0,132	0,132	0,130	0,132	0,132	0,130
Communication equip., δ_4	0,111	0,106	0,111	0,091	0,109	0,113	0,106	0,094	0,108	0,112	0,104	0,106	0,111	0,107	0,109
Hardware, δ_5	0,241	0,243	0,243	0,256	0,237	0,246	0,220	0,215	0,238	0,240	0,251	0,241	0,243	0,233	0,242
Software, δ_6	0,408	0,426	0,418	0,431	0,422	0,426	0,394	0,429	0,420	0,427	0,433	0,420	0,418	0,407	0,419
Investment weights $\{\omega_i\}$															
Constructions, ω_1	0,446	0,395	0,423	0,442	0,504	0,418	0,541	0,439	0,364	0,461	0,385	0,577	0,382	0,381	0,361
Transport equipment, ω_2	0,120	0,145	0,130	0,094	0,110	0,126	0,144	0,218	0,133	0,152	0,134	0,102	0,075	0,118	0,111
Machinery equipment, ω_3	0,316	0,281	0,278	0,294	0,296	0,318	0,223	0,264	0,363	0,253	0,359	0,221	0,347	0,341	0,295
Communication equip., ω_4	0,049	0,035	0,019	0,046	0,032	0,045	0,048	0,020	0,062	0,013	0,038	0,030	0,039	0,031	0,071
Hardware, ω_5	0,046	0,103	0,083	0,035	0,024	0,053	0,031	0,036	0,041	0,061	0,071	0,035	0,075	0,068	0,086
Software, ω_6	0,024	0,041	0,066	0,089	0,034	0,041	0,013	0,023	0,037	0,060	0,012	0,034	0,082	0,062	0,076

Table 2: Growth Accounting Decompositions

	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Nether.	Portugal	Spain	Sweden	U.K.	U.S.A.
Productivity, *ln(g)* (a)	1,88%	2,00%	2,16%	2,72%	2,27%	2,37%	1,15%	4,23%	1,44%	1,36%	2,08%	1,73%	1,97%	2,35%	1,83%
Neutral Change (or TFP)															
Solow ($\gamma_{A,S}$)	0,73%	0,97%	0,76%	1,85%	0,91%	1,37%	0,49%	3,04%	0,37%	0,73%	1,15%	0,73%	0,96%	1,27%	0,88%
Hulten ($\gamma_{A,H}$)	0,44%	0,54%	0,26%	1,80%	0,45%	1,06%	0,28%	2,97%	-0,01%	0,48%	0,90%	0,48%	0,62%	0,75%	0,27%
Jorgenson ($\gamma_{A,J}$)	0,58%	0,77%	0,49%	1,79%	0,67%	1,24%	0,31%	2,96%	0,12%	0,58%	0,93%	0,55%	0,74%	1,00%	0,54%
Capital contribution (b = b1+b2+b3)	1,15%	1,03%	1,39%	0,87%	1,36%	1,00%	0,66%	1,18%	1,07%	0,63%	0,93%	1,00%	1,00%	1,07%	0,95%
Constructions (b1)	0,59%	0,28%	0,52%	0,50%	0,66%	0,44%	0,27%	0,67%	0,36%	0,20%	0,65%	0,55%	0,27%	0,44%	0,15%
Non-ICT (b2)	0,14%	0,05%	0,18%	-0,08%	0,39%	0,10%	0,20%	0,24%	0,33%	0,02%	-0,02%	0,14%	0,13%	0,11%	0,09%
ICT (b3)	0,43%	0,71%	0,70%	0,45%	0,31%	0,46%	0,20%	0,27%	0,39%	0,42%	0,30%	0,30%	0,60%	0,53%	0,71%
Implicit change-Hulten (c = c1+c2+c3)	0,29%	0,43%	0,51%	0,05%	0,47%	0,32%	0,21%	0,08%	0,38%	0,24%	0,25%	0,25%	0,34%	0,52%	0,61%
Constructions (c1)	0,08%	0,12%	0,03%	-0,05%	0,13%	0,12%	0,04%	-0,16%	-0,06%	0,03%	0,05%	-0,01%	-0,03%	0,22%	0,01%
Non-ICT (c2)	-0,08%	-0,21%	0,01%	-0,14%	0,15%	-0,13%	0,07%	0,09%	0,18%	-0,09%	-0,03%	0,07%	0,00%	0,01%	0,09%
ICT (c3)	0,29%	0,52%	0,47%	0,25%	0,19%	0,33%	0,10%	0,15%	0,25%	0,30%	0,23%	0,19%	0,37%	0,29%	0,51%
Implicit change-Jorgenson (d = d1+d2+d3)	0,14%	0,20%	0,27%	0,06%	0,25%	0,14%	0,18%	0,09%	0,25%	0,15%	0,22%	0,18%	0,23%	0,27%	0,34%
Constructions (d1)	0,03%	0,05%	0,01%	-0,02%	0,05%	0,05%	0,02%	-0,05%	-0,02%	0,01%	0,03%	-0,01%	-0,01%	0,08%	0,00%
Non-ICT (d2)	-0,04%	-0,13%	0,00%	-0,08%	0,10%	-0,08%	0,06%	0,05%	0,10%	-0,05%	0,00%	0,05%	0,01%	0,01%	0,05%
ICT (d3)	0,16%	0,28%	0,26%	0,16%	0,10%	0,17%	0,10%	0,09%	0,16%	0,19%	0,19%	0,14%	0,23%	0,19%	0,28%
Importance of Capital Accummulation (b/a)	61%	52%	65%	32%	60%	42%	58%	28%	74%	47%	45%	58%	51%	46%	52%
Importance of Neutral Change															
Solow ($\gamma_{A,S}$/a)	39%	48%	35%	68%	40%	58%	42%	72%	26%	53%	55%	42%	49%	54%	48%
Hulten ($\gamma_{A,H}$/a)	23%	27%	12%	66%	20%	45%	24%	70%	-1%	36%	43%	28%	32%	32%	15%
Jorgenson ($\gamma_{A,J}$/a)	31%	38%	23%	66%	29%	52%	27%	70%	9%	43%	45%	32%	37%	43%	30%
Importance of Implicit Change															
Solow (0/a)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Hulten (c/a)	16%	22%	24%	2%	21%	13%	18%	2%	26%	18%	12%	14%	17%	22%	33%
Jorgenson (d/a)	8%	10%	13%	2%	11%	6%	16%	2%	17%	11%	10%	10%	12%	12%	19%

Table 2 (continued): Growth Accounting Decompositions

	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Nether.	Portugal	Spain	Sweden	U.K.	U.S.A.
Cost shares $\{v_i\}$															
Constructions, v_1	0,189	0,146	0,167	0,163	0,208	0,157	0,148	0,199	0,178	0,183	0,114	0,160	0,145	0,155	0,140
Transport equipment, v_2	0,031	0,031	0,032	0,025	0,026	0,028	0,027	0,053	0,031	0,030	0,033	0,026	0,016	0,029	0,025
Machinery equipment, v_3	0,095	0,069	0,080	0,092	0,074	0,082	0,045	0,085	0,099	0,061	0,131	0,057	0,091	0,096	0,074
Communication equip., v_4	0,014	0,007	0,005	0,007	0,007	0,011	0,008	0,005	0,014	0,003	0,008	0,007	0,009	0,006	0,015
Hardware, v_5	0,015	0,032	0,027	0,011	0,008	0,018	0,005	0,009	0,010	0,017	0,014	0,010	0,020	0,016	0,026
Software, v_6	0,004	0,007	0,012	0,017	0,006	0,007	0,002	0,004	0,007	0,009	0,002	0,007	0,014	0,010	0,013
Investment rates $\{z_i\}$															
Constructions, z_1	0,053	0,044	0,046	0,049	0,046	0,049	0,035	0,038	0,055	0,039	0,060	0,040	0,053	0,048	0,044
Transport equipment, z_2	0,020	0,022	0,021	0,016	0,017	0,019	0,023	0,031	0,020	0,024	0,022	0,019	0,012	0,017	0,016
Machinery equipment, z_3	0,074	0,061	0,069	0,074	0,079	0,064	0,086	0,062	0,055	0,072	0,063	0,105	0,058	0,054	0,053
Communication equip., z_4	0,008	0,016	0,014	0,006	0,004	0,008	0,005	0,005	0,006	0,010	0,012	0,006	0,012	0,010	0,013
Hardware, z_5	0,008	0,005	0,003	0,007	0,005	0,007	0,008	0,003	0,009	0,002	0,006	0,006	0,006	0,004	0,010
Software, z_6	0,004	0,006	0,011	0,015	0,005	0,006	0,002	0,003	0,005	0,009	0,002	0,006	0,013	0,009	0,012

Table 3: General Equilibrium Decomposition

	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Nether.	Portuga	Spain	Sweden	U.K.	U.S.A.
Observed productivity *ln(g)*	1,88%	2,00%	2,16%	2,72%	2,27%	2,37%	1,15%	4,23%	1,44%	1,36%	2,08%	1,73%	1,97%	2,35%	1,83%
Calibrated productivity $\ln(g_{GE})$ (a=b+c)	1,56%	1,96%	1,84%	2,63%	2,05%	2,42%	0,92%	4,84%	1,11%	1,39%	1,70%	1,26%	1,82%	2,51%	2,10%
Neutral change $\ln(g_A)/(1-\alpha_L)$ (b)	1,19%	1,56%	1,23%	2,56%	1,38%	2,08%	0,66%	4,60%	0,54%	1,14%	1,25%	1,04%	1,39%	1,71%	1,37%
Implicit change (c = d+e)	0,37%	0,40%	0,61%	0,08%	0,67%	0,33%	0,26%	0,24%	0,58%	0,26%	0,45%	0,22%	0,43%	0,80%	0,73%
Non-ICT (d=d1+d2+d3)	0,00%	-0,15%	0,05%	-0,26%	0,43%	-0,03%	0,13%	-0,05%	0,19%	-0,08%	0,07%	0,05%	-0,03%	0,32%	0,14%
Constructions (d1)	0,12%	0,17%	0,05%	-0,08%	0,18%	0,16%	0,06%	-0,22%	-0,08%	0,04%	0,08%	-0,02%	-0,04%	0,30%	0,02%
Transport equipment (d2)	0,00%	0,03%	-0,04%	0,00%	0,06%	-0,02%	0,03%	0,14%	0,02%	0,03%	0,07%	0,03%	0,04%	0,02%	0,03%
Machinery equipment (d3)	-0,12%	-0,35%	0,05%	-0,18%	0,19%	-0,17%	0,04%	0,03%	0,25%	-0,15%	-0,08%	0,03%	-0,02%	0,01%	0,10%
ICT (e = e1+e2+e3)	0,37%	0,56%	0,55%	0,34%	0,24%	0,37%	0,12%	0,29%	0,38%	0,34%	0,38%	0,18%	0,46%	0,48%	0,59%
Communication equip. (e1)	0,07%	0,04%	0,03%	0,05%	0,06%	0,06%	0,03%	0,03%	0,12%	0,01%	0,04%	0,03%	0,04%	0,04%	0,09%
Hardware (e2)	0,26%	0,47%	0,44%	0,18%	0,14%	0,26%	0,08%	0,23%	0,23%	0,26%	0,32%	0,12%	0,33%	0,36%	0,40%
Software (e3)	0,03%	0,05%	0,08%	0,11%	0,05%	0,05%	0,01%	0,03%	0,04%	0,07%	0,01%	0,03%	0,09%	0,08%	0,10%
Neutral change (b/a)	76%	79%	67%	97%	67%	86%	72%	95%	48%	82%	73%	82%	76%	68%	65%
Implicit change (c/a)	24%	21%	33%	3%	33%	14%	28%	5%	52%	18%	27%	18%	24%	32%	35%
Time discount rate, β	0,9523	0,9535	0,9550	0,9604	0,9560	0,9570	0,9453	0,9749	0,9481	0,9474	0,9542	0,9509	0,9532	0,9568	0,9518
Investment rate, 1-c	0,1714	0,1386	0,1192	0,1495	0,1559	0,1558	0,1103	0,2496	0,1428	0,1303	0,1603	0,1185	0,1187	0,1494	0,1262
Technology parameters $\{\alpha_i\}$															
Constructions, α_1	0,193	0,142	0,173	0,170	0,197	0,152	0,159	0,177	0,174	0,181	0,148	0,187	0,148	0,143	0,142
Transport equipment, α_2	0,032	0,034	0,034	0,024	0,028	0,031	0,023	0,068	0,033	0,033	0,032	0,019	0,017	0,032	0,026
Machinery equipment, α_3	0,092	0,075	0,077	0,081	0,081	0,086	0,038	0,086	0,097	0,062	0,094	0,043	0,086	0,097	0,074
Communication equip., α_4	0,014	0,009	0,005	0,013	0,009	0,012	0,008	0,007	0,017	0,003	0,010	0,006	0,010	0,009	0,018
Hardware, α_5	0,011	0,022	0,020	0,008	0,006	0,012	0,004	0,011	0,009	0,012	0,016	0,006	0,016	0,017	0,019
Software, α_6	0,006	0,009	0,015	0,021	0,008	0,009	0,002	0,007	0,008	0,011	0,003	0,006	0,017	0,015	0,016
Model *versus* observations, 1980-2004															
Standard deviation (Observed)	0,021	0,016	0,020	0,017	0,015	0,016	0,031	0,023	0,016	0,020	0,028	0,019	0,012	0,012	0,011
Standard deviation (Model)	0,013	0,013	0,012	0,019	0,012	0,012	0,027	0,024	0,011	0,013	0,025	0,013	0,015	0,021	0,009
Correlation coeff. (Model vs Observed)	0,892	0,776	0,774	0,704	0,825	0,908	0,946	0,712	0,668	0,758	0,718	0,788	0,567	0,303	0,751

El Centro de Estudios Andaluces es una entidad de carácter científico y cultural, sin ánimo de lucro, adscrita a la Consejería de la Presidencia de la Junta de Andalucía.
El objetivo esencial de esta institución es fomentar cuantitativa y cualitativamente una línea de estudios e investigaciones científicas que contribuyan a un más preciso y detallado conocimiento de Andalucía, y difundir sus resultados a través de varias líneas estratégicas.

El Centro de Estudios Andaluces desea generar un marco estable de relaciones con la comunidad científica e intelectual y con movimientos culturales en Andalucía desde el que crear verdaderos canales de comunicación para dar cobertura a las inquietudes intelectuales y culturales.

Las opiniones publicadas por los autores en esta colección son de su exclusiva responsabilidad

Depósito Legal: 7353-08

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

E2008/13

LABOR DEMAND AND INFORMATION TECHNOLOGIES: EVIDENCE FOR SPAIN, 1980-2005*

Manuel A. Hidalgo Pérez
Jesús Rodríguez López*
José María O.Kean Alonso

UPO

Resumen
Utilizando la base de datos EU KLEMS, se contrasta la hipótesis de complementariedad entre habilidad y capital en los distintos sectores productivos en España en el periodo 1980-2005. Se analizan tres tipos de trabajadores clasificados según su nivel de habilidad sea alto, medio o bajo. Los activos de capital se van a clasificar entre activos TIC (tecnologías de la información y la comunicación) y activos no-TIC. La adquisición y el uso de activos TIC son costosos pero ha ido disminuyendo en el periodo en consideración en términos relativos a otros activos y al factor trabajo. El principal resultado que se obtiene es que existe un grado de sustituibilidad entre los trabajadores y los activos TIC a medida que la habilidad del trabajador va aumentando. De hecho, los activos TIC son muy complementarios con los trabajadores de alta habilidad. A lo largo del periodo analizado, la fracción de trabajadores con habilidad media y alta ha crecido un 21% y un 12%, respectivamente, en detrimento de los trabajadores de baja habilidad. Después de descomponer estos cambios, se descubre que existe un ajuste dentro de los sectores más que un ajuste del trabajo entre sectores.

Clasificación JEL: E22, J24, J31, O33.
Palabras Clave: complementariedad capital-habilidad, TIC, elasticidad de sustitución.

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

* Autor correspondencia: jrodlop@upo.es

Abstract

Using the EU KLEMS dataset we test the capital-skill complementarity hypothesis in a cross-section of sectors in Spain between 1980 and 2005. We analyze three groups of workers, who are classed according to skill level: high, medium and low. Capital assets have been broken down into ICT (information and communication technologies) assets and non-ICT assets. Acquisition and usage costs of ICT assets declined throughout the period studied, both in absolute terms and relative to the other capital assets and workers. Our principal finding is that the substitutability between workers and ICT assets falls as worker skill level rises. In fact, the ICT assets were strongly complement with highly skilled workers and were not substitutive with them. Throughout the period analyzed, the fraction of employed medium- and high-skill workers rose by 21% and 12%, respectively, to the disadvantage of low-skill workers. After decomposing these changes, we found that the latter were dominated by an adjustment within sectors more than by a composition effect or adjustment between sectors. These adjustments may be explained by reference to the estimated elasticities of substitution.

JEL codes: E22, J24, J31, O33.
Keywords: capital-skill complementarity, ICT, translog cost function, elasticity of substitution

Labor Demand and Information Technologies: Evidence for Spain, 1980-2005[1]

Manuel A. Hidalgo Pérez   Jesús Rodríguez López
José María O'Kean Alonso
Universidad Pablo de Olavide

November 18, 2008

[1]The study forms part of the project "The impact of information systems on economic growth", financed by Microsoft Ibérica S.A. The authors would like to thank E. Alonso, M. Camacho, J.C. Conesa, M. Lindqvist, M. Mas, M. Saam, J. L. Torres and A. Villar for their insightful comments and suggestions. Matilde Mas helped to guide us in the management of the data. Corresponding author is Jesús Rodríguez-López: jrodlop@upo.es, Departamento de Economía, Métodos Cuantitativos e Historia Económica, Universidad Pablo de Olavide de Sevilla, Carretera de Utrera km. 1, 41013 Sevilla (Spain)

Abstract: Using the EU KLEMS dataset we test the capital-skill complementarity hypothesis in a cross-section of sectors in Spain between 1980 and 2005. We analyze three groups of workers, who are classed according to skill level: high, medium and low. Capital assets have been broken down into ICT (information and communication technologies) assets and non-ICT assets. Acquisition and usage costs of ICT assets declined throughout the period studied, both in absolute terms and relative to the other capital assets and workers. Our principal finding is that the substitutibility between workers and ICT assets falls as worker skill level rises. In fact, the ICT assets were strongly complement with highly skilled workers and were not substitutive with them. Throughout the period analyzed, the fraction of employed medium- and high-skill workers rose by 21% and 12%, respectively, to the disadvantage of low-skill workers. After decomposing these changes, we found that the latter were dominated by an ajustment within sectors more than by a composition effect or adjustment between sectors. These adjustments may be explained by reference to the estimated elasticities of substitution.

JEL codes: E22, J24, J31, O33.

Keywords: capital-skill complementarity, ICT, translog cost function, elasticity of substitution.

1 Introduction

Information and communication technologies (ICT), which have spread more rapidly and bolstered productivity more effectively than earlier technologies, have had a definite impact on the economy. In particular, numerous studies have pointed to the special role played by these technologies in the recovery of productivity growth since the mid-1990s in the United States and some European countries.

Such change implies an active adaptation process, as worker skills are changed to suit the new technologies and firms reorganize in new ways, because the complementarity and substituability relations (Griliches, 1969; Samaniego, 2006), replacing unqualified, unskilled workers with others whose training and experience is appropriate to the new context.

ICT-driven changes in the commercial realm have intensified the need for a skilled workforce, increasing both the demand for and the productivity of qualified workers and causing a rise in the relative wage of this group, especially in ICT-intensive countries such as the U.S., the U.K. and Sweden (Autor, 2002; Acemoglu, 2003). The fact that the price and cost of active ICT use has fallen steadily worldwide during the past two decades –more intensely if we take hedonic prices into account—suggest that a complementary relationship between assets and highly skilled workers represents the driving force behind such change. On the other hand, the weight of low-skill workers, who tend to concentrate in productive sectors where computers and information systems are little used, such as agriculture, construction and small business, is increasingly diminished.

These complementary or substitutive relationships can be measured using elasticity of substitution, which indicates how a firm changes its production plans in response to changes in the relative prices of the resources it uses. Estimating these elasticities helps to explain the sectoral adjustments in the composition of labor demand caused by price variation, in light of some basic principles regarding the maximization of profits.

In Spain, the composition of labor demand has changed as the use of ICT in the productive sectors has risen. Mas and Quesada (2006) have shown that human capital accumulation has been stronger in ICT-intensive sectors since 1980. The aim of this study is to estimate for Spain the elasticities of substitution between a number of productive resources, including workers of different skill levels and different capital assets (ICT and non-ICT). By combining the resources available in the Ivie-FBBVA and EU KLEMS databases, we can perform this estimation for a decomposition of 24 productive sectors between 1980 and 2005, comprising industrial and service activities. To aid our understanding of such fact, we differentiate between productive sectors that are ICT-intensive from those that are not, following the classification proposed by Mas and Quesada (2006). The results obtained confirm some of our a priori hypotheses. First, upon decomposing the changes in the composition of employed workers, we found that these changes were dominated by an adjustment *within* sectors, more than by a composition effect or by an adjustment *between* sectors. Throughout the period analyzed, the percentage of medium- and high-skill workers rose by 21% and 12%, respectively, to the detriment of low-skill workers, whose participation fell by 33%. Second, the substitutability between capital assets and workers fell as the skill level of the latter increased. Specifically, for low-skill workers, the elasticity of substitution was 2.76 with respect to communications equipment, 4.53 with respect to computer hardware, and 6.9 with respect to computer software and licenses. When applied to medium-skill workers, this elasticity was unitary in the three cases and became negative when applied to high-skill workers, indicating a complementary rather than a substitutive relationship. On the other hand, the elasticity of substitution with non-ICT capital assets was approximately 1.80 for all workers, regardless of skill level. Third, using a translog cost function allows us to estimate series of (non-constant) elasticities of substitution. The estimated elasticity series show a substitutability that is downward sloping for highly skilled workers, stable at about one for medium-skill workers, and upward sloping for low-skill workers. Fourth, and as expected, ICT assets were very complementary between each other and were substitutive with non-ICT assets.

From the perspective of industrial organization, these results provide a reasonable explanation of how technology has conditioned labor demand and human capital accumulation. In this vein, the result that a worker's substitutability decreases as her or his skill level increases accords with the results of similar research analyses for Spain and other countries.

From a macroeconomic analysis perspective, the result that elasticities of substitution are non-unitary and evolve unevenly, either increasing or decreasing, can serve as a guide when modeling a firm's production technology. The finding that a number of the elasticities are non-unitary explains why the participation of labor income in national income changed over the course of the period studied here, 1980 to 2005. Results of this type, using aggregate production function, can also be found in Duffy, Papageorgiou and Pérez (2004) and Papageorgiou and Chmelarova 2005), for a panel of countries. The framework of analysis can be compared to that of Falk and Koebel (2004), where they use yearly data for 35 sectors in Germany. Their paper is particularly focused to explore the relationship between ICT assets and workers with different skills.

This article is structured as follows. In Section 2 we study the relationship between ICT and human capital in Spain. Using simple techniques, we decompose the changes in the fraction of workers employed for each category in two sources: inter-sectoral and intra-sectoral changes. In Section 3, we propose a translog costs function to estimate the functions of factorial demand and elasticities of substitution. In Section 4 we show the evolution of prices relative to the factors considered in our cost function estimation, from which some of our observed facts derive. The econometric results of this estimation are presented in Section 5. In Section 6, we conclude. Transformations and the sources for the data used in this study are described in an appendix.

2 ICT, productivity and education

Studies by Jorgenson and Stiroh (2000), Jorgenson (2001) Colecchia and Schreyer (2002), Stiroh (2002), Daveri (2000), Timmer, Ypma and van Ark (2003, 2007) and Mas and Quesada (2006) have confirmed the following: (1) ICT asset accumulation in the European Union and U.S. economies over the past thirty years has risen more sharply than non-ICT asset accumulation; (2) productivity growth has increased with increased ICT use; (3) ICT represents the principal source of growth in countries where the use of this technology is most intense; (4) because ICT use in Spain is relatively low in comparison with the United States, the United Kindgom and Sweden, non-ICT capital has a greater impact on Spanish productivity growth than does ICT capital (Mas and Quesada (2006)).

The underlying explanation for this relationship between productivity growth and the intensity of ICT use lies with the technological progress embodied in these assets. For instance, the purchase of a computer represents not only the acquisition of a work tool, but also a means of technological accumulation, which can translate into greater productive efficiency and, thus, enhanced productivity. On the other hand, technological progress that incorporates traditional non-ICT assets, as compared with ICT ones, is very limited (Pakko, 2002 and 2005). A simple way to evaluate the implicit technological change of an asset is through the evolution of the hedonic price, which takes into account changes in the attributes and qualities associated with that asset (in this case, computer hardware).

The adoption of new technologies is not cost-free, but requires firms to implement changes with respect to organization and personnel and, in short, that they embrace new ways of doing business. Because this process of technological adaptation involves a high volume of resources, the advantages associated with ICT use tend to surface are not immediately evident.[1]

One effect of ICT use has been to eliminate a great many repetitive and tiring routine tasks, thereby freeing up large blocks of time which could then be filled with other tasks. As ICT use intensified during the 1990s, the aggregate production growth and labor productivity rates began to rise above the levels that they had displayed during the 1970s.

It should be noted that an integral part of this process has been the substitution of many existing workers, who had never used ICT on the job and were unprepared to do so, by new and better-trained ones more familiar with the new equipment. The latter have reaped the greatest benefits from the technological revolution, which spurred a rise in their wages. The same cannot be said of unskilled workers. Changes of this type have been observed for periods marked by other kinds of technological change. For example, Goldin and Katz (1998) have shown how the electrical revolution significantly altered the shape of labor demand in the United States in the early twentieth century (see also Berman, Bound and Griliches, 1994; Papageorgiou and Chmelarova 2005).

Mas and Quesada (2006) have classified the intensity of ICT use by studying the proportion of ICT assets represented in the overall capital stock of a sector, characterizing as ICT-intensive those sectors for which this proportion exceeded the average in 2004, the final year of their study. According to this criterion, eight productive sectors –listed in the first column of Table 1—may be classified as ICT-intensive. The other columns in Table 1 list data on the percentage of hours worked for three skill-level groups in each productive sector during the three central years of our sample –1985, 1995 and 2005— drawn from the EU KLEMS database. The EU KLEMS classification of the skilled levels is: *high* skill is for those workers with an university title or above; *medium* skill refers to secondary eduation; and *low* skilled is at most primary eduation or illiterate. These data show the evolution of the quality of the labor factor in each sector analyzed. In 1985, the percentage of low-skill workers was very high in all of sectors, especially in those classified as non-ICT intensive.

The mean proportion of highly skilled workers grew continually in all of the sectors studied, most notably in the ICT-intensive ones. For example, the observed mean for this characteristic practically doubled between 1985 and 2000, averaging 17.7% in 1985, 24.6% in 1995 and 33.6% in 2005. The most important changes can be seen precisely in the drastic reduction in the proportion of employed low-skill workers, which fell from 84.7% in 1985 to 54.5% in 2005. In general, the work employed in nearly all of the productive sectors was more highly skilled in 2005 than it was in 1985, with this change in the composition of labor being more marked in ICT-intensive sectors than in non-ICT intensive ones.

Nevertheless, it can be observed that the aggregate averages shown in Table 1 are also affected by changes in productive structure. Thus, the greater weight

[1] See Hornstein and Krusell (1996); Pakko (2002); Samaniego (2006). For an application of these ideas to the Spanish case, see Martínez, Rodríguez and Torres (2008).

of skilled labor-intensive activities sometimes increases the weight of skilled workers as a group. We proceed to decompose these weights in order to evaluate the dynamic behind this change. The aim is to learn how much of the weight variation for each group was caused by a change in the composition of productive activity which specifically favored that group, and how much of it resulted from the increased demand for such workers, regardless of the sector in which it occurred. To this end, we adapt the analysis of Berman, Bound and Griliches (1994) for the United States, in which the authors use occupational categories instead of skill levels, as we do here.

Let us consider three skill levels: high, medium and low, denoted respectively using the subindex $j \in \{h, m, \ell\}$, and let $h(j)$ be the proportion of hours worked by those of skill level j during any given year. This proportion can be obtained as the weighted average of the participation of these workers in each of our sectors, that is

$$h(j) = \sum_{s=1}^{S} h(s, j)\, e(s), \tag{1}$$

for sectors $s = 1, \ldots, S$ and where

$$e(s) = \frac{\sum_{j\in\{h,m,\ell\}} \text{hours}(s, j)}{\sum_{s=1}^{S} \sum_{j\in\{h,m,\ell\}} \text{hours}(s, j)},$$

is the weight in employment terms (hours worked) of sector s, for any given year. At the same time, $h(s, j)$ is participation, in hours, of workers of skill level j in sector s,

$$h(s, j) = \frac{\text{hours}(s, j)}{\sum_{i\in\{h,m,\ell\}} \text{hours}(s, i)}.$$

hours (s, i) indicates the total number of hours worked in sector s by workers of skill level $j \in \{h, m, \ell\}$. The weight of each sector is denoted by $0 < e(s) < 1$, in such a way that $\sum_{s=1}^{S} e(s) = 1$. At the same time, it can be shown that $\sum_{j\in\{h,m,\ell\}} h(j) = 1$.

On the basis of expression (1), the annual rise in participation $\Delta h(j)$ for a given two-year period can be decomposed as follows

$$\Delta h(j) = \sum_{s=1}^{S} \bar{h}(s, j)\, \Delta e(s) + \sum_{s=1}^{S} \Delta h(s, j)\, \bar{e}(s), \tag{2}$$

where the upper line reflects the mean value for the two years under comparison.

1. The first term, $\sum_{s=1}^{S} \bar{h}(s, j)\, \Delta e(s)$, represents the variation in the proportion of workers of skill level j resulting from changes in sectoral structure or production specialization. We will call this component the *composition effect* or *between-group effect*.

2. The second term, $\sum_{s=1}^{S} \Delta h(s, j)\, \bar{e}(s)$, refers to the changes in the demand for workers of skill level j within a given sector, regardless of the activity

taking place in other sectors. We call this component the *within-group effect*.

Starting from the expression (2) it is possible to learn which part of the change in the proportion $h(j)$ is associated with ICT usage intensity. To this end, we decompose the first observed effect as

$$\sum_{s=1}^{S} \bar{h}(s,j)\,\Delta e(s) = \sum_{s\in\mathcal{A}_1} \bar{h}(s,j)\,\Delta e(s) + \sum_{s\in\mathcal{A}_2} \bar{h}(s,j)\,\Delta e(s)\,, \tag{3}$$

where $\mathcal{A}_1 = \{1,\ldots,\bar{s}\}$ groups together the eight ICT-intensive sectors and $\mathcal{A}_2 = \{\bar{s}+1,\ldots,S\}$ groups together the remaining sectors. The criterion for classifying sectors by the intensity of ICT usage follows the scheme set forth by Mas and Quesada (2006), which is reported in Table 1. The second intra-group effect is similarly decomposed.

Tables 2 and 3 show the results of this decomposition for high- and medium-skill workers, respectively. By default, the results for low-skill workers can be derived from these two categories, making it redundant to list them here. Table 2 shows incremental increases in the participation of highly skilled workers caused by the composition effect (column 1) and the intra-group effect (column 2), as well as the total increase (column (3) = (1) + (2)), the weight of each sectoral group in the total number of hours worked (column (4)) and, finally, the increases observed for each group, $\mathcal{A}_1$ and $\mathcal{A}_2$, (column (5)). The decomposition is given for the entire period and for five 5-year periods.

For the 1980-2005 period, the percentage of highly skilled workers employed in Spain rose by 12.16 percentage points. Of these, 8.68 points resulted from changes in intra-sectoral demand while the remaining 3.48 points resulted from changes in sectoral composition. Thus, 71.4% of the change during this two-year period was caused by intra-group changes (=8.68/12.16). The growth in the participation rate was very homogeneous throughout the period under study, averaging approximately 2.5%. With the exception of the first five-year period, the intra-group effect surpassed the inter-group effect. This result accords with the changes taking place in the Spanish economy between 1980 and 1985, during which an important country's industrial transformation took place. From 1996 to the present, nearly all of the changes in this rate can be explained by reference to intra-group changes.

With respect to the *between*-group differentiation between ICT-intensive sectors and non-ICT-intensive ones, despite the greater weight of non-intensive activities, the rise in the demand for highly skilled workers can be evenly attributed to both groups. The increase of the percentage of highly skilled workers employed was 16.6 points in the ICT-intensive sectors and 6.0 points in the non-ICT-intensive ones.Thus, these data imply that for the entire period under study, 6.6% of the overall 12.16% variation rate took place in the ICT-intensive sectors while the rest corresponds to non-ICT-intensive sectors. Of the 8.68% variation in the proportion of intra-group change, that attributable to ICT-intensive versus non-ICT- intensive sectors was roughly equal (4.12% versus 4.56%, respectively). These figures call into evidence the dynamic contribution of the ICT-intensive sectors to the employment of highly skilled workers throughout the period under study. Also, 2.53 of the 3.48 points attributed to the composition effect resulted from changes that worked in favor of the ICT-intensive sectors, versus 0.95 points resulting from changes that favored the non-ICT-intensive ones.

When we look at the 5-year intervals into which this 25-year period was divided, the important role played by ICT-intensive sectors in the evolution of the demand for skilled workers becomes clear. In short, this period witnessed the rise in widespread employment of highly skilled workers, regardless of ICT usage patterns.

Table 3 gives the salient results for workers in the medium-skill group. In the first place, the total variation for this group (21%) exceeds that observed for highly skilled workers (12.16%). This implies that the greatest adjustment in the composition of the employed workforce in Spain resulted from the greater employment of medium-skill workers. This fact accords with the strong increase in the number of job-seekers in this category since the late 1970s. The percentage of variation in low-skill workers was -33.2%, which implies that those who replaced them were largely of a medium skill level.

The changes in this proportion – $\Delta h\,(m)$ – almost exclusively responded to changes within each sector. In fact, sectoral adjustments contributed negatively to their variation, probably in favour of highly skilled workers. That is, while 22.6% of the overall change can be associated with direct substitutions of low-skill workers by medium-skill ones within each sector, the changes in sectoral composition also gave rise to a weak substitution rate of 1.6% of medium-skill workers by highly skilled ones.

The structure of this adjustment was very homogeneous throughout the established 5-year intervals, with the changes dominated by intra-group effects.

The contribution of the percentual variation was greater during the first three five-year periods, between 1980 and 1995, than it was during the final period, between 1996 and 2005.

In conclusion, the results mentioned above indicate that most of the changes observed here cannot be attributed to alterations in the productive structure of the Spanish economy, but rather to changes within the sectors studied. Such changes may have had multiple causes, as dictated by the substitutive and complementary relationships between different factors. In order to know how and why substitutions between workers of different skill levels occurred, we must consider the dynamic behind the sectors' adoption of these technologies, an econometric task that will be our focus in the next section.

[**Tables 1, 2 and 3 here**]

3 The demand for factors of production

In order to associate the changes in demand for workers of different skill levels to the variables that can explain these changes, we develop a specification using a trans-log cost function and Shepard's lemma in order to come up with a system of estimable equations. The resultant estimated parameters allow us to calculate the elasticities of substitution between various different resources involved in the productive process. Berman, Bound and Griliches (1993), Machin and Van Reenen (1998) and O'Mahoney, Robinson and Vecchi (2006), among others, have used this type of function for similar analytical ends.

We consider production to result from the combination of seven productive factors per sector and unit of time: workers of high, medium and low skill levels, indexed as $\{h, m, \ell\}$ respectively, three ICT capital assets (hardware, communications and software), and the non-ICT capital assets, indexed as $\{hard, com, soft, k\}$, respectively. Our data for these three worker sets, and for the production and cost fractions associated with each factor of production, comes from the EU KLEMS database. We use the capital and investment series in Spain estimated by Ivie-FBBVA.

Non-ICT capital is an aggregation of various items associated with traditional physical capital assets: non-residential structures and constructions, transportation equipment, metallic products, machines and mechanical equipment, and workshop and construction tools. We aggregated the items using a Törnqvist index, which takes into account variations in the relative prices (marginal products) of capital assets.

Suppose that the cost function of sector s is approximated by the following second-order translog:

$$\ln C_{st} = \ln (p_{st})' [\eta_s t + \phi] + \frac{1}{2} \ln (p_{st})' B \ln (p_{st}), \tag{4}$$

where p_{st} is the price vector of the seven productive factors under consideration at moment t. This vector denotes the wages of three categories of workers per sector and unit of time, w_{ist} for $i \in \{h, m, \ell\}$,and the usage or rental costs of four capital assets, R_{sjt} for $j \in \{hard, com, soft, k\}$

$$p_{st} = [w_{hst}, w_{mst}, w_{\ell st}, R_{hard,st}, R_{com,st}, R_{soft,st}, R_{kst}]'. \tag{5}$$

Time t is explicitly included in cost function (4) and represents the change in cost not captured by the two capital assets or human capital. The vector that captures this effect is denoted by $\eta_s = \left[\eta_{hs}, \eta_{ms}, \eta_{\ell s}, \eta_{hard,s}, \eta_{com,s}, \eta_{soft,s}, \eta_{ks}\right]'$. On the other hand, ϕ is a parameter vector common to all productive sectors,

$$\phi = \left[\phi_h, \phi_m, \phi_\ell, \phi_{hard}, \phi_{com}, \phi_{soft}, \phi_k\right]'.$$

Finally, B is a symmetrical matrix, so that

$$\beta_{ij} = B(i, j) = B(j, i) = \beta_{ji}, \tag{6}$$

with $i, j \in \{h, m, \ell, hard, com, soft, k\}$.

According to Shephard's lemma, the demand conditioned by any factor i may be obtained through the partial derivative of the cost function with respect to the price of that factor, $\partial C_{st}/\partial p_{ist}$, where p_{ist} is the $i-$th element of vector p_{st}

in (5), $i \in \{h, m, \ell, hard, com, soft, k\}$. Given that cost function (4) is specified in logarithms, if we multiply this derivative by p_{ist} and divide it by C_{st} we obtain that the cost share of factor i can be defined as

$$\alpha_{ist} = \frac{p_{ist}}{C_{st}} \frac{\partial C_{st}}{\partial p_{ist}} = \frac{\partial \ln C_{st}}{\partial \ln p_{ist}}. \tag{7}$$

The variable α_{ist} measures the participation of a factor over total cost,

$$\sum_{i \in \{h,m,\ell\}} \alpha_{ist} + \sum_{i \in \{hard,com,soft,k\}} \alpha_{ist} = 1.$$

If we apply expression (7) to cost function (4), we obtain

$$\alpha_{ist} = \eta_{is} t + \beta_i + \sum_{j \in \{h,m,\ell\}} \beta_{ij} \ln w_{jst} + \sum_{j \in \{hard,com,soft,k\}} \beta_{ij} \ln R_{jst}, \tag{8}$$

for $i \in \{h, m, \ell, hard, com, soft, k\}$. We impose on this condition the following homogeneity condition of degree one of the cost function:

$$\mathbf{1}_{(1\times 7)}\phi = 1, \tag{9}$$

$$\mathbf{1}_{(1\times 7)}B = B\mathbf{1}_{(7\times 1)} = 0. \tag{10}$$

where ϕ and B are the matrixes of parameters defined in cost function (4), and $\mathbf{1}_{(7\times 1)}$ is a vector of ones.

Bearing in mind the symmetry of matrix B, $\beta_{ij} = \beta_{ji}$, and the restrictions in (9) and (10), and taking first differences, the system of equations in (8) can be represented as follows:

$$\Delta\alpha_{hst} = \eta_{hs} - \sum_i \beta_{hi} \Delta \ln \left(\frac{w_{hst}}{p_{ist}} \right) + \varepsilon_{hst}, \tag{11}$$

$$\Delta\alpha_{mst} = \eta_{ms} - \sum_i \beta_{mi} \Delta \ln \left(\frac{w_{mst}}{p_{ist}} \right) + \varepsilon_{mst}, \tag{12}$$

$$\Delta\alpha_{\ell st} = \eta_{\ell s} - \sum_i \beta_{\ell i} \Delta \ln \left(\frac{w_{\ell st}}{p_{ist}} \right) + \varepsilon_{\ell st}, \tag{13}$$

$$\Delta\alpha_{hard,st} = \eta_{hard,s} - \sum_i \beta_{hard,i} \Delta \ln \left(\frac{R_{hard,st}}{p_{ist}} \right) + \varepsilon_{hard,st}, \tag{14}$$

$$\Delta\alpha_{com,st} = \eta_{com,s} - \sum_i \beta_{com,i} \Delta \ln \left(\frac{R_{com,st}}{p_{ist}} \right) + \varepsilon_{com,st}, \tag{15}$$

$$\Delta\alpha_{soft,st} = \eta_{soft,s} - \sum_i \beta_{soft,i} \Delta \ln \left(\frac{R_{soft,st}}{p_{ist}} \right) + \varepsilon_{soft,st}, \tag{16}$$

which includes an error term ε_{ist}, to be specified below. The equation for the non-ICT capital asset, k, is redundant, due to our assumptions of symmetry and the restrictions of (9) and (10). Note that the terms $\Delta \ln(p_{jst}/p_{ist})$ in equations (11) to (16) cancel for $i = j$. The coefficient η_{is} can be interpreted as the effect of technological change on factor i in sector s.[2] More specifically, $\eta_{is} + \varepsilon_{ist}$ represents the specific bias of each sector in factor i.

The partial elasticity of substitution for each factor pair can be obtained from the system estimations (11)-(16). We define the Allen-Uzawa partial elasticity of substitution between the two factors i and j as

$$\begin{aligned} ES\,(i,j)_{st} &= C_{st}\left(\frac{\partial^2 C_{st}}{\partial p_{ist}\partial p_{jst}}\right)\left(\frac{\partial C_{st}}{\partial p_{ist}}\frac{\partial C_{st}}{\partial p_{jst}}\right)^{-1} \\ &= 1+\frac{\beta_{ij}}{\alpha_{ist}\alpha_{jst}}, \end{aligned} \tag{17}$$

with $i, j \in \{h, m, \ell, hard, com, soft, k\}$. The elasticity of substitution provides a way of measuring how a firm adjusts its production plans in response to changes in relative prices. When this elasticity approaches zero, $ES\,(i,j)_{st} \approx 0$, the factors of production are complementary, given that their relationship remains stable regardless of any changes in relative prices. When this elasticity is greater than or equal to one, the adjustment in the relative combination of two productive resources, i and j, is proportionally greater than that of the change in the relative price. In this case, $ES\,(i,j)_{st} \geq 1$ factors i and j are said to be substitutive.

Parameter β_{ij} in equation (12) is associated with the (logarithm of) the relative price of factors i and j. If β_{ij} is postive, the elasticity of substitution will be greater than one; that is, factors i and j will be substitutive. An increment in the relative price of factor i with respect to factor j would reduce the relative demand for the former, thereby also reducing its participation in costs. On the other hand, if β_{ij} is negative, the elasticity of substitution will be less than unitary, so that the percentage increase in the relative wage will exceed the rise in the relative demand for this factor. As a result, their participation in overall costs would increase as a result of this complementarity. Finally, in the specific case in which $\beta_{ij} = 0$, the elasticity of substitution between factors i and j is one. In this way, the relative price increase of i is counterbalanced by a proportional increase in the relative demand for j, so that the participation in costs α_{ist} remains unchanged. The latter case is similar to that of the Cobb-Douglas production function, which is a unitary and constant elasticity of substitution.

From expression (17) it can be seen that the elasticity of substitution varies from one moment to the next in accordance with the cost proportions α_{ist} and α_{jst}. This equality allows us to estimate the elasticity of substitution for the entire period under consideration, once parameter β_{ij} has been estimated.

[2] The parameter η_{is} is is the marginal effect of time on the cost share of factor i. A positive value of it indicates an increase in the demand for this factor. Some authors interpret the effect of this parameter as the technological impact on factor demand (see Acemoglu, 2002, or Autor 2002, for an overview).

In order to specify the structure of the system of equations to be estimated, let us suppose that the error terms ε_{ist} have the following structure:

$$\varepsilon_{ist} \sim iidN\left(0, \sigma_i^2\right). \tag{18}$$

Let us also assume that:

$$\begin{aligned} E\left(\varepsilon_{ist}\varepsilon_{is't}\right) &\neq 0, & (19)\\ E\left(\varepsilon_{ist}\varepsilon_{is't-\tau}\right) &= 0, & (20)\end{aligned}$$

for $s \neq s'$, and $i \in \{h, m, \ell, hard, com, soft, k\}$, for $\tau = 1, 2, ...$ On the other hand, let us suppose a certain correlation between the error terms of the two equations *within* each sector:

$$\begin{aligned} E\left(\varepsilon_{ist}\varepsilon_{jst}\right) &= \sigma_{ij}, & (21)\\ E\left(\varepsilon_{ist}\varepsilon_{jst-\tau}\right) &= 0, & (22)\end{aligned}$$

for $i \neq j$ and $i, j \in \{h, m, \ell, hard, com, soft, k\}$. This specification implies that equations (11)-(16) can be estimated using generalized least squares. We also correct for potential heteroskedasticity.

4 Wages and user costs of capital

The wage calculation for each of our three worker categories and for each branch of activity, obtained using data from the EU KLEMS database, is described in the appendix at the end of this study. For each category and sector, the nominal hourly wage was obtained by dividing the total wage costs by the total number of hours worked. These series provided by the EU KLEMS dataset are take account for the age of the workers (that can be a proxy for experience) and the sex.

The capital usage cost represents the rental price for each unit of capital asset over a given time period, and can be found by means of the following financial argument. Let q_{jt-1} be the acquisition price of one unit of asset j at time $t-1$. Let R_{jt} be the rental price for this asset during any given time period. When the asset rental period has ended, the capital that remains once depreciation has been taken into account, $(1-\delta_j)$, can be sold at price q_{jt}, where δ_j is the depreciation rate for that asset. The monetary amount q_{jt-1} invested in a unit of capital may be invested in a homogeneous financial asset which pays a nominal interest i_t. Using a log-linear version of this approximation, the calculation is finally performed using the expression

$$R_{jst} = q_{jst}\left(i_t + \delta_{js} - \Delta \ln q_{jst}\right), \tag{23}$$

q_{jt} denotes the implicit deflator of investment in asset j.[3]

[3] Note that the user cost of capital, R_{jt}, is subindexed by the sector, s. This implies that the user cost of capital can change with the sector. The reason is that capital is an aggregate meassure that combines a portfolio of physical assets. This portfolio is different across sectors, and this produces different user costs of capital.

Nominal interest rate is denoted by $i_t = r_t + E_t(\pi_{t+1})$, where r_t is the real interest rate and $E_t(\pi_{t+1})$ is the expected rate of inflation. Following Mas, Pérez and Uriel (2005), we use a constant value for the 4% true interest rate, $r_t = 0.04$. For the expected rate of inflation, we use a third-order centered moving average, where the rate of inflation π_t is calculated using the percentage variation of the overall CPI.

The depreciation rate is calculated as the total depreciation ratio over the total capital fund. Finally, $\Delta \ln q_{jst} = \ln q_{jst} - \ln q_{jst-1}$, is the price variation rate for asset j.

Once an estimation for the price vector p_{st} in (5), has been obtained, the calculation of the total cost of both labor and capital per unit of time and sector is expressed as

$$C_{st} = \sum_{i \in \{h,m,\ell\}} w_{ist} L_{ist} + \sum_{j \in \{hard,com,soft,k\}} R_{jst} K_{jst},$$

where L_{ist} and K_{jst} denote the quantities of work and capital employed, respectively. This expression can be used to calculate cost fractions α_{ist}.

Graphics 1 and 2 show the temporary evolution of relative prices. For the sake of simplicity, wages have been aggregated for each of the three skill groups and for all sectors, including both ICT-intensive and non-ICT intensive ones (graph 1). These wages were obtained by considering the mean wage for each sector together with the fraction of hours worked for each activity group. At the same time, in order to simplify our presentation we aggregated over ICT and non-ICT, the two main items used here, to obtain capital usage cost (graph 2). Some interesting facts emerge when these graphs are used to interpret the results of the estimated elasticities of substitution, forthcoming in the following section.

Graphs 1.a and 1.b reflect two opposing tendencies, observable since at least 1995, in the relative wage of qualified workers with respect to medium- and low-skill ones. For all sectors, from the beginning of our study period until the mid-1990s the wage gap grew between highly skilled and medium-skill workers, w_{hst}/w_{mst}, (graph 1.a), while that between highly skilled and low-skill workers, $w_{hst}/w_{\ell st}$, decreased during the same period until the beginning of the 1990s (graph 1.b). This tendency appears not to apply to all of the sectors studied, since the relative wage of highly skilled and medium-skill workers rose steadily in ICT-intensive sectors during that time. In all sectors, the wage gap between medium- and low-skill workers, $w_{mst}/w_{\ell st}$, fell from the beginning of the study period until the early 1990s. From 1995 on, this relative wage appears to have remained stable (graph 1.e). From 1995 on, the position of highly skilled workers relative to medium- and low-skill ones fell as wages for the latter two groups began to evolve in parallel and the wage gap narrowed.

Hidalgo (2008) has found similar results for the evolution of relative wages in Spain for 1980, 1990 and 2000, using the wage data published in the Family Budget Surveys for 1980-81 and 1990-91 and the quarterly Continuous Family Budget Survey for 2000 and 2001. Despite he compares college versus the rest of workers, his results show similar patterns. For example the wage gap between both groups of workers slighltly grew in favor of college graduates during the 1980s, although it fell slightly during the 1990s.

Graphs 1.a- 1.c outline just one of a wide range of possible scenarios. Katz, Loveman and Blanchflower (1995), Gottschalk and Smeeding (1997), Gottschalk and Joyce (1998) and Acemoglu (2003) provide empirical evidence for a broad cluster of countries where the principal characteristic is great diversity in the evolution of the relative wage of skilled and unskilled workers. Thus, the relative wage for both of these groups rose in some countries (such as the United States and the United Kingdom) while it fell in others (such as Belgium and Sweden) and remained constant in still others (such as Germany). All of these cases were established with reference to time periods similar to the one studied here. As Acemoglu (2003) points out, different patterns of change in the relative supply and demand for skilled workers may account for this diversity.[4] For example, in countries where a strong increase in the supply of skilled workers was observed, the relative wage either fell or remained stable. For the Spanish case, although we can detect a clear rise in firms' demand for skilled workers, the changes in the evolution of the wage gap between workers of different skill levels has principally been governed by changes in relative supply (Hidalgo, 2008): the significant growth in the supply of workers of average education, which was far greater than that of the other groups, explains why the wage gap between university graduates and those in this group (i.e. w_{hst}/w_{mst}) grew during the 1980s; the greater growth in university graduates with respect to workers of other educational levels in the Spanish labor market from the early 1990s would explain the fall in relative wages vis-a-vis that of other workers. This explanation fits well with the data shown in graphs 1.a, 1.c and 1.e.

When we compare wages with the costs of using ICT capital equipment, the cost of the latter fell in comparison with that of the three worker groups we studied, $w_{ist}/R_{tic,t}$, for $i \in \{h, m, \ell\}$ (graphs 1.d, 1.f and 1.h). In this case, if the ICT capital and the labor input were substitutive, the behavior of the relative prices would imply a substitution of the latter by the former.

Finally, graph 2 shows that the price of ICT capital fell in relation to non-ICT capital; if both are substitutive, therefore, this tendency must have caused the former to replace the latter.

[**Figures 1 and 2 here**]

5 Results

System (11)-(16) was estimated three times: (i) for the 24 productive sectors analyzed here (excluding the primary sector), (ii) for the 8 sectors classed as ICT-intensive, and (iii) for the remaining 16, non-ICT-intensive sectors. The results for system parameters are listed in columns I, II and III of Table 4, and

[4] Alternative explanations can be related to different labor market institutions, the influence of labor unions, or the globalization of economies (Acemoglu, 2003).

those for elasticities of substitution are given in Table 5.[5] These elasticities represent the weighted average of all of the sectors analyzed during the defined study period, 1980-2005. Standard deviations have been calculated following Anderson and Thursby (1986), to contrast the null hypothesis with an elasticity of substitution that is equal to one $(H_0 : E(i,j) = 1)$.

On the basis of these estimates, we reach the following conclusions. First, classifying our data by sector did not produce significant differences in the parameters we estimated; although there are slightly differences between the values estimated, we obtain similar signs for $\beta' s$, as is shown in columns I, II and III of Table 4. Given that cost fractions α_{ist} were used to calculate the elasticities listed in Table 5, as the value of these fractions changes, we do find that these elasticities are different depending on the usage intensity of the ICT.

Second, the substitutability between ICT assets and labor decreases as the worker's skill level rises. Highly skilled workers and ICT assets were complementary in each and all of the sectors analyzed, as shown by the negative $\beta_{hj} < 0$ for $j = hard, com, soft$, but they are substitutive for non-ICT capital assets, $\beta_{h,k} > 0$. All of these estimators are statistically significant. With regard to the relationship between highly skilled workers and medium- or low-skill workers, it is substitutive. Since the estimator is not statistically significant for high- and medium-skill workers, we cannot reject our null hypothesis that the substitution elasticity is unitary. By contrast, the estimator is significant, $\beta_{h,\ell} = 0.052$, for highly skilled and low-skill workers, and the elasticity of substitution is greater than 1.

Third, most of the parameters associated with medium-skill workers are insignificant, which means that we cannot reject our null hypothesis that the elasticity of substitution is unitary. Only the value of the substitution elasticity between these workers and the non-ICT assets, $ES(m,k)$ –about 1.8- deviates from 1 (Table 5). In the non-ICT-intensive sectors, there appears to be a certain degree of complementarity between these workers and ICT hardware and software assets ($\beta_{m,hard} = -0.005$, $\beta_{m,soft} = -0.006$).

Fourth, low-skill workers are substitutive of all other factors studied. The estimated parameters and elasticities are statistically significant in every case, regardless of sector. This result, together with the evolution of relative wages shown in graph 1, explains why throughout our study period the employment rate for this type of worker fluctuated more than that of any other group (between 1980 and 2005, the fraction of low-skill workers fell by 33%).

Fifth, ICT capital assets are complementary amongst themselves and substitutive of traditional capital assets. Especially since the 1970s, the supply of skilled workers in Spain has grown, thanks largely to a rise in secondary education. More specifically, a sharp increase in the relative supply of educated workers, particularly high school graduates and college graduates during 1980s and 1990s, respectively, caused a drop in the relative wage of low-skill workers. This relative increase in the price of low-skill labor coincided with the

[5] The elasticities have been separately calculated for all sectors, both intensive and non-intensive ones. Average cost shares, α_{ist}, are used to weight expression (17).

substitution and complementary relationships found here, inducing a number of adjustments within the ICT-intensive and non-ICT-intensive sectors. Thus, the complementarity between ICT capital and skilled labor and the lower price of such capital relative to that of non-ICT capital encouraged the accumulation of skilled workers in ICT-intensive sectors. This accumulation put unskilled workers –who were highly substitutable with both ICT capital and skilled workers- at a disadvantage.

These results accord with those found for countries other than Spain. For example, Krusell, Ohanian, Ríos-Rull and Violante (2000) have estimated the elasticities of substitution between capital equipment and skilled and unskilled labor for the United States between 1963 and 1992. They found an elasticity of substitution of 0.67 for skilled labor and capital equipment, and one of 1.67 for unskilled labor and capital equipment. Using the same data, Polgreen and Silos (2008) calculated the Allen-Uzawa partial elasticities for equipment capital and skilled and unskilled labor, respectively, as -1.20 and 1.79. For comparative purposes, these authors re-estimated these elasticities using capital price series other than those used by Krussel et al. Using NIPA deflators, they thus obtained partial elasticities between capital equipment and skilled and unskilled work of 0.64 and 9.88, respectively. When the data employed in Greenwood Herkowitz and Krussell (1997) were used, they found these elasticities to be 1.01 and 12.08, respectively.

Other results for countries other than Spain show similarities and differences with those obtained in this study. For instance, Falk and Koebel (2004) study the case of Germany between 1974 and 1998, and find similar results to ours, although a clear evidence of the substituibility between unskilled workers and ICT assets is only found for the non-manufacturing sectors. A second example with similar results is the work of O'Mahony, Robinson and Vecchi (2006) for the U.S., the U.K., France and Germany, using a translog framework. Biscourp et al (2002) found a partial elasticity of -1.7 between skilled workers and computers, and other 3.5 for unskilled workers with respect to the same capital, for France during the 1994-1997 period. Finally, in various sectors for Japan between 1980 and 1998, Nishimura et. al. (2002) have estimated partial substitution elasticities between ICT and young skilled and unskilled workers. Their results vary within intervals ranging from -22.26 to -0.58 for the case of skilled workers and between 1.32 and 10.44 for unskilled ones.

To end this survey of our results, graphs 3, 4 and 5 show the evolution of elasticities over time. In each of these graphs a dotted line has been inserted at value one, as a reference of the statistical significance. The shadowed area is a 95% confidence band, following the estimate by Anderson and Thursby (1986). Statistically significant estimations can be found where the band deviates from the dotted line. Graphs 3, 4 and 5 have a similar profile.

The downward-sloping substitution elasticities for workers with high and medium skill levels ($ES\,(h,m)$, graphs 3.1, 4.1 and 5.1) and for highly skilled workers and non-ICT assets ($ES\,(h,k)$ graphs 3.6, 4.6 and 5.6) indicate a fall in substitutability with respect to these factors. Such workers are complementary with ICTs, for which the values of this series appear to approach zero gradually going from negative values towards zero; that is, they display perfect complementarity as described in a Leontieff technology. In the case of medium-skill workers, where we have not been able to reject the null hypothesis of unitary elasticity, the series have a flat profile and the 95% confidence band reaches unity in all cases. Finally, for highly skilled workers the series is upward-sloping, especially $ES(\ell, hard)$ in graphs 3.12, 4.12 and 5.12, $ES(\ell, com)$ in graphs 3.13, 4.13 and 5.13 and $ES(\ell, k)$ in graphs 3.15, 4.15 and 5.15. This indicates that their substitutability rose over the course of our study period. In short, substitutability fell for those highly skilled workers, remained stable for medium-skill ones, and rose for low-skill ones.

Graphs 1.b and 1.e call into evidence narrowing of the wage gap between high- and low-skill workers and medium- and low-skill workers, $w_{hst}/w_{\ell st}$ and $w_{mst}/w_{\ell st}$, respectively. On the other hand, the relative wage of high- and medium-skill workers, w_{hst}/w_{mst}, has been decreasing since the mid-1990s in these non-ICT-intensive sectors (graph 1.a). The narrowing of the wage gaps has allowed medium- and high-skill workers to substitute low-skill ones in the sectors where ICT usage is relatively low. Given the reduction in the relative usage cost between ICT capital and non-ICT capital (graph 2), had there been a widening of the wage gap, the non-ICT-intensive sectors would have substituted high-skill workers for low-skill ones.

The confidence bands estimated for the substitution elatisticities between the different capital assets discussed above, both ICT and non-ICT ones, do not coincide with the unitary dotted line. These series do, however, display a relatively stable profile and this confirms the relationships of complementarity and substitution described in Tables 4 and 5, above.

Finally, when we have estimated the system of equations (11) to (16) splitting the sample for the time intervals 1980-1990 and 1991-2005, the estimated parameters $\beta's$ as well as the elasticities of substitution do not suffer mentionable alterations.[6] The previous conclusions are therefore robust to the selection of the sample period.

[**Tables 4 and 5 and figures 3, 4 and 5 here**]

6 Conclusions

The combination of productive resources used by a given firm is determined by relationships of complementarity or substitutability. The aim of this study has been to estimate for Spain the elasticities of substitution between a wide range of productive resources, including workers of different skill levels (high, medium and low) and different types of capital assets (ICT and non-ICT ones). The combined use of available sources of data on capital and work has allowed us to estimate these elasticities for 24 productive sectors from 1980 to 2005. In this way, we have tried to evaluate the impact of ICT diffusion on labor demand in these productive sectors. While most Spanish sectors show a non-intensive

[6] These results, not reported here, can be seen upon request to the authors.

use of ICT capital equipment, the data for the few sectors with high rates of ICT usage is more positive with respect to productivity and the accumulation of human capital than that for other sectors (Mas and Quesada, 2006). As pointed out by Gust and Márquez (2004), some labour market regulatory practices have slowed the ICT adoption in a number of industrial countries, including Spain.

Our results can be summed up in three points. First, the substitutability between capital assets falls as worker skill level rises; second, the estimated elasticities suggest that ICT equipment and highly skilled workers are complementary; and third, the estimated elasticity series allow us to conclude that substitutability is downward-sloping for highly skilled workers, stable at about one for medium-skill workers and upward-sloping for low-skill workers.

Given the evaluation of relative prices, these estimations provide a reasonable explanation of the dynamic behind the demand for workers in specific skill-level groups. The process of human capital accumulation of the eight ICT-intensive sectors is the result of the complementarity observed here between highly skilled workers and ICT equipment and the evolution of relative prices. Low-skill workers were strongly substitutive with the capital assets we considered. The price of both kinds of assets has fallen in Spain and worldwide since the mid-1970s, changing the shape of the labor market such that the job opportunities for low-skill workers are becoming less and less abundant. As a consequence, the lower the worker's skill level, the more marked has been the adjustment in the demand for workers of that level and the greater the intensity of ICT usage. This substitutive tendency will continue to grow more striking as ICT usage gradually spreads into the other productive sectors.

Finally, and in the vein of this argument, it must be noted that the process of ICT diffusion may have been determined by the high adjustment or installation costs associated with these technologies. Such costs fall as ICT usage rises. During the 1980s, sectors currently considered to be ICT-intensive invested heavily in the new technologies; they have already paid for the costs of the adjustment process, which required that they make important organizational changes (both horizontal and vertical). In other words, certain productive sectors which the data now describe as being non-ICT intensive may, in fact, become ICT-intensive once their installation costs have been paid off. In this way, the technological and work relationships within these sectors may become assimilated into those of the existing ICT-intensive ones. The secret of how the labor work will respond to this adaptive process lies in how the Spanish educational system will adapt its contents to ICT and to the rigors of the marketplace.

Nevertheless, academic rigor obliges us to note that these results should not be interpreted as predictions. In the future, production of ICT may be adapted to fit the needs of less-skilled users and not the other way around, as has been the case until now. In such a context, technological relationships could shift from being complementary to being substitutive. Our goal has been to explain the unfolding of events between 1980 and 2005, using sample data that falls into that date range. However, there is no indication that these estimations will remain stable over time.

References

[1] Acemoglu, D.: Technical Change, Inequality, and the Labor Market". *Journal of Economic Literature* 2002; 40, 7-72.

[2] Acemoglu, D.: Cross-Country Inequality Trends". *Economic Journal* 2003; 113, 121-149.

[3] Anderson and Thursby: Confidence Intervals for Elasticity Estimators in Translog Models. *The Review of Economics and Statistics* 1986; 68(4); 647-656.

[4] Autor, D.: Skill Biased Technical Change and Rising Inequality: What is the Evidence? What are the Alternatives? Mimeograph, 2002:

[5] Berman, E. and Bound, J. and Griliches, Z.: Changes in the Demand for Skilled Labor within U.S. Manufacturing: Evidence from the Annual Survey of Manufactures. *The Quarterly Journal of Economics* 1994; 109; 367-97.

[6] Biscourp, P; Crépon, B.; Heckel, T. and N. Riedinger: How do firms respond to cheaper computers? Microeconometric evidence for France based on a production function approach. Série des documents de travail de la Direction des Etudes et Synthèses Économiques, Institut National De La Statistique Et Des Études Économiques, Paris, (2002).

[7] Colecchia, A. and P. Schreyer: ICT investment and economic growth in the 1990's: Is the United States a unique case? A comparative study of nine OECD countries. *Review of Economic Dynamics* 2002; April 5(2); 408-442.

[8] Daveri, F.: Is Growth an ICT-Story in Europe Too? Università Bocconi, IGIER, Working paper, n^o 168 (2000).

[9] Duffy, J., C. Papageorgiou and F. Pérez-Sebastian: Capital Skill Complementarity? Evidence from a Panel of Countries?. *The Review of Economics and Statistics* 2004; 86(1); 327-344.

[10] Falk, M., and B.M. Koebel: The impact of office machinery, and computer capital on the demand for heterogeneous labour. *Labour Economics* 2004; 11; 99–117.

[11] Freeman, R. and L. F. Katz: Differences and Changes in Wage Structures. Chapter Introduction and Summary, University of Chicago Press, Freeman, Richard and Lawernce F. Katz (Eds); 1995.

[12] Goldin, C. and L. F. Katz: The Origins of Technology-Skill Complementarity. *Quarterly Journal of Economics* 1998; 113; 693-732.

[13] Gottschalk, P., and M. Joyce: Cross-National Differences In The Rise In Earnings Inequality: Market And Institutional Factors. *The Review of Economics and Statistics* 1998; 80(4); 489-502.

[14] Gottschalk, P., and T. M. Smeeding: Cross-National Comparasions of Earnings and Income Inequality. *Journal of Economic Literature* 1997; 35; 633-687.

[15] Greenwood, J; Hercowitz, Z. and P. Krusell: Long-Run Implications of Investment-Specific Technological Change. *American Economic Review* 1997; 87(3); 342-362.

[16] Griliches, Z.: Capital-Skill Complementarity. *The Review of Economics and Statistics* 1969; 51(4); 465-68.

[17] Gust, C. and J. Márquez: International comparisons of productivity growth: the role of information technology and regulatory practices. *Labour Economics* 2004; 11; 33– 58.

[18] Hidalgo, M.A.: A Demand-Supply Analysis of the Spanish Education Wage Premium in the 1980s and 1990s. Universidad Pablo de Olavide, Working Paper 08.01 (2008).

[19] Hornstein, A., Krusell, P.: Can Technology Improvements Cause Productivity Slowdowns? In: Bernanke, B., Rotemberg, J. (Eds.), *NBER Macroeconomics Annual* 1996; 11; 209-259.

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

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

[22] Katz, L., G. Loveman, and D. Blanchflower: Differences and Changes in Wage Structureschap. A Comparison of Changes in the Structure of Wages in Four OECD Countries. University of Chicago Press, Chicago, Freeman, Richard and Lawernce F. Katz ed (1995).

[23] Krusell, P., Ohanian, L., Rios-Rull, V. and G. Violante: Capital Skill Complementary and Inequality: A Macroeconomic Analysis. *Econometrica* (2000); 68(5); 1029-1053.

[24] Machin, S and J. Van Reenen: Technology and Changes in Skill Structure: Evidence from Seven OECD Countries. *The Quarterly Journal of Economics* 1998; 113(4) 1215-1244.

[25] Mas, M., Pérez, F. and Uriel, E.: El stock y los servicios de capital en España. Nueva Metodología (1964-2002). Fundación BBVA, Bilbao; 2005.

[26] Mas, M., Pérez, F. and Uriel, E.: El stock y los servicios de capital en España, 1964-2005. Fundación BBVA, Bilbao; 2007.

[27] Mas, M. and J. Quesada: "The Role of ICT in the Spanish Productivity Slowdown. Documentos de Trabajo de la Fundación BBVA 2006-5.

[28] Martínez, D.; Rodríguez, J and J.L. Torres: The productivity paradox and the new economy: The Spanish case. *Journal of Macroeconomics* 2008; 30(4); 1569-1586.

[29] Nishimura, K.G.; Minetaki, K.; Shirai, M. and F. Kurokawa: Effects of Information Technology and Anging Work Force on Labor Demand and Technological Progress in Japanese Industries: 1980-1998. CIRJE F-Series CIRJE-F-145, CIRJE, Faculty of Economics, University of Tokyo (2002).

[30] O'Mahony, M., C. Robinson and M. Vecchi: The Impact of ICT on the Demand for Skilled Labour: A Cross-Country Comparison. Mimeo; 2006.

[31] Pakko, M.R.: What Happens When the Technology Growth Trend Changes? Transition Dynamics, Capital Growth, and the New Economy. *Review of Economic Dynamics* 2002; 5(2); 376-407.

[32] Pakko, M.R.: Changing technology trends, transition dynamics and growth accounting. Working Papers 2000-014, Federal Reserve Bank of St. Louis; 2005.

[33] Papageorgiou, C. and V. Chmelarova: Nonlinearities in Capital–Skill Complementarity. *Journal of Economic Growth* 2005; 10; 59–89.

[34] Polgreen, L. and P. Silos: Capital-Skill Complementarity and Inequality: A Sensitivity Analysis. *Review of Economic Dynamics* 2008; 11(2), 302-313.

[35] Samaniego, R.M.: Organizational capital, technology adoption and the productivity slowdown. *Journal of Monetary Economics* 2006; 53; 1555–1569.

[36] Stiroh, K: "Information technology and U.S. productivity revival: What do the industry data say? *American Economic Review* 2002; 92(5); 1559-1576.

[37] Timmer, M. P., G. Ypma and B. van Ark: "IT in the European Union: Driving Productivity Divergence? GGDC Research Memorandum GD-67; 2003.

[38] Timmer, M. P., M. O'Mahoney and B. van Ark: "EU KLEMS Growth and Productivity Accounts: An Overview; 2007.

A Datos

EU KLEMS. We use data samples for Spain taken from the EU KLEMS database[7]. This database contains data series from 1980 to 2008 for 29 productive sectors with economic variables that are relevant to the study of production, work and capital, the transformation of which will be explained below.

[7] For a description of this methodology, see Timmer, O'Mahony and van Ark (2007), and van Ark, O'Mahony and Ypma (2007). The data base site is `http://www.euklems.net/`

We will use the same notations referred to in this database for the calculation and transformation of our variables. Let h_{ist} be the total number of hours work by workers of skill level $i \in \{h, m.\ell\}$ in sector s, calculated as

$$
\begin{aligned}
h_{hst} &= H\_HS_{st} \times H\_EMP_{st}, && (24)\\
h_{mst} &= H\_MS_{st} \times H\_EMP_{st}, && (25)\\
h_{\ell st} &= H\_LS_{st} \times H\_EMP_{st}, && (26)
\end{aligned}
$$

where H_HS_{st}, H_MS_{st}, H_LS_{st}, are the proportion of hours worked by workers of high, medium and low skill levels, respectively. H_EMP_{st} is the total number of hours worked by hired employees, and EMP_{st} represents the total number of hired employees in sector s at moment t.

The fraction of income to work for workers of skill level $i \in \{h, m, \ell\}$, is directly calculated in the EU KLEMS database as LABHS, LABMS y LABLS, respectively, LABHS + LABMS + LABLS = 1.

Total labor incomes measured in current euro values, that include self-employment wages and payments, are designated by the variable LAB. Fractions of the earned income used to pay ICT and non-ICT capital have been calculated as described in Section 3.

The wage paid to a worker of skill level $i \in \{h, m, \ell\}$ in sector s at moment t, w_{ist}, is calculated as follows:

$$
\begin{aligned}
w_{hst} &= \frac{LABHS_{st} \times LAB_{st}}{h_{ast}}, && (27)\\
w_{mst} &= \frac{LABMS_{st} \times LAB_{st}}{h_{mst}}, && (28)\\
w_{\ell st} &= \frac{LABLS_{st} \times LAB_{st}}{h_{\ell st}}, && (29)
\end{aligned}
$$

where LAB_{st} is the total labor compensation, in millions of euros.

Ivie-FBBVA. Capital series are drawn from the database compiled by Mas, Pérez and Uriel (2005, 2007), which divides the data into eighteen physical capital assets for 1964-2005.[8] Non-ICT captial assets have been grouped into three categories: non-residential constructions and buildings, elements of transportation, and machinery and other equipment. ICT capital series have also been grouped into three categories: computers and office equipment, program and software licenses. These ICT series have been deflated using the hedonic prices of the BEA (see Mas, Pérez and Uriel, 2005, pp. 71 and 168-173). The database also offers real and nominal investment series for the different assets.

[8] `http://www.fbbva.es/`

B Tables

Table 1: Percentage of hours worked according to skill

	1985			1995			2005		
	High	Medium	Low	High	Medium	Low	High	Medium	Low
Intensive ICT users	17.7	17.8	64.5	24.6	28.9	46.5	33.6	35.5	30.8
Pulp, paper, printing & publish.	5.8	13.0	81.2	8.9	24.8	66.3	15.0	33.9	51.1
Energy and water	12.5	18.3	69.2	19.6	32.2	48.2	33.0	37.8	29.2
Electric, electronic, optic equip.	8.9	22.1	69.0	15.6	37.8	46.6	24.1	45.2	30.7
Transport and communication	6.0	14.1	79.9	9.5	25.7	64.7	17.0	37.8	45.3
Financial intermediation	15.5	35.8	48.7	29.8	44.5	25.7	50.3	39.0	10.6
Business services	25.1	22.1	52.8	30.4	29.1	40.5	39.8	32.1	28.2
Private health & social services	43.6	12.4	44.0	46.3	25.0	28.7	49.0	34.3	16.7
Other community services	7.2	14.0	78.8	14.1	26.3	59.6	24.2	36.9	38.9
Non-Intensive ICT users	7.5	7.8	84.7	10.7	18.6	70.7	15.3	30.2	54.5
Food, drink and tobacco	3.3	8.3	88.5	5.7	18.0	76.3	11.1	29.1	59.8
Textiles, leather and footwear	2.8	7.1	90.1	3.3	13.8	82.9	6.4	25.8	67.8
Wood and crok products	5.8	13.0	81.2	8.9	24.8	66.3	15.0	33.9	51.1
Oil refin., coke & nuclear fuel	5.8	13.0	81.2	8.9	24.8	66.3	15.0	33.9	51.1
Chemicals	5.8	13.0	81.2	8.9	24.8	66.3	15.0	33.9	51.1
Rubber & plastics	5.8	13.0	81.2	8.9	24.8	66.3	15.0	33.9	51.1
Other non-metallic mineral	5.8	13.0	81.2	8.9	24.8	66.3	15.0	33.9	51.1
Fabricated metal products	5.8	13.0	81.2	8.9	24.8	66.3	15.0	33.9	51.1
Machinery and mechanical eq.	7.4	20.5	72.1	7.4	32.9	59.7	13.6	46.5	39.9
Transport equip. manufact.	4.2	14.2	81.6	8.2	29.6	62.2	17.0	41.7	41.3
Miscellaneous manufact.	2.9	7.7	89.5	2.8	14.5	82.7	7.6	28.9	63.6
Construction	3.7	5.3	91.0	4.3	15.3	80.4	7.7	25.1	67.2
Wholesale & retail trade; Repairs	3.5	11.3	85.2	6.5	25.0	68.5	12.1	38.7	49.2
Hotels and catering	1.6	6.6	91.8	3.4	17.5	79.1	9.1	34.5	56.4
Real estate	25.1	22.1	52.8	30.4	29.1	40.5	39.8	32.1	28.2
Private education	74.3	8.1	17.6	74.4	11.8	13.8	77.9	13.0	9.1

Source: EU KLEMS and own calculation

Table 2: Decomposition in the increase of high skilled workers

	Composition effect (1)	Within sector effect (2)	Total increase (3)=(1)+(2)	Weight in total hours (4)	Increase (2)/(4)
			1980-2005		
Total industries	3.48	8.68	12.16		
Intensive ICT users	2.53	4.12	6.66	0.25	16.03
Non intensive ICT users	0.95	4.56	5.51	0.75	6.06
			1980-1985		
Total industries	1.22	0.81	2.03		
Intensive ICT users	0.64	0.38	1.02	0.21	1.83
Non intensive ICT users	0.58	0.43	1.01	0.79	0.54
			1986-1990		
Total industries	0.77	1.03	1.81		
Intensive ICT users	0.57	0.58	1.15	0.23	2.56
Non intensive ICT users	0.21	0.45	0.66	0.77	0.58
			1991-1995		
Total industries	1.13	1.49	2.63		
Intensive ICT users	0.84	0.81	1.64	0.26	3.11
Non intensive ICT users	0.29	0.69	0.98	0.74	0.74
			1996-2000		
Total industries	-0.08	2.75	2.67		
Intensive ICT users	0.14	1.40	1.54	0.27	5.14
Non intensive ICT users	-0.23	1.35	1.13	0.73	1.86
			2000-2005		
Total industries	0.45	2.58	3.03		
Intensive ICT users	0.35	0.95	1.29	0.28	3.40
Non intensive ICT users	0.10	1.64	1.73	0.72	2.27

Source: EU KLEMS and own calculations.

Table 3: Decomposition in the increase of medium skilled workers

	Composition effect (1)	Within sector effect (2)	Total increase (3)=(1)+(2)	Weight in total hours (4)	Increase (2)/(4)
			1980-2005		
Total industries	-1.61	22.66	21.06		
Intensive ICT users	-1.00	8.09	7.09	0.39	20.66
Non intensive ICT users	-0.60	14.57	13.97	0.61	23.95
			1980-1985		
Total industries	-0.18	4.02	3.84		
Intensive ICT users	-0.11	1.93	1.82	0.38	5.01
Non intensive ICT users	-0.08	2.10	2.02	0.62	3.41
			1986-1990		
Total industries	-0.53	6.59	6.06		
Intensive ICT users	-0.61	2.62	2.01	0.38	6.91
Non intensive ICT users	0.08	3.97	4.05	0.62	6.39
			1991-1995		
Total industries	-0.38	4.71	4.33		
Intensive ICT users	0.50	1.68	2.18	0.40	4.18
Non intensive ICT users	-0.87	3.03	2.15	0.60	0.60
			1996-2000		
Total industries	-0.45	5.64	5.19		
Intensive ICT users	-1.15	1.57	0.42	0.39	3.98
Non intensive ICT users	0.71	4.07	4.78	0.61	6.72
			2000-2005		
Total industries	-0.07	1.71	1.64		
Intensive ICT users	0.38	0.30	0.67	0.39	0.76
Non intensive ICT users	-0.44	1.41	0.97	0.61	2.32

Source: EU KLEMS and own calculations.

Table 4: Estimated parameters

	Column I All sectors		Column II Intensive users		Column III Non intensive users	
$\beta_{h,m}$	0.016	[1.14]	0.029	[1.08]	0.007	[0.44]
$\beta_{h,\ell}$	0.052	[2.74]***	0.009	[0.28]***	0.067	[2.93]***
$\beta_{h,hard}$	-0.009	[3.14]***	-0.013	[2.69]**	-0.007	[2.13]**
$\beta_{h,com}$	-0.008	[2.74]***	-0.012	[2.50]***	-0.006	[1.62]
$\beta_{h,soft}$	-0.009	[3.39]***	-0.013	[2.84]***	-0.007	[2.22]**
$\beta_{h,k}$	0.038	[13.88]***	0.032	[6.78]***	0.041	[12.41]***
$\beta_{m,\ell}$	-0.002	[0.11]	-0.038	[1.08]	0.021	[0.97]
$\beta_{m,hard}$	-0.002	[0.63]	0.005	[1.15]	-0.005	[1.69]*
$\beta_{m,com}$	-0.001	[0.35]	0.005	[1.13]	-0.005	[1.43]
$\beta_{m,soft}$	-0.001	[0.50]	0.006	[1.27]	-0.006	[2.05]**
$\beta_{m,k}$	0.032	[13.37]***	0.029	[6.11]***	0.035	[12.81]***
$\beta_{\ell,hard}$	0.015	[4.35]***	0.015	[2.79]***	0.015	[3.52]***
$\beta_{\ell,com}$	0.013	[3.70]***	0.014	[2.64]***	0.012	[2.80]***
$\beta_{\ell,hard}$	0.014	[4.33]***	0.015	[2.75]***	0.016	[3.71]***
$\beta_{\ell,k}$	0.064	[19.56]***	0.056	[10.24]***	0.068	[16.90]***
$\beta_{hard,soft}$	-0.003	[2.05]**	-0.004	[1.89]*	-0.002	[1.17]
$\beta_{hard,com}$	-0.003	[2.15]**	-0.005	[1.99]**	-0.002	[1.19]
$\beta_{hard,k}$	0.004	[1.81]*	0.006	[1.33]	0.003	[1.20]
$\beta_{com,soft}$	-0.003	[2.02]**	-0.004	[1.91]*	-0.002	[1.11]
$\beta_{com,k}$	0.004	[1.82]*	0.006	[1.34]	0.003	[1.20]
$\beta_{soft,k}$	0.004	[1.80]*	0.006	[1.33]	0.003	[1.19]
Obs.	575		200		375	

Figures into brackets ate t−students in absolute terms.
** significative at 10%; ** significative at 5%; *** significative at 1%.*

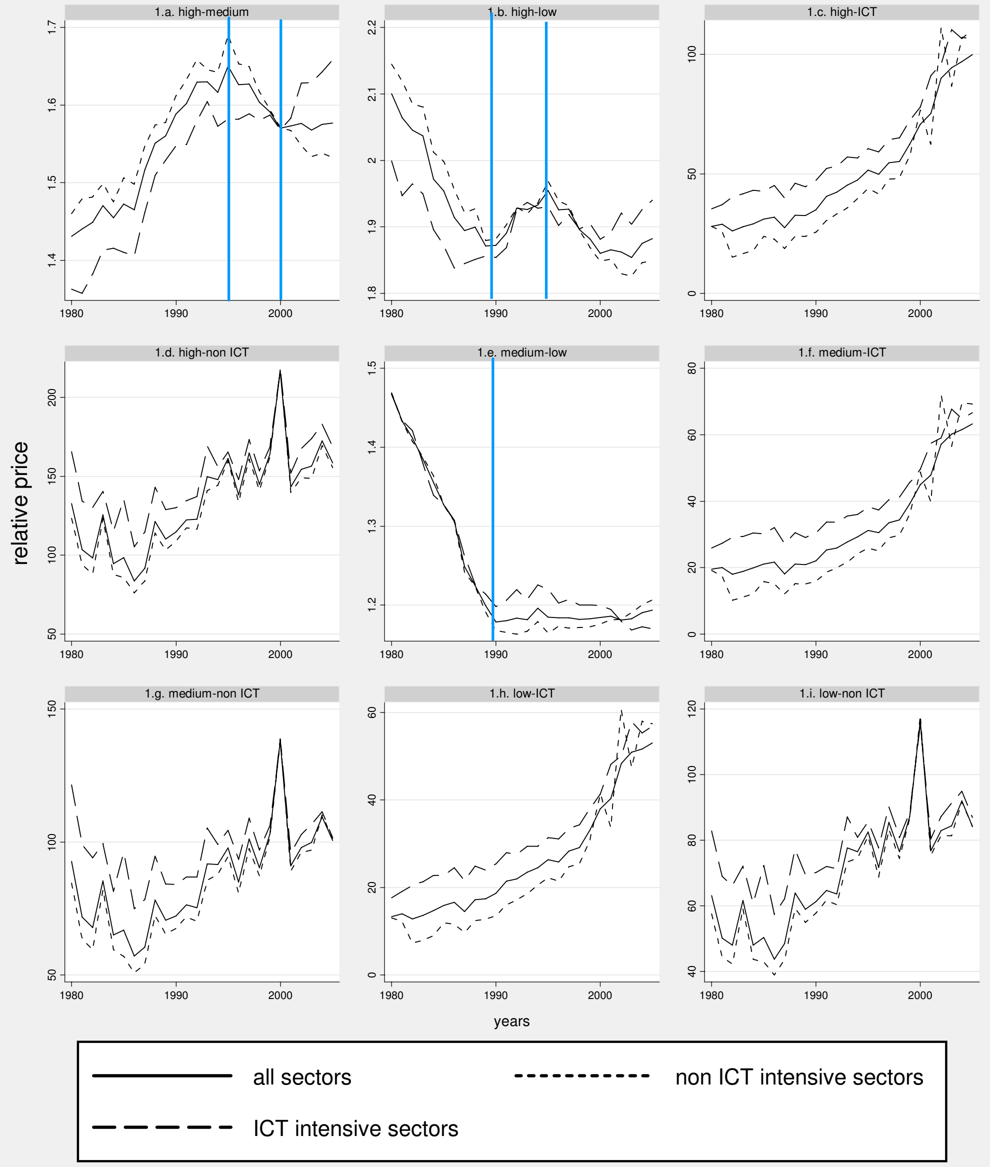
Table 5: Average elasticities of substitution 1980-2005

	Column I		**Column II**		**Column III**	
	All sectors		**Intensive users**		**Non intensive users**	
$ES\,(h,m)$	1.56	[1.16]	1.64	[1.07]	1.34	[0.47]
$ES\,(h,\ell)$	1.77	[2.75]***	1.12	[0.27]	2.11	[2.93]***
$ES\,(h,hard)$	-3.95	[3.28]***	-1.96	[2.76]***	-7.03	[2.11]**
$ES\,(h,com)$	-1.53	[2.89]***	-0.63	[2.57]***	-2.75	[1.75]*
$ES\,(h,soft)$	-7.85	[3.34]***	-3.09	[2.76]***	-25.14	[2.14]**
$ES\,(h,k)$	1.97	[13.92]***	1.67	[6.72]***	2.24	[12.40]***
$ES\,(m,\ell)$	0.97	[0.10]	0.36	[1.08]	1.31	[0.97]
$ES\,(m,hard)$	-0.12	[0.79]	2.40	[1.09]	-4.06	[1.67]*
$ES\,(m,com)$	0.68	[0.38]	1.83	[1.09]	-1.76	[1.56]
$ES\,(m,soft)$	0.00	[0.40]	3.32	[1.30]	-18.75	[2.04]**
$ES\,(m,k)$	1.83	[13.17]***	1.75	[6.21]***	1.93	[12.92]***
$ES\,(\ell,hard)$	4.53	[4.45]***	3.63	[2.74]***	6.21	[3.53]***
$ES\,(\ell,com)$	2.76	[3.79]***	2.46	[2.57]***	3.27	[2.70]***
$ES\,(\ell,hard)$	6.90	[4.21]***	4.64	[2.72]***	19.08	[3.82]***
$ES\,(\ell,k)$	1.70	[19.52]***	1.91	[10.17]***	1.62	[16.81]***
$ES\,(hard,soft)$	-14.12	[2.30]**	-7.60	[2.13]**	-25.21	[1.32]
$ES\,(hard,com)$	-46.06	[2.31]**	-14.98	[1.69]*	-155.57	[1.36]
$ES\,(hard,k)$	2.63	[1.90]*	2.60	[1.36]	2.90	[1.38]
$ES\,(com,soft)$	-26.04	[2.32]**	-8.52	[1.70]*	-84.26	[1.33]
$ES\,(com,k)$	1.94	[1.90]*	1.95	[1.37]	2.04	[1.37]
$ES\,(soft,k)$	3.92	[1.88]*	3.21	[1.35]	7.19	[1.36]
Obs.	575		200		375	

Figures into brackets ate $t-$students in absolute terms.

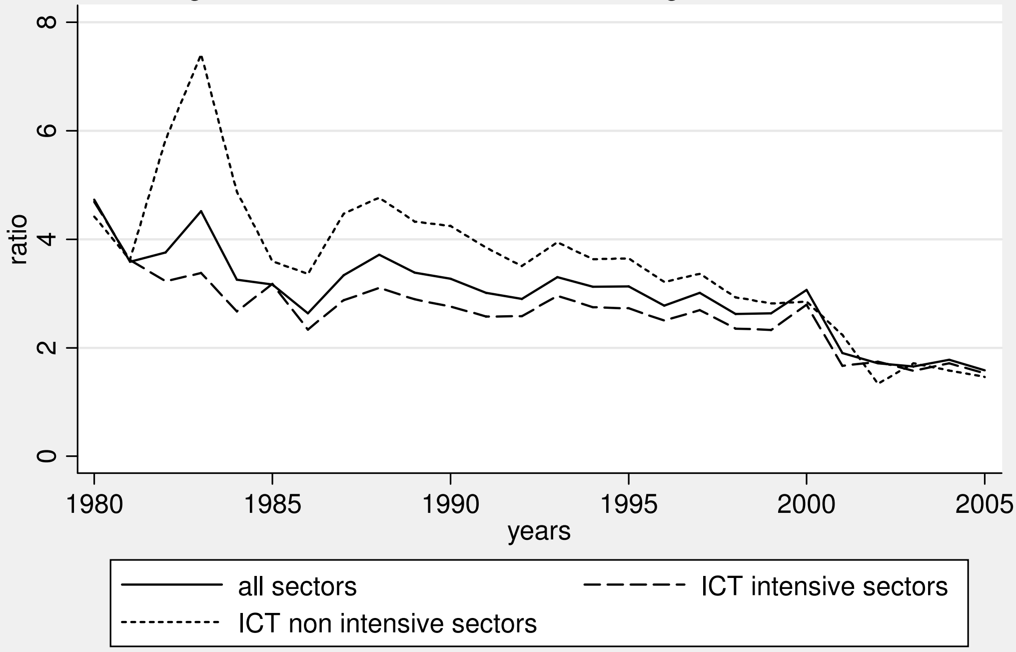
** significative at 10%; ** significative at 5%; *** significative at 1%.*

Figure 1.a Relative prices of factors, 1980-2005



Source: EUKLEMS, Ivie-FBBVA and own estimations

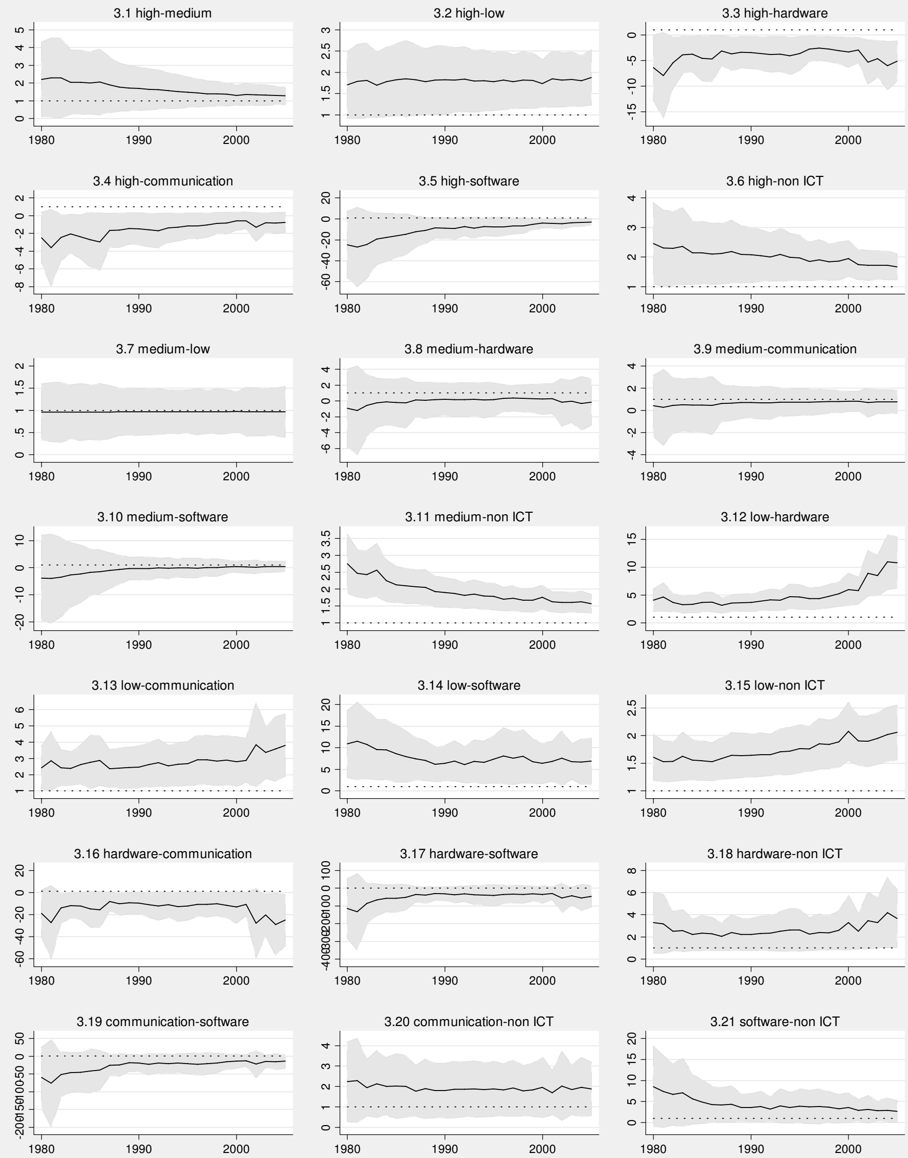
Figure 2. ICT and non ICT relative usage cost, 1980-2005



Source: EUKLEMS, Ivie-FBBVA and own estimations

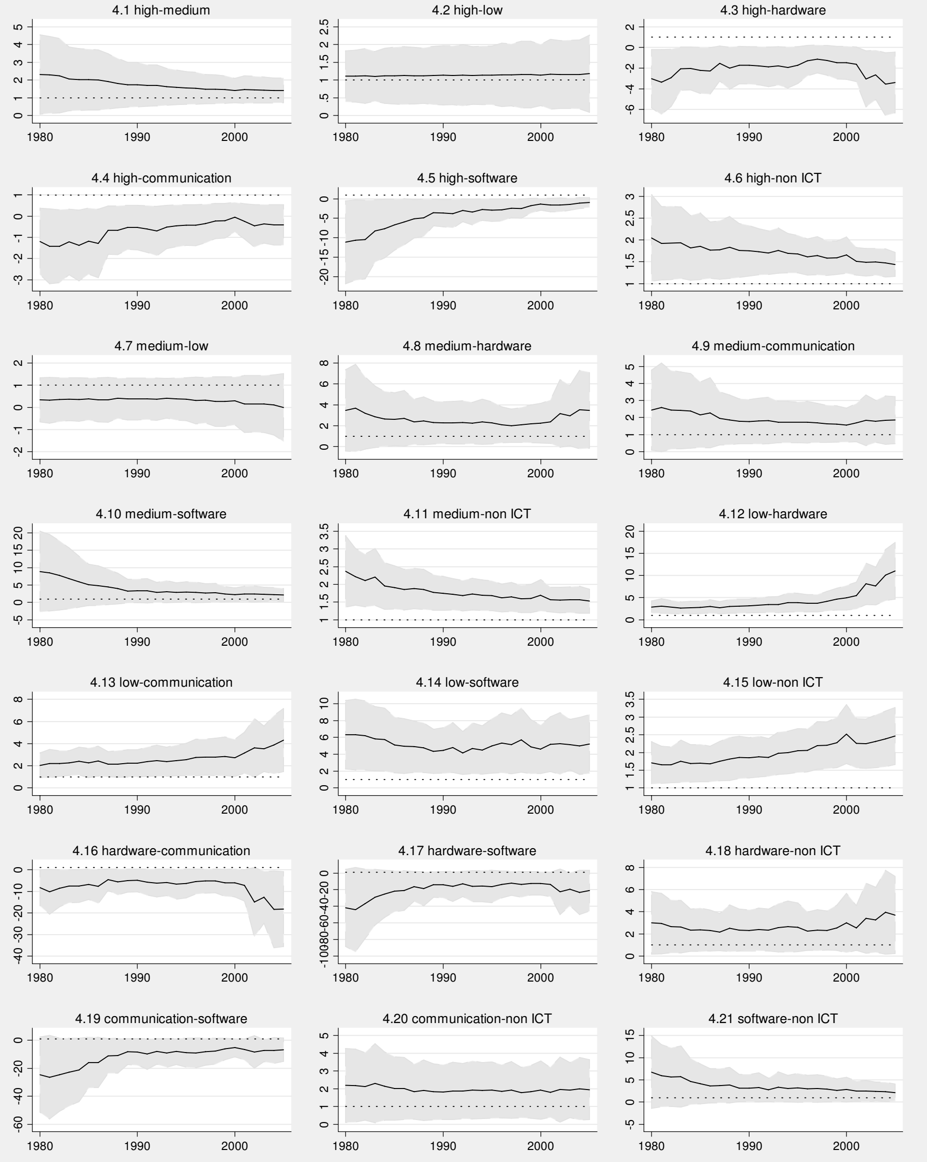
Figure 3. Elasticities of substitution, 1980-2005

(all sectors)



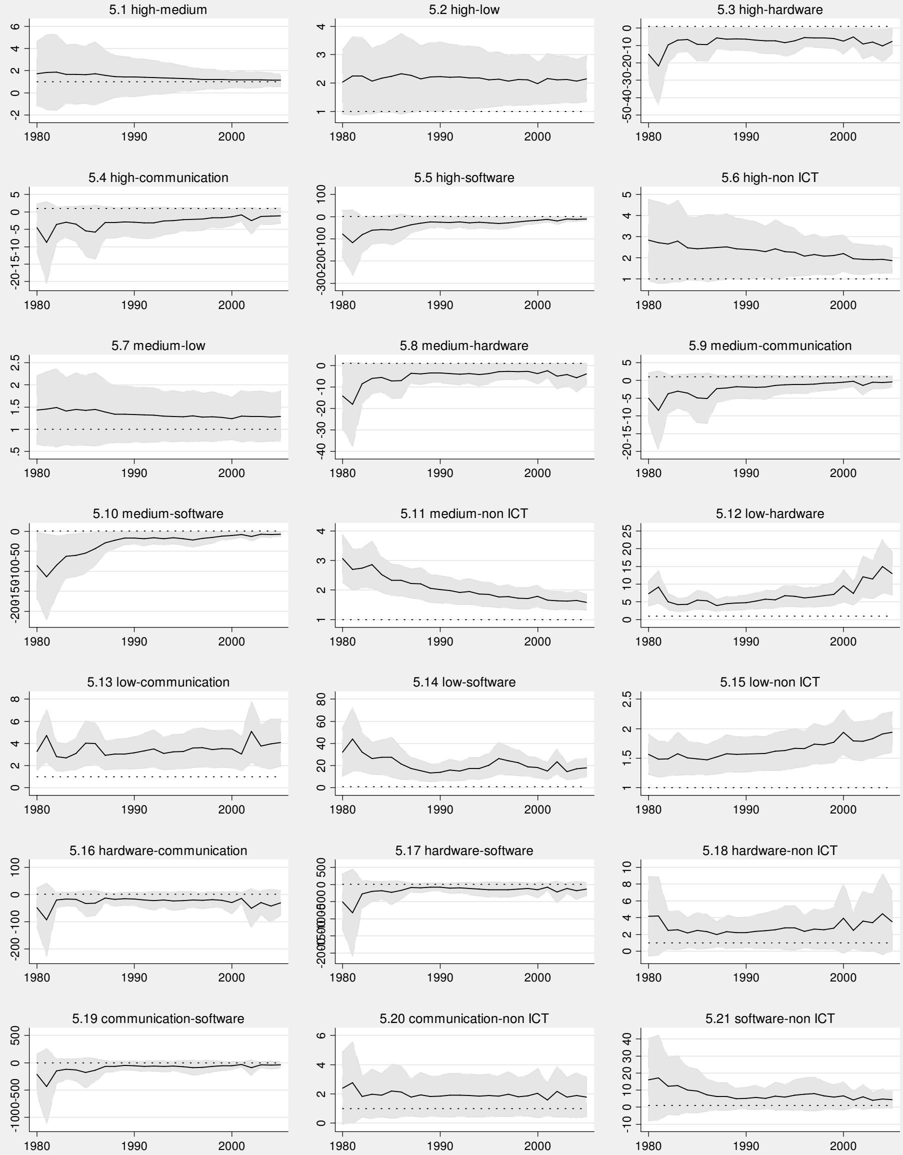
Note: Shadowed areas represent 95% confidence intervals. Dotted lines are fixed to one

Figure 4. Elasticities of substitution, 1980-2005
(ICT intensive sectors)



Note: Shadowed areas represent 95% confidence intervals. Dotted lines are fixed to one

Figure 5. Elasticities of substitution, 1980-2005
(ICT non intensive sectors)



Note: Shadowed areas represent 95% confidence intervals. Dotted lines are fixed to one

El Centro de Estudios Andaluces es una entidad de carácter científico y cultural, sin ánimo de lucro, adscrita a la Consejería de la Presidencia de la Junta de Andalucía.
El objetivo esencial de esta institución es fomentar cuantitativa y cualitativamente una línea de estudios e investigaciones científicas que contribuyan a un más preciso y detallado conocimiento de Andalucía, y difundir sus resultados a través de varias líneas estratégicas.

El Centro de Estudios Andaluces desea generar un marco estable de relaciones con la comunidad científica e intelectual y con movimientos culturales en Andalucía desde el que crear verdaderos canales de comunicación para dar cobertura a las inquietudes intelectuales y culturales.

Las opiniones publicadas por los autores en esta colección son de su exclusiva responsabilidad

Depósito Legal: SE-7351-08

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

E2008/14

PUBLIC AND PRIVATE SECTOR WAGES: CO-MOVEMENT AND CASUALITY*

Ana Lamo *
European Central Bank
Javier J. Pérez
Bank of Spain
Ludger Schuknecht
European Central Bank

Resumen

Este artículo se centra en las interacciones entre salaries públicos y privados en la zona euro y países de la OCDE desde 1960s. Se utilizan técnicas empíricas robustas. Los resultados muestran una correlación anual positiva muy fuerte entre los salarios públicos y privados a lo largo del ciclo económico. Además se encuentra dicha relación también en el largo plazo. La causalidad indica además que la interacción entre salarios públicos y privados ocurre de manera directa e importante también vía precios. Mientras las influencias del sector privado parecen en su conjunto ser fuertes, en el caso del sector público hay influencias directas e indirectas. Es por esta razón que en este artículo se muestran características específicas de cada país en términos de trabajo y mercados de productos para obtener información adicional que nos permita explicar la heterogeneidad entre países y sus efectos en la relación de salarios públicos y privados.

Clasificación JEL: C32; J30; J51; J52; E62; E63; H50.
Palabras Clave: salarios públicos, salarios privados, causalidad, co-movimiento.

* Autor correspondencia: ana.lamo@ecb.int

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

Abstract

This paper looks at public and private sector wages interactions since the 1960s in the euro area, euro area countries and a number of other OECD countries. It focuses on co-movements and causal relationships. To obtain the most robust results possible, we apply a number of alternative empirical methodologies, and perform the analysis for two data samples and different price deflators. The paper reports, first, a strong positive annual contemporaneous correlation of public and private sector wages over the business cycle; this finding is robust across methods and measures of wages and quite general across countries. Second, we show evidence of long-run relationships between public and private sector wages in all countries. Finally, causality analysis suggests that feedback effects between private and public wages occur in a direct manner and, importantly also via prices. While influences from the private sector appear on the whole to be stronger, there are direct and indirect feedback effects from public wage setting in a number of countries as well. We show how country-specific institutional features of labour and product markets contain helpful information to explain the heterogeneity across countries of our results on public/private wage leadership.

JEL code: C32; J30; J51; J52; E62; E63; H50.
Keywords: government wages; private sector wages; causality; co-movement.

Public and private sector wages: co-movement and causality †

Ana Lamo (European Central Bank, ana.lamo@ecb.int)

Javier J. Pérez (Bank of Spain, javierperez@bde.es)

Ludger Schuknecht (European Central Bank, ludger.schuknecht @ecb.int)

Corresponding author:

Javier J. Pérez

Department of Economic Analysis and Forecasting, Directorate Economics, Statistics and Research

Bank of Spain, c/Alcalá 48, 28014 Madrid, Spain

E-mail: javierperez@bde.es, Tel: +34913388856

Abstract

This paper looks at public and private sector wages interactions since the 1960s in the euro area, euro area countries and a number of other OECD countries. It focuses on co-movements and causal relationships. To obtain the most robust results possible, we apply a number of alternative empirical methodologies, and perform the analysis for two data samples and different price deflators. The paper reports, first, a strong positive annual contemporaneous correlation of public and private sector wages over the business cycle; this finding is robust across methods and measures of wages and quite general across countries. Second, we show evidence of long-run relationships between public and private sector wages in all countries. Finally, causality analysis suggests that feedback effects between private and public wages occur in a direct manner and, importantly also via prices. While influences from the private sector appear on the whole to be stronger, there are direct and indirect feedback effects from public wage setting in a number of countries as well. We show how country-specific institutional features of labour and product markets contain helpful information to explain the heterogeneity across countries of our results on public/private wage leadership.

JEL code: C32; J30; J51; J52; E62; E63; H50.

Keywords: government wages; private sector wages; causality; co-movement.

† The views expressed in this paper are those of the authors and do not necessarily reflect those of the European Central Bank (ECB) or the Bank of Spain. Thanks are due to J. von Haguen, H. Lebihan, D. Pedregal, A. van Riet, C. Robalo Marques, P. Rother, A. J. Sánchez, F. Smets and participants at the Wage Dynamics Network (WDN) Macro Group for helpful comments.

1. Introduction

This paper empirically analyses the interaction between public and private sector wages for the euro area and a number of other OECD countries over the period 1960-2006. It looks at the two related issues of co-movement and causal linkages between public and private sector wages.

This issue is relevant from an analytical and a policy perspective, notably in the euro area. Wage spillovers across sectors of an economy might lead to wage costs growing faster than productivity or than other fundamentals in some sectors and may affect international cost competitiveness of countries' tradable sectors. In this regards, the interaction between public sector wages with the wages of the rest of the economy deserves a separate treatment for several reasons. First, public wages and employment comprise almost one quarter of the total dependent work force and total compensation of employees in the OECD. Second, public wages are not necessarily determined by market forces to the same extent as wages in the private sector. The wage setting behaviour of the public sector is likely to differ from that of the private sector due to a number of factors such as a higher degree of unionisation, political objectives, [1] the difficulties of measuring labour productivity in the public sector, the different status that civil servants enjoy and that might make public wages less reactive to the business cycle, or the separate agenda of public employees (rent-seeking behaviour). [2]

In addition, there may be institutional linkages between private and public labour market behaviour. First, there may be direct links via the wage bargaining process. If by design the government is the wage "leader", it is likely that the private sector will follow more the government than market processes (at least in the short run) and quantities (private employment) are likely to adjust. If the private sector is the wage "leader" it is more likely that prices (wages) adjust which, in turn, reduces incentives for quantity adjustment. Second, there may be more indirect institutional linkages. If social

[1] Government employment and wage decisions may indeed depart from the standard profit maximisation behaviour expected in the private sector. As discussed by Gregory and Borland (1999) or Forni and Giordano (2003), there are two main theoretical approaches in the literature to understanding how public employer's decisions are taken. One approach treats public sector decision-makers as making choices to achieve socially optimal outcomes; the alternative approach introduces some personal objective of the politicians. Public sector decision-makers that seek to maximise social welfare may have both efficiency goals (minimise the cost of production of output in the public sector, or resolve labor market imperfections) but also equity goals (for example use public employment as a redistribution tool, as signalled by Alesina, Danninger and Rostagno, 2001, and Alesina, Baquir and Easterly, 2000).

[2] For example, to explain increasing public employment in developing countries Gelb *et al.* (1991) state that in line with theories of rent seeking behaviour, public sector surplus is viewed as the consequence of lobbying for higher wages and employment. As regards developing countries, the data seem to confirm the predictions of rent-seeking theories: there appear to be little correlation between public and private sector wages (Agénor, 1995). An alternative hypothesis is provided by Rodrick (2000): relatively safe government jobs represent partial insurance against undiversifiable external risks faced by some developing economies. On different grounds, Matschke (2003) shows empirical evidence of public employees' pressure in Germany ahead of political elections.

benefits and minimum wage levels are tied to wage developments in the public sector, then these indirectly influence private wage setting, even if wage bargaining is “officially” independent. Finally, not only the direct interaction between public and private wages has repercussions on inflation but there is also evidence of indirect feedback effects via prices. For example, public wage shocks may raise the inflation rate which in turn could lead to increases in private (and further increases in public) wages. From this perspective the subject might turn out to be also highly relevant from a monetary policy perspective.

Our study analyses the interaction between public and private wages in many industrialised countries: the euro area aggregate, ten euro area countries (Germany, France, Italy, Spain, Netherlands Austria, Belgium, Greece, Ireland, Portugal, Finland), Sweden, Denmark, Norway, United States, United Kingdom, Canada and Japan. Using annual data (for the period 1960-2006) is imposed by the absence of quarterly data for the variables in this study for most of the European countries in the sample. We also look at the results for the sample 1980-2006, given an apparent change in trend around 1980 in public employment.

The study aims to obtain the most robust results possible, by examining nominal wages, and also nominal wages deflated with two alternative price deflators (private consumption deflator and GDP deflator), by using a large number of detrending techniques, and by applying a host of approaches to correlation, co-movement and causality over different time horizons.

The paper provides, firstly, robust empirical evidence on the correlation of public and private wages over the business cycle. We look at the unconditional correlations between detrended series (at the standard business cycle frequencies) using eleven methods. The study finds that in the euro area and for most of the countries of our sample private wages are positively and strongly correlated with public wages over the business cycle in a mostly contemporaneous manner. This is a very robust result across countries, in spite of very different institutional settings and different inflation regimes witnessed in the different decades covered by our study.

Secondly, the paper provides an analysis of short-, medium-, and long-run co-movements between public and private sector wages using the methodology of den Haan (2000). For the short-run correlations the results of the previous (robust) analysis are confirmed. For the co-movements at longer frequencies than the standard business cycle frequencies our results show a strong correlation between public and private sector wages. Thirdly, following up on these pieces of evidence, the paper reports the existence of a long-run relationship (co-integration) between public and private sector wages in all the countries of the analysed sample. Wages in both sectors share a common driving trend.

Moreover, the paper conducts a thorough analysis of causality. We run Granger-Causality tests for different empirical specifications comprising nominal wage variables and the price level. First, we focus on the Granger-causal links over the business cycle by looking at VARs between detrended variables (using eleven detrending methods). Second, we run VARs in levels (logs) of the variables, as suggested by Toda and Yamamoto (1995) and Dolado and Lütkephol (1996). The analysis suggests that feedback effects between private and public wages occur in a direct manner and, importantly also via prices. While influences from the private sector appear on the whole to be stronger, there are direct and indirect feedback effects from public wage setting in a number of countries. Third, we carry out an empirical exercise aiming at understanding the rationale behind the heterogeneity across countries of our results on causality, i.e. why in some instances we find private sector wages Granger-causing public sector wages and in others the opposite direction of causation. We show how country-specific institutional features of labour and product markets contain helpful information to explain the heterogeneity across countries of our results on public/private wage leadership.

The paper is organised as follows. Following a brief literature survey in Section 2, we describe the data set and some stylised facts on the developments of public wages for the period 1960-2006 in section 3. Section 4 looks at the co-movements of public and private wages over the business cycles, while section 5 analyses medium- and long-term co-movements and co-integration. Section 6 looks at the causal relationships between the two sectors and the link to labour and product market institutional features. Section 7 concludes and provides some policy implications and avenues for further research.

2. The literature

The literature has so far paid very limited attention to the correlation between public and private wages. In theoretical models (real) public wages are assumed to be exogenous or to follow the same determination patterns as private wages (Quadrini and Trigari, 2007, Ardagna, 2007, Holmund, 1997, or Calmfors and Horn, 1986). On related grounds Demekas and Kontolemis (2000) develop a static model in which increases in government wages lead through the worker flow channel to increases in private sector wages. The existing empirical work focuses on quantity links (employment) rather than price links (wages) between the public and the private sector. [3] [4] An exception would be Afonso and Gomes (2008) who conduct a pooled analysis of public and private sector wage growth in OECD and European Union countries. The authors find that nominal and deflated compensation per public sector employee display a statistically significant positive contemporaneous correlation with private sector wages.

[3] Alesina et al. (2002) find a sizeable negative effect of public spending and in particular of its wage component (wage bill) on private sector profits and on business investment. Ardagna (2007) claims that the latter results are consistent with the different theoretical models in which government employment creates wage pressure for the private sector, and thus can be used as anecdotal evidence supporting that the direction of causality would go from public sector wages and employment to private sector wages and employment. She claims that this supports her theoretical assumption of exogenous public wages and employment.

[4] See for example Algan, Cahuc and Zylberberg (2002) or Forni and Giordano (2003), and the literature quoted therein.

The main theoretical reference as regards expected causality is the so-called Scandinavian model of inflation that assumes that the traded-goods sector is the wage leader, i.e. that wage leadership is exerted by the sectors that are more open to competition (see for example Strom, 1997). Bemmels and Zaidi (1990) look at Canadian industries and find a confirmation of the Scandinavian model, namely the tradable sector leading wage setting. Nevertheless, this model is sometimes at odds with the empirical literature. In the case of public/private wages sectoral interactions Friberg (2007) does not find evidence of the Scandinavian model for Sweden (along these lines see also Holmlund and Ohlsson, 1992, and Tagtstrom, 2000). In response to Friberg, Lindquist and Vilhelmsson (2004) apply a vector error correction approach to wage setting in Sweden with annual data for the period 1970-2002, and find long run wage leadership of the private sector and no Granger causation from the public to the private sector in the short run, in line with the results already obtained by Jacobson and Ohlsson (1994).

Apart from the case of Sweden, country studies on public-private sector wages causality are also scarce. Demekas and Kontolemis (1999) find *weak exogeneity* of real government wages for private sector behaviour in a VAR analysis for Greece (1971-1993). For Chile, Mizala and Romaguera (1995) find evidence of the private sector leading public wages after labour market liberalisation in the early 1980s. An IMF report for Romania (see Christou, Klemm and Tiffin, 2007) shows a bi-directional relationship between private and public wages using monthly data for 1993-2006; it also finds that government wages lead those in state-owned enterprises which, in turn, influence private wages.

3. Data and stylised facts

3.1 Data sources and definition of variables

We use a standard OECD dataset that has been used in related studies like Algan, Cahuc and Zylberberg (2002), Alesina *et al.* (2002), Lane (2003), or Lamo, Pérez and Schuknecht (2007), among others. In particular we use the OECD Economic Outlook database December 2007 Issue. Missing variables for some specific time periods/variables in this issue of the OECD have been completed with information coming from the Spring 2007, the Spring 2006, and the Spring 2005 issues.

Regarding the measures of wages we take compensation of employees and compensation per employee both in nominal and real terms. Given that deflators have been pointed out as a source of disparity of results in the empirical literature on cyclicality of wages (Abraham and Haltiwanger, 1995), we use two different indices to deflate nominal wages, namely the private consumption deflator and GDP deflator. We compute compensation per employee using compensation of employees and employment data. Compensation of private sector employees is defined as total economy compensation of employees minus compensation of government employees. Compensation per private employee is defined as private compensation of employees divided by private sector employees minus government employment minus self-employment. [5]

The concept of total compensation of employees in the government sector is a well-defined statistical concept and in particular for European countries it is a homogeneous concept as defined by the European System of National Accounts (ESA95). A different story applies to government employment, needed to compute compensation per employee, especially for European countries. EU member states do not report to Eurostat (the EU's statistical agency) standardized employment figures for the general government sector. Thus it is necessary to resort to national sources, and the issue of homogeneity across countries is more delicate. The OECD presents the best choice as regards cross-country availability and homogeneity of data in this respect. For statistical issues regarding the definition of government employment see OECD (1997). [6]

3.2 Some stylised facts on public wages

When looking at developments in wages per employee, it is noteworthy that public and private wages in the euro area converged between the 1960s and the late 1980s before diverging again in more recent years with public wages at increasingly higher levels than private wages (Figure 1, panel 1). By contrast, in the US this ratio has fluctuated relatively little over recent decades. Within the euro area, France (with one of the highest public employment ratios) also features a broadly constant ratio, with public and private wages at similar levels (Figure 1, panel 2). In other euro area countries private wages tend to be lower than public wages per employee. [7]

Private wages grew much more strongly than in the public sector until about 1990 before this pattern reversed (Figure 2). The pattern of US wage developments was similar to the euro area in the 1970s and in most recent years but not in between. Figure 2 also reflects the different behaviour of public

[5] The euro area aggregate excludes Luxembourg, Slovenia, Cyprus and Malta, due to lack of data for these countries.

[6] Within the ESA95 framework, a rough proxy allowing for a homogeneous measure of the public sector wage bill consistent with a corresponding measure of public employment is to be found by adding the items "Public Administration and defence", "Health and social work" and "Education" (NACE classifications L, M and N). Nevertheless, this proxy is far from being appropriate for a our study, to the extent that part of compensation of employees and employment under the items "Health and social work" and "Education" do include activities that should be labelled under market/private services. In this respect, it could also vary markedly across euro area member states. Another source of concern with this source is the heterogeneous availability of data across countries and the limited sample size available.

[7] Private and public wage patterns are a mirror image of employment patterns. High public employment coupled with proportionate wages per employee might unveil a higher low skill concentration in the public sector. Domeij and Ljungqvist (2006) report that the dramatic decline of the skill premium in Sweden since the 1970s is the result of an expanding public sector, with the expansion taking the form of drawing low-skilled workers into local government jobs that service the welfare state.

employment between the euro area and the US. Euro area public employment growth was very strong in the early observation period and below that of the private sector more recently. US public employment growth was broadly in line with that of the private sector over recent decades. Figure 2 also shows that the public sector in the euro area has displayed a much more stable hiring behaviour and job security (in terms of annual employment growth rates) than the private sector. By contrast, there is not much difference in the volatility of euro area public and private wages per employee (in annual growth rates). Hence, signs of interaction between the two sectors are more likely to be found on the wages side. US public employment growth appears much more volatile than in Europe and almost as volatile as that in the private sector.

4. The co-movement of public and private sector wages over the business cycle

4.1 Methodology

In this section we focus on co-movements of detrended measures of public and private wages, as it is general practice in the empirical business cycle literature, using a variety of detrending methods. Following standard practice we measure the co-movement between two series using the cross correlation function (CCF thereafter). For each pair of variables, the CCF computed using different detrending methods yield different information. Deciding that one of them is the preferred one, independently of the criteria used to take the decision, will discard useful information contained in the CCFs that are not selected. To avoid this, we take an agnostic approach by applying the idea of *thick modelling* as proposed by Granger and Jeon (2004). We combine the correlation coefficients following David (1949) and use Fisher transformations to normalize their distribution and stabilize their variance. [8] The transformed coefficients can then be averaged as usual. Once the average is computed, we need to undo the Fisher transformation to get the correlation coefficient that summarizes the information contained in the combined correlation coefficients. This transformation greatly reduces the skew in the distribution, potentially yielding a more accurate estimate of the population correlation. In addition, the result of the transformation is minimally biased in small samples. [9]

As regards detrending methods, we use a variety of filters. The underlying assumption to detrending filters is that aggregate seasonally-adjusted economic time series can be decomposed into a trend component T_t, the so-called cyclical component C_t that fluctuates around the trend, and an

[8] The standard approach in the literature is to just take one single detrending method and base the subsequent analysis on the detrended time series computed using that detrending method. A significant deviation from this practice is Lamo, Pérez and Schuknecht (2007), which serves as a model for this Section of the paper. Camacho, Pérez-Quirós and Sainz (2006) and Lamo, Pérez and Schuknecht (2007) also use Fisher transformations to combine correlation coefficients.

[9] Following Ganger and Jeon’s suggestion, we exclude from the combined measure methods yielding extreme results (we exclude methods yielding a relative volatility above 10).

unpredictable random component ε_t, i.e. a given series y_t can be decomposed as $y_t = T_t + C_t + \varepsilon_t$. Most of the detrending filters take out the trend component from the original time series, so that both the cyclical and irregular components $C_t + \varepsilon_t$ are taken as measure of the cycle. Among these standard detrending methods we take the following (see Appendix A for a brief description): (i) first difference filter; (ii) deterministic trends; (iii) Hodrick-Prescott filter (with two different band-pass parameters); (iv) Band pass filter (with two different band-pass parameters); (iv) Unobserved components models: we estimate up to 5 different models that differ in the model of the trend and the cycle, including linear trend plus fixed-period cycle, local level model plus fixed-period cycle, local linear trend model plus fixed-period cycle, local level model plus estimated-period cycle, local linear trend model plus estimated-period cycle. The models allow for cycles of 2 to 6 years to be estimated (not just imposed as in the basic case) using the so-called DHR (Dynamic Harmonic Regression) methods as in Young, Pedregal and Tych (1999).

4.2 Results

Table 1 gives an overview of the results for all the analysed countries. [10] It shows the co-movement results for total compensation per private and public employees, both for the variables in nominal terms and in real terms (deflated using the two selected deflators), for the two considered samples (1960-2006 and 1980-2006).

Each row of this table displays the robust CCF between a measure of detrended private wages at time t, and a measure of detrended public wages at time t-k. Following the standard discussion in the literature, it is said that the two variables commove in the same direction over the cycle if the maximum value in absolute terms of the estimated correlation coefficient of the detrended series (call it dominant correlation) is positive, that they co-move in opposite directions if it is negative, and that they do not co-move if it is close to zero. We take maximum values of the combined correlations in the ranges 0.20-0.39 and 0.40-0.49 as evidence of weak and moderate correlation respectively. We refer to strong correlation if in absolute terms it is larger or equal to 0.50. The cut-off point 0.20 was chosen because it roughly corresponds in our sample to the value required to reject at the 5% level of significance the null hypothesis that the population correlation coefficient is zero.[11] Finally, the public

[10] Appendix B, Tables B1 to B16 provides detailed results for each country for all detrending methods for the full sample.

[11] The cut-off point for the combined correlation in the case of combining independent correlation coefficient estimates, which is not strictly our case, would be slightly above 0.1. Nevertheless, some studies recommend (see Rosenthal, 1991) to calculate the probabilities for combined correlations by combining the individual probability values of each correlation coefficient, in which case our cut-off point would be close to 0.3. We take 0.2 as a compromise between the two alternatives which is in line with the cut-off values normally used in the literature.

sector variable is said to be leading (lagging) the private sector variable if the maximum correlation coefficient is reached for negative (positive) values of k.

For nominal compensation per employee (Table 1) we find a dominant strong contemporaneous correlation for most countries of the sample and the euro area aggregate. The only exceptions are Spain, the Netherlands and Sweden, in which the dominant correlation is also strong and positive, but we find that private sector wage movements lead (precede) wage movements in the public sector. Belgium is the only case in which public sector wages lead private sector developments (moderate correlation). In most of the cases the results by method (see tables in Appendix B) tend to be in line with the dominant correlations according to the combined correlation. Even though there is some variation in the specific quantitative values, the qualitative message is quite robust.

The pattern of dominant contemporaneous correlations is also present when looking at the CCFs between variables in real terms. [12] The size of the correlations is smaller, though. The euro area, Germany, France, Greece, Norway and Japan present a strong contemporaneous correlation, and Spain, Netherlands, Ireland, Portugal, Finland, Sweden and the United States present moderate or weak dominant correlations. Among big euro area countries Italy is an exception as it only shows a weak (lagged) positive correlation; nevertheless, this pattern is reversed when considering the sample 1980-2006. The difference between the correlations of nominal versus real variables is likely to be related to the fact that part of the correlation between nominal wages might be explained by price developments over the business cycle. At the same time, this evidence shows that public and private sector wages are correlated due to other factors than prices, most likely developments in productivity, institutional agreements or labour market linkages.

The annual (contemporaneous) correlation between public and private sector wages is a robust and generalised feature of our data. This is a very homogenous result in spite of very different institutional settings in the countries. It is worth noting that within the sample we have countries with highly unionised labour forces (like the Nordic countries) and countries with low unionisation like the US or Canada. A priori there would be no reason to expect that the observed patterns are the same for different countries given the important differences in institutions, organisation of the government sector and monetary policy. There would be no reasons either not to expect changes over time, given the different inflation regimes witnessed in the 60s, 70s, 80s and 90s. Nevertheless, our findings appear quite robust both across countries and periods of time (1960-2006 and 1980-2006).

Interestingly, according to the relative standard deviations (public/private) shown in the first column of each panel, the cyclical components of public sector wages are more volatile than those of private sector wages for most countries (Table 1).

[12] For each country, and to obtain the most robust results, we averaged the (Fisher transformed) correlations of the 11 detrending methods using the two alternative deflators.

5. Medium- and long-run co-movements, and co-integration

5.1 den Haan's medium- and long-term co-movements

In this section we analyse the co-movement between public and private sector wages using the correlation coefficients of forecast errors from vector autoregressive (VAR) systems at different forecast horizons, as proposed in den Haan (2000). This procedure adds two relevant features to the methods used in the previous section: (i) it is suited for the discussion of short-term, medium-, and long-term correlations; (ii) den Haan's procedure can be used for stationary as well as integrated series, so that no prior de-trending of the series is required. [13]

Figure 3 presents the correlations (with significance values) for nominal wages per employee and real wages per employee for the 1960-2006 sample for some selected euro area (euro area aggregate, Germany, France, Italy, Spain) and non-euro area countries (Sweden, US, UK, Canada, Japan). The whole set of results for all countries and both sample periods is presented in Appendix C in tables C1, C2 and C3.

As compared to the detrending methods presented in the previous section, den Haan's method focuses on the correlations between the irregular components, after having removed the trend and the inertia of the series, i.e. $T_t + C_t$. Correlations for $h=1$ would be directly comparable with the correlations for lag $k=0$ shown in Table 1 if the latter would be between irregular components instead of detrended series. When applying den Haan's method and thus filtering out the dynamics of the series due to the systematic autocorrelation (C_t), the co-movement patterns between public and private sector wages at horizon 1 are very similar than for the detrended series, with coefficients ranging from 0.4 to 0.8 for nominal wages, and from 0.4 to 0.7 for real wages. Figure 3 shows these correlations, which are the points vertically aligned at horizon 1. In addition, these charts display the correlation of forecast errors at longer horizons, which gives an idea of medium term co-movements, being also positive correlated. Correlation coefficients between public and private sector wages tend to become larger when the forecast horizon increases, and then stabilise, typically at forecast horizons between 3 to 4 years.

Two countries are special. In line with the results for correlations between detrended wages, Italy shows a statistically insignificant correlation between real wages for the 1960-2006 sample, at all forecasting horizons. However, this pattern is reversed when looking at the 1980-2006 sample (see Table C1), in which case the results for Italy are in line with other big euro area economies. After removing the effect of prices, medium term correlations for Spain also lose significance, pointing to

[13] We run Den Haan's method assuming: (i) unit root in the variables, (ii) no unit root in the variables. For the sake brevity only the first set is shown, as the qualitative messages did not change by using (i) or (ii).

the fact that medium-term co-movements might be led by price developments, rather than by other factors like productivity.

5.2 Long-run relationship (co-integration)

Co-integration reflects the long term relationship or long term co-movement among non-stationary variables, therefore this section focuses on long term co-movements rather than co-movements at the business cycle frequency, and thus can be seen as further evidence on long-run correlations on top of the one already presented in the previous section.

Wages (nominal and deflated) exhibit a single unit root as confirmed by several test under different specifications [14] and thus we test for the presence of co-integrating relationships within a vector error-correction model (VEC henceforth). To determine the optimal number of lags we estimate an unrestricted vector autoregressive models (VAR) using the data in levels, and then choose the appropriate lag length using the Akaike, Schwarz and Hannan-Quinn information criteria. [15] Then we rewrite the VAR(p) in error-correction form as a VEC(p-1),

$$\Delta y_t = \Pi \gamma_{t-1} + \sum_{s=1}^{p} \pi_s \Delta y_{t-s} + Ch_t + \varepsilon_t \tag{1}$$

where y_t is a *k* vector of non stationary I(1) variables. γ_{t-1} includes y_{t-1} and deterministic variables that enter the co-integration relation. h_t is a vector of deterministic variables (constant and/or trend). Testing for co-integration between the non-stationary variables y_t amounts to determining the rank of matrix Π. The standard strategy for determining the co-integrating rank is to test the sequence of null hypotheses, H_0: rank(Π) = 0, H_0: rank(Π) = 1. To test this sequence we use two standard Johansen tests: the Maximum eigenvalue and the Trace test (see, for example, Johansen, 1995).

Table 2 summarises the results of the standard Johansen tests for the most plausible VEC specifications. [16] We find that in most cases public and private sector nominal and real (deflated) wages are co-integrated, given that the null hypothesis H_0: rank (Π) = 0 is rejected in most cases and for most of the countries, while it is not the case for H_0: rank (Π) = 1. Nominal wages in Norway and the UK are the only cases in which according to both co-integration tests H_0: rank (Π) = 0 is not

[14] The existence of a second unit root is rejected in all cases, and we therefore safely assume that all series are I(1). Unit root test results are available from the authors upon request.

[15] When the outcomes of these criteria differ we take the smaller number of lags (p) that guarantees that the residuals of the VAR are normally distributed and do not present significant autocorrelation.

[16] The presence of deterministic components in the model affects the properties of the test for co-integration, therefore we tried all the possible different combinations of deterministic components in the data and/or the co-integrating equation. The selected specifications are available from the authors upon request.

rejected at the 5% level (though they are borderline cases). In the case of real variables, the only exceptions are the euro area aggregate, France, Belgium and Denmark when using the private consumption deflator (but not the GDP deflator); in the cases of France and Belgium the tests would signal that real wages are stationary.

6. Who is in the driver seat?

6.1 Empirical specification

One of the most common concepts of causality in empirical analyses is the one defined by Granger (1969). If a variable *x* affects a variable *z*, the former should help improving the predictions of the later variable. A standard Granger-causality test can be implemented in a VAR framework.

In a *first exercise* we test for Ganger-causality for a stationary and stable process (detrended variables). In a *second exercise* we test Granger-causality between pairs of original variables (i.e. non-detrended). The restrictions characterising Granger-causality are exactly the same as in the stable case. Following Toda and Yamamoto (1995) and Dolado and Lütkephol (1996) we use a Wald test based on a lag augmented VAR. These authors show that a standard Wald test can be used to test linear constraints in this framework by just adding an extra lag in estimating the parameters of the process. This approach is quite appealing because the least-squared estimation may be applied to the levels of the VAR(p+1) model. To carry out the causality test it is not necessary to perform a VEC reparameterisation of the process to account for cointegration, because the least-squares estimators of the relevant matrices do not change due to the reparameterisation.

The model we are interested in contains public sector wages, private sector wages and expected prices

$$\begin{bmatrix} w_t^{PU} \\ w_t^{PR} \\ E_t(p_{t+1}) \end{bmatrix} = C + \sum_{j=1}^{p} A_j \begin{bmatrix} w_{t-j}^{PU} \\ w_{t-j}^{PR} \\ E_{t-j}(p_{t-j-1}) \end{bmatrix} + \varepsilon_t \qquad (2)$$

where *C* is a 3x1 vector of constant coefficients, each A_j is a 3x3 matrix, *p* the order of the VAR, and ε a 3x1 vector of random disturbances. w_t^{PU} denotes nominal wages in the public sector, w_t^{PR} nominal wages in the private sector, and $E_t(p_{t+1})$ the expected price level in t+1. If expected prices at time t are proxied by actual prices, the corresponding equations for public and private sector wages turn out to be

$$w_t^{PU} = C_1 + a_0^{PU}\ p_t + a_1^{PU}\ p_{t-1} + \cdots + a_p^{PU}\ p_{t-p} + A_{PU}^1(L)\, w_t^{PU} + A_{PR}^1(L)\, w_t^{PR} + \varepsilon_t^{PU} \qquad (3)$$

$$w_t^{PR} = C_2 + a_0^{PR}\ p_t + a_1^{PR}\ p_{t-1} + \cdots + a_p^{PR}\ p_{t-p} + A_{PU}^2(L)\, w_t^{PU} + A_{PR}^2(L)\, w_t^{PR} + \varepsilon_t^{PR} \qquad (4)$$

Within this formulation we can accommodate our previous discussion on nominal and real wages. In order to make a general discussion of the impact of prices on the relationship between wages in both sectors, we look at the results of two comparable sets of estimated equations:

(i) [*Nominal wages*] Impose in (3) and (4) the constraints $a_0^i = a_1^i = \cdots = a_p^i = 0$, for $i = PU, PR$.

(ii) [*Nominal wages and prices*] Equations (3) and (4) without constraints on the coefficients.

Notice that in the standard practice real wages are defined in such a way that $a_0^i = 1$. Imposing this constraint and rearranging the resulting coefficients to express all wage variables in, say, equation (3), as real (deflated) wages (i.e. $w_t^{PU} - p_t$), the following particular case of equation (3) can be obtained: $w_t^{PU} - p_t = C_1 + A_{PU}^{1*}(L)\left(w_t^{PU} - p_t\right) + A_{PR}^{1*}(L)\left(w_t^{PR} - p_t\right) + A^*(L)p_t + \varepsilon_t^{PU}$. If, in addition, the constraint $A^*(L) = 0$ is imposed, thus restricting the VAR to include only real (deflated) public and private wages), the previous equation turns out to be $w_t^{PU} - p_t = C_1 + A_{PU}^{1*}(L)\left(w_t^{PU} - p_t\right) + A_{PR}^{1*}(L)\left(w_t^{PR} - p_t\right) + \varepsilon_t^{PU}$. This specification is a quite restricted formulation of equation (3), and the equivalent equation (4), and thus we preferred to contemplate the two, more general cases (i) and (ii) above as a parallel to the exercise carried out in the previous sections with nominal and real (deflated) variables.

6.2 Causality analysis

Table 3 shows the results of the *first exercise* analysing causality. It summarises the results of running Granger-Causality tests with VAR models with nominal compensation per employee in the public and private sector (exercise (i) above), and the same vector but including expected prices (exercise (ii) above). For each 2-variables or 3-variables specification we detrended the variables using the 11 detrending methods described in a previous section (first differences being one, and the other ten shown under "Other filters"), and then we run the corresponding Granger-causality tests for each group. We show an arrow when at least 6 methods out of 11 showed significant evidence of Granger-causality. [17]

For nominal wages (first two columns of Table 3), the dominant pattern is one in which private sector developments *over the business cycle* cause public sector developments. This is correct for the euro area aggregate and most member countries in the sample: Germany, France, Italy, Spain, Netherlands, Greece, Portugal and Finland. Finland, Sweden and Denmark show bi-directional causality, whereby past developments in private sector wages do have an influence on public sector today but also past

[17] Results for 1980-2006 can be found in Appendix D, Table D1.

public sector wages do contain valuable information to predict today's private wages. In the Anglo-Saxon group the US, the UK and Canada show causality from the private to the public sector, while in Belgium and Japan the causality flows in the opposite direction (from public to private).

When prices are taken explicitly into account in the VAR (columns 3 onwards in Table 3) some leading behaviour from public to private sector wages arises in the case of Ireland, France, Finland and Italy (in the latter case weak evidence: 5 out of 11 methods) and Germany and Belgium only when applying the private consumption deflator. A remarkable result is that the dominant leading behaviour of the private sector wages vanishes for the Anglo-Saxon countries as well as for Italy, Spain, Greece and Portugal. In general comparing results for bi-variate nominal wage VARs with those when prices are taken into account it seems that prices are likely to play an important role in the transmission of private wage leadership.

Table 4 presents the results of the *second exercise* carried out to analyze causality. It shows Granger-causality results using VARs in the levels of the variables. In this section causality results do not only show linkages over business cycle frequencies, but rather have to be interpreted as a mixture of short- and long-run linkages. [18] As regards nominal wages (columns 1 and 2, Table 4) there is again broad evidence in favour of private sector wages leading public sector wages; this is found for all countries except Netherlands, Ireland and Norway. There are a number of instances in which nominal wages in the public sector do have some explanatory power for future private sector nominal wages: Italy, Netherlands, Greece, Portugal and, in line with the results for the VARs with detrended variables, also Finland, Sweden and Denmark.

There are quite a few instances of Granger-causality from private to public wages when the VARs are extended to account for expected inflation (columns 3 to 6). In line with the earlier analysis, Ireland, France, Finland and the Netherlands (and Italy for GDP deflator only) also show Granger causality from public to private wages for both inflation measures. Again, it is remarkable that the evidence on Granger causality from private to public nominal wages fades away for some countries and the euro area once price development are accounted for. Results from both causality *exercises* in table 3 and 4 therefore suggest that prices are a relevant factor behind the private wage leadership. The results from the VARs described above allow us to look at the interaction between public and private sector wages and prices, which nevertheless would deserve an even deeper investigation.

Table 5 complements table 4 by showing the causality links between prices and wages when the VARs are extended to account for expected inflation. Prices Granger cause private wages.[19] Prices also affect public wages in most countries although the evidence is weaker in a few cases (Austria, Greece,

[18] Detailed results of running these tests with different specifications and p-values for the relevant null hypothesis are presented in Appendix E (Tables E1, E2 and E3).

[19] With the only exception of Belgium which is somewhat surprising given institutionalised wage indexation in this country. In any case, the results for Belgium have to be taken with care given some observed outliers in the dataset used for this country.

Portugal, Finland) where only one of the deflators shows significant results. When looking at causality from wages to prices, private wage increases help explain future price increases. The only clear exceptions are the Anglo-Saxon countries. As regards public wages, in the case of Spain, Netherlands and Finland they seem to feed back to prices with both deflators. For the rest of the countries in our sample the evidence on public wages causing prices is mixed and depends on the deflator. Again there is no feedback in the case of the Anglo-Saxon countries.

Overall, there are significant indirect influences from private wages on the price level which we find for all countries plus the euro area aggregate (Column 3). While this influence can also be found for public wages, the evidence is in many cases weaker and depends on the deflator. Price level changes are found to affect private and (in somewhat fewer cases) public wages. Second round effects therefore could play an important role on wage and prices dynamics in EU countries and the euro area (although a deeper analysis to confirm this finding is warranted).

6.3 Public wage leadership and wage setting institutions

Contrary to the robust results that we get for the co-movement of public and private sector wages, our causality results show a large degree of country heterogeneity. Thus, in this section we try to answer the following question: is there any relationship between empirical findings on public wage leadership and institutional features of labour and product markets, notably wage setting institutions, across countries?

We examine the role of institutional features in raising the probability of public sector wage leadership (i.e. granger-causality from public to private wages) with the help of a Probit analysis. In those instances where public sector wage leadership was statistically significant, i.e. public sector wages caused private sector wages, our dependent variable takes the value of 1 (183 observations), otherwise it is set as zero (249 observations). Observations are derived from the findings on wage leadership that includes 12 methods (11 detrending methods and VARs in levels) and 2 deflators for the 18 industrial countries in our sample (which yields up to 432 observations). Independent variables include a set of standard OECD-based variables of labour and product market institutions, a set of variables on wage bargaining institutions in Europe, the US and Japan generated from the information collected within the European System of Central Banks Wage Dynamics Network (WDN), [20] and a measure of globalisation (see Appendix F for details and sources). The fact that the OECD data base is not available for Greece and the WDN-based institutional data is not available for Canada and Norway reduces the maximum number of observations from 432 to 360.

As regards variables available from the OECD-based data set, we formulate some testable hypotheses on the expected impact of labour market institutions on public wage leadership: (i) stronger

[20] Based on a standardised questionnaire answered by national experts from central banks of each one of the 22 countries considered, for 2 years (1995 and 2006) (see Du Caju *et al*., 2008).

bargaining coordination between negotiating parties (being state-sponsored and state-imposed co-ordination one defining feature) and higher *union membership* may suggest a strong role for a wage negotiation benchmark and this may most easily be in the public sector due to the higher degree of unionisation; (ii) the impact of *bargaining centralisation* is less clear; on the one hand the same arguments as for bargaining coordination apply while, on the other hand, centralisation may be conducive to internalise more of the external effects of wage setting across all negotiating parties (hence, less public wage leadership); (iii) stricter *employment protection legislation* gives unions a stronger bargaining power in the private sector, independent of public sector outcomes and, hence, one might expect a weaker influence of public wages.

The variables on wage setting institutions collected via the WDN suggest the following hypotheses: (i) the degree of *government involvement in collective bargaining* is likely to be positively correlated with a public wage leadership role; (ii) a higher degree of *price indexation* is less likely to be positively correlated with public than with private sector wage leadership, as private wages, by comprising about 80% of countries' wage bill, are a key driver of inflation. This, in turn, determines the next round of wages increases (wage price spiral); (iii) a prevalence of *occupational and company-level wage setting* is likely to focus negotiations on the specific (private) occupation or firm situation and, hence, less likely to coincide with a strong lead role for the public sector; (iv) more *regional wage setting* (coupled with social safety nets and inter-regional redistribution more or less prevalent in all industrialised countries) may allow more of a public sector lead role as regions can externalise at least part of the costs (with, e.g., higher unemployment "automatically" leading to more transfers).

As to other control variables, we hypothesise that: (i) stronger exposure to global competition constraints (*index of globalisation*) limits the lead role of the public sector in wage setting; (ii) stronger exposure to competition pressures in the domestic product markets also limits the leadership of public wages as market constraints are more binding and firms have less scope to accommodate other influences (*product market regulation index*). Or, arguing the other way round, stronger product market regulation facilitates public sector leadership. A measure of the public sector size (public employment rate) which is likely to be positively correlated with a higher probability of public wage leadership is also included in the regression.

The findings as reported in Table 6 largely confirm these hypotheses. [21] Column 1 illustrates the positive correlation between public wage leadership on the one hand and co-ordinated wage bargaining, government involvement, union membership and product market regulation on the other.

A high globalisation index, wage indexation and employment protection show a negative sign of the respective coefficients. When including additional WDN variables (column 2), the expected negative

[21] The estimated coefficients shown in this table yield the marginal effect of a change in independent variables on the probability of public wage causation. The estimations include method dummies and deflator dummies in columns 1 and 2. However, they do not include country dummies, given that these would capture the cross country institutional variation which we want to be reflected in the explanatory variables.

correlation between occupational and company-level wage bargaining and public wages causing private wages becomes visible. Predominant wage bargaining at the regional level coincides with public wage leadership as expected though somewhat less robustly. With the inclusion of these variables, bargaining coordination (unsurprisingly) loses significance and so does globalisation as there is likely to be multicollinearity. The share of public employment turns to have a significant and positive coefficient as expected; also unsurprisingly, government involvement loses significance when the share of public employment is introduced in the regressions (column 3). Columns 4 and 5 illustrate that the findings are robust across the two deflators of wages (GDP deflator and private consumption deflator).

7. Conclusions

The paper provides, firstly, empirical evidence on the correlation of public and private wages over the business cycle. The study finds that in the euro area and most of the countries of our sample private wages are positively and strongly correlated with public wages over the business cycle mostly contemporaneously. Our findings appear quite robust both across countries and periods (1960-2006 and 1980-2006).

Secondly, the paper finds short- medium and long-run co-movements between public and private sector wages. For the short-run correlations, the results of the previous (robust) analysis are confirmed. For the co-movements at longer frequencies than the standard business cycle, our results show a strong correlation between public and private sector wages. Thirdly, (and unsurprisingly) the paper reports the existence of a long-run relationship between public and private sector wages in all the countries of the analysed sample. Wages in both sectors share a common driving trend that can be interpreted as a combination of long-run trends in prices and aggregate productivity.

Fourthly, the paper conducts a thorough analysis of causality. We run Granger-causality tests for different transformations of the nominal and deflated wage variables. First, we look at VARs between detrended variables (using eleven detrending methods), and thus focus on the Granger-causal links over the business cycle. We find a dominant pattern of private sector wage leadership over the business cycle for nominal wages and a few cases of bi-directional causality. When prices are explicitly taken into account, the dominant private sector lead vanishes, suggesting that the price level is an important adjustment parameter. Moreover, some leading behaviour from the public to the private sector arises. In a second exercise, we run VARs in levels (logs) of the variables which broadly confirm the findings of the first approach. A first look at the role of prices seem to indicate that there are significant feedback effects from private wages on the price level which we find for all countries plus the euro area aggregate. While this influence can also be found for public wages, the evidence is in many cases weaker and depends on the deflator.

Finally, we examine labour and product market institutional features in relation to the results found on public sector wage leadership. Factors that are conducive to public wage leadership include strong bargaining coordination with government involvement in collective bargaining, strong product market regulation, a high ratio of union membership in employment, and regional wage bargaining. Factors that appear to have a negative relationship with public wage leadership include decentralised bargaining at the company or occupational level, strong employment protection legislation, a high globalisation index (less robust), and a high coverage of wage setting by inflation indexation mechanisms.

From a policy perspective, we can conclude: public and private wages do not decouple. Private sector wages seem to exert mostly a stronger influence on public wages than the other way round. However, on the whole and in a number of countries results of correlation and causality analysis also suggest an important influence from the public sector on private wages both directly and indirectly via prices. This has important policy implications in that private but also public wage setting are important for overall wage and competitiveness developments. Moreover, second round effects seem to play an important role in wage and prices dynamics.

In the light of the obtained results, some follow-up work is warranted to further improve the understanding of the subject matter of this paper. First, the concept of Granger-causality captures the idea of the predictive power that past values of a given variable do have when forecasting another variable. Thus, given the annual frequency used for the data we cannot analyse empirically the intra-annual causal links, i.e. which sector leads within the current year. This might be a potentially relevant issue if indeed there were to be intra-year linkages between wages in the public and the private sector. These could operate irrespective of the fact that nominal wage contracts are typically fixed for a year, i.e. a 4-quarter period, or even for longer time periods by reflecting staggered sectoral wage negotiations or discretionary within-the-year wage increases (bonuses, promotions etc). Second, with EMU or perhaps already with the signing of the Maastricht Treaty public and private wage interaction may have adjusted in the euro area. Empirical analysis that wants to address these two caveats would have to overcome the data shortcoming that has induced us to conduct the analysis with annual data.

References

Abraham, K. and J.C. Haltiwanger (1995), “Real wages and the Business Cycle", Journal of Economic Literature 33, pp. 1215-1264.

Agénor, P.-R. (1995), “The labor market and economic adjustment”, IMF WP 95/125, Washington D.C.

Alesina, A., S. Ardagna, R. Perotti and F. Schiantarelli (2002), “Fiscal policy, profits and investment”, American Economic review 92, pp. 571-589.

Alesina, A., R. Baquir and W. Easterly (2000), “Redistributive public employment”, Journal of Urban Economics 48, pp. 219-241.

Alesina, A., S. Danninger and M. Rostagno (2001), “Redistribution through pubic employment: the case of Italy”, IMF Staff Papers 48, pp. 447-473.

Afonso, A. and P. Gomes (2008), “Some Determinants of Public and Private Sector Wages”, Mimeo: ECB.

Algan, Y., P. Cahuc and A. Zylberberg (2002), “Public employment: does it increase unemployment?”, Economic Policy, pp. 9-65.

Allard, G. (2005), “Measuring Job Security Over Time: In Search of a Historical Indicator”, Instituto de Empresa Working Paper WP-05. (http://www.ie.edu/eng/claustro/claustro_working_papers.asp).

Ardagna, S. (2007), “Fiscal policy in unionized labor markets”, Journal of Economic Dynamics and Control 31, pp. 1498-1534.

Bemmels, B. G. and M. A. Zaidi (1990), “Wage leadership in Canadian industry”, Applied Economics 22, pp. 553-567.

Demekas, D. G. and Z. G. Kontolemis (2000), “Government Employment and Wages and Labour Market Performance”, Oxford Bulletin of Economics and Statistics 62, pp. 391-415..

Calmfors, L. and H. Horn (1986), “Employment policies and centralized wage setting”, Economica 53, pp. 281-302.

Camacho, M., G. Pérez-Quirós and L. Saiz (2006), "Are European business cycles close enough to be just one?", Journal of Economic Dynamics and Control 30, pp. 1687-1706.

Christiano L.J. and T.J. Fitzgerald (2003), "The Band Pass Filter", International Economic Review 44, pp. 435-465.

Christou, C., A. Klemm and A. Tiffin (2007), “Wage Dynamics in the Romanian Economy”, IMF Article IV, Selected Issues, pp. 34-50.

Conway, P., V. Janod and G. Nicoletti (2005), “Product Market Regulation in OECD countries, 1998 to 2003”, OECD Economics Department Working Paper, No. 419.

David, F. (1949), "The moments of the z and F distributions", Biometrika 36, pp. 394-403.

den Haan, W. (2000), "The Co-movement Between Output And Prices", Journal of Monetary Economics 46, pp. 3-30.

Dolado, J.J. and H. Lütkeppohl (1996). “Making Wald test work for cointegrated VAR systems” Econometric Reviews 15: 369-386.

Dreher, A. (2008), “Measuring Globalisation – Gauging its Consequence”, New York: Springer.

Du Caju, P., E. Gautier, D. Momferatou, and M. Ward-Warmedinger (2008), “Institutional Features of Wage Bargaining in 22 EU countries, the US and Japan”, Frankfurt am Main: Mimeo.

Forni, L. and R. Giordano (2003), “Employment in the public sector”, CESIFO Working Paper n. 1085.

Friberg, K. (2007), “Intersectoral Wage linkages: the case of Sweden”, Empirical Economics 32, pp. 161-184.

Gelb, A., J. B. Knight and R. H. Sabot (1994), “Public sector employment, rent seeking and economic growth”, Economic Journal 101, pp. 1186-1199.

Granger, C. W. J. (1969), “Investigating casual relations by econometric models and cross-spectral methods”, Econometrica 37, pp. 424-438.

Granger, C. W. J. and Y. Jeon (2004), “Thick Modeling”, Economic Modelling 21, pp. 323-343.

Gregory, R. G. and J. Borland (1999), “Recent developments in public sector labor markets”, in O. Ashenfelter and D. Card (eds.), Handbook of Labor Economics vol. III, Elsevier, Netherlands.

Gylfason, T. and A. Lindbeck (1984), “Union rivalry and wages. An oligopolistic approach”, Eocnomica 51, pp. 129-139.

Harvey, A. (1989), Structural Time Series Models and the Kalman Filter, Cambridge University Press, Cambridge, UK.

Holmlund, B. (1993), “Wage setting in private and public sectors in a model with endogenous government behaviour”, European Journal of Political Economy 9, pp. 149-62.

Holmlund, B. and H. Ohlson (1992), “Wage linkages between private and public sectors in Sweden”, Labour 6, pp. 3-17.

Jacobson, T. and H. Ohlsson (1994), “Long run relations between private and public sector wages in Sweden”, Empirical Economics 19, pp. 343-360.

Johansen, S. (1995), “Likelihood-Based Inference in Cointegrated Vector Autoregressive Models”. Oxford: Oxford University Press.

Lamo, A., J. J. Pérez and L. Schuknecht (2007), “The cyclicality of consumption, wages and employment of the public sector in the euro area”, European Central Bank Working Paper 757.

Lindquist, M. J. and R. Vilhelmsson (2004), “Is the Swedish Central Government a Wage Leader?”, Working Paper 8/2004 Swedish Institute for Social Research, Stockholm University.

Matschke, X. (2003), “Are there election cycles in wage agreements? An analysis of German public employees”, Public Choice 114, pp. 103-135.

Mizala, A. and P. Romaguera (1995), “Testing for wage leadership processes in the Chilean economy”, Applied Economics 27, 303-310.

Nunziata, L. (2005), “Institutions and Wage Determination: a Multi-country Approach”, Oxford Bulletin of Economics and Statistics 67, 4, pp. 435-465.

Ochel , W. (2000), “Collective bargaining (centralisation/coordination)”, Munich: IFO Institute.

OECD (1997), "Measuring public employment in OECD countries: sources, methods and results", Paris.

Osterwald-Lenum, M. (1992), “A note with quantiles of the asymptotic distribution of the maximum likelihood cointegration rank test statistics”. Oxford Bulletin of Economics and Statistics 54, pp. 461-472.

Bulletin of Economics and Statistics 54: 461–472. Pedersen, P. J., J. B. Schmidt-Sorensen, N. Smith, and N. Westegard-Nielsen (1990), “Wage differentials between the public an private sectors”, Journal of Public Economics 41, pp. 125-145.

Quadrini, V. and A. Trigari (2007), “Public employment and the business cycle”, Scandinavian Journal of Economics 109, pp. 723-742.

Rodrick, D. (2000), “What drives public employment in developing countries?”, Review of Development Economics 4, pp. 229-243.

Rosenthal, R. (1991), Meta-analytic procedures for social research. Sage Publications Inc., Newbury Park, CA (USA).

Strom, B. (1997), “Envy, fairness and political influence in local government wage determination: evidence from Norway”, Economica 62, pp. 389-409.

Tagtstrom, S. (2000), “The wage spread between different sectors in Sweden”, Sveriges Riskbank Economic Review 4, pp. 77-82.

Toda, H. Y. and T. Yamamoto (1995), “Statistical inference in vector autoregressions with possibly integrated processes”, Journal of Econometrics 66, pp. 225-250.

Visser, J. (2006), “Union Membership Statistics in 24 Countries”, Monthly Labour Review, January, pp. 38-49.

Young, P. C., D. Pedregal, and W. Tych (1999), "Dynamic Harmonic Regression", Journal of Forecasting 18, pp. 369-394.

Table 1. The correlations of detrended public and private wages per employee. Combinations of Fisher transformations. Annual data 1960-2006 and 1980-2006.

		Correlation of private sector (t) and public sector (t+k) variable											
		Nominal compensation per employee						Deflated compensation per employee (private consumption and GDP deflators)					
		Relative standard deviation	***k (lags)***					**Relative standard deviation**	***k (lags)***				
			-2	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**
Euro area	1960-2007	*1.13*	0.54*	0.58*	0.71*	0.57*	0.39*	*1.09*	0.37*	0.60*	0.66*	0.19	-0.13
	1980-2007	*0.83*	0.07	0.69*	0.87*	0.40*	-0.14	*1.20*	-0.11	0.30*	0.64*	0.08	-0.31*
Germany	1960-2007	*1.19*	-0.11	0.46*	0.78*	0.47*	-0.17	*1.03*	-0.16	0.40*	0.77*	0.43*	-0.38*
	1980-2007	*1.08*	-0.23*	0.35*	0.86*	0.66*	-0.12	*1.26*	-0.50*	0.24*	0.86*	0.51*	-0.37*
France	1960-2007	*1.23*	0.34*	0.75*	0.89*	0.71*	0.35*	*1.32*	0.18	0.51*	0.63*	0.22*	0.20
	1980-2007	*0.96*	0.25*	0.63*	0.88*	0.63*	-0.05	*1.61*	-0.26*	-0.13	0.51*	-0.13	-0.48*
Italy	1960-2007	*1.13*	0.21*	0.37*	0.70*	0.70*	0.49*	*1.71*	-0.01	-0.01	0.22*	0.25*	0.22*
	1980-2007	*1.29*	0.17	0.65*	0.91*	0.57*	0.06	*2.52*	-0.02	0.19	0.70*	0.35*	0.01
Spain	1960-2007	*1.49*	0.52*	0.46*	0.33*	0.45*	0.65*	*2.08*	0.19	0.42*	0.43*	-0.10	0.09
	1980-2007	*1.34*	0.46*	0.69*	0.71*	0.53*	0.37*	*2.05*	0.36*	0.39*	0.26*	0.18	0.28*
Netherlands	1960-2007	*0.81*	0.38*	0.18	0.60*	0.70*	0.22*	*1.05*	-0.18	-0.15	0.37*	0.22*	-0.23*
	1980-2007	*1.05*	0.22*	0.16	0.36*	0.39*	-0.05	*1.27*	0.02	-0.13	0.23*	0.22*	-0.22*
Austria	1960-2007	*0.86*	0.12	0.47*	0.57*	0.52*	0.30*	*0.94*	0.14	0.15	0.37*	0.14	-0.10
	1980-2007	*1.68*	0.23*	0.24*	0.55*	0.73*	0.48*	*1.63*	-0.10	-0.02	0.22*	0.60*	0.29*
Belgium	1960-2007	*1.12*	0.26*	0.40*	0.23*	0.09	0.05	*1.29*	-0.14	0.10	0.17	-0.31*	-0.31*
	1980-2007	*1.26*	-0.26*	-0.21*	0.12	0.30*	-0.05	*1.63*	-0.23*	0.13	0.37*	0.07	-0.13
Greece	1960-2007	*1.11*	-0.05	0.30*	0.75*	0.62*	0.25*	*0.91*	-0.03	0.38*	0.69*	0.42*	0.12
	1980-2007	*1.22*	-0.31*	0.43*	0.81*	0.31*	-0.12	*1.26*	-0.09	0.39*	0.82*	0.56*	0.15
Ireland	1960-2007	*1.08*	0.50*	0.61*	0.80*	0.65*	0.26*	*1.60*	-0.07	-0.14	0.27*	0.11	-0.27*
	1980-2007	*0.97*	0.37*	0.43*	0.58*	0.43*	0.25*	*1.92*	0.23*	-0.14	0.18	0.41*	0.08
Portugal	1960-2007	*1.42*	0.10	0.20*	0.45*	0.53*	0.43*	*1.52*	0.01	0.15	0.35*	0.16	0.11
	1980-2007	*1.53*	0.19	0.38*	0.44*	0.28*	-0.02	*1.98*	0.10	0.34*	0.51*	0.32*	-0.03
Finland	1960-2007	*1.04*	-0.15	0.53*	0.82*	0.63*	0.25*	*1.09*	-0.20*	0.05	0.49*	0.26*	0.02
	1980-2007	*1.08*	0.15	0.33*	0.67*	0.73*	0.58*	*1.51*	0.16	0.25*	0.53*	0.49*	0.46*
Sweden	1960-2007	*1.15*	0.26*	0.42*	0.37*	0.56*	0.64*	*0.95*	-0.03	0.26*	0.48*	0.23*	0.19
	1980-2007	*1.10*	0.00	0.35*	0.65*	0.70*	0.52*	*1.13*	-0.03	0.32*	0.49*	0.14	0.31*
Denmark	1960-2007	*0.84*	0.17	0.43*	0.57*	0.68*	0.37*	*1.42*	-0.40*	-0.02	-0.20	-0.19	-0.11
	1980-2007	*1.08*	0.17	0.59*	0.79*	0.46*	-0.21*	*1.39*	-0.51*	-0.24*	0.37*	0.17	-0.13
Norway	1960-2007	*1.08*	-0.21*	0.56*	0.90*	0.50*	-0.16	*1.03*	-0.08	0.37*	0.85*	0.23*	-0.24*
	1980-2007	*0.99*	0.20	0.69*	0.81*	0.41*	-0.01	*1.00*	0.06	0.31*	0.80*	0.20	-0.15
United States	1960-2007	*1.04*	-0.32*	0.29*	0.73*	0.49*	0.14	*1.11*	-0.04	0.35*	0.47*	0.07	-0.16
	1980-2007	*1.35*	-0.18	0.20*	0.69*	0.44*	-0.11	*1.06*	-0.36*	0.18	0.43*	0.11	-0.12
United Kingdom	1960-2007	*1.15*	-0.10	0.23*	0.79*	0.67*	0.06	*1.40*	-0.08	-0.23*	0.20	0.48*	0.24*
	1980-2007	*1.48*	0.30*	0.47*	0.68*	0.64*	0.50*	*1.25*	0.04	-0.20*	-0.34*	0.32*	0.57*
Canada	1960-2007	*0.94*	0.26*	0.59*	0.77*	0.69*	0.40*	*1.06*	-0.24*	-0.08	0.24*	0.33*	0.10
	1980-2007	*1.06*	0.00	0.30*	0.65*	0.49*	0.27*	*1.10*	-0.31*	-0.35*	0.06	0.26*	0.22*
Japan	1960-2007	*1.38*	-0.08	0.38*	0.88*	0.76*	0.04	*1.34*	0.39*	0.60*	0.78*	0.74*	0.56*
	1980-2007	*1.19*	0.26*	0.52*	0.74*	0.71*	0.40*	*1.74*	0.00	0.24*	0.48*	0.58*	0.22*

Note: an asterisk indicates significance at the 5% level.

Table 2. Cointegration tests: Johansen approach. Annual data 1960-2006.

		Nominal compensation per employee				Deflated compensation per employee (deflated = nominal / price level)							
						Private consumption deflator				**GDP deflator**			
	Max Rank	**Max Statistic**	Critical Values	**Trace Statistic**	Critical Values	**Max Statistic**	Critical Values	**Trace Statistic**	Critical Values	**Max Statistic**	Critical Values	**Trace Statistic**	Critical Values
Euro area	**0**	28.0*	19.0	33.3*	25.3	13.1	19.0	21.0	25.3	20.5*	19.0	32.7*	25.3
	1	5.2	12.5	5.2	12.3	7.9	12.5	7.9	12.3	12.1	12.5	12.1	12.3
Germany	**0**	20.6*	19.0	25.0	25.3	13.9	14.1	16.2*	15.4	18.1*	15.7	23.9*	20.0
	1	4.4	12.5	4.4	12.3	2.3	3.8	2.3	3.8	5.9	9.2	5.9	9.4
France	**0**	15.5	15.7	20.4*	20.0	24.0*	14.1	29.0*	15.4	46.7*	15.7	51.5*	20.0
	1	4.9	9.2	4.9	9.4	4.9*	3.8	4.9*	3.8	4.8	9.2	4.8	9.4
Italy	**0**	24.7*	19.0	29.7*	25.3	27.1*	15.7	29.5*	20.0	21.0*	19.0	32.6*	25.3
	1	5.0	12.5	5.0	12.3	2.4	9.2	2.4	9.4	11.6	12.5	11.6	12.3
Spain	**0**	17.3*	15.7	22.8*	20.0	21.8*	16.9	25.4*	18.2	23.0*	11.4	23.4*	12.5
	1	5.5	9.2	5.5	9.4	3.6	3.7	3.6	3.7	0.3	3.8	0.3	3.8
Netherlands	**0**	19.3*	15.7	21.2*	20.0	20.3*	15.7	27.0*	20.0	12.6	14.1	16.1*	15.4
	1	1.9	9.2	1.9	9.4	6.7	9.2	6.7	9.4	3.5	3.8	3.5	3.8
Austria	**0**	18.9*	15.7	27.3*	20.0	22.7*	15.7	29.3*	20.0	22.2*	15.7	28.1*	20.0
	1	8.3	9.2	8.3	9.4	6.6	9.2	6.6	9.4	5.9	9.2	5.9	9.4
Belgium	**0**	20.8*	14.1	23.6*	15.4	22.8*	19.0	36.6*	25.3	20.9*	14.1	24.2*	15.4
	1	2.8	3.8	2.8	3.8	13.8*	12.5	13.8*	12.3	3.3	3.8	3.3	3.8
Greece	**0**	16.6	19.0	26.9*	25.3	19.5*	15.7	21.9*	20.0	19.3*	15.7	21.1*	20.0
	1	10.3	12.5	10.3	12.3	2.4	9.2	2.4	9.4	1.7	9.2	1.7	9.4
Ireland	**0**	25.2*	19.0	36.3*	25.3	34.0*	15.7	40.7*	20.0	25.8*	15.7	33.4*	20.0
	1	11.1	12.5	11.1	12.3	6.7	9.2	6.7	9.4	7.6	9.2	7.6	9.4
Portugal	**0**	16.6*	15.7	23.4*	20.0	23.3*	15.7	28.2*	20.0	26.2*	15.7	28.5*	20.0
	1	6.7	9.2	6.7	9.4	4.9	9.2	4.9	9.4	2.3	9.2	2.3	9.4
Finland	**0**	23.4*	15.7	28.3*	20.0	19.5*	15.7	22.9*	20.0	21.1*	15.7	24.2*	20.0
	1	4.9	9.2	4.9	9.4	3.4	9.2	3.4	9.4	3.1	9.2	3.1	9.4
Sweden	**0**	23.9*	16.9	24.8*	18.2	12.2*	11.4	14.3*	12.5	30.9*	15.7	35.9*	20.0
	1	0.9	3.7	0.9	3.7	2.2	3.8	2.2	3.8	5.0	9.2	5.0	9.4
Denmark	**0**	25.9*	15.7	29.7*	20.0	19.6*	15.7	19.4*	18.2	32.0*	15.7	41.2*	20.0
	1	3.8	9.2	3.8	9.4	7.7	9.2	4.0*	3.7	9.2	9.2	9.2	9.4
Norway	**0**	12.4	15.7	17.1	20.0	21.9*	19.0	27.8*	25.3	17.0*	15.7	23.7*	20.0
	1	4.7	9.2	4.7	9.4	5.8	12.5	5.8	12.3	6.7	9.2	6.7	9.4
United States	**0**	13.9	15.7	22.1*	20.0	12.9	15.7	20.4*	20.0	19.5*	15.7	28.1*	20.0
	1	8.3	9.2	8.3	9.4	7.5	9.2	7.5	9.4	8.6	9.2	8.6	9.4
United Kingdom	**0**	10.6	15.7	19.2	20.0	26.3*	15.7	33.6*	20.0	23.3*	15.7	27.7*	20.0
	1	8.5	9.2	8.5	9.4	7.3	9.2	7.3	9.4	4.4	9.2	4.4	9.4
Canada	**0**	13.6	15.7	21.7*	20.0	25.8*	19.0	29.7*	25.3	17.5*	15.7	25.3*	20.0
	1	8.1	9.2	8.1	9.4	3.9	12.5	3.9	12.3	7.8	9.2	7.8	9.4
Japan	**0**	21.9*	19.0	30.7*	25.3	17.9	19.0	28.4*	25.3	15.6	19.0	26.4*	25.3
	1	8.8	12.5	8.8	12.3	10.5	12.5	10.5	12.3	10.8	12.5	10.8	12.3

Note: an asterisk indicates significance at the 5% level. Osterwald-Lenum critical values for both the Maximum-eigenvalue and Trace test statistics.

Table 3. Granger Causality tests I: detrended variables. Annual data 1960-2006.

	Nominal comp. per employee		Nominal comp. per employee (model including price level)			
			Private consumption deflator		GDP deflator	
	Public → Private	**Public ← Private**	**Public → Private**	**Public ← Private**	**Public → Private**	**Public ← Private**
Euro area	-	←	-	-	-	-
First difference	0	1	0	0	0	0
Other filters	2	6	2	4	4	3
Germany	-	←	→	←	-	←
First difference	0	1	0	1	0	1
Other filters	4	9	7	8	5	8
France	-	←	→	-	→	-
First difference	0	1	0	1	0	1
Other filters	3	10	6	4	10	4
Italy	-	←	-	-	-	-
First difference	0	1	0	1	0	0
Other filters	2	6	5	2	5	0
Spain	-	←	-	-	-	-
First difference	0	1	0	0	0	0
Other filters	0	5	3	3	1	3
Netherlands	-	←	-	←	-	←
First difference	0	0	0	0	0	0
Other filters	2	6	4	10	2	6
Austria	-	-	-	-	-	-
First difference	0	1	0	0	0	0
Other filters	2	4	3	2	3	3
Belgium	→	-	→	-	-	-
First difference	0	0	0	0	0	1
Other filters	6	3	6	2	5	2
Greece	-	←	-	-	-	-
First difference	0	1	0	1	0	0
Other filters	1	6	3	3	2	2
Ireland	-	-	→	-	→	←
First difference	0	1	1	0	0	1
Other filters	3	4	10	3	6	7
Portugal	-	←	-	-	-	-
First difference	0	1	0	0	0	1
Other filters	3	7	3	3	2	4
Finland	→	←	→	←	→	-
First difference	1	1	1	1	1	0
Other filters	8	8	9	7	6	5
Sweden	→	←	-	←	-	←
First difference	0	1	0	1	0	1
Other filters	7	7	4	8	2	6
Denmark	→	←	-	←	-	←
First difference	1	1	0	0	0	0
Other filters	8	8	3	10	3	6
Norway	-	-	-	-	-	-
First difference	0	1	0	0	0	0
Other filters	4	1	5	0	3	1
United States	-	←	-	-	-	←
First difference	0	1	0	0	0	0
Other filters	2	7	3	5	3	6
United Kingdom	-	←	-	-	-	-
First difference	0	1	0	0	0	0
Other filters	3	5	5	5	3	3
Canada	-	←	-	-	→	←
First difference	0	1	0	1	1	1
Other filters	4	8	4	3	6	9
Japan	→	-	→	-	→	←
First difference	0	1	0	1	0	1
Other filters	9	3	9	3	8	10

Table 4. Granger Causality tests II: VARs in levels. Annual data 1960-2006.

	Nominal compensation per employee		Nominal compensation per employee (model with price level)			
			Private consump. deflator		GDP deflator	
	Public → Private	**Public ← Private**	**Public → Private**	**Public ← Private**	**Public → Private**	**Public ← Private**
Euro area	-	←	-	←	-	←
Germany	-	←	-	-	-	←
France	-	←	→	←	→	←
Italy	→	←	-	←	→	-
Spain	-	←	-	-	-	-
Netherlands	→	-	→	←	→	←
Austria	-	←	-	-	-	-
Belgium	-	←	-	-	-	-
Greece	→	←	-	←	-	←
Ireland	-	-	→	-	→	←
Portugal	→	←	-	←	-	←
Finland	→	←	→	←	→	-
Sweden	→	←	-	←	-	←
Denmark	→	←	→	←	-	←
Norway	-	-	-	-	-	-
United States	-	←	-	←	-	←
United Kingdom	-	←	-	←	-	←
Canada	-	←	-	←	→	-
Japan	-	←	→	←	-	←

Table 5. Granger Causality tests II Con't (Wages and Prices): VARs in levels. Annual data 1960-2006.

	Nominal compensation per employee (model with price level)							
	Private consump. deflator				GDP deflator			
	Prices → Public wages	**Prices → Private wages**	**Public wages → Prices**	**Private wages → Prices**	**Prices → Public wages**	**Prices → Private wages**	**Public wages → Prices**	**Private wages → Prices**
Euro area	→	→	→	→	→	→	-	→
Germany	→	→	-	→	→	→	-	→
France	→	→	-	→	→	→	→	→
Italy	→	→	-	→	→	→	→	→
Spain	→	→	→	→	→	→	→	→
Netherlands	→	→	→	-	→	→	→	→
Austria	-	→	-	→	→	→	-	→
Belgium	-	-	-	→	-	-	→	→
Greece	-	→	-	→	→	-	-	→
Ireland	→	→	→	→	→	→	-	-
Portugal	-	→	→	-	-	→	-	→
Finland	→	→	→	→	-	→	→	→
Sweden	-	→	→	→	-	→	→	→
Denmark	→	→	→	→	→	→	→	→
Norway	→	→	→	-	→	→	-	-
United States	→	→	-	-	→	→	→	→
United Kingdom	→	→	-	-	→	→	-	→
Canada	→	→	→	-	→	→	-	-
Japan	→	→	→	→	→	→	→	→

Table 6. Institutional determinants of public wage leadership.

The dependent variable takes a value of 1 if public wages cause private wages. Method of estimation: Probit.

	Specification (1)	Specification (2)	Specification (3)	Specification (4) GDP deflator	Specification (5) Private cons. Def.
OECD labour market indicators					
1) Index of bargaining coordination	0.231	-0.083	0.167	-0.255	0.125
	[2.73]**	[0.66]	[1.07]	[1.37]	[0.71]
2) Index of bargaining centralisation	-0.022				
	[0.26]				
3) Employment protection legislation	-0.318	-0.838	-1.24	-0.929	-0.873
	[3.16]**	[4.97]**	[5.25]**	[3.61]**	[3.77]**
4) Union membership/employment	0.003	0.022	0.011	0.026	0.02
	[1.33]	[3.60]**	[1.59]	[2.72]**	[2.52]*
Product market regulation index					
5) Product market regulation index	0.434	1.119	1.857	1.309	1.112
	[1.76]	[3.84]**	[4.39]**	[3.22]**	[2.58]**
Other control variables					
6) KOF index of globalisation	-0.011	-0.002	-0.005	0	-0.006
	[2.85]**	[0.49]	[1.05]	[0.05]	[0.82]
7) Public employment ratio			5.645		
			[2.47]*		
WDN variables					
8) Government involvement in collective bargaining	0.415	0.676	0.103	0.801	0.643
	[2.67]**	[4.31]**	[0.28]	[4.03]**	[3.38]**
9) High coverage by indexation mechanisms (76-100%)	-0.214	-0.626	-0.552	-0.623	-0.695
	[1.51]	[4.96]**	[2.85]**	[4.15]**	[3.65]**
10) Dominant level of collective bargaining: sectoral		0.374	0.505	0.533	0.112
		[1.70]	[2.40]*	[1.81]	[0.35]
11) Dominant level of collective bargaining: occupational		-0.442	-0.45	-0.423	-0.473
		[3.25]**	[3.48]**	[2.38]*	[2.30]*
12) Dominant level of collective bargaining: national		0.365	0.473	0.475	0.266
		[1.43]	[1.97]*	[1.32]	[0.68]
13) Dominant level of collective bargaining: regional		0.341	0.325	0.378	0.335
		[2.38]*	[2.22]*	[1.75]	[1.72]
14) Dominant level of collective bargaining: company-level		-0.469	-0.521	-0.376	-0.629
		[4.69]**	[5.25]**	[2.84]**	[4.57]**
Number of observations (maximum possible 432)	*360*	*360*	*360*	*180*	*180*

Notes: Robust z statistics in brackets: * significant at 5%; ** significant at 1%. The estimated coefficients shown in this table yield the marginal effect of a change in independent variables on the probability of public wage causation. The estimations include method dummies and deflator dummies in columns 1 and 2.

Figure 1. The evolution of relative wages per employee in the OECD: ratio of wages per employee in the public sector over wages per employee in the private sector.

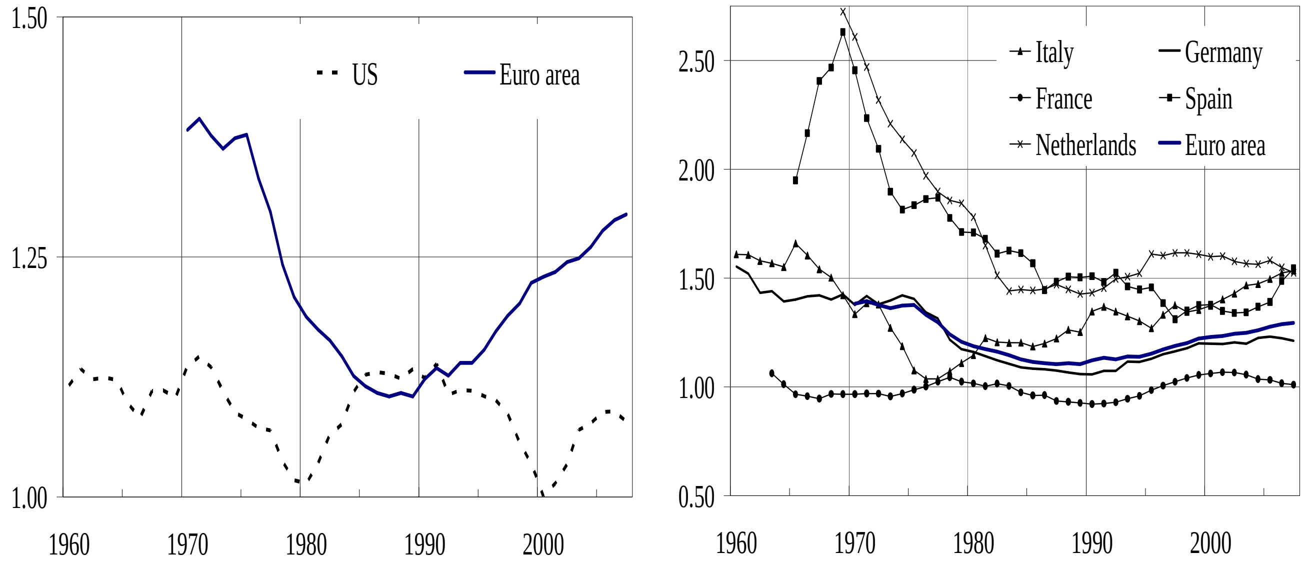
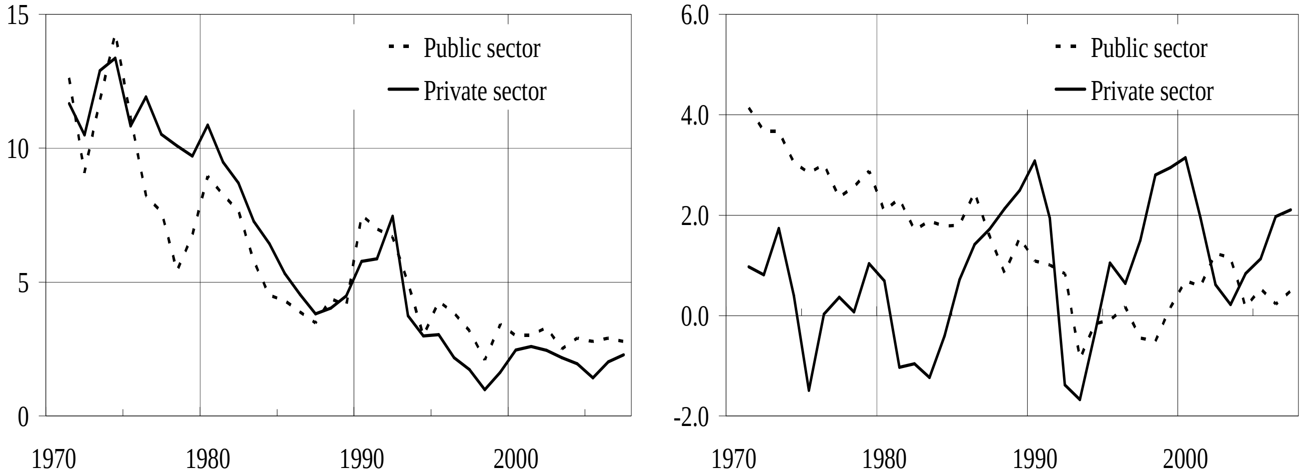


Figure 2. The growth rate of nominal wages per employee (left panels) and employment (right panels)

Nominal wages per employee | **Employment**

Euro area



United States

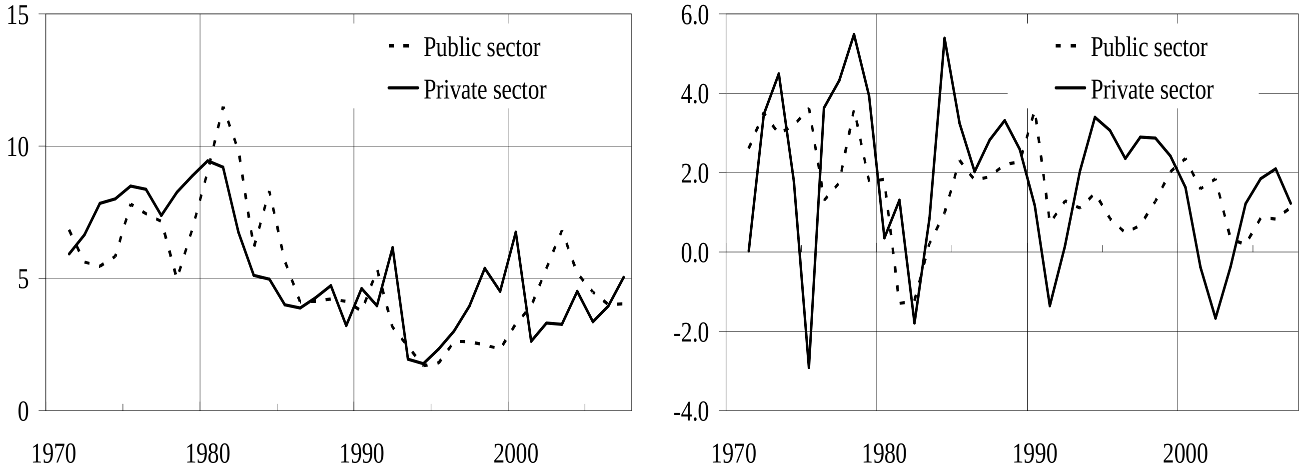
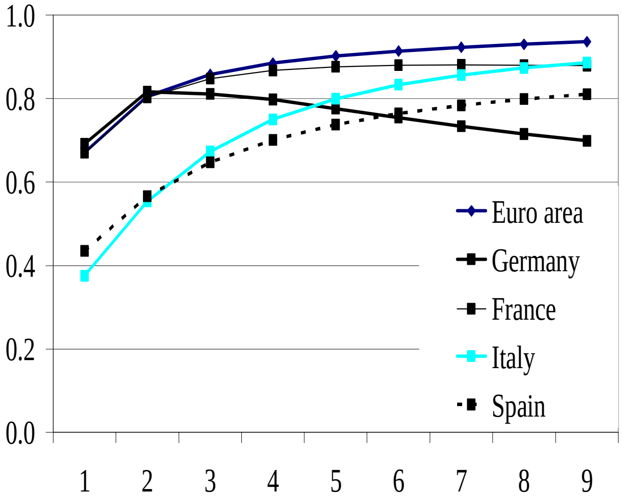


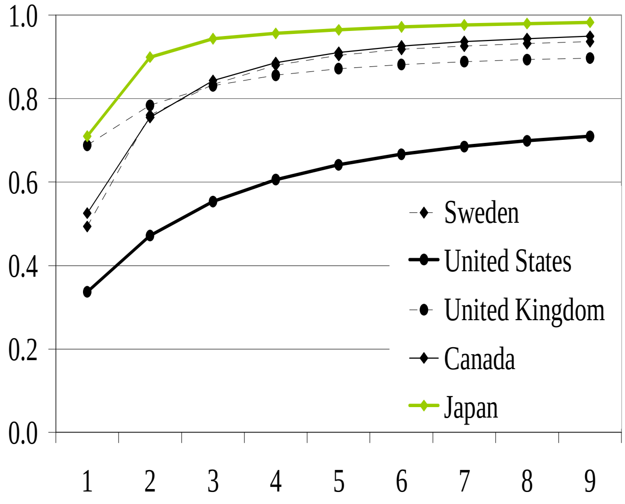
Figure 3. Correlations of forecast errors from VARs between public and private wages per employee. h-step ahead forecast errors, h=1, 2, …, 9.

VAR specification with unit root imposed. Sample 1960-2006.

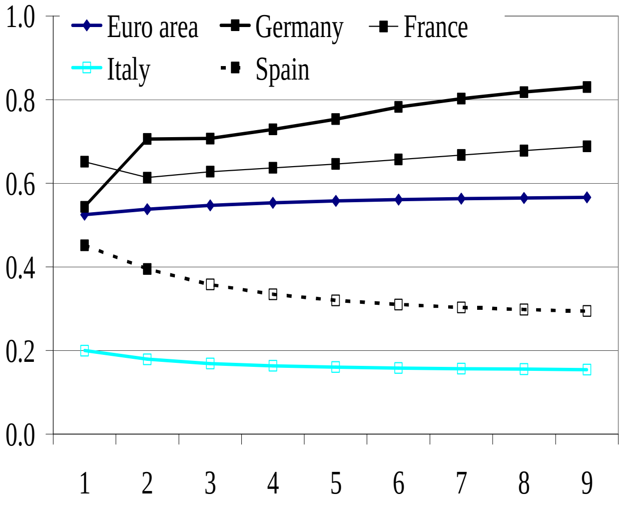
Euro area
Nominal compensation per employee



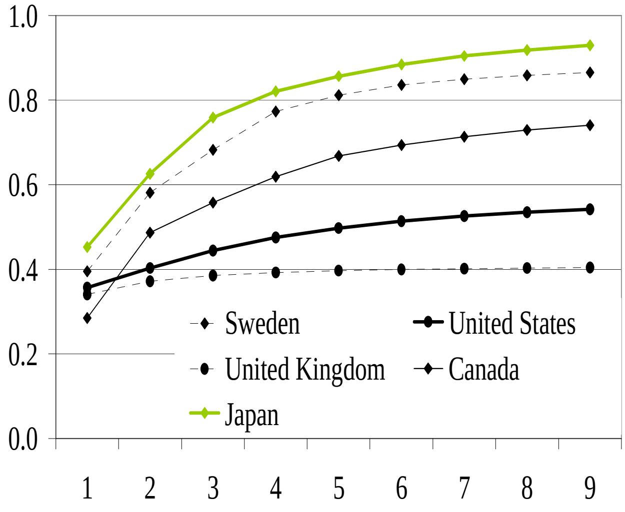
Non euro area
Nominal compensation per employee



Euro area
Real compensation per employee
(private consumption deflator)



Non euro area
Real compensation per employee
(private consumption deflator)



Note: These panels plot the correlation coefficients of the h-period ahead forecast errors of the indicated variables. Significance levels are based on Monte-Carlo confidence intervals. Markers filled-in with colour denote significance at the 5% level, while markers filled-in white denote correlations not significantly different from zero at the 5% level.

Appendix A. Description of the detrending methods used in Section 3

The following methods are used in Section 3 to estimate detrended variables:

First difference filter: First order differencing takes the cycle to be the variable in first differences. In other words, it assumes that the trend is the lagged variable, or similarly the series is a random walk with no drift. Therefore y_t can be represented as: $y_t = y_{t-1} + C_t + \varepsilon_t$, where the trend is $T_t = y_{t-1}$ and an estimate of the detrended component is obtained as $y_t - y_{t-1}$.

Deterministic trends: T_t is taken to be a deterministic process which can be approximated with polynomial functions of time such that $T_t = f(t)$, $f(t) = a_0 + a_1 t + a_2 t^2 ... + a_h t^h$. h is the order of the polynomial. Even though the disturbance may be serially correlated, it can be shown that the unknown parameters in $f(t)$ can be estimated efficiently by ordinary least squares. In this paper we take h=2.

Hodrick-Prescott: The Hodrick and Prescott filter (HP Filter) extracts a stochastic trend that moves smoothly over time and is not correlated with the cycle. The HP filter crucially depends on a smoothing parameter (λ) that penalizes large fluctuations. A large λ implies a higher penalty and, therefore, a smoother cycle. For annual data the value of λ typically used has been 100, although recent studies suggest that lower values leave cycles of more reasonable duration. In particular, it has been shown that λ values of 6.25 deliver cycles of similar length to the cycles resulting with quarterly data when using λ of 1600, which is the standard value. We calculate two versions of the HP filter, one with λ equal 100 and another one with λ equal 6.25.

Band pass filter: We use an optimal finite sample approximation for the band pass filter as proposed by Christiano and Fitzgerald (2003). The band pass filter is a frequency domain based filter. It assumes that the trend component has the power at lower frequencies of the spectrum. The choice in this procedure is to define the limits of the frequency band, say p_l and p_u, to isolate the cyclical component with a period of oscillation between p_l and p_u. We make two choices for the cycle length between 2 and 8 years, $\{p_l , p_u\}=\{2,8\}$, and between 2 and 6 years, $\{p_l , p_u\}=\{2,6\}$, removing thus all the fluctuations that have a periodicity larger than 8(6) or smaller the 2 years.

Unobserved components models: We consider structural time series models in the vein of the basic structural model in Harvey (1989). The trend is specified as $T_t = T_{t-1} + S_t + \varepsilon_t^T$, $S_t = S_{t-1} + \varepsilon_t^S$, where ε_t^T and ε_t^S are mutually uncorrelated white noise disturbances with zero means and variances $\sigma_T^{\ 2}$ and $\sigma_S^{\ 2}$ respectively. This model is known as the local linear trend model. The cyclical component C_t is assumed to be a stochastic cycle, a mixture of sine-cosine waves in a given period shocked with disturbances.

The estimated models for the empirical exercise are the following. First, we take the basic structural model and adjust the smoothness of the trend, looking at three cases: (i) linear trend model ($\sigma_T^{\ 2}$=0 and

$\sigma_S{}^2$=0) plus cycle; (ii) local level model ($\sigma_T{}^2$=0) plus cycle; and (iii) local linear trend model plus cycle. Next, we preserve assumptions (ii) and (iii) for the trend, and adjust the model for the cycle allowing for cycles of period 2 to 6 years to be estimated (not just imposed as in the basic case) using the so-called DHR (Dynamic Harmonic Regression) methods as in Young, Pedregal and Tych (1999). Thus, all in all, 5 different unobserved components models are fitted to the data.

Appendix B.
Detailed country tables: the co-movement between public and private wages and employment, 1960-2006

Table B1. Euro area: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee Private consumption deflator**						**Deflated compensation per employee GDP deflator**					
	Relative standard deviation	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**
First difference	*0.80*	0.86*	0.88*	0.92*	0.87*	0.77*	*0.74*	0.72*	0.70*	0.74*	0.57*	0.43*	*0.72*	0.76*	0.71*	0.73*	0.61*	0.45*
HP Filter λ=100	*1.24*	0.48*	0.70*	0.79*	0.58*	0.17	*1.18*	0.72*	0.73*	0.65*	0.34*	-0.01	*1.20*	0.74*	0.70*	0.57*	0.31*	-0.02
HP Filter λ =6.25	*1.44*	0.12	0.46*	0.77*	0.46*	-0.16	*0.87*	0.21*	0.31*	0.46*	-0.05	-0.44*	*1.19*	0.22*	0.14	0.33*	0.01	-0.42*
Band Pass Fillter (2,8)	*1.56*	-0.34*	-0.19	0.62*	0.22*	0.06	*0.84*	-0.15	0.18	0.56*	-0.10	-0.38*	*1.11*	-0.16	-0.21*	0.21*	0.00	-0.15
Band Pass Filter (2,6)	*1.54*	-0.08	-0.16	0.70*	-0.23*	-0.54*	*1.20*	-0.09	0.20	0.63*	-0.29*	-0.61*	*1.14*	-0.03	-0.06	0.39*	-0.14	-0.52*
Quadratic polynomial	*0.95*	0.71*	0.78*	0.76*	0.61*	0.33*	*1.21*	0.79*	0.77*	0.66*	0.44*	0.15	*1.11*	0.85*	0.80*	0.67*	0.48*	0.20
UC local level plus cycle	*0.65*	0.90*	0.96*	0.98*	0.96*	0.87*	*0.44*	0.75*	0.80*	0.81*	0.71*	0.52*	*0.44*	0.80*	0.84*	0.84*	0.75*	0.58*
UC local level drift & cycle	*1.13*	0.57*	-0.07	-0.52*	0.10	0.52*	*1.80*	-0.58*	0.15	0.56*	-0.08	-0.57*	*0.38*	-0.77*	0.65*	0.77*	-0.63*	-0.77*
UC smooth trend plus cycle	*1.09*	0.57*	-0.06	-0.52*	0.09	0.52*	*2.61*	-0.71*	0.69*	0.71*	-0.71*	-0.71*	*0.38*	-0.78*	0.64*	0.78*	-0.62*	-0.77*
DHR local level drift&cycle	*0.54*	0.87*	0.93*	0.94*	0.90*	0.78*	*0.82*	0.82*	0.86*	0.85*	0.71*	0.47*	*1.06*	0.88*	0.93*	0.91*	0.81*	0.62*
DHR smooth trend & cycle	*1.36*	0.08	0.34*	0.51*	0.36*	0.18	*0.93*	0.58*	0.61*	0.56*	0.18	-0.19	*1.63*	0.59*	0.56*	0.37*	0.20	-0.08
Combination of Fisher transformations																		
Average		**0.54***	**0.58***	**0.71***	**0.57***	**0.39***		**0.36***	**0.60***	**0.67***	**0.18**	**-0.15**		**0.37***	**0.61***	**0.65***	**0.20***	**-0.11**
Median	***1.13***	**0.57***	**0.46***	**0.76***	**0.46***	**0.33***	***0.93***	**0.58***	**0.69***	**0.65***	**0.18**	**-0.19**	***1.11***	**0.59***	**0.65***	**0.67***	**0.20**	**-0.08**

Table B2. Germany: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee**						**Deflated compensation per employee**					
							Private consumption deflator						**GDP deflator**					
	Relative standard deviation	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**
First difference	*0.98*	0.53*	0.67*	0.81*	0.74*	0.48*	*1.02*	0.35*	0.59*	0.71*	0.62*	0.29*	*1.11*	0.32*	0.45*	0.54*	0.54*	0.21*
HP Filter λ=100	*1.31*	0.42*	0.68*	0.83*	0.71*	0.37*	*1.34*	0.36*	0.63*	0.74*	0.57*	0.19	*1.65*	0.34*	0.44*	0.51*	0.43*	0.12
HP Filter λ =6.25	*1.19*	-0.33*	0.20	0.71*	0.54*	-0.11	*0.91*	-0.31*	0.29*	0.67*	0.39*	-0.35*	*1.16*	-0.38*	-0.03	0.34*	0.30*	-0.38*
Band Pass Fillter (2,8)	*1.14*	-0.56*	0.01	0.63*	0.32*	-0.45*	*0.89*	-0.45*	0.26*	0.72*	0.43*	-0.32*	*1.03*	-0.45*	-0.03	0.38*	0.28*	-0.40*
Band Pass Filter (2,6)	*1.28*	-0.55*	0.07	0.71*	0.22*	-0.78*	*1.18*	-0.56*	0.18	0.66*	0.18	-0.76*	*1.24*	-0.46*	0.02	0.45*	0.21*	-0.75*
Quadratic polynomial	*1.57*	0.74*	0.78*	0.74*	0.57*	0.31*	*2.01*	0.84*	0.91*	0.92*	0.83*	0.68*	*2.24*	0.90*	0.90*	0.85*	0.75*	0.59*
UC local level plus cycle	*0.76*	0.89*	0.93*	0.94*	0.90*	0.83*	*0.82*	0.74*	0.78*	0.79*	0.73*	0.63*	*0.80*	0.69*	0.69*	0.68*	0.61*	0.50*
UC local level drift & cycle	*1.18*	-0.92*	0.35*	0.91*	-0.40*	-0.91*	*0.90*	-0.93*	-0.09	0.95*	0.08	-0.96*	*0.97*	-0.88*	-0.15	0.92*	0.07	-0.95*
UC smooth trend plus cycle	-	-0.78*	0.04	0.76*	-0.09	-0.72*	*0.94*	-0.94*	-0.09	0.96*	0.08	-0.96*	*0.98*	-0.89*	-0.15	0.92*	0.07	-0.95*
DHR local level drift&cycle	*1.95*	-0.31*	0.17	0.62*	0.43*	-0.18	-	-	-	-	-	-	-	-	-	-	-	-
DHR smooth trend & cycle	*0.92*	-0.12	0.30*	0.66*	0.48*	-0.04	*1.14*	-0.06	0.42*	0.66*	0.37*	-0.10	-	-	-	-	-	-
Combination of Fisher transformations																		
Average		**-0.11**	**0.46***	**0.78***	**0.47***	**-0.17**		**-0.20**	**0.46***	**0.82***	**0.47***	**-0.35***		**-0.13**	**0.32***	**0.69***	**0.39***	**-0.41***
Median	***1.19***	**-0.31***	**0.30***	**0.74***	**0.48***	**-0.11**	***0.98***	**-0.19**	**0.36***	**0.73***	**0.41***	**-0.21***	***1.11***	**-0.38***	**0.02**	**0.54***	**0.30***	**-0.38***

Table B3. France: the co-movement between public and private wages and employment

Correlation of private sector (t) and public sector (t+k) variable

	Nominal compensation per employee						**Deflated compensation per employee – Private consumption deflator**						**Deflated compensation per employee – GDP deflator**					
	Relative standard deviation	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**
First difference	*1.04*	0.81*	0.88*	0.93*	0.87*	0.78*	*1.21*	0.45*	0.42*	0.63*	0.35*	0.43*	*1.20*	0.43*	0.41*	0.58*	0.51*	0.46*
HP Filter λ=100	*1.35*	0.51*	0.76*	0.84*	0.68*	0.35*	*2.10*	0.12	0.29*	0.37*	0.23*	0.27*	*2.16*	-0.04	0.14	0.27*	0.29*	0.22*
HP Filter λ =6.25	*1.23*	-0.31*	0.36*	0.79*	0.47*	-0.11	*1.59*	-0.02	0.10	0.48*	-0.23*	-0.23*	*1.51*	-0.15	0.03	0.42*	0.21*	-0.12
Band Pass Fillter (2,8)	*1.38*	-0.39*	0.39*	0.84*	0.45*	-0.24*	*1.46*	0.00	0.17	0.48*	-0.31*	-0.34*	*1.52*	-0.21*	0.06	0.45*	0.18	-0.17
Band Pass Filter (2,6)	*0.99*	-0.40*	0.13	0.69*	0.07	-0.46*	*1.19*	-0.20	-0.13	0.61*	-0.29*	-0.21*	*1.02*	-0.03	-0.16	0.44*	-0.02	-0.35*
Quadratic polynomial	*1.04*	0.85*	0.94*	0.94*	0.82*	0.60*	*1.54*	0.75*	0.79*	0.80*	0.78*	0.73*	*1.70*	0.68*	0.72*	0.72*	0.71*	0.64*
UC local level plus cycle	*0.95*	0.95*	0.98*	0.99*	0.98*	0.94*	*0.98*	0.84*	0.88*	0.89*	0.86*	0.82*	*0.95*	0.83*	0.87*	0.89*	0.87*	0.83*
UC local level drift & cycle	-	-	-	-	-	-	*1.06*	-0.81*	0.56*	0.76*	-0.62*	-0.70*	*0.70*	-0.28*	0.58*	0.31*	-0.63*	-0.24*
UC smooth trend plus cycle	-	-	-	-	-	-	*1.11*	-0.82*	0.59*	0.79*	-0.62*	-0.75*	*0.40*	-0.29*	0.88*	0.26*	-0.89*	-0.26*
DHR local level drift&cycle	*1.49*	0.49*	0.76*	0.85*	0.70*	0.34*	*0.89*	0.82*	0.85*	0.84*	0.81*	0.76*	*1.81*	0.80*	0.86*	0.89*	0.89*	0.87*
DHR smooth trend & cycle	*1.25*	-0.14	0.42*	0.74*	0.44*	-0.08	*1.42*	0.06	0.17	0.41*	0.06	0.07	*1.42*	-0.04	0.11	0.32*	0.29*	0.27*
Combination of Fisher transformations																		
Average		**0.34***	**0.75***	**0.89***	**0.71***	**0.35***		**0.14**	**0.50***	**0.68***	**0.16**	**0.11**		**0.22***	**0.51***	**0.56***	**0.27***	**0.28***
Median	***1.23***	**-0.04**	**0.76***	**0.84***	**0.68***	**0.34***	***1.21***	**0.06**	**0.42***	**0.63***	**0.06**	**0.07**	***1.42***	**-0.04**	**0.41***	**0.44***	**0.29***	**0.22***

Table B4. Italy: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						Deflated compensation per employee Private consumption deflator						Deflated compensation per employee GDP deflator					
	Relative standard deviation	k (lags) -2	-1	0	1	2	Relative standard deviation	k (lags) -2	-1	0	1	2	Relative standard deviation	k (lags) -2	-1	0	1	2
First difference	0.97	0.62*	0.69*	0.82*	0.82*	0.75*	1.19	0.25*	0.28*	0.46*	0.42*	0.40*	1.11	0.27*	0.21*	0.31*	0.28*	0.34*
HP Filter λ=100	1.29	0.24*	0.47*	0.67*	0.69*	0.56*	2.47	-0.33*	-0.08	0.27*	0.37*	0.25*	2.40	-0.31*	-0.35*	-0.20	-0.07	0.06
HP Filter λ =6.25	1.37	-0.11	0.02	0.41*	0.28*	-0.12	2.36	-0.40*	-0.17	0.37*	0.50*	0.41*	2.37	-0.27*	-0.36*	-0.05	0.12	0.35*
Band Pass Fillter (2,8)	1.13	-0.37*	-0.20	0.39*	0.39*	-0.02	1.76	-0.45*	-0.36*	0.20	0.41*	0.44*	1.71	-0.23*	-0.41*	-0.12	0.11	0.45*
Band Pass Filter (2,6)	1.23	-0.37*	-0.25*	0.47*	0.27*	-0.30*	2.04	0.02	-0.14	0.21*	-0.08	0.00	1.71	0.01	-0.08	0.11	-0.10	0.05
Quadratic polynomial	1.11	0.75*	0.87*	0.95*	0.97*	0.94*	1.21	0.04	0.07	0.13	0.05	-0.09	1.00	0.09	0.04	0.02	-0.07	-0.16
UC local level plus cycle	0.81	0.86*	0.92*	0.96*	0.97*	0.96*	0.51	0.75*	0.79*	0.81*	0.77*	0.68*	0.45	0.74*	0.76*	0.77*	0.72*	0.63*
UC local level drift & cycle	-	-	-	-	-	-	0.97	-0.01	-0.21*	-0.03	0.26*	0.07	1.90	-0.24*	-0.15	0.17	0.19	-0.13
UC smooth trend plus cycle	-	-	-	-	-	-	0.91	-0.02	-0.20	-0.02	0.26*	0.05	1.72	-0.20	-0.16	0.13	0.20	-0.08
DHR local level drift&cycle	1.22	-0.24*	-0.16	0.37*	0.32*	-0.09	1.08	-0.06	0.02	0.14	0.08	-0.06	-	-	-	-	-	-
DHR smooth trend & cycle	0.70	-0.20	-0.15	0.29*	0.33*	0.03	2.11	-0.18	-0.04	0.30*	0.31*	0.34*	2.04	-0.08	-0.13	0.07	0.10	0.31*
Combination of Fisher transformations																		
Average		0.21*	0.37*	0.70*	0.70*	0.49*		-0.02	0.02	0.29*	0.33*	0.24*		0.00	-0.05	0.15	0.17	0.20
Median	1.13	-0.11	0.02	0.47*	0.39*	0.03	1.21	-0.02	-0.08	0.21*	0.31*	0.25*	1.71	-0.14	-0.14	0.09	0.12	0.19

Table B5. Spain: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee Private consumption deflator**						**Deflated compensation per employee GDP deflator**					
	Relative standard deviation	***k (lags)*** -2	-1	0	1	2	**Relative standard deviation**	***k (lags)*** -2	-1	0	1	2	**Relative standard deviation**	***k (lags)*** -2	-1	0	1	2
First difference	*1.10*	0.65*	0.69*	0.76*	0.75*	0.77*	*1.81*	0.40*	0.38*	0.52*	0.23*	0.24*	*1.80*	0.39*	0.31*	0.42*	0.19	0.20
HP Filter λ=100	*1.49*	0.17	0.40*	0.59*	0.72*	0.66*	*2.83*	0.20	0.16	0.26*	0.05	0.00	*2.81*	0.19	0.02	0.04	-0.10	-0.06
HP Filter λ =6.25	*2.19*	0.07	0.23*	0.46*	0.28*	0.19	*2.74*	-0.08	-0.13	0.18	-0.19	0.00	*2.95*	-0.09	-0.22*	0.05	-0.19	0.04
Band Pass Fillter (2,8)	*2.03*	-0.10	-0.13	0.18	-0.09	0.00	*2.37*	-0.28*	-0.28*	0.27*	-0.14	0.05	*2.87*	-0.27*	-0.38*	0.18	-0.11	0.15
Band Pass Filter (2,6)	*1.99*	-0.14	0.04	0.46*	-0.15	-0.16	*2.21*	-0.33*	-0.11	0.59*	-0.23*	-0.16	*2.50*	-0.25*	-0.13	0.52*	-0.20	-0.12
Quadratic polynomial	*0.98*	0.47*	0.69*	0.79*	0.85*	0.78*	*1.82*	0.61*	0.63*	0.65*	0.52*	0.35*	*1.92*	0.55*	0.47*	0.44*	0.34*	0.23*
UC local level plus cycle	*0.85*	0.93*	0.97*	0.98*	0.97*	0.92*	*0.81*	0.76*	0.75*	0.72*	0.58*	0.33*	*0.75*	0.77*	0.75*	0.72*	0.61*	0.40*
UC local level drift & cycle	*1.68*	0.92*	0.39*	-0.92*	-0.38*	0.92*	*2.55*	-0.31*	0.23*	0.31*	-0.32*	-0.22*	*1.98*	-0.26*	0.97*	0.26*	-0.97*	-0.26*
UC smooth trend plus cycle	*1.59*	0.94*	0.34*	-0.94*	-0.33*	0.94*	-	-	-	-	-	-	*1.88*	-0.16	0.99*	0.16	-0.99*	-0.15
DHR local level drift&cycle	*0.59*	0.25*	0.36*	0.42*	0.49*	0.47*	*1.46*	0.76*	0.78*	0.78*	0.67*	0.44*	*2.08*	0.65*	0.64*	0.65*	0.55*	0.38*
DHR smooth trend & cycle	*1.08*	-0.21*	-0.02	0.42*	0.32*	0.15	*1.89*	-0.15	0.05	0.53*	0.07	-0.12	*2.17*	-0.05	-0.18	0.04	-0.12	0.02
Combination of Fisher transformations																		
Average		**0.52***	**0.46***	**0.33***	**0.45***	**0.65***		**0.21***	**0.30***	**0.51***	**0.15**	**0.10**		**0.17**	**0.52***	**0.34***	**-0.32***	**0.08**
Median	***1.49***	**0.25***	**0.36***	**0.46***	**0.32***	**0.66***	***2.05***	**0.06**	**0.20**	**0.53***	**0.06**	**0.03**	***2.08***	**-0.05**	**0.31***	**0.26***	**-0.11**	**0.04**

Table B6. Netherlands: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee**						**Deflated compensation per employee**					
							Private consumption deflator						**GDP deflator**					
	Relative standard deviation	***k (lags)*** -2	-1	0	1	2	**Relative standard deviation**	***k (lags)*** -2	-1	0	1	2	**Relative standard deviation**	***k (lags)*** -2	-1	0	1	2
First difference	*0.70*	0.70*	0.76*	0.80*	0.75*	0.63*	*0.87*	0.16	0.15	0.38*	0.28*	0.10	*0.91*	0.02	0.05	0.23*	0.16	-0.01
HP Filter λ=100	*0.96*	0.38*	0.62*	0.77*	0.74*	0.54*	*1.07*	0.07	0.24*	0.55*	0.56*	0.46*	*1.09*	0.03	0.21*	0.48*	0.51*	0.42*
HP Filter λ =6.25	*0.70*	-0.19	0.16	0.52*	0.56*	0.31*	*0.88*	-0.52*	-0.46*	0.23*	0.39*	0.16	*0.90*	-0.41*	-0.31*	0.18	0.32*	0.10
Band Pass Fillter (2,8)	*0.77*	0.06	-0.07	0.03	-0.18	-0.18	*1.01*	-0.52*	-0.49*	0.31*	0.32*	0.01	*1.11*	-0.34*	-0.32*	0.19	0.18	-0.12
Band Pass Filter (2,6)	*0.87*	0.03	0.04	0.24*	-0.15	-0.34*	*0.95*	-0.45*	-0.35*	0.46*	0.24*	-0.29*	*1.04*	-0.37*	-0.24*	0.37*	0.21*	-0.31*
Quadratic polynomial	*0.81*	0.86*	0.90*	0.88*	0.78*	0.60*	*0.92*	0.62*	0.61*	0.58*	0.40*	0.18	*1.02*	0.49*	0.46*	0.41*	0.25*	0.04
UC local level plus cycle	*0.55*	0.81*	0.81*	0.77*	0.62*	0.39*	*1.11*	0.22*	0.04	-0.09	-0.25*	-0.39*	*1.19*	-0.05	-0.19	-0.30*	-0.42*	-0.52*
UC local level drift & cycle	*1.92*	-0.25*	-0.97*	0.26*	0.97*	-0.26*	*2.19*	-0.23*	-0.78*	0.91*	-0.03	-0.89*	*2.62*	-0.76*	-0.48*	0.71*	0.52*	-0.65*
UC smooth trend plus cycle	*1.94*	-0.28*	-0.96*	0.28*	0.97*	-0.28*	*1.24*	-0.71*	-0.70*	0.72*	0.70*	-0.73*	*2.56*	-0.77*	-0.48*	0.73*	0.53*	-0.66*
DHR local level drift&cycle	*0.56*	0.82*	0.82*	0.77*	0.62*	0.38*	*1.06*	0.25*	0.08	-0.05	-0.22*	-0.36*	*1.17*	-0.01	-0.16	-0.26*	-0.39*	-0.50*
DHR smooth trend & cycle	*1.08*	0.22*	0.42*	0.64*	0.54*	0.39*	*0.05*	0.17	0.25*	-0.02	-0.13	-0.21*	*1.05*	-0.07	0.02	0.34*	0.29*	0.15
Combination of Fisher transformations																		
Average		**0.38***	**0.18**	**0.60***	**0.70***	**0.22***		**-0.10**	**-0.16**	**0.43***	**0.23***	**-0.24***		**-0.24***	**-0.14**	**0.31***	**0.21***	**-0.22***
Median	***0.81***	**0.22***	**0.42***	**0.64***	**0.62***	**0.38***	***1.01***	**0.07**	**0.04**	**0.38***	**0.28***	**-0.21***	***1.09***	**-0.07**	**-0.19**	**0.34***	**0.25***	**-0.12**

Table B7. Austria: the co-movement between public and private wages and employment

Correlation of private sector (t) and public sector (t+k) variable

	Nominal compensation per employee						Deflated compensation per employee Private consumption deflator						Deflated compensation per employee GDP deflator					
	Relative standard deviation	k (lags) -2	-1	0	1	2	Relative standard deviation	k (lags) -2	-1	0	1	2	Relative standard deviation	k (lags) -2	-1	0	1	2
First difference	*0.86*	0.67*	0.71*	0.76*	0.73*	0.64*	*0.92*	0.39*	0.33*	0.44*	0.22*	0.09	*0.92*	0.40*	0.34*	0.36*	0.19	0.12
HP Filter λ=100	*0.69*	0.11	0.37*	0.54*	0.52*	0.38*	*0.68*	0.27*	0.32*	0.33*	0.06	-0.19	*0.80*	0.22*	0.24*	0.20	-0.05	-0.25*
HP Filter λ =6.25	*1.13*	-0.06	0.22*	0.46*	0.35*	0.00	*1.15*	-0.03	0.09	0.41*	0.13	-0.14	*1.20*	0.00	0.11	0.29*	0.17	0.05
Band Pass Fillter (2,8)	*1.00*	-0.24*	-0.01	0.33*	0.31*	-0.01	*1.13*	-0.21*	-0.02	0.40*	0.19	-0.08	*1.12*	-0.29*	-0.20	0.17	0.25*	0.27*
Band Pass Filter (2,6)	*1.33*	0.04	-0.05	0.09	-0.03	-0.19	*1.47*	-0.17	-0.23*	0.29*	0.02	-0.07	*1.33*	0.00	-0.13	0.03	-0.11	0.12
Quadratic polynomial	*0.49*	0.51*	0.73*	0.86*	0.84*	0.73*	*0.64*	0.35*	0.20	0.02	-0.20	-0.40*	*0.61*	0.27*	0.10	-0.08	-0.31*	-0.47*
UC local level plus cycle	*0.86*	0.94*	0.97*	0.97*	0.95*	0.92*	*0.78*	0.89*	0.88*	0.83*	0.77*	0.68*	*0.73*	0.88*	0.86*	0.81*	0.74*	0.66*
UC local level drift & cycle	*1.66*	-0.68*	0.74*	-0.50*	0.05	0.42*	*1.25*	0.36*	-0.48*	0.45*	-0.31*	0.06	*1.21*	-0.34*	0.44*	-0.27*	-0.08	0.42*
UC smooth trend plus cycle	*1.00*	-0.65*	-0.20	0.65*	0.21*	-0.65*	*0.50*	-0.53*	-0.73*	0.62*	0.65*	-0.70*	*1.32*	-0.89*	-0.36*	0.91*	0.33*	-0.92*
DHR local level drift&cycle	*0.80*	0.00	0.30*	0.50*	0.42*	0.20	*0.27*	0.04	0.08	0.16	0.00	-0.13	*1.97*	0.49*	0.25*	0.00	-0.11	-0.20
DHR smooth trend & cycle	*0.71*	-0.06	0.16	0.37*	0.33*	0.10	*0.91*	0.22*	0.30*	0.37*	0.08	-0.20	*0.96*	0.22*	0.25*	0.23*	-0.02	-0.23*
Combination of Fisher transformations																		
Average		**0.12**	**0.47***	**0.57***	**0.52***	**0.30***		**0.19**	**0.09**	**0.42***	**0.18**	**-0.10**		**0.09**	**0.21***	**0.32***	**0.11**	**-0.09**
Median	***0.86***	**0.00**	**0.30***	**0.50***	**0.35***	**0.20**	***0.91***	**0.22***	**0.09**	**0.40***	**0.08**	**-0.13**	***1.12***	**0.22***	**0.24***	**0.20**	**-0.02**	**0.05**

Table B8. Belgium: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee – Private consumption deflator**						**Deflated compensation per employee – GDP deflator**					
	Relative standard deviation	***k (lags)***					**Relative standard deviation**	***k (lags)***					**Relative standard deviation**	***k (lags)***				
		-2	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**
First difference	*1.00*	0.51*	0.52*	0.48*	0.33*	0.14	*1.62*	0.12	0.15	0.15	-0.07	-0.16	*1.49*	-0.01	0.01	0.03	-0.21*	-0.32*
HP Filter λ=100	*2.58*	0.60*	0.70*	0.58*	0.28*	-0.12	*3.03*	0.42*	0.49*	0.48*	0.26*	0.04	*2.95*	0.21*	0.20	0.17	-0.07	-0.25*
HP Filter λ =6.25	*1.46*	0.14	0.57*	0.63*	0.24*	-0.22*	*1.19*	-0.20	0.11	0.28*	-0.03	0.05	*1.19*	-0.28*	0.09	0.31*	-0.05	-0.08
Band Pass Fillter (2,8)	*1.17*	-0.11	0.27*	0.40*	0.03	-0.31*	*0.97*	-0.39*	0.17	0.52*	0.12	0.01	*0.97*	-0.39*	0.15	0.50*	0.01	-0.15
Band Pass Filter (2,6)	*1.07*	-0.19	0.21*	0.38*	-0.02	-0.34*	*1.09*	-0.16	0.26*	0.34*	-0.32*	-0.09	*1.00*	-0.28*	0.25*	0.48*	-0.18	-0.29*
Quadratic polynomial	*1.81*	0.57*	0.52*	0.39*	0.15	-0.15	-	-	-	-	-	-	*3.09*	0.42*	0.28*	0.12	-0.15	-0.42*
UC local level plus cycle	*0.50*	0.29*	0.28*	0.24*	0.01	-0.29*	*1.64*	-0.41*	-0.49*	-0.54*	-0.66*	-0.76*	*1.44*	-0.50*	-0.58*	-0.64*	-0.76*	-0.84*
UC local level drift & cycle	*0.80*	-0.78*	0.52*	-0.09	-0.40*	0.74*	*1.17*	0.01	-0.02	0.01	-0.02	0.00	*0.42*	0.60*	-0.59*	0.49*	-0.27*	0.03
UC smooth trend plus cycle	*2.58*	0.87*	-0.12	-0.84*	0.22*	0.83*	*1.57*	-0.57*	0.71*	0.40*	-0.78*	-0.25*	*1.29*	-0.55*	0.86*	0.38*	-0.93*	-0.20
DHR local level drift&cycle	*0.62*	0.32*	0.32*	0.28*	0.05	-0.26*	*1.61*	-0.34*	-0.40*	-0.45*	-0.60*	-0.71*	*1.96*	-0.37*	-0.47*	-0.55*	-0.69*	-0.80*
DHR smooth trend & cycle	-	-	-	-	-	-	*1.18*	-0.02	0.37*	0.57*	0.22*	-0.11	*1.23*	-0.13	0.23*	0.46*	0.08	-0.24*
Combination of Fisher transformations																		
Average		**0.26***	**0.40***	**0.23***	**0.09**	**0.05**		**-0.16**	**0.15**	**0.19**	**-0.23***	**-0.24***		**-0.12**	**0.06**	**0.16**	**-0.38***	**-0.37***
Median	***1.12***	**0.31***	**0.43***	**0.39***	**0.10**	**-0.19**	***1.38***	**-0.18**	**0.16**	**0.31***	**-0.05**	**-0.10**	***1.29***	**-0.28***	**0.15**	**0.31***	**-0.18**	**-0.25***

Table B9. Greece: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee**						**Deflated compensation per employee**					
							Private consumption deflator						**GDP deflator**					
	Relative standard deviation	***k (lags)***					**Relative standard deviation**	***k (lags)***					**Relative standard deviation**	***k (lags)***				
		-2	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**
First difference	*1.10*	0.50*	0.62*	0.75*	0.69*	0.68*	*0.91*	0.06	0.32*	0.64*	0.31*	0.24*	*0.91*	0.15	0.36*	0.55*	0.28*	0.30*
HP Filter λ=100	*1.22*	0.12	0.42*	0.65*	0.56*	0.38*	*0.99*	-0.09	0.35*	0.70*	0.49*	0.21*	*0.98*	-0.01	0.38*	0.63*	0.47*	0.28*
HP Filter λ =6.25	*1.25*	-0.13	0.13	0.40*	0.22*	0.06	*0.92*	-0.32*	0.14	0.58*	0.22*	-0.07	*0.92*	-0.20	0.18	0.45*	0.14	0.02
Band Pass Fillter (2,8)	*1.28*	-0.20	0.11	0.41*	0.24*	0.04	*0.88*	-0.35*	0.13	0.56*	0.18	-0.17	*0.87*	-0.22*	0.12	0.36*	0.01	-0.10
Band Pass Filter (2,6)	*1.62*	-0.14	-0.07	0.18	-0.13	0.03	*1.12*	-0.47*	-0.06	0.49*	0.03	-0.08	*1.21*	-0.30*	0.00	0.29*	-0.17	0.00
Quadratic polynomial	*1.11*	0.88*	0.96*	0.99*	0.97*	0.90*	*0.87*	0.77*	0.88*	0.95*	0.92*	0.85*	*0.86*	0.79*	0.89*	0.95*	0.93*	0.86*
UC local level plus cycle	*0.90*	0.71*	0.82*	0.90*	0.95*	0.97*	*0.60*	0.84*	0.87*	0.87*	0.81*	0.72*	*0.59*	0.84*	0.85*	0.83*	0.77*	0.68*
UC local level drift & cycle	*1.03*	-0.85*	-0.53*	0.85*	0.51*	-0.86*	*0.48*	-0.76*	0.11	0.75*	-0.04	-0.75*	-	-	-	-	-	-
UC smooth trend plus cycle	*0.97*	-0.85*	-0.53*	0.86*	0.51*	-0.86*	*0.37*	-0.95*	-0.24*	0.95*	0.26*	-0.95*	*1.34*	-0.33*	0.01	0.35*	0.06	-0.36*
DHR local level drift&cycle	-	-	-	-	-	-	-	-	-	-	-	-	*2.75*	0.37*	0.50*	0.58*	0.56*	0.51*
DHR smooth trend & cycle	*1.08*	-0.43*	-0.19	0.32*	0.38*	0.18	*1.17*	-0.33*	0.08	0.50*	0.31*	0.03	*1.26*	-0.18	0.12	0.37*	0.22*	0.13
Combination of Fisher transformations																		
Average		**-0.05**	**0.30***	**0.75***	**0.62***	**0.25***		**-0.21***	**0.34***	**0.76***	**0.43***	**-0.05**		**0.15**	**0.42***	**0.60***	**0.41***	**0.29***
Median	***1.11***	**-0.14**	**0.12**	**0.70***	**0.51***	**0.12**	***0.89***	**-0.33***	**0.14**	**0.67***	**0.29***	**-0.02**	***0.95***	**-0.10**	**0.27***	**0.50***	**0.25***	**0.21***

Table B10. Ireland: the co-movement between public and private wages and employment

Correlation of private sector (t) and public sector (t+k) variable

	Nominal compensation per employee						Deflated compensation per employee Private consumption deflator						Deflated compensation per employee GDP deflator					
	Relative standard deviation	k (lags) -2	-1	0	1	2	Relative standard deviation	k (lags) -2	-1	0	1	2	Relative standard deviation	k (lags) -2	-1	0	1	2
First difference	*0.91*	0.71*	0.72*	0.80*	0.71*	0.61*	*1.61*	0.06	-0.31*	0.34*	0.09	-0.07	*1.46*	-0.07	0.00	0.35*	0.23*	-0.31*
HP Filter λ=100	*1.25*	0.39*	0.56*	0.64*	0.44*	0.17	*1.85*	0.17	0.03	0.41*	0.26*	-0.02	*1.91*	0.15	0.33*	0.56*	0.36*	-0.14
HP Filter λ =6.25	*1.68*	0.15	0.30*	0.48*	0.07	-0.36*	*1.83*	-0.11	-0.41*	0.29*	0.21*	-0.05	*1.83*	-0.21*	0.03	0.47*	0.28*	-0.38*
Band Pass Fillter (2,8)	*1.71*	0.10	0.19	0.40*	0.04	-0.37*	*1.68*	-0.14	-0.39*	0.34*	0.27*	-0.03	*1.80*	-0.29*	0.00	0.49*	0.31*	-0.39*
Band Pass Filter (2,6)	*1.67*	-0.06	-0.15	0.30*	0.05	-0.30*	*1.59*	-0.15	-0.67*	0.27*	0.30*	0.07	*1.58*	-0.41*	-0.16	0.47*	0.38*	-0.35*
Quadratic polynomial	*0.82*	0.82*	0.92*	0.95*	0.89*	0.78*	*1.20*	0.33*	0.29*	0.42*	0.21*	-0.09	*1.23*	0.26*	0.37*	0.47*	0.29*	-0.07
UC local level plus cycle	*0.72*	0.92*	0.97*	0.99*	0.96*	0.90*	*1.17*	-0.15	-0.33*	-0.35*	-0.51*	-0.67*	*0.80*	-0.16	-0.21*	-0.25*	-0.37*	-0.55*
UC local level drift & cycle	*0.47*	-0.63*	-0.77*	0.57*	0.81*	-0.51*	*1.76*	-0.13	-0.49*	0.32*	0.27*	-0.05	-	-	-	-	-	-
UC smooth trend plus cycle	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DHR local level drift&cycle	*0.64*	0.93*	0.97*	0.98*	0.94*	0.86*	*1.13*	-0.17	-0.33*	-0.34*	-0.49*	-0.65*	*0.81*	-0.16	-0.21*	-0.23*	-0.36*	-0.54*
DHR smooth trend & cycle	*1.58*	0.37*	0.44*	0.39*	-0.06	-0.35*	-	-	-	-	-	-	*1.98*	-0.02	0.21*	0.50*	0.27*	-0.28*
Combination of Fisher transformations																		
Average		**0.50***	**0.61***	**0.80***	**0.65***	**0.26***		**-0.03**	**-0.31***	**0.20**	**0.06**	**-0.20***		**-0.10**	**0.04**	**0.33***	**0.16**	**-0.34***
Median	***1.08***	**0.38***	**0.50***	**0.61***	**0.59***	**-0.07**	***1.61***	**-0.13**	**-0.33***	**0.32***	**0.21***	**-0.05**	***1.58***	**-0.16**	**0.00**	**0.47***	**0.28***	**-0.35***

Table B11. Portugal: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee Private consumption deflator**						**Deflated compensation per employee GDP deflator**					
	Relative standard deviation	***k (lags)***					**Relative standard deviation**	***k (lags)***					**Relative standard deviation**	***k (lags)***				
		-2	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**
First difference	*1.13*	0.40*	0.44*	0.56*	0.60*	0.64*	*1.54*	0.04	0.23*	0.36*	0.17	0.13	*1.43*	0.10	0.08	0.29*	0.16	0.09
HP Filter λ=100	*1.44*	0.20	0.26*	0.36*	0.46*	0.44*	*1.52*	0.10	0.34*	0.46*	0.45*	0.39*	*1.52*	0.19	0.28*	0.38*	0.38*	0.31*
HP Filter λ =6.25	*1.48*	-0.02	-0.09	0.08	0.16	0.06	*2.36*	-0.14	0.22*	0.40*	0.08	-0.16	*1.82*	0.02	0.00	0.22*	0.10	-0.07
Band Pass Fillter (2,8)	*1.59*	-0.17	-0.17	0.13	0.26*	0.14	*2.24*	-0.24*	0.25*	0.51*	0.13	-0.26*	*1.84*	-0.18	-0.10	0.31*	0.24*	-0.03
Band Pass Filter (2,6)	*1.40*	-0.12	-0.18	0.11	0.18	0.05	*1.99*	-0.23*	0.08	0.33*	0.02	-0.12	*1.62*	-0.22*	-0.26*	0.25*	0.24*	0.02
Quadratic polynomial	*1.14*	0.79*	0.89*	0.94*	0.96*	0.93*	*0.90*	0.63*	0.71*	0.73*	0.71*	0.63*	*0.91*	0.56*	0.62*	0.64*	0.63*	0.56*
UC local level plus cycle	*0.76*	0.56*	0.69*	0.80*	0.87*	0.91*	*0.60*	0.12	0.14	0.14	0.07	-0.01	*0.51*	0.05	0.07	0.08	0.00	-0.08
UC local level drift & cycle	-	0.14	0.05	-0.21*	0.23*	-0.12	*2.85*	-0.32*	-0.16	0.60*	-0.78*	0.64*	-	-	-	-	-	-
UC smooth trend plus cycle	*1.15*	-0.28*	-0.10	0.27*	0.04	-0.32*	*1.12*	0.00	0.06	-0.04	-0.06	0.01	*0.99*	-0.24*	-0.07	0.21*	0.01	-0.26*
DHR local level drift&cycle	*1.63*	-0.02	-0.11	0.03	0.16	0.09	-	-	-	-	-	-	*0.87*	0.02	0.03	0.15	0.13	0.06
DHR smooth trend & cycle	*1.62*	-0.59*	-0.27*	0.38*	0.58*	0.13	-	-	-	-	-	-	*1.98*	-0.22*	-0.04	0.39*	0.29*	-0.11
Combination of Fisher transformations																		
Average		**0.10**	**0.20***	**0.45***	**0.53***	**0.43***		**0.01**	**0.23***	**0.41***	**0.08**	**0.16**		**0.01**	**0.07**	**0.30***	**0.23***	**0.06**
Median	***1.42***	**-0.02**	**-0.10**	**0.32***	**0.36***	**0.14**	***1.54***	**0.00**	**0.22***	**0.40***	**0.08**	**0.01**	***1.48***	**0.02**	**0.02**	**0.27***	**0.20***	**-0.01**

Table B12. Finland: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee Private consumption deflator**						**Deflated compensation per employee GDP deflator**					
	Relative standard deviation	***k (lags)*** -2	-1	0	1	2	**Relative standard deviation**	***k (lags)*** -2	-1	0	1	2	**Relative standard deviation**	***k (lags)*** -2	-1	0	1	2
First difference	*0.87*	0.44*	0.67*	0.88*	0.85*	0.69*	*0.90*	0.03	0.15	0.55*	0.33*	0.20	*1.17*	-0.20	-0.04	0.53*	0.10	0.06
HP Filter λ=100	*0.93*	-0.16	0.35*	0.76*	0.79*	0.51*	*0.84*	0.07	0.25*	0.50*	0.43*	0.22*	*1.12*	-0.27*	0.02	0.41*	0.32*	0.18
HP Filter λ =6.25	*1.15*	-0.47*	0.19	0.79*	0.71*	0.19	*0.90*	-0.52*	-0.16	0.51*	0.40*	0.11	*1.23*	-0.50*	-0.09	0.59*	0.22*	-0.05
Band Pass Fillter (2,8)	*1.15*	-0.63*	0.08	0.76*	0.62*	-0.03	*1.07*	-0.64*	-0.29*	0.51*	0.38*	0.04	*1.32*	-0.41*	-0.02	0.62*	0.07	-0.31*
Band Pass Filter (2,6)	*1.04*	-0.61*	0.06	0.75*	0.27*	-0.57*	*1.02*	-0.56*	-0.18	0.67*	0.22*	-0.30*	*1.20*	-0.52*	-0.05	0.77*	0.10	-0.35*
Quadratic polynomial	*0.85*	0.53*	0.75*	0.90*	0.92*	0.85*	*1.15*	0.34*	0.36*	0.38*	0.26*	0.06	*1.36*	0.01	0.09	0.20	0.09	-0.05
UC local level plus cycle	*0.78*	0.91*	0.96*	0.98*	0.98*	0.95*	*0.53*	0.64*	0.64*	0.64*	0.54*	0.38*	*0.56*	0.17	0.18	0.19	0.05	-0.12
UC local level drift & cycle	*2.82*	-0.75*	0.67*	0.75*	-0.66*	-0.74*	-	-	-	-	-	-	-	-	-	-	-	-
UC smooth trend plus cycle	*2.08*	-0.57*	0.54*	0.59*	-0.51*	-0.61*	-	-	-	-	-	-	-	-	-	-	-	-
DHR local level drift&cycle	*0.86*	-0.04	0.41*	0.75*	0.78*	0.56*	*0.37*	-0.23*	-0.04	0.29*	0.22*	0.05	*2.29*	-0.21*	0.00	0.27*	0.21*	0.11
DHR smooth trend & cycle	*1.11*	-0.47*	0.20	0.74*	0.42*	-0.21*	*0.91*	-0.25*	0.00	0.47*	0.38*	0.10	*1.19*	-0.38*	-0.04	0.47*	0.26*	0.04
Combination of Fisher transformations																		
Average		**-0.15**	**0.53***	**0.82***	**0.63***	**0.25***		**-0.14**	**0.10**	**0.51***	**0.36***	**0.10**		**-0.27***	**0.01**	**0.47***	**0.16**	**-0.06**
Median	***1.04***	**-0.47***	**0.41***	**0.76***	**0.71***	**0.19**	***0.90***	**-0.23***	**0.00**	**0.51***	**0.38***	**0.10**	***1.20***	**-0.27***	**-0.02**	**0.47***	**0.10**	**-0.05**

Table B13. Sweden: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee Private consumption deflator**						**Deflated compensation per employee GDP deflator**					
	Relative standard deviation	***k (lags)*** -2	-1	0	1	2	**Relative standard deviation**	***k (lags)*** -2	-1	0	1	2	**Relative standard deviation**	***k (lags)*** -2	-1	0	1	2
First difference	*0.98*	0.22*	0.48*	0.62*	0.66*	0.56*	*0.95*	0.16	0.14	0.41*	0.31*	0.32*	*0.93*	0.13	0.07	0.22*	0.11	0.17
HP Filter λ=100	*1.32*	-0.06	0.32*	0.64*	0.76*	0.63*	*1.01*	-0.14	0.15	0.48*	0.60*	0.60*	*1.15*	-0.15	-0.08	0.10	0.19	0.35*
HP Filter λ =6.25	*1.28*	-0.45*	0.03	0.42*	0.49*	0.23*	*1.07*	-0.08	-0.01	0.31*	0.26*	0.24*	*1.09*	-0.04	-0.08	0.06	-0.03	0.09
Band Pass Fillter (2,8)	*1.15*	-0.55*	-0.08	0.33*	0.37*	0.02	*0.98*	-0.11	-0.24*	0.09	0.00	0.09	*0.97*	-0.06	-0.17	-0.01	-0.10	0.10
Band Pass Filter (2,6)	*1.14*	-0.59*	-0.02	0.35*	0.26*	-0.15	*1.19*	-0.07	-0.17	0.22*	-0.05	-0.05	*1.13*	-0.04	-0.05	0.13	-0.15	-0.06
Quadratic polynomial	*1.26*	0.73*	0.86*	0.94*	0.93*	0.83*	*0.83*	0.70*	0.82*	0.91*	0.92*	0.88*	*0.82*	0.73*	0.81*	0.86*	0.86*	0.84*
UC local level plus cycle	*0.76*	0.83*	0.90*	0.94*	0.96*	0.95*	*0.78*	0.67*	0.66*	0.62*	0.57*	0.49*	*0.77*	0.61*	0.54*	0.47*	0.43*	0.38*
UC local level drift & cycle	*0.56*	0.91*	0.43*	-0.91*	-0.40*	0.91*	*0.43*	-0.61*	0.57*	0.61*	-0.53*	-0.60*	*0.59*	-0.97*	0.29*	0.92*	-0.41*	-0.85*
UC smooth trend plus cycle	*0.58*	0.86*	0.52*	-0.86*	-0.49*	0.87*	*0.41*	-0.65*	0.56*	0.65*	-0.53*	-0.64*	-	-	-	-	-	-
DHR local level drift&cycle	*2.64*	-0.12	0.18	0.44*	0.55*	0.43*	*0.35*	0.10	0.22*	0.32*	0.38*	0.40*	-	-	-	-	-	-
DHR smooth trend & cycle	*1.49*	-0.32*	0.11	0.50*	0.63*	0.43*	*1.25*	-0.04	0.07	0.32*	0.34*	0.41*	-	-	-	-	-	-
Combination of Fisher transformations																		
Average		**0.26***	**0.42***	**0.37***	**0.56***	**0.64***		**0.00**	**0.30***	**0.50***	**0.27***	**0.23***		**-0.08**	**0.21***	**0.45***	**0.17**	**0.13**
Median	***1.15***	**-0.06**	**0.32***	**0.44***	**0.55***	**0.56***	***0.95***	**-0.07**	**0.15**	**0.41***	**0.31***	**0.32***	***0.95***	**-0.04**	**0.01**	**0.18**	**0.04**	**0.14**

Table B14. Denmark: the co-movement between public and private wages and employment

Correlation of private sector (t) and public sector (t+k) variable

Nominal compensation per employee

	Relative standard deviation	k (lags) -2	-1	0	1	2
First difference	*0.83*	0.43*	0.65*	0.58*	0.68*	0.67*
HP Filter λ=100	*1.83*	-0.12	0.48*	0.48*	0.51*	0.21*
HP Filter λ =6.25	*2.06*	-0.29*	0.48*	0.39*	0.20	-0.18
Band Pass Fillter (2,8)	*2.14*	-0.27*	0.38*	0.19	0.18	-0.04
Band Pass Filter (2,6)	*1.06*	-0.31*	0.44*	-0.03	0.01	-0.08
Quadratic polynomial	*0.79*	0.62*	0.79*	0.84*	0.87*	0.76*
UC local level plus cycle	*0.63*	0.89*	0.96*	0.98*	0.97*	0.92*
UC local level drift & cycle	*0.31*	-0.13	-0.33*	0.14	0.35*	-0.15
UC smooth trend plus cycle	*0.84*	-0.32*	-0.94*	0.32*	0.93*	-0.32*
DHR local level drift&cycle	*0.49*	0.71*	0.81*	0.81*	0.85*	0.76*
DHR smooth trend & cycle	*1.58*	-0.17	0.29*	0.21*	0.52*	0.47*
Combination of Fisher transformations						
Average		**0.17**	**0.43***	**0.57***	**0.68***	**0.37***
Median	***0.84***	**-0.13**	**0.48***	**0.39***	**0.52***	**0.21***

Deflated compensation per employee — Private consumption deflator

	Relative standard deviation	k (lags) -2	-1	0	1	2
First difference	*1.37*	-0.24*	0.05	-0.22*	-0.24*	0.02
HP Filter λ=100	*1.40*	0.05	0.34*	0.12	0.26*	0.30*
HP Filter λ =6.25	*1.45*	-0.15	0.21*	-0.07	-0.08	0.06
Band Pass Fillter (2,8)	*1.42*	-0.18	0.06	-0.24*	-0.18	0.08
Band Pass Filter (2,6)	*1.23*	-0.38*	0.37*	0.15	-0.02	-0.07
Quadratic polynomial	*1.15*	0.05	0.19	-0.02	0.12	0.09
UC local level plus cycle	*2.13*	-0.40*	-0.46*	-0.61*	-0.56*	-0.54*
UC local level drift & cycle	*1.37*	-0.41*	0.37*	0.21*	-0.09	-0.15
UC smooth trend plus cycle	*0.79*	-0.88*	-0.41*	0.88*	0.40*	-0.88*
DHR local level drift&cycle	*1.93*	-0.38*	-0.43*	-0.59*	-0.54*	-0.52*
DHR smooth trend & cycle	*1.44*	-0.12	0.11	-0.26*	0.01	0.15
Combination of Fisher transformations						
Average		**-0.32***	**0.03**	**-0.03**	**-0.09**	**-0.19**
Median	*1.40*	**-0.24***	**0.11**	**-0.07**	**-0.08**	**0.02**

Deflated compensation per employee — GDP deflator

	Relative standard deviation	k (lags) -2	-1	0	1	2
First difference	*1.28*	-0.45*	0.05	-0.34*	-0.35*	0.07
HP Filter λ=100	*1.55*	-0.31*	0.15	-0.21*	0.00	0.33*
HP Filter λ =6.25	*1.37*	-0.37*	0.15	-0.18	-0.11	0.22*
Band Pass Fillter (2,8)	*1.46*	-0.38*	0.05	-0.27*	-0.13	0.25*
Band Pass Filter (2,6)	*1.07*	-0.48*	0.47*	0.06	-0.11	0.06
Quadratic polynomial	*1.42*	-0.31*	-0.08	-0.37*	-0.19	0.00
UC local level plus cycle	*1.93*	-0.76*	-0.75*	-0.84*	-0.77*	-0.65*
UC local level drift & cycle	*1.61*	-0.33*	0.22*	-0.21*	-0.15	0.21*
UC smooth trend plus cycle	*0.35*	-0.35*	0.00	0.26*	0.00	-0.25*
DHR local level drift&cycle	*1.79*	-0.76*	-0.73*	-0.83*	-0.76*	-0.63*
DHR smooth trend & cycle	*1.49*	-0.43*	-0.01	-0.36*	-0.02	0.34*
Combination of Fisher transformations						
Average		**-0.47***	**-0.08**	**-0.36***	**-0.27***	**-0.02**
Median	*1.46*	**-0.38***	**0.05**	**-0.27***	**-0.13**	**0.07**

Table B15. Norway: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee Private consumption deflator**						**Deflated compensation per employee GDP deflator**					
	Relative standard deviation	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**
First difference	*0.94*	0.47*	0.64*	0.88*	0.66*	0.51*	*1.04*	0.45*	0.34*	0.75*	0.24*	0.32*	*1.03*	-0.16	0.11	0.91*	0.10	-0.26*
HP Filter λ=100	*1.08*	0.15	0.56*	0.83*	0.64*	0.31*	*1.14*	0.27*	0.43*	0.66*	0.32*	0.15	*1.12*	-0.06	0.41*	0.90*	0.36*	-0.17
HP Filter λ =6.25	*1.09*	-0.30*	0.26*	0.78*	0.37*	-0.11	*1.03*	0.01	0.12	0.62*	-0.05	-0.09	*1.09*	-0.38*	0.17	0.92*	0.10	-0.50*
Band Pass Fillter (2,8)	*1.08*	-0.46*	0.13	0.72*	0.21*	-0.32*	*0.86*	-0.02	-0.05	0.52*	-0.30*	-0.21*	*1.05*	-0.50*	0.09	0.91*	0.00	-0.64*
Band Pass Filter (2,6)	*1.11*	-0.48*	0.17	0.82*	0.04	-0.57*	*0.99*	-0.13	-0.17	0.69*	-0.34*	-0.18	*1.01*	-0.56*	0.01	0.95*	-0.04	-0.67*
Quadratic polynomial	*0.92*	0.70*	0.87*	0.94*	0.83*	0.65*	*1.14*	0.89*	0.94*	0.96*	0.90*	0.80*	*1.13*	0.31*	0.62*	0.89*	0.59*	0.24*
UC local level plus cycle	*0.83*	0.94*	0.98*	0.99*	0.97*	0.93*	*1.04*	0.92*	0.91*	0.86*	0.73*	0.57*	*0.76*	0.48*	0.71*	0.87*	0.67*	0.38*
UC local level drift & cycle	*0.97*	-0.97*	0.23*	0.97*	-0.23*	-0.97*	*0.91*	-0.17	0.00	0.66*	-0.27*	-0.29*	*1.16*	-0.85*	0.06	0.85*	-0.08	-0.86*
UC smooth trend plus cycle	*0.96*	-0.97*	0.25*	0.97*	-0.25*	-0.97*	*0.69*	-0.98*	0.17	0.98*	-0.21*	-0.98*	*1.08*	-0.92*	0.07	0.92*	-0.08	-0.92*
DHR local level drift&cycle	*1.54*	0.07	0.48*	0.78*	0.59*	0.25*	*0.57*	0.30*	0.38*	0.50*	0.28*	0.14	*0.76*	0.48*	0.71*	0.87*	0.67*	0.38*
DHR smooth trend & cycle	*1.09*	-0.22*	0.30*	0.77*	0.36*	-0.10	*1.03*	0.22*	0.28*	0.53*	0.14	0.04	*1.03*	-0.19	0.30*	0.85*	0.25*	-0.32*
Combination of Fisher transformations																		
Average		**-0.21***	**0.56***	**0.90***	**0.50***	**-0.16**		**0.15**	**0.41***	**0.78***	**0.20**	**-0.06**		**-0.31***	**0.33***	**0.90***	**0.26***	**-0.40***
Median	***1.08***	**-0.22***	**0.30***	**0.83***	**0.37***	**-0.10**	***1.03***	**0.22***	**0.28***	**0.66***	**0.14**	**0.04**	***1.05***	**-0.19**	**0.17**	**0.90***	**0.10**	**-0.32***

Table B16. United States: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						Deflated compensation per employee Private consumption deflator						Deflated compensation per employee GDP deflator					
	Relative standard deviation	k (lags) -2	-1	0	1	2	Relative standard deviation	k (lags) -2	-1	0	1	2	Relative standard deviation	k (lags) -2	-1	0	1	2
First difference	*1.04*	0.41*	0.50*	0.65*	0.67*	0.72*	*1.18*	0.15	0.37*	0.46*	0.13	0.04	*1.11*	0.12	0.27*	0.32*	0.05	0.04
HP Filter λ=100	*1.20*	-0.24*	0.02	0.34*	0.50*	0.58*	*1.64*	0.06	0.28*	0.36*	0.21*	0.14	*1.50*	0.00	0.16	0.22*	0.16	0.19
HP Filter λ =6.25	*1.06*	-0.29*	-0.11	0.20	0.27*	0.29*	*1.17*	-0.03	0.33*	0.34*	-0.20	-0.43*	*1.01*	0.01	0.23*	0.17	-0.25*	-0.35*
Band Pass Fillter (2,8)	*1.16*	-0.09	0.01	0.21*	0.10	0.01	*1.11*	0.12	0.56*	0.47*	-0.30*	-0.68*	*0.99*	0.24*	0.52*	0.31*	-0.39*	-0.63*
Band Pass Filter (2,6)	*0.96*	-0.16	-0.01	0.34*	0.08	-0.06	*1.05*	-0.30*	0.38*	0.60*	-0.19	-0.57*	*0.94*	-0.19	0.35*	0.48*	-0.21*	-0.48*
Quadratic polynomial	*1.14*	0.59*	0.75*	0.87*	0.90*	0.88*	*1.06*	0.51*	0.64*	0.69*	0.65*	0.59*	*1.17*	0.37*	0.48*	0.54*	0.49*	0.44*
UC local level plus cycle	*1.04*	0.86*	0.92*	0.95*	0.97*	0.96*	*1.05*	0.53*	0.65*	0.70*	0.65*	0.59*	*1.17*	0.39*	0.49*	0.54*	0.49*	0.45*
UC local level drift & cycle	*0.75*	-0.98*	0.19	0.98*	-0.16	-0.98*	*0.42*	-0.61*	0.22*	0.55*	-0.31*	-0.54*	*0.33*	-0.43*	0.10	0.40*	-0.13	-0.40*
UC smooth trend plus cycle	*0.75*	-0.98*	0.19	0.98*	-0.16	-0.98*	*0.44*	-0.53*	0.15	0.50*	-0.20	-0.50*	*0.78*	-0.92*	0.13	0.91*	-0.13	-0.91*
DHR local level drift&cycle	*0.84*	-0.33*	-0.07	0.26*	0.42*	0.46*	-	-	-	-	-	-	*1.47*	0.23*	0.37*	0.45*	0.40*	0.37*
DHR smooth trend & cycle	*0.85*	-0.26*	-0.02	0.31*	0.41*	0.44*	*1.36*	0.06	0.32*	0.35*	0.12	0.03	*1.31*	0.01	0.17	0.20	0.04	0.04
Combination of Fisher transformations																		
Average		**-0.32***	**0.29***	**0.73***	**0.49***	**0.14**		**0.00**	**0.39***	**0.49***	**0.08**	**-0.13**		**-0.07**	**0.30***	**0.46***	**0.05**	**-0.18**
Median	***1.04***	**-0.24***	**0.02**	**0.34***	**0.41***	**0.44***	***1.08***	**0.06**	**0.33***	**0.47***	**0.06**	**0.03**	***1.11***	**0.01**	**0.27***	**0.40***	**0.04**	**0.04**

Table B17. United Kingdom: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee Private consumption deflator**						**Deflated compensation per employee GDP deflator**					
	Relative standard deviation	***k (lags)***					**Relative standard deviation**	***k (lags)***					**Relative standard deviation**	***k (lags)***				
		-2	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**
First difference	*1.13*	0.41*	0.62*	0.85*	0.70*	0.49*	*1.38*	-0.21*	0.01	0.32*	0.16	0.26*	*1.42*	-0.04	0.08	0.12	0.31*	0.22*
HP Filter λ=100	*1.18*	0.36*	0.64*	0.82*	0.63*	0.25*	*1.80*	-0.07	0.20	0.49*	0.52*	0.45*	*1.99*	0.14	0.30*	0.44*	0.51*	0.35*
HP Filter λ =6.25	*1.48*	-0.38*	0.18	0.75*	0.41*	-0.23*	*1.66*	-0.31*	-0.05	0.35*	0.29*	0.26*	*1.69*	-0.12	-0.02	0.15	0.41*	0.26*
Band Pass Fillter (2,8)	*1.53*	-0.51*	0.11	0.77*	0.37*	-0.39*	*1.57*	-0.39*	-0.18	0.30*	0.25*	0.22*	*1.47*	-0.31*	-0.27*	0.01	0.45*	0.37*
Band Pass Filter (2,6)	*1.55*	-0.71*	-0.08	0.75*	0.37*	-0.38*	*1.45*	-0.31*	-0.26*	0.15	0.02	0.20	*1.37*	-0.09	-0.32*	-0.28*	0.27*	0.38*
Quadratic polynomial	*1.15*	0.54*	0.76*	0.90*	0.87*	0.72*	*0.95*	-0.12	0.04	0.19	0.25*	0.26*	*1.03*	0.03	0.08	0.12	0.15	0.09
UC local level plus cycle	*0.96*	0.88*	0.94*	0.98*	0.98*	0.95*	*0.79*	0.09	0.24*	0.37*	0.42*	0.44*	*0.86*	0.11	0.18	0.22*	0.25*	0.22*
UC local level drift & cycle	*1.16*	-0.65*	-0.76*	0.66*	0.75*	-0.66*	*1.02*	-0.30*	-0.95*	0.32*	0.94*	-0.34*	*0.29*	0.14	-0.34*	-0.14	0.33*	0.11
UC smooth trend plus cycle	*1.13*	-0.66*	-0.75*	0.66*	0.75*	-0.66*	*1.07*	-0.30*	-0.95*	0.31*	0.95*	-0.31*	*0.72*	0.41*	-0.91*	-0.41*	0.91*	0.40*
DHR local level drift&cycle	*0.16*	0.00	0.07	0.13	0.09	0.00	*2.07*	-0.05	0.21*	0.47*	0.52*	0.47*	*0.99*	0.08	0.16	0.20	0.23*	0.19
DHR smooth trend & cycle	*1.10*	-0.44*	0.08	0.71*	0.46*	-0.24*	*1.95*	-0.20	0.01	0.33*	0.38*	0.35*	*2.01*	0.00	0.09	0.22*	0.40*	0.30*
Combination of Fisher transformations																		
Average		**-0.10**	**0.23***	**0.79***	**0.67***	**0.06**		**-0.20***	**-0.30***	**0.33***	**0.53***	**0.21***		**0.03**	**-0.15**	**0.06**	**0.43***	**0.27***
Median	***1.15***	**-0.38***	**0.11**	**0.75***	**0.63***	**-0.23***	***1.45***	**-0.21***	**0.01**	**0.32***	**0.38***	**0.26***	***1.37***	**0.03**	**0.08**	**0.12**	**0.33***	**0.26***

Table B18. Canada: the co-movement between public and private wages and employment

Correlation of private sector (t) and public sector (t+k) variable

	Nominal compensation per employee						**Deflated compensation per employee – Private consumption deflator**						**Deflated compensation per employee – GDP deflator**					
	Relative standard deviation	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**	**Relative standard deviation**	***k (lags)*** **-2**	**-1**	**0**	**1**	**2**
First difference	*1.17*	0.53*	0.66*	0.78*	0.78*	0.64*	*1.16*	0.02	0.06	0.30*	0.28*	0.27*	*1.22*	-0.29*	-0.16	0.14	0.45*	-0.09
HP Filter λ=100	*1.04*	-0.07	0.36*	0.68*	0.73*	0.49*	*0.92*	-0.19	-0.07	0.19	0.35*	0.41*	*1.26*	-0.53*	-0.26*	0.15	0.41*	0.19
HP Filter λ =6.25	*0.94*	-0.32*	0.20	0.60*	0.56*	0.15	*0.89*	-0.36*	-0.22*	0.14	0.20	0.18	*1.11*	-0.42*	-0.13	0.32*	0.56*	0.05
Band Pass Fillter (2,8)	*0.87*	-0.22*	0.36*	0.70*	0.44*	-0.17	*0.93*	-0.20	-0.02	0.31*	0.17	-0.01	*1.00*	-0.29*	0.05	0.50*	0.60*	-0.15
Band Pass Filter (2,6)	*0.90*	0.02	0.15	0.26*	0.02	-0.35*	*0.91*	-0.05	-0.03	0.20	-0.03	-0.18	*0.89*	-0.16	-0.12	0.25*	0.42*	-0.47*
Quadratic polynomial	*1.19*	0.59*	0.80*	0.89*	0.83*	0.64*	*1.28*	0.53*	0.66*	0.77*	0.77*	0.73*	*1.27*	-0.47*	-0.27*	0.03	0.21*	0.09
UC local level plus cycle	*1.26*	0.94*	0.98*	0.99*	0.97*	0.92*	*1.61*	0.16	0.33*	0.51*	0.64*	0.73*	*1.87*	-0.63*	-0.52*	-0.35*	-0.24*	-0.28*
UC local level drift & cycle	-	-	-	-	-	-	*0.17*	-0.79*	0.62*	0.79*	-0.60*	-0.79*	*0.24*	0.28*	-0.92*	-0.29*	0.92*	0.31*
UC smooth trend plus cycle	-	-	-	-	-	-	*0.29*	-0.67*	0.75*	0.66*	-0.74*	-0.66*	*0.10*	0.53*	-0.61*	-0.54*	0.60*	0.56*
DHR local level drift&cycle	*0.61*	0.07	0.38*	0.62*	0.65*	0.47*	*1.85*	0.25*	0.42*	0.58*	0.68*	0.72*	*1.66*	-0.62*	-0.50*	-0.31*	-0.17	-0.23*
DHR smooth trend & cycle	*0.87*	-0.12	0.36*	0.64*	0.49*	0.06	*0.83*	-0.31*	-0.18	0.13	0.31*	0.38*	*1.24*	-0.48*	-0.24*	0.12	0.37*	0.18
Combination of Fisher transformations																		
Average		**0.26***	**0.59***	**0.77***	**0.69***	**0.40***		**-0.18**	**0.25***	**0.46***	**0.20***	**0.18**		**-0.30***	**-0.39***	**0.00**	**0.44***	**0.02**
Median	***0.94***	**0.02**	**0.36***	**0.68***	**0.65***	**0.47***	***0.92***	**-0.19**	**0.06**	**0.31***	**0.28***	**0.27***	***1.22***	**-0.42***	**-0.26***	**0.12**	**0.42***	**0.05**

Table B19. Japan: the co-movement between public and private wages and employment

	Correlation of private sector (t) and public sector (t+k) variable																	
	Nominal compensation per employee						**Deflated compensation per employee Private consumption deflator**						**Deflated compensation per employee GDP deflator**					
	Relative standard deviation	***k (lags)***					**Relative standard deviation**	***k (lags)***					**Relative standard deviation**	***k (lags)***				
		-2	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**		**-2**	**-1**	**0**	**1**	**2**
First difference	*1.05*	0.82*	0.89*	0.96*	0.94*	0.84*	*1.09*	0.73*	0.78*	0.85*	0.84*	0.82*	*1.15*	0.71*	0.77*	0.85*	0.79*	0.74*
HP Filter λ=100	*1.27*	0.44*	0.75*	0.93*	0.85*	0.51*	*1.34*	0.26*	0.51*	0.72*	0.77*	0.65*	*1.59*	0.20	0.50*	0.73*	0.66*	0.46*
HP Filter λ =6.25	*1.46*	-0.24*	0.27*	0.80*	0.67*	-0.05	*1.48*	-0.27*	-0.01	0.36*	0.40*	0.18	*1.84*	-0.21*	0.16	0.55*	0.30*	-0.05
Band Pass Fillter (2,8)	*1.41*	-0.57*	0.05	0.77*	0.51*	-0.34*	*1.36*	-0.34*	0.08	0.48*	0.26*	-0.12	*1.64*	-0.23*	0.23*	0.62*	0.13	-0.29*
Band Pass Filter (2,6)	*1.38*	-0.67*	-0.08	0.75*	0.51*	-0.40*	*1.37*	-0.48*	-0.17	0.37*	0.37*	0.06	*1.84*	-0.36*	-0.10	0.50*	0.22*	-0.05
Quadratic polynomial	*1.07*	0.78*	0.91*	0.97*	0.92*	0.76*	*1.08*	0.81*	0.91*	0.95*	0.94*	0.85*	*1.09*	0.82*	0.91*	0.95*	0.92*	0.82*
UC local level plus cycle	-	-	-	-	-	-	*0.96*	0.92*	0.97*	0.99*	0.98*	0.93*	*0.96*	0.93*	0.97*	0.99*	0.98*	0.93*
UC local level drift & cycle	*1.39*	-0.77*	-0.62*	0.77*	0.62*	-0.78*	*1.02*	-0.13	-0.22*	0.07	0.28*	0.06	-	-	-	-	-	-
UC smooth trend plus cycle	*1.41*	-0.78*	-0.62*	0.78*	0.62*	-0.79*	*0.46*	-0.03	-0.20	-0.04	0.17	0.07	-	-	-	-	-	-
DHR local level drift&cycle	*2.05*	0.34*	0.68*	0.90*	0.80*	0.42*	*1.67*	0.66*	0.83*	0.93*	0.96*	0.91*	*0.50*	0.86*	0.89*	0.89*	0.85*	0.76*
DHR smooth trend & cycle	*1.31*	-0.03	0.44*	0.85*	0.72*	0.13	*1.35*	-0.04	0.25*	0.44*	0.56*	0.40*	-	-	-	-	-	-
Combination of Fisher transformations																		
Average		**-0.08**	**0.38***	**0.88***	**0.76***	**0.04**		**0.30***	**0.51***	**0.72***	**0.74***	**0.57***		**0.50***	**0.70***	**0.85***	**0.74***	**0.54***
Median	***1.38***	**-0.14**	**0.36***	**0.83***	**0.70***	**0.04**	***1.34***	**-0.03**	**0.25***	**0.48***	**0.56***	**0.40***	***1.37***	**0.50***	**0.66***	**0.80***	**0.73***	**0.62***

Appendix C.

Table C1. The correlations of forecast errors derived from VARs between public and private nominal wages per employee (den Haan's 2000 methodology). Short-, medium-, and long-run co-movements.

	Sample 1960 - 2007									Sample 1980 - 2007								
	h(horizon)									*h(horizon)*								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Euro area	0.67*	0.81*	0.86*	0.88*	0.90*	0.91*	0.92*	0.93*	0.94*	0.67*	0.81*	0.86*	0.87*	0.87*	0.87*	0.87*	0.86*	0.86*
Germany	0.69*	0.82*	0.81*	0.80*	0.78*	0.75*	0.73*	0.71*	0.70*	0.84*	0.90*	0.91*	0.92*	0.92*	0.92*	0.92*	0.92*	0.91*
France	0.67*	0.80*	0.85*	0.87*	0.88*	0.88*	0.88*	0.88*	0.88*	0.17	0.15	0.15	0.11	0.09	0.05	0.01	-0.03	-0.07
Italy	0.38*	0.55*	0.67*	0.75*	0.80*	0.83*	0.86*	0.87*	0.89*	0.57*	0.65*	0.71*	0.75*	0.78*	0.80*	0.82*	0.83*	0.84*
Spain	0.43*	0.57*	0.65*	0.70*	0.74*	0.76*	0.78*	0.80*	0.81*	-0.03	0.43*	0.70*	0.82*	0.87*	0.88*	0.89*	0.90*	0.90*
Netherlands	0.38*	0.46*	0.52*	0.57*	0.61*	0.64*	0.67*	0.69*	0.71*	0.53*	0.68*	0.75*	0.79*	0.81*	0.83*	0.84*	0.84*	0.85*
Austria	0.26*	0.36*	0.44*	0.50*	0.54*	0.58*	0.60*	0.62*	0.64*	-0.07	0.23	0.45	0.60*	0.69*	0.75*	0.79*	0.82*	0.85*
Belgium	0.20	0.25	0.31	0.37	0.41	0.45	0.47	0.50	0.51	0.37*	0.53*	0.49	0.46	0.41	0.37	0.33	0.29	0.26
Greece	0.59*	0.76*	0.85*	0.91*	0.93*	0.95*	0.95*	0.96*	0.97*	0.55*	0.65*	0.69*	0.68*	0.68*	0.69*	0.69*	0.70*	0.70*
Ireland	0.51*	0.67*	0.76*	0.82*	0.85*	0.88*	0.90*	0.91*	0.92*	0.14	0.37*	0.42	0.51*	0.57*	0.60*	0.63*	0.65*	0.67*
Portugal	0.38*	0.59*	0.70*	0.76*	0.80*	0.83*	0.84*	0.86*	0.87*	-0.31*	-0.21	-0.29	-0.41	-0.48	-0.51	-0.53	-0.54	-0.54
Finland	0.63*	0.69*	0.75*	0.79*	0.81*	0.83*	0.84*	0.85*	0.86*	0.66*	0.80*	0.86*	0.88*	0.89*	0.90*	0.90*	0.91*	0.91*
Sweden	0.49*	0.76*	0.83*	0.88*	0.90*	0.92*	0.93*	0.93*	0.94*	0.74*	0.87*	0.85*	0.82*	0.83*	0.84*	0.85*	0.86*	0.87*
Denmark	0.33	0.60*	0.71*	0.73*	0.77*	0.80*	0.82*	0.84*	0.85*	0.30	0.41	0.48	0.52	0.54	0.56	0.57	0.58	0.58
Norway	0.77*	0.84*	0.87*	0.89*	0.90*	0.90*	0.91*	0.91*	0.91*	0.48*	0.68*	0.76*	0.81*	0.83*	0.85*	0.86*	0.87*	0.88*
United States	0.34*	0.47*	0.55*	0.61*	0.64*	0.67*	0.68*	0.70*	0.71*	0.03	0.15	0.22	0.28	0.32	0.35	0.37	0.39	0.40
United Kingdom	0.69*	0.78*	0.83*	0.86*	0.87*	0.88*	0.89*	0.89*	0.90*	0.04	0.42*	0.61*	0.70*	0.76*	0.80*	0.82*	0.84*	0.86*
Canada	0.53*	0.76*	0.84*	0.89*	0.91*	0.93*	0.94*	0.94*	0.95*	0.31	0.44*	0.52*	0.57*	0.60*	0.63*	0.65*	0.66*	0.68*
Japan	0.71*	0.90*	0.94*	0.96*	0.96*	0.97*	0.98*	0.98*	0.98*	0.21	0.51*	0.69*	0.70*	0.67*	0.70*	0.70*	0.70*	0.71*

Note: These panels plot the correlation coefficients of the h-period ahead forecast errors of the indicated variables. An asterisk denotes significance at the 5% significance level. Significance levels are based on Monte-Carlo confidence intervals.

Table C2. The correlations of forecast errors derived from VARs between public and private deflated (real) wages per employee, sample 1960-2006 (den Haan's 2000 methodology). Short-, medium-, and long-run co-movements.

	Deflated compensation per employee: private consumption deflator									**Deflated compensation per employee: GDP deflator**								
	h(horizon)									***h(horizon)***								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Euro area	0.52*	0.54*	0.55*	0.55*	0.56*	0.56*	0.56*	0.56*	0.57*	0.47*	0.50*	0.53*	0.54*	0.56*	0.56*	0.57*	0.57*	0.57*
Germany	0.54*	0.71*	0.71*	0.73*	0.75*	0.78*	0.80*	0.82*	0.83*	0.37*	0.54*	0.50*	0.53*	0.58*	0.63*	0.66*	0.69*	0.71*
France	0.65*	0.61*	0.63*	0.64*	0.65*	0.66*	0.67*	0.68*	0.69*	0.54*	0.54*	0.55*	0.56*	0.56*	0.56*	0.57*	0.57*	0.57*
Italy	0.20	0.18	0.17	0.16	0.16	0.16	0.16	0.16	0.15	-0.04	-0.15	-0.20	-0.23	-0.25	-0.26	-0.27	-0.28	-0.28
Spain	0.45*	0.39*	0.36	0.33	0.32	0.31	0.30	0.30	0.29	0.36*	0.28	0.22	0.19	0.17	0.15	0.14	0.13	0.13
Netherlands	0.18	0.13	0.07	0.05	0.06	0.08	0.10	0.11	0.13	0.09	0.09	0.04	0.00	0.00	0.01	0.02	0.03	0.04
Austria	0.34*	0.26	0.22	0.19	0.17	0.15	0.14	0.14	0.13	0.18	0.12	0.08	0.06	0.04	0.03	0.02	0.01	0.01
Belgium	0.06	0.04	0.06	0.09	0.11	0.13	0.14	0.16	0.17	0.06	-0.04	-0.07	-0.09	-0.09	-0.10	-0.10	-0.10	-0.10
Greece	0.68*	0.77*	0.84*	0.86*	0.87*	0.87*	0.88*	0.88*	0.88*	0.59*	0.71*	0.80*	0.84*	0.85*	0.86*	0.87*	0.88*	0.88*
Ireland	0.29	0.19	0.15	0.14	0.13	0.12	0.12	0.11	0.11	0.36*	0.57*	0.59*	0.56*	0.54*	0.55*	0.55*	0.55*	0.56*
Portugal	0.45*	0.51*	0.56*	0.58*	0.60*	0.62*	0.63*	0.64*	0.64*	0.37*	0.41*	0.44*	0.46*	0.48*	0.49*	0.50*	0.50*	0.51*
Finland	0.53*	0.49*	0.47*	0.46*	0.46*	0.46*	0.46*	0.46*	0.46*	0.64*	0.50*	0.40*	0.33	0.29	0.25	0.23	0.21	0.19
Sweden	0.40*	0.58*	0.68*	0.77*	0.81*	0.84*	0.85*	0.86*	0.86*	0.29	0.39*	0.48*	0.60*	0.65*	0.69*	0.71*	0.73*	0.74*
Denmark	0.14	0.27	0.32	0.34	0.35	0.36	0.37	0.37	0.38	-0.08	-0.04	-0.14	-0.18	-0.17	-0.17	-0.18	-0.19	-0.19
Norway	0.68*	0.71*	0.77*	0.81*	0.83*	0.85*	0.86*	0.87*	0.88*	0.90*	0.90*	0.90*	0.89*	0.89*	0.89*	0.89*	0.89*	0.89*
United States	0.36*	0.40*	0.44*	0.48*	0.50*	0.51*	0.53*	0.53*	0.54*	0.23	0.25	0.28	0.30	0.32	0.33	0.34	0.35	0.36
United Kingdom	0.34	0.37	0.39	0.39	0.40	0.40	0.40	0.40	0.40	0.04	0.21	0.30	0.36	0.39	0.41	0.42	0.43	0.44
Canada	0.28*	0.49*	0.56*	0.62*	0.67*	0.69*	0.71*	0.73*	0.74*	0.08	0.28*	0.17	0.07	0.01	0.00	-0.02	-0.03	-0.05
Japan	0.45*	0.63*	0.76*	0.82*	0.86*	0.88*	0.90*	0.92*	0.93*	0.54*	0.66*	0.77*	0.81*	0.84*	0.87*	0.89*	0.90*	0.92*

Note: These panels plot the correlation coefficients of the h-period ahead forecast errors of the indicated variables. An asterisk denotes significance at the 5% significance level. Significance levels are based on Monte-Carlo confidence intervals.

Table C3. The correlations of forecast errors derived from VARs between public and private deflated (real) wages per employee, sample 1980-2006 (den Haan's 2000 methodology). Short-, medium-, and long-run co-movements.

	Deflated compensation per employee: private consumption deflator									Deflated compensation per employee: GDP deflator								
	h(horizon)									*h(horizon)*								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Euro area	0.72*	0.67*	0.58*	0.45*	0.34	0.26	0.20	0.16	0.11	0.50*	0.51*	0.52*	0.53*	0.54*	0.54*	0.54*	0.55*	0.55*
Germany	0.74*	0.82*	0.80*	0.78*	0.77*	0.76*	0.76*	0.76*	0.76*	0.66*	0.74*	0.78*	0.80*	0.82*	0.83*	0.84*	0.84*	0.84*
France	0.48*	0.08	-0.13	-0.26	-0.35	-0.41	-0.45	-0.49	-0.51	0.33	0.16	0.04	-0.04	-0.11	-0.15	-0.19	-0.22	-0.24
Italy	0.71*	0.80*	0.83*	0.84*	0.85*	0.85*	0.85*	0.85*	0.86*	0.35	0.29	0.28	0.28	0.27	0.27	0.27	0.26	0.26
Spain	0.15	0.31	0.39	0.43	0.46	0.47	0.49	0.49	0.50	0.16	0.32	0.40	0.45	0.48	0.50	0.51	0.52	0.53
Netherlands	0.50*	0.57*	0.60*	0.62*	0.64*	0.64*	0.65*	0.65*	0.66*	0.38	0.53	0.52	0.50	0.50	0.51	0.52	0.52	0.53
Austria	0.11	0.20	0.28	0.33	0.36	0.37	0.38	0.39	0.40	-0.06	0.02	0.07	0.10	0.11	0.12	0.13	0.13	0.13
Belgium	0.63*	0.72*	0.74*	0.70*	0.71*	0.72*	0.73*	0.73*	0.74*	0.28	0.28	0.29	0.30	0.31	0.31	0.31	0.32	0.32
Greece	0.70*	0.82*	0.85*	0.87*	0.88*	0.88*	0.89*	0.89*	0.89*	0.55*	0.68*	0.71*	0.73*	0.74*	0.74*	0.75*	0.75*	0.75*
Ireland	-0.17	-0.12	0.03	0.15	0.17	0.16	0.19	0.21	0.21	0.25	0.33	0.47	0.55	0.56	0.57	0.60	0.61	0.62
Portugal	-0.46*	-0.24	-0.15	-0.11	-0.10	-0.08	-0.06	-0.05	-0.04	0.15	0.18	0.20	0.22	0.23	0.23	0.24	0.24	0.24
Finland	0.63*	0.65*	0.66*	0.67*	0.67*	0.67*	0.67*	0.67*	0.67*	0.70*	0.63*	0.68*	0.72*	0.75*	0.76*	0.77*	0.77*	0.78*
Sweden	0.27	0.36	0.44*	0.56*	0.59*	0.61*	0.62*	0.63*	0.63*	0.21	0.15	0.14	0.13	0.13	0.13	0.13	0.12	0.12
Denmark	0.46*	0.46*	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.41*	0.43	0.26	0.09	0.04	0.05	0.03	0.01	0.00
Norway	0.37*	0.29	0.27	0.25	0.24	0.24	0.23	0.23	0.23	0.88*	0.87*	0.84*	0.82*	0.81*	0.81*	0.80*	0.80*	0.80*
United States	0.11	0.20	0.26	0.31	0.34	0.37	0.38	0.40	0.41	0.10	0.13	0.16	0.18	0.19	0.20	0.21	0.22	0.22
United Kingdom	-0.30	-0.03	0.14	0.25	0.32	0.36	0.40	0.43	0.45	-0.24	-0.06	0.02	0.07	0.09	0.11	0.12	0.13	0.14
Canada	0.39*	0.35	0.24	0.15	0.08	0.02	-0.03	-0.07	-0.10	0.13	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15
Japan	0.30	0.43	0.52*	0.39	0.22	0.18	0.13	0.08	0.06	0.11	0.34	0.44	0.32	0.16	0.11	0.08	0.04	0.02

Note: These panels plot the correlation coefficients of the h-period ahead forecast errors of the indicated variables. An asterisk denotes significance at the 5% significance level. Significance levels are based on Monte-Carlo confidence intervals.

Table C4. Cointegration tests. Model with price level. Annual data 1960-2006.

		Nominal compensation per employee (model with price level)							
		Private consumption deflator				**GDP deflator**			
	Max Rank	**Max Statistic**	Critical Values	**Trace Statistic**	Critical Values	**Max Statistic**	Critical Values	**Trace Statistic**	Critical Values
Euro area	**1**	10.2	14.1	10.3	15.4	10.6	14.1	10.6	15.4
	2	0.0	3.8	0.0	3.8	0.0	3.8	0.0	3.8
Germany	**1**	6.8	11.4	6.9	12.5	9.8	11.4	9.8	12.5
	2	0.1	3.8	0.1	3.8	0.0	3.8	0.0	3.8
France	**1**	7.4	11.4	8.7	12.5	18.0*	15.7	28.4*	20.0
	2	1.3	3.8	1.3	3.8	10.4*	9.2	10.4*	9.4
Italy	**1**	12.5	15.7	19.3	20.0	13.3	19.0	24.4	25.3
	2	6.8	9.2	6.8	9.4	11.1	12.5	11.1	12.3
Spain	**1**	5.9	11.4	6.0	12.5	8.3	14.1	10.5	15.4
	2	0.0	3.8	0.0	3.8	2.2	3.8	2.2	3.8
Netherlands	**1**	10.2	11.4	10.4	12.5	10.8	15.7	16.2	20.0
	2	0.1	3.8	0.1	3.8	5.4	9.2	5.4	9.4
Austria	**1**	13.1	16.9	15.0	18.2	20.7*	15.7	29.6*	20.0
	2	1.9	3.7	1.9	3.7	8.9	9.2	8.9	9.4
Belgium	**1**	11.4	11.4	12.2	12.5	9.9	11.4	10.5	12.5
	2	0.8	3.8	0.8	3.8	0.6	3.8	0.6	3.8
Greece	**1**	9.8	11.4	10.7	12.5	9.9	11.4	10.4	12.5
	2	0.9	3.8	0.9	3.8	0.5	3.8	0.5	3.8
Ireland	**1**	9.0	11.4	9.1	12.5	11.5	15.7	17.4	20.0
	2	0.0	3.8	0.0	3.8	5.9	9.2	5.9	9.4
Portugal	**1**	9.9	11.4	10.2	12.5	8.8	11.4	9.5	12.5
	2	0.3	3.8	0.3	3.8	0.8	3.8	0.8	3.8
Finland	**1**	10.6	11.4	10.6	12.5	14.3*	11.4	14.3*	12.5
	2	0.0	3.8	0.0	3.8	0.0	3.8	0.0	3.8
Sweden	**1**	10.9	16.9	11.9	18.2	17.4	19.0	24.2	25.3
	2	1.0	3.7	1.0	3.7	6.8	12.5	6.8	12.3
Denmark	**1**	6.8	11.4	6.8	12.5	6.4	11.4	6.7	12.5
	2	0.0	3.8	0.0	3.8	0.3	3.8	0.3	3.8
Norway	**1**	12.8	15.7	19.8	20.0	10.8	14.1	10.8	15.4
	2	7.0	9.2	7.0	9.4	0.0	3.8	0.0	3.8
United States	**1**	8.0	14.1	12.8	15.4	9.5	15.7	17.4	20.0
	2	4.8*	3.8	4.8*	3.8	7.9	9.2	7.9	9.4
United Kingdom	**1**	8.8	14.1	15.0	15.4	7.4	14.1	11.9	15.4
	2	6.2*	3.8	6.2*	3.8	4.5*	3.8	4.5*	3.8
Canada	**1**	8.7	11.4	8.9	12.5	7.9	11.4	9.9	12.5
	2	0.2	3.8	0.2	3.8	2.0	3.8	2.0	3.8
Japan	**1**	13.7	14.1	14.2	15.4	2.0	11.4	3.0	12.5
	2	0.5	3.8	0.5	3.8	0.9	3.8	0.9	3.8

Note: an asterisk indicates significance at the 5% level. Osterwald-Lenum critical values for both the Maximum-eigenvalue and Trace test statistics.

Appendix D.

Table D1. Granger Causality tests I: detrended variables. Annual data 1980-2006.

	Nominal comp. per employee		Nominal comp. per employee (model including price level)			
			Private consumption deflator		GDP deflator	
	Public → Private	Public ← Private	Public → Private	Public ← Private	Public → Private	Public ← Private
Euro area	→	←	→	←	→	←
First difference	0	0	0	0	0	0
Other filters	7	6	6	6	6	6
Germany	-	←	-	←	→	-
First difference	0	1	0	1	0	0
Other filters	5	7	4	6	6	3
France	-	←	→	←	-	←
First difference	0	0	1	1	1	0
Other filters	3	6	6	8	4	6
Italy	-	-	-	-	-	-
First difference	0	1	0	0	0	0
Other filters	0	4	4	2	5	2
Spain	→	←	→	-	→	-
First difference	1	1	1	0	1	0
Other filters	8	7	6	5	9	4
Netherlands	-	←	-	←	-	-
First difference	0	0	0	0	0	0
Other filters	3	6	0	6	0	4
Austria	-	←	-	←	-	←
First difference	0	1	0	1	0	1
Other filters	2	9	2	8	2	7
Belgium	-	-	-	-	-	-
First difference	0	0	0	0	0	0
Other filters	0	4	5	3	3	3
Greece	-	←	-	←	-	-
First difference	0	1	0	1	0	0
Other filters	1	8	2	7	2	3
Ireland	-	←	→	-	→	←
First difference	0	1	0	0	0	1
Other filters	2	7	7	4	8	5
Portugal	-	-	→	-	-	←
First difference	0	1	1	0	0	0
Other filters	2	4	6	5	4	6
Finland	→	←	→	←	-	←
First difference	0	1	1	1	0	0
Other filters	6	7	9	9	3	8
Sweden	-	←	-	-	-	-
First difference	0	1	1	0	0	0
Other filters	4	9	3	5	2	4
Denmark	-	←	-	←	-	←
First difference	0	1	0	0	0	1
Other filters	1	8	1	7	4	7
Norway	→	-	→	-	→	-
First difference	1	0	1	0	1	0
Other filters	8	1	5	3	8	0
United States	-	-	-	-	-	-
First difference	0	0	0	0	0	0
Other filters	3	4	2	4	3	3
United Kingdom	-	←	-	←	-	←
First difference	0	1	0	1	0	1
Other filters	2	6	1	5	4	8
Canada	-	-	-	-	→	-
First difference	0	0	0	0	0	1
Other filters	4	2	5	4	7	4
Japan	→	-	→	←	→	←
First difference	0	1	0	1	0	1
Other filters	9	1	9	5	8	10

Appendix E.

Table E1. Granger Causality tests II: VARs in levels. Annual data 1960-2006.

	Nominal compensation per employee					Nominal compensation per employee (model with price level)									
						Private consumption deflator					GDP deflator				
	VAR lag order selection			**Public → Private**	**Public ← Private**	*VAR lag order selection*			**Public → Private**	**Public ← Private**	*VAR lag order selection*			**Public → Private**	**Public ← Private**
	SIC	HQC	AIC	*p-value*	*p-value*	SIC	HQC	AIC	*p-value*	*p-value*	SIC	HQC	AIC	*p-value*	*p-value*
	order p			VAR(p+1)	VAR(p+1)	*order p*			VAR(p+1)	VAR(p+1)	*order p*			VAR(p+1)	VAR(p+1)
Euro area	*2*	*2*	*2*	0.983	0.018**	*1*	*2*	*2*	0.557	0.025**	*1*	*2*	*2*	0.557	0.055*
Germany	*2*	*2*	*2*	0.744	0.000***	*1*	*1*	*1*	0.298	0.176	*1*	*1*	*2*	0.262	0.003***
France	*2*	*2*	*2*	0.231	0.000***	*2*	*2*	*2*	0.079*	0.002***	*2*	*2*	*2*	0.016**	0.035**
Italy	*1*	*2*	*2*	0.005***	0.000***	*2*	*2*	*2*	0.560	0.030**	*2*	*2*	*2*	0.086*	0.467
Spain	*2*	*2*	*2*	0.821	0.000***	*2*	*2*	*2*	0.970	0.842	*2*	*2*	*2*	0.874	0.353
Netherlands	*2*	*2*	*2*	0.004***	0.275	*2*	*2*	*2*	0.000***	0.001***	*2*	*2*	*2*	0.017**	0.006***
Austria	*2*	*2*	*2*	0.315	0.004***	*2*	*2*	*2*	0.262	0.392	*2*	*2*	*2*	0.105	0.475
Belgium	*1*	*1*	*1*	0.287	0.060*	*1*	*2*	*2*	0.500	0.292	*1*	*2*	*2*	0.653	0.154
Greece	*1*	*2*	*2*	0.006***	0.000***	*2*	*2*	*2*	0.193	0.013**	*2*	*2*	*2*	0.258	0.068*
Ireland	*2*	*2*	*2*	0.175	0.272	*2*	*2*	*2*	0.000***	0.754	*2*	*2*	*2*	0.019**	0.028**
Portugal	*1*	*2*	*2*	0.015**	0.000***	*1*	*2*	*2*	0.174	0.002***	*1*	*1*	*2*	0.486	0.001***
Finland	*2*	*2*	*2*	0.010**	0.000***	*1*	*1*	*2*	0.014**	0.037**	*2*	*2*	*2*	0.086*	0.660
Sweden	*1*	*1*	*1*	0.044**	0.000***	*1*	*1*	*1*	0.161	0.000***	*1*	*1*	*1*	0.527	0.014**
Denmark	*1*	*2*	*2*	0.017**	0.025**	*2*	*2*	*2*	0.003***	0.076*	*2*	*2*	*2*	0.317	0.019**
Norway	*1*	*2*	*2*	0.911	0.373	*1*	*2*	*2*	0.282	0.616	*2*	*2*	*2*	0.548	0.534
United States	*2*	*2*	*2*	0.973	0.000***	*2*	*2*	*2*	0.725	0.000***	*2*	*2*	*2*	0.723	0.000***
United Kingdom	*1*	*2*	*2*	0.589	0.006***	*1*	*2*	*2*	0.448	0.007***	*1*	*1*	*2*	0.624	0.027**
Canada	*1*	*2*	*2*	0.533	0.017**	*1*	*2*	*2*	0.188	0.006***	*2*	*2*	*2*	0.006***	0.203
Japan	*2*	*2*	*2*	0.660	0.000***	*1*	*1*	*2*	0.051*	0.000***	*2*	*2*	*2*	0.101	0.000***

Note: An asterisk denotes significance at the 10% significance level, two asterisks denote significance at the 5% significance level, three asterisks denote significance at the 1% significance level.

Table E2. Granger Causality tests II (wages and prices): VARs in levels. Annual data 1960-2006.

	Nominal compensation per employee (model with price level)																				
	Private consumption deflator										GDP deflator										
	VAR lag order selection			**Prices → Public wages**	**Prices → Private wages**	*VAR lag order selection*			**Public wages → Prices**	**Private wages → Prices**	*VAR lag order selection*			**Prices → Public wages**	**Prices → Private wages**	*VAR lag order selection*			**Public wages → Prices**	**Private wages → Prices**
	SIC	HQC	AIC	*p-value*	*p-value*	SIC	HQC	AIC	*p-value*	*p-value*	SIC	HQC	AIC	*p-value*	*p-value*	SIC	HQC	AIC	*p-value*	*p-value*
	order p			VAR(p+1)	VAR(p+1)	*order p*			VAR(p+1)	VAR(p+1)	*order p*			VAR(p+1)	VAR(p+1)	*order p*			VAR(p+1)	VAR(p+1)
Euro area	*1*	*2*	*2*	0.006***	0.012**	*1*	*2*	*2*	0.032**	0.005***	*1*	*2*	*2*	0.006***	0.009***	*1*	*2*	*2*	0.291	0.075*
Germany	*1*	*1*	*1*	0.001***	0.007***	*1*	*1*	*1*	0.260	0.002***	*1*	*1*	*2*	0.000***	0.000***	*1*	*1*	*2*	0.279	0.000***
France	*2*	*2*	*2*	0.000***	0.000***	*2*	*2*	*2*	0.278	0.010**	*2*	*2*	*2*	0.000***	0.000***	*2*	*2*	*2*	0.071*	0.000***
Italy	*2*	*2*	*2*	0.044**	0.000***	*2*	*2*	*2*	0.103	0.002***	*2*	*2*	*2*	0.006***	0.000***	*2*	*2*	*2*	0.099*	0.000***
Spain	*2*	*2*	*2*	0.078*	0.001***	*2*	*2*	*2*	0.003***	0.000***	*2*	*2*	*2*	0.010***	0.000***	*2*	*2*	*2*	0.015**	0.003***
Netherlands	*2*	*2*	*2*	0.000***	0.000***	*2*	*2*	*2*	0.003***	0.156	*2*	*2*	*2*	0.001***	0.000***	*2*	*2*	*2*	0.002***	0.090*
Austria	*2*	*2*	*2*	0.242	0.019**	*2*	*2*	*2*	0.486	0.000***	*2*	*2*	*2*	0.016**	0.000***	*2*	*2*	*2*	0.939	0.002***
Belgium	*1*	*2*	*2*	0.415	0.183	*1*	*2*	*2*	0.213	0.000***	*1*	*2*	*2*	0.130	0.435	*1*	*2*	*2*	0.067*	0.012**
Greece	*2*	*2*	*2*	0.356	0.089*	*2*	*2*	*2*	0.670	0.009***	*2*	*2*	*2*	0.052*	0.107	*2*	*2*	*2*	0.270	0.006***
Ireland	*2*	*2*	*2*	0.029**	0.000***	*2*	*2*	*2*	0.002***	0.035**	*2*	*2*	*2*	0.001***	0.000***	*2*	*2*	*2*	0.111	0.173
Portugal	*1*	*2*	*2*	0.489	0.000***	*1*	*2*	*2*	0.013**	0.114	*1*	*1*	*2*	0.730	0.004***	*1*	*1*	*2*	0.797	0.054*
Finland	*1*	*1*	*2*	0.006***	0.000***	*1*	*1*	*2*	0.001***	0.000***	*2*	*2*	*2*	0.122	0.000***	*2*	*2*	*2*	0.016**	0.002***
Sweden	*1*	*1*	*1*	0.765	0.023**	*1*	*1*	*1*	0.005***	0.008***	*1*	*1*	*1*	0.334	0.001***	*1*	*1*	*1*	0.011**	0.003***
Denmark	*2*	*2*	*2*	0.069*	0.000***	*2*	*2*	*2*	0.000***	0.000***	*2*	*2*	*2*	0.000***	0.004***	*2*	*2*	*2*	0.002***	0.000***
Norway	*1*	*2*	*2*	0.006***	0.000***	*1*	*2*	*2*	0.083*	0.263	*2*	*2*	*2*	0.014**	0.002***	*2*	*2*	*2*	0.499	0.182
United States	*2*	*2*	*2*	0.000***	0.002***	*2*	*2*	*2*	0.171	0.210	*2*	*2*	*2*	0.001***	0.003***	*2*	*2*	*2*	0.069*	0.097*
United Kingdom	*1*	*2*	*2*	0.000***	0.000***	*1*	*2*	*2*	0.446	0.161	*1*	*1*	*2*	0.000***	0.000***	*1*	*1*	*2*	0.140	0.012**
Canada	*1*	*2*	*2*	0.000***	0.003***	*1*	*2*	*2*	0.069*	0.490	*2*	*2*	*2*	0.000***	0.000***	*2*	*2*	*2*	0.396	0.196
Japan	*1*	*1*	*2*	0.000***	0.000***	*1*	*1*	*2*	0.036**	0.000***	*2*	*2*	*2*	0.000***	0.000***	*2*	*2*	*2*	0.005***	0.000***

Table E3. Granger Causality tests II: VARs in levels. Annual data 1980-2006.

	Nominal compensation per employee					Nominal compensation per employee (model with price level)									
						Private consumption deflator					GDP deflator				
	VAR lag order selection			**Public → Private**	**Public ← Private**	*VAR lag order selection*			**Public → Private**	**Public ← Private**	*VAR lag order selection*			**Public → Private**	**Public ← Private**
	SIC	HQC	AIC	*p-value*	*p-value*	SIC	HQC	AIC	*p-value*	*p-value*	SIC	HQC	AIC	*p-value*	*p-value*
	order p			VAR(p+1)	VAR(p+1)	*order p*			VAR(p+1)	VAR(p+1)	*order p*			VAR(p+1)	VAR(p+1)
Euro area	*2*	*2*	*2*	0.099*	0.033**	*2*	*2*	*2*	0.019**	0.006***	*2*	*2*	*2*	0.000***	0.006***
Germany	*1*	*1*	*1*	0.187	0.005***	*1*	*1*	*1*	0.023**	0.024**	*1*	*1*	*1*	0.189	0.358
France	*2*	*2*	*2*	0.178	0.022**	*1*	*2*	*2*	0.005***	0.005***	*2*	*2*	*2*	0.060*	0.102
Italy	*1*	*1*	*1*	0.426	0.441	*1*	*1*	*1*	0.615	0.464	*1*	*1*	*1*	0.853	0.976
Spain	*1*	*1*	*1*	0.038**	0.423	*1*	*1*	*1*	0.119	0.311	*1*	*1*	*1*	0.140	0.199
Netherlands	*1*	*2*	*2*	0.142	0.269	*2*	*2*	*2*	0.024**	0.067*	*2*	*2*	*2*	0.374	0.123
Austria	*1*	*1*	*1*	0.630	0.000***	*1*	*1*	*1*	0.340	0.002***	*1*	*1*	*1*	0.269	0.145
Belgium	*1*	*1*	*1*	0.304	0.010**	*1*	*1*	*1*	0.236	0.089*	*1*	*1*	*1*	0.351	0.467
Greece	*1*	*1*	*1*	0.972	0.201	*1*	*1*	*1*	0.306	0.045**	*1*	*1*	*1*	0.414	0.048**
Ireland	*1*	*1*	*1*	0.001***	0.000***	*1*	*2*	*2*	0.006***	0.061*	*1*	*2*	*2*	0.058*	0.001***
Portugal	*1*	*2*	*2*	0.758	0.021**	*1*	*2*	*2*	0.000***	0.017**	*1*	*2*	*2*	0.000***	0.103
Finland	*1*	*1*	*1*	0.114	0.001***	*1*	*1*	*1*	0.002***	0.000***	*1*	*1*	*1*	0.485	0.086*
Sweden	*1*	*1*	*1*	0.346	0.003***	*1*	*1*	*1*	0.432	0.000***	*1*	*1*	*1*	0.869	0.005***
Denmark	*1*	*1*	*1*	0.005***	0.699	*1*	*1*	*1*	0.047**	0.043**	*1*	*1*	*1*	0.304	0.000***
Norway	*1*	*1*	*1*	0.004***	0.928	*1*	*1*	*1*	0.087*	0.241	*1*	*1*	*1*	0.003***	0.964
United States	*1*	*1*	*1*	0.393	0.031**	*1*	*1*	*1*	0.505	0.000***	*1*	*1*	*1*	0.516	0.003***
United Kingdom	*1*	*1*	*1*	0.749	0.009***	*1*	*1*	*1*	0.065*	0.001***	*1*	*2*	*2*	0.718	0.000***
Canada	*1*	*1*	*1*	0.579	0.019**	*1*	*1*	*1*	0.879	0.073*	*1*	*2*	*2*	0.008***	0.214
Japan	*1*	*1*	*1*	0.329	0.003***	*1*	*1*	*1*	0.971	0.003***	*1*	*1*	*1*	0.834	0.001***

Note: An asterisk denotes significance at the 10% significance level, two asterisks denote significance at the 5% significance level, three asterisks denote significance at the 1% significance level.

Appendix F.

Table F1. Institutional variables used in the empirical analysis of section 6.3.

Independent variable	Source
Index of bargaining coordination and centralisation	Ochel (2000) based on OECD
Employment protection legislation	Allard (2005) based on OECD labour market statistics database (lmsd)
Union membership/ employment	Udnet based on OECD lmsd and Visser (2006)
Index of globalisation	Dreher (2006)
Product market regulation index	Conway, Janod and Nicoletti (2005)
Government involvement in collective bargaining	DuCaju et al. (2008)
High coverage of indexation (75-100%)	DuCaju et al. (2008)
Dominant level of collective bargaining: sectoral, occupational national, regional, company-level	DuCaju et al. (2008)

El Centro de Estudios Andaluces es
una entidad de carácter científico y
cultural, sin ánimo de lucro, adscrita
a la Consejería de la Presidencia
de la Junta de Andalucía.
El objetivo esencial de esta institución
es fomentar cuantitativa y cualitativamente
una línea de estudios e investigaciones
científicas que contribuyan a un más
preciso y detallado conocimiento de
Andalucía, y difundir sus resultados
a través de varias líneas estratégicas.

El Centro de Estudios Andaluces desea
generar un marco estable de relaciones
con la comunidad científica e intelectual
y con movimientos culturales en
Andalucía desde el que crear verdaderos
canales de comunicación para dar
cobertura a las inquietudes intelectuales y culturales.

**Las opiniones publicadas por los autores en
esta colección son de su exclusiva responsabilidad**

Depósito Legal: SE- 7354-08

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

E2008/15

Technological sources of productivity growth in Japan, the U.S. and Germany: What makes the difference?*

Jesús Rodríguez
UPO
José L. Torres
UMA

Resumen

En este artículo se trata de analizar las contribuciones de las tecnologías de la información y la comunicación (TIC) al crecimiento económico y la productividad del trabajo en tres economías: Japón, Alemania y Estados Unidos. Se utiliza un modelo de equilibrio general dinámico para cuantificar la contribución al crecimiento de la productividad en los tres países con distintos progresos tecnológicos. Los resultados muestran que la contribución de los activos TIC es de alrededor del 40 por ciento en Japón y Alemania, mientras que en Estados Unidos esta contribución es del 65 por ciento. La fuente de crecimiento es el progreso tecnológico neutral en Japón y Alemania, mientras que en Estados Unidos es progreso tecnológico es más específico de la inversión, principalmente asociado a los activos TIC.

Clasificación JEL: O3; O4.
Palabras Clave: Crecimiento de la productividad, cambio tecnológico específico de la inversión, cambio tecnológico neutral, tecnologías de la información y la comunicación.

* Autor correspondencia: jrodlop@upo.es

Centro de Estudios Andaluces
CONSEJERÍA DE LA PRESIDENCIA

Abstract

This paper studies the contribution of Information and Communication Technologies (ICT) on economic growth and labor productivity across the three leading economies in the world: Japan, Germany and the US. We use a dynamic general equilibrium growth model with investment-specific technological change to quantify the contribution to productivity growth in the three countries from different technological progress. We find that contribution to productivity growth due to ICT capital assets is about 0.40 percentage points for Japan and Germany, whereas it is about 0.65 percentage points in the case of the US. Neutral technological change is the main source of productivity growth in Japan and Germany. For the US, the main source of productivity growth derives from investment-specific technological change, mainly associated to ICT.

JEL classification: O3; O4.
Keywords: Productivity growth; Investment-specific technological change; Neutral technological change; Information and communication technology.

Abstract. This paper studies the contribution of Information and Communication Technologies (ICT) on economic growth and labor productivity across the three leading economies in the world: Japan, Germany and the US. We use a dynamic general equilibrium growth model with investment-specific technological change to quantify the contribution to productivity growth in the three countries from different technological progress. We find that contribution to productivity growth due to ICT capital assets is about 0.40 percentage points for Japan and Germany, whereas it is about 0.65 percentage points in the case of the US. Neutral technological change is the main source of productivity growth in Japan and Germany. For the US, the main source of productivity growth derives from investment-specific technological change, mainly associated to ICT.

JEL classification: O3; O4.

Keywords: Productivity growth; Investment-specific technological change; Neutral technological change; Information and communication technology.

1 Introduction

In this paper we investigate the contribution of different sources of technological progress to productivity growth in three leading world economies, i.e., Japan, Germany and the United States. 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 first of them is associated to the multifactor productivity, the second one is the amount of technology that can be acquired by using one unit of a particular physical capital asset.

Implicit technology can widely vary from one to another asset. Indeed recent typologies recommend using disaggregated measures of capital, as for instance, structures and equipment. Equipment are in turn divided into information and communication technologies (ICT) equipment -hardware, software and communication networks-, and non-ICT equipment -machinery, transport equipment, etc. The amount of technology incorporated in a computer, for instance, is much higher than that in an 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 decrease goes beyond the 25 per cent 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. Thereby, both the acquisition prices and the rental prices of capital equipment have been reducing in the last fifteen years.

Several recent studies have stressed the importance of the ICT on economy as a key factor behind the upsurge in the United States productivity after 1995 (see Collechia and Schreyer 2001; Stiroh 2002; Jorgenson, 2002, among others). As regards Europe, indexes show that E.U. countries fall well below the United States in terms of ICT penetration (see for instance Daveri, 2000; and Timmer and van Ark, 2005). Whereas there exist a huge literature for the case of the US 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 (2003), which show that total factor productivity growth in Germany since the mid 1990s has been much slower than in the US, especially in market services. Additionally, Inklaar, Timmer and van Ark (2006) show that TFP growth in ICT-intensive industries in the EU countries since 1995 has been much lower than in the US.[2]

Of particular interest is the case of Japan. Hayashi and Prescott (2002) calibrate a simple neoclassical growth model of 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 the analysis of Hayashi and Prescott (2002) 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 US, and that more than 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 US until 2013. They obtained that economic growth in Japan will continue to lag behind the US but that labor productivity growth in both economies will be similar.

In this paper we investigate the contribution of different sources of tech-

[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.

[2] Martínez, Rodríguez and Torres (2008b), using the Groningen Economic Growth Accounting Database, analyze the contribution of ICT to productivity growth in the European countries and the US, showing that the contribution of ICT in Germany is much lower than that in the US.

nological progress to productivity growth in three leading economies, Japan, Germany and the United States, for the period 1977-2005. 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 implicit change from different capital assets. Capital is disaggregated into three assets: structures, non-ICT equipment and ICT equipment. Fukao and Miyagawa (2007) also use the EU-KLEMS database and make a comparison between Japan and the mayor EU countries and the US. As in the mayor European countries, also Japan experienced a slowdown in TFP growth after 1995 of a similar magnitude.

The comparison of productivity growth contribution from technological progress across these three 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, the economic performance has been different in each of these three country, 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 evinced an upsurge of productivity ever since, while 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 contrast with the evolution of the European economies and specially with the performance of the US economy. Third, it is expected that ICT plays a key role in the economic growth as in these economies the ratio of ICT capital on total capital is high. Therefore, it seems to be very important to quantify how considerable this contribution is.

Our results show some important differences in the performance of these three economies. We find that neutral technological change is the driving source of productivity in Japan and Germany, accounting for about 75% of its growth. For the US economy, the main source of productivity derives from investment-specific technological change, mainly associated to ICT. The contribution to average productivity growth from implicit technological change is around 0.5 percentage points for Japan and Germany whereas it is about 0.75 percentage points for the US. 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 about 0.36 percentage points for Germany, around 0.42 percentage points for Japan and 0.62 percentage points for the US.

Finally, we study the effects of the four different technological change in the short-run. Whereas a neutral technological shocks has a positive impact on productivity growth, specific technological shock to structures and non-ICT equipment have a negative impact on productivity growth. This is provoked by the fact that a specific technological shock has a positive impact on hours worked. Additionally, specific technological shocks also have a negative impact on consumption growth and a positive impact on investment growth. Nevertheless, 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 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 focus 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 (2008a) which, in turn, is an extension of the Greenwood *et al.* (1997) model, incorporating two new features. *First*, 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. *Second*, denote $Q_{i,t}$ as the amount of asset i that can be purchased by one unit of output at time t. This price reflects the current state of technology for producing each capital asset. Greenwood *et al.* (1997) consider that this price is constant for structures, but is allowed to vary for equipment assets. In our model, we consider the existence of technological progress for the three capital assets.

2.1 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, $\{C_t\}_{t=0}^{\infty}$, and leisure, $\{O_t\}_{t=0}^{\infty}$. Preferences are represented by the following utility function:

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

where β is the discount factor and $\gamma \in (0,1)$ is the 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 ($H = 96 \times 52 = 4992$), times population in the age of taking labor-leisure decisions (N_t), minus the aggregated number of hours worked a year ($L_t = N_t h_t$, with h_t representing annual hours worked per worker).

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

$$\begin{aligned} & (1+\tau^c)\, C_t + I_{str,t} + I_{nict,t} + I_{ict,t} \\ = \; & \left(1-\tau^l\right) W_t L_t + \left(1-\tau^k\right) \left(R_{str,t} K_{str,t} + R_{nict,t} K_{nict,t} + R_{ict,t} K_{ict,t}\right) \\ & + T_t \end{aligned} \tag{2}$$

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 τ^c, τ^l, τ^k, are the consumption tax, the labor income tax and the capital income tax, respectively.

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

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

where δ_i is the depreciation rate of asset $i \in \{str, nict, ict\}$. $Q_{i,t}$ determines the amount of asset i than can be purchased by one unit of output, representing the current state of technology for producing capital i. In the standard neoclassical one-sector growth model $Q_{i,t} = 1$ for all t, that is, the amount of capital that can be purchased from one unit of final output is constant. 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.

The problem faced by the consumer is to choose C_t, O_t, and I_t to maximize the utility (1):

$$\max_{(C_t,I_t,O_t)} \sum_{t=0}^{\infty} \beta^t \left[\gamma \log C_t + (1-\gamma) \log O_t\right], \tag{4}$$

with $O_t = N_t\overline{H} - L_t$, subject to the budget constraint (2) and the law of motion (3), given taxes $\left\{\tau^c, \tau^k, \tau^l\right\}$ and the initial conditions K_{i0}, for $i \in \{str, nict, ict\}$.

2.2 Firms

The problem of firms is to find optimal values for the utilization of labor and the different types of capital. The production of final output Y requires the services of labor L and 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,

$$Y_t = A_t L_t^{\alpha_L} K_{str,t}^{\alpha_{str}} K_{nict,t}^{\alpha_{nict}} K_{ict,t}^{\alpha_{ict}} \tag{5}$$

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,

$$Y_t = C_t + I_{str,t} + I_{nict,t} + I_{ict,t} \tag{6}$$

Both output and investment are measured in units of consumption.

2.3 Government

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

$$\tau^c C_t + \tau^l W_t L_t + \tau^k \left(R_{str,t} K_{str,t} + R_{nict,t} K_{nict,t} + R_{ict,t} K_{ict,t}\right) = T_t. \tag{7}$$

2.4 Equilibrium

The first order conditions for the consumer are:

$$
\begin{aligned}
\frac{\gamma}{C_t} &= \lambda_t \left(1+\tau_c\right), &(8)\\
\frac{1-\gamma}{N_t H - L_t} &= \lambda_t \left(1-\tau_l\right) W_t, &(9)\\
\beta\lambda_{t+1}\left[\left(1-\tau_k\right) R_{i,t+1} + \frac{\left(1-\delta_i\right)}{Q_{i,t+1}}\right] &= \frac{\lambda_t}{Q_{i,t}}, &(10)
\end{aligned}
$$

for each $i \in \{str, nict, ict\}$. λ_t is the Lagrange multiplier assigned to date's t restriction.

Combining (8) and (9) we obtain the condition that equates the marginal rate of substitution between consumption and leisure to the opportunity cost of one additional unit of leisure:

$$
\frac{1-\gamma}{\gamma}\frac{C_t}{N_t H - L_t} = \frac{1-\tau_l}{1+\tau_c} W_t. \tag{11}
$$

Combining (10) and (8) gives

$$
\frac{1}{\beta}\frac{C_{t+1}}{C_t} = \left(1-\tau_k\right) Q_{i,t} R_{i,t+1} + \left(1-\delta_i\right)\frac{Q_{i,t}}{Q_{i,t+1}}, \tag{12}
$$

for $i \in \{str, nict, ict\}$. Hence, the (inter-temporal) marginal rate of consumption equates the after-tax rates of return of the three investment assets.

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

$$
R_{i,t} = \alpha_i \frac{Y_t}{K_{i,t}}, \tag{13}
$$

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

$$
W_t = \alpha_L \frac{Y_t}{L_t}, \tag{14}
$$

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

Additionally, the economy must satisfy the feasibility constraint:

$$
\begin{aligned}
& C_t + I_{str,t} + I_{nict,t} + I_{ict,t} &(15)\\
= \; & R_{str,t}K_{str,t} + R_{nict,t}K_{nict,t} + R_{ict,t}K_{ict,t} + W_t L_t = Y_t
\end{aligned}
$$

First order conditions for the household (8), (9) and (10), together with the first order conditions of the firm (13) and (14), the budget constraint of the government (7), and the feasibility constraint of the economy (15), characterize a competitive equilibrium for the economy.

2.5 The balanced growth path

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

According to a balanced growth path, output, consumption and investment must all grow at the same rate, which is denoted by g. However, the different types of capital would grow at a different rate depending on the evolution of their relative prices. From the production function (5) the balanced growth path implies that:

$$g = g_A g_{str}^{\alpha_{str}} g_{nict}^{\alpha_{nict}} g_{ict}^{\alpha_{ict}}, \tag{16}$$

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 law of motion (3) we have that the growth of each capital input is given by:

$$g_i = \eta_i g, \tag{17}$$

with η_i being the exogenous growth rate of $Q_{i,t}$, $i \in \{str, nict, ict\}$. 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 (17) says that the capital stock growth also depends on technological progress in the process producing the different capital goods. Therefore, it is possible to express output growth as a function of the exogenous growth rates of production technologies as:

$$g = \underbrace{g_A^{1/\alpha_L}}_{\text{Neutral change}} \times \underbrace{\eta_{str}^{\alpha_{str}/\alpha_L} \eta_{nict}^{\alpha_{nict}/\alpha_L} \eta_{ict}^{\alpha_{ict}/\alpha_L}}_{\text{Implicit change}}. \tag{18}$$

Expression (18) implies that the log of output growth can be decomposed as weighted sum of the neutral technological progress growth and implicit technological progress, as given by η_i for $i \in \{str, nict, ict\}$. Growth rate of each capital asset can be different, depending on the relative price of the new capital in terms of output.

Define the following steady state ratios

$$\rho_i \equiv \left(Q_i \frac{Y}{K_i}\right)_{ss}, \tag{19}$$

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

$$\omega_i (1-c) = s_i \equiv \left(\frac{I_i}{Y}\right)_{ss}, \tag{21}$$

$$v \equiv \left(\frac{L}{NH}\right)_{ss} = \left(\frac{h}{4992}\right)_{ss} \in (0,1), \tag{22}$$

where the subscript ss denotes the steady state reference. Using these ratios, the balanced growth path can be characterized as

$$g/\beta = \eta_i^{-1} \left[(1-\tau_k)\, \alpha_i \rho_i + 1 - \delta_i\right], \tag{23}$$

$$\eta_i g = \rho_i s_i + 1 - \delta_i, \tag{24}$$

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

$$1 = c + s_{str} + s_{nict} + s_{ict}, \tag{25}$$

$$1 = \alpha_L + \alpha_{str} + \alpha_{nict} + \alpha_{ict}. \tag{26}$$

$$c = \alpha_L \frac{\gamma}{1-\gamma} \frac{1-\tau_l}{1+\tau_c} \left(v^{-1} - 1\right), \tag{27}$$

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 US 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 of 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

[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.

linked to the growth rates from 1991 to 2005 using the data from reunified Germany.

A Törnqvist index has been used to construct aggregate series of Non-ICT and ICT (capital and investment) series, that takes 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 throughout this analysis.

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 US and (reasonably) stable in Germany. The Japanese growth rate is now almost a half during 2000-2005 as relative to the nineties, while the US growth rate is just the double. However, average productivity growth in Japan during the period 2000-2005 is similar to the US productivity growth and higher than in Germany. 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). Indeed some studies have highlighted that the higher the ICT deepening within a sector or an economy, the higher its productivity (see Oliner and Sichel, 2000, and Baily and Lawrence, 2001). As regards the Japanese rates, a similar (more dramatic) contraction is also documented in Hayashi 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

$$\Omega = \left\{ g, v, \alpha_L, \{\delta_i, s_i, \eta_i\}_{i \in \{str, nict, ict\}}, \tau^c, \tau^l, \tau^k \right\}. \tag{28}$$

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. In the case of Germany, this first order moment is calculated for the period 1991-2005. Note notwithstanding that the this figure is almost identical to the one in table 1 using observations from 1977 to 2005. Following is the fraction of hours worked over total hours, $v = h/4992$. 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 0.425 in 1977, up to a stable value of 0.35 in the mid of the nineties (see Hayashi and Prescott, 2002). This decrease is concerned with institutional reforms in the labor market, that have limited the workweek since the late eighties. For the case of the US, this ratio is very stable using the EU-KLEMS data. Greenwood *et al.* (1997, 2000) use instead a value of $v = 0.24$ for the US.

As regards the cost shares, the EU-KLEMS data base also provides estimated series of labor compensation and capital compensation that allow 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 cases of the US 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 US 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 (21) and (25), note that $s_i = (1-c)\,\omega_i$, and $\sum_i \omega_i = 1$. Non-ICT assets have the highest weight, specially in Japan

[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.

and Germany, 47%. The US 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 US and Germany. Greenwood *et al.* (1997) assume that the price of structures moves according to the price index of durable goods. In our case, this prices fluctuates by 0.17% in the US and Germany, but has a negative decay in Japan, -0.4%. The change in the price of non ICT equipment is 0.4% per cent in the US and Germany. In the case of Japan, this variation is 1%. Finally, the amount of ICT equipment that can be purchased by one unit of output has increased by 9% per year in the US and Germany, and 6.3% per year in Japan. Implicit technological change, as measured by the evolution of the Q_i, is thereby stronger of the ICT equipment.

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 structures shows moderately long swings around one, which is the assumption used by Greenwood *et al.* (1997) and Bakhshi and Larsen (2005). The implicit change for non-ICT equipment shows a slightly upward trend. Finally, we also observe a significant upward trend in the case of the implicit change of ICT equipment at an accelerate rate, 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 1980-2001. Tax structure is similar in Japan and the US, where labor income taxes are higher than capital income taxes. In Germany, the consumption tax rates doubles those of Japan and the US, but the labor income tax is higher that the capital income tax.

3.1 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. Figure 2 plots the observed productivity growth and the calibrated one derived from the model for the three countries. We use series of $Q_{i,t}$ and the total factor productivity A_t as exogenous. As we can observe, the calibrated model makes an impressive very good job in explaining movements in labor productivity growth. This means that our model is able to replicate non only 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 US, and 0.8542 for Germany. For the US economy we observe some important differences in the period 1981-1985, with observed productivity growth larger than the predicted one.

Therefore, we conclude that the model replicates the empirical figures reasonably well, despite it is built in terms of the steady state, thus, from a long-run perspective. However, results presented in figure 2 show that the model can also replicate productivity growth behavior in the short-run.

4 Long-run analysis

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

This calculation is given by expression (18), 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 (23) to (27) to solve for the following nine unknowns

$$\left\{ \{\alpha_i, \rho_i\}_{i\in\{str,nict,ict\}}, c, \beta, \gamma \right\}, \tag{29}$$

given the set of parameters Ω given in (28) 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 (18).

Notice that table 2 proposes a vector of investment weights for the portfolio of physical assets, ω_i. The investment-saving rate on asset i would be given by $s_i = (1-c)\,\omega_i$, and the total investment-saving rate is $(1-c)$. 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 (23). 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 (23) 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. Bakhshi and Larsen (2005) use an after tax real rate of return of 5.3% for the UK economy. In this paper, in order to overcome the uncertainty associated to this rate, we will calibrate the parameters of the model in (29) 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 1.51 and 1.58 percentage points, while implicit technological change produces changes from 0.65 to 0.55 percentage points. Therefore, neutral technological change account for a fraction of around 80% of productivity growth. The remaining 20% is accounted for the investment-specific technological change. ICT equipment provide most of this contribution, from 0.49 to 0.43 percentage points, whereas contribution from non-ICT equipment provide around 0.20 percentage points. It is important to note that the contribution from structures is negative, around -0.2 percentage points. This results from the fact that relative prices of structures decreased in Japan during the sample period.[6] The calibrated

[6] Martínez, Rodríguez and Torres (2008b) also find negative contribution from struc-

saving rate moves within an interval from 15.5% 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 $\beta = 0.976$ and Hayashi and Nomura (2005) use a value of 0.964. Our benchmark model produces this same discount factor when the after tax discount rate of 6-7%, with a stationary investment rate of 15-17%.

Miyagawa, Ito and Harada (2004) study the contribution of IT 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 IT capital, show the existence of an overinvestment in IT capital relative to non-IT capital in the US, 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.

U.S.A. Results are reported in table 4. The calibrated value of productivity growth is again nearby 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, 0.70. This ICT contribution widely exceeds that of the neutral change. Neutral technological change contribution to productivity growth is between 0.32 and 0.47 percentage points. Therefore, the implicit technical change account for a fraction between 70% and 60% of the total productivity growth. This is in line with the 58% result provided by Greenwood *et al.* (1997). The contribution of structures is very low, 0.03 percentage points. This results is also in line with the one in Greenwood *et al.* (1997) as they assume that the contribution of structures to productivity growth is zero, given the assumption of no technological progress associated to this capital asset. The contribution to productivity growth from non-ICT equipment is around 0.05 percentage points. The saving rate moves within an interval from 14.2% to 11.2%. Greenwood *et al.* (1997) propose a discount factor for the US of $\beta = 0.97$, and an investment rate of 11.4%. Like in the case of Japan, our exercise produces this rates

tures in the case of some European countries.

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.

Germany. Results are finally reported in table 5. The calibrated value of productivity growth fits the observed one. Productivity growth is now dominated by the neutral technological change as in the case of Japan. Neutral change produces increases in productivity of around 1.85 percentage points. Therefore, the neutral technical change account for a fraction of 80% of total productivity growth with implicit technical change accounting for the rest. The contribution of ICT equipment is between 0.36 and 0.41 percentage points. Contribution from non-ICT equipment is about 0.07 percentage points whereas contribution from structures is of 0.02 percentage points. These results are very similar to the ones obtained for the US. The saving rate moves within an interval from 13.2% to 16.7%. Fernández de Córdoba and Kehoe (2000) and 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%.

In view of these tables, there are four results that we would like to highlight. *First*, neutral technological change dominates productivity growth in Japan, 70%, and Germany, 80%, while investment specific technological change accounts for a fraction of 60% of the US productivity growth. This implies that the sources of long run productivity growth are very different in the US 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 US. The contribution to productivity growth from implicit technological change is around 0.45 percentage points for Japan, 0.5 percentage points for Germany and 0.75 percentage points for the U.S. Another difference is found in the contribution from neutral technological change. In this case we obtain a value of 1.71 percentage points for Japan, 1.85 percentage points for Germany and only a value of 0.4 percentage points for the U.S. This factor accounts for an important fraction of productivity growth in Japan and Germany with respect to the US economy during the sample period.

Second, technology embedded in the ICT assets are the main source of the specific change. With only ICT investment-specific technological change, productivity growth would have increased by 0.41% in Japan, 0.46% in Germany and 0.71% in the US. Table 1 reported that productivity growth is declining in Japan, increasing in the US and stable in Germany, and table

2 reported that the US has invested in ICT assets more than Japan and Germany have done, while the amount of technology implicit in the ICT assets is the highest one, as measured by the $\eta_i's$, $i \in \{str, nict, ict\}$. This supports other results that make the ICT responsible of the upsurge in the US 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 US and Germany, in the case of Japan this figure is 0.25 percentage points. This implies that technological change associate to non-ICT equipment is much larger in the Japanese economy than in the other two countries, being an important factor explaining the larger productivity growth in Japan as compared with Germany and the US.

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 US is the leading economy in the new information and communication era. However, if we pay attention at the contribution from total (ICT and non-ICT) investment-specific technological change, during the period 1977-2005, Japan have been the leading country. Average contribution to productivity growth from specific-technological change have been of about 1.5 percentage points for Japan, 0.75 points for the US and 0.5 points for Germany. On the other hand, Japan have been the country with the larger average productivity growth during the period. 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. Our results are consistent with the ones presented by Fukao and Miyagawa (2007) for the three countries. These authors show that the US has experienced a very rapid increases in ICT capital after 1995. On the contrary, ICT capital in Japan in 2004 were less than twice as high as their 1995 level. Jorgenson and Motohashi (2005) show that the contribution of IT 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.

In the US we obtain that ICT contribution to productivity growth is similar in both sub-periods, about 0.62 percentage points. 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. However, contribution from investment-specific technological change decreases in the second subperiod for the US. This result is affected by the negative contribution of structures. Whereas average contribution from structures is close to zero for the whole period, we find important differences across time. In fact, whereas in the period 1977-1995 average contribution is 0.16 percentages points, contribution from structures is negative (-0.2 percentage points) during the period 1995-2005.

Neutral technological change is the main source of productivity growth for the three countries and about 75-80% of total productivity growth is due to this source of technological change during 1995-2005. Comparing both subperiods of time, we obtain that neutral technological change contribution to productivity growth decreases in Japan, increases in the US 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 to the reduction in total factor productivity growth. Average neutral technological change contribution is negative in the US 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.

5 Short-run analysis

In this section we analyze the quantitative effects of cyclical fluctuations both from neutral and investment-specific technological shocks. Whereas neutral technological shocks have been extensively studied in the literature, the model developed in the previous sections allows us to study the effect of three additional types of investment-specific technological shocks. That is, we can study the effects of technological shocks to the three types of capita assets under consideration (structures, non-ICT equipment and ICT equipment. For instance, it is possible to quantify the effect of a shock to equipment as compared with a shock to structures.

We assume that the stochastic structure governing the evolution of the implicit technological shocks is given by

$$
\begin{aligned}
\ln Q_{i,t} &= a_i + \ln(\eta_i)\, t + u_{i,t}, \qquad (30)\\
u_{i,t} &= \rho_i u_{i,t-1} + \varepsilon_{i,t}\\
\varepsilon_{i,t} &\sim iid\mathcal{N}\left(0, \sigma_i^2\right).
\end{aligned}
$$

with $0 < \rho_i < 1$, for $i \in \{str, nict, ict\}$. This means that this process is the sum of a trend and a cycle. 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 ρ_i The long run growth rate of $Q_{i,t}$ is $\ln \eta_i$. Analogously the process for the neutral technological change is:

$$
\begin{aligned}
\ln A_t &= a_A + \ln(g_A)\, t + u_{A,t}. \qquad (31)\\
u_{A,t} &= \rho_A u_{A,t-1} + \varepsilon_{A,t},\\
\varepsilon_{A,t} &\sim iid\mathcal{N}\left(0, \sigma_A^2\right).
\end{aligned}
$$

We also assume that these shocks are orthogonal $E(\varepsilon_{i,t}\varepsilon_{j,t}) = 0$, for any $i, j \in \{str, nict, ict, A\}$ and $i \neq j$. These processes are filtered and written as

$$
\begin{aligned}
\ln Q_{i,t} &= \gamma_{i,0} + \gamma_{i,1} t + \rho_i \ln Q_{i,t-1} + \varepsilon_{i,t}, \qquad (32)\\
\text{with } \gamma_{i,0} &= (1-\rho_i)\, a_i + \rho_i \ln(\eta_i),\\
\gamma_{i,1} &= (1-\rho_i) \ln(\eta_i),\\
&\quad \text{given } \ln(\eta_i),
\end{aligned}
$$

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

We next study how these shocks affect the economy around the balance growth path, using the impulse response functions from a log-linear version of previous model. The neutral shock, $\varepsilon_{A,t}$, has a direct 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 (12), and a substitution between consumption

[7] Greenwood *et al.* (2000) for the US 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, very similar to our estimates.

and leisure. Output is therefore affected in the current period through the impact on labor supply and on saving decisions.

Instead, a non neutral shock in asset $i \in \{str, nict, ict\}$ 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. 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 $i \in \{str, nict, ict\}$ impulses the marginal product of own and the remaining factors in the production function, which implies the existence of a complementary effect.

Labor productivity therefore 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 $i \in \{str, nict, ict\}$, 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.[8]

Figures 3 to 5 plot the impulse response of productivity growth, consumption growth and investment growth, respectively, in response to a 1% increase in the four shocks. In the impulse response figures, steady state productivity growth have been normalized to zero. So, the figures show deviations of variables growth rates with respect to the steady state.

In the three economies under consideration, labor productivity increases in response to a positive neutral technological shock. The highest (positive) 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 1% neutral shock. Specific technological shocks have a negative impact effect on productivity growth, showing a hump-shaped impulse response. A technological shock to structures has a negative impact on productivity, according to the previous arguments. Only a few periods afterwards the effect turns out positive, given that the effect of this shock on labor is larger than on output. In quantitative terms, the larger negative impact is observed for the Japanese economy. A technologi-

[8]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 of investment.

cal shock to non-ICT equipment also has a negative impact on productivity but it becomes positive thereafter. The short run effect of an ICT shock on productivity is also negative but negligible. Concerning the persistency of these shocks, all shocks have a cumulative positive effect on productivity in the medium and the long term.

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. Again the larger effects correspond to a technological shock to structures while the effect of a technological shocks to ICT equipment is negligible.

Figure 5 shows the impulse-responses for investment growth. For each country we compute four impulse-response functions, corresponding to (the growth rates of) structures, non-ICT equipment, ICT equipment and total investment, in terms of the four technological shocks. 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 period with a total investment growth rate below the steady state value. A similar qualitative effect of neutral technological shocks is observed with respect to structures investment growth but of lesser quantitative importance. However, structures technological shocks has a very positive impact effect on structures investment growth but in the next period the effect becomes negative as structures investment growth lower than its steady state growth value. A non-ICT technological shock has a negative impact effect on structures investment growth

The most interesting result is the response of ICT equipment investment growth and non-ICT equipment investment growth. On the one, 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 revert in the next period, indicating that the different capital assets are complementaries in the short-run, in spite of the rivalry existing among different capital assets in the investment process. On the other hand, a structures technological shock has important effects on equipment, both ICT and non-ICT, investment growth. In fact, a positive structures technological shock has an immediate negative effect on investment growth in both ICT and non-ICT equipment indicating the existence of a substitution effect which provokes a reallocation in the portfolio assets. 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.

Finally, table 8 reports the variance decomposition of productivity, consumption and investment. It is worth mentioning that most in 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 shock is the responsible of about 80% of productivity variability in the US and about 75% in Germany. In Japan, the non neutral shocks account for a fraction of a 40% of this variance in the medium and the long term.[9] As regards consumption and saving decisions, most of this variability is due to the shock to structures. Note that this shock has been usually neglected in another similar analysis (i.e. $Q_{str,1} = 1$ constant for all period). The variability of ICT investment is mainly guided 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.

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 to decompose productivity growth in four different technology progress sources: neutral technological change and three different investment-specific technological change, associated to three different capital assets: structures, non-ICT equipment and ICT.

The results obtained from the calibration of the model suggests 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 US than in Japan and, specially, than in Germany. This differences is mainly due to the technological progress associated to ICT capital assets, more intensive in the US than in the other two economies. On the

[9] 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.

other hand, contribution from neutral technological change is much more important in Japan and Germany, than in the US. This factor is the main responsible of the larger productivity growth showed by the Japanese and German economies, as compared with the US economy. However, the contribution to productivity growth from ICT capital is much larger in the US than in Japan and Germany. Additionally, we obtain that "traditional" non-ICT capital technological progress plays an important role in the Japanese productivity growth, whereas its contribution in Germany and the US is very low.

Our results seems to provide an "optimistic" rather than a "pessimistic" view of the Japanese economy, showing a similar behavior 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 US, but with output growth larger in the US, due to the slower growth in labor input in the Japanese economy.

Finally, we show how the different technology shocks induce different responses of the economy. Particularly of interest is that a technological shock in non-ICT equipment and structures moves labor productivity and consumption growth downward their balanced growth paths. Technological shocks specific to each capital asset change the portfolio weight of the economy. We find a high degree of substitution between structures and equipment, whereas we find a high degree of complementarity between ICT equipment and non-ICT equipment in the investment decision process.

References

[1] Baily, M. and Lawrence, R. (2001): Do We Have a New E-Conomy?, *American Economic Review,* 91, 308-312.

[2] Bems, R. and K.J. Hartelius (2006): Trade deficits in the Baltic States: How long will the party last?, *Review of Economic Dynamics,* 9, pp. 179-209.

[3] Boscá, J., García, J. and Taguas, D. (2008): Taxation in the OECD: 1965-2004, Working Paper, Misterio de Economía y Hacienda, Spain.

[4] Braun, R. and Shioji, E. (2007): Investment specific technological changes in Japan, *Seoul Journal of Economics*, 20, n. 1.

[5] Cummins, J.G. and Violante, G. L. (2002): Investment-specific technical change in the US (1947-2000): Measurement and macroeconomic consequences, *Review of Economic Dynamics*, 5, 243-284.

[6] Fernández de Córdoba, G. and T. Kehoe (2000): Capital flows and real exchange rate fluctuations following Spain's entry into the European Community. *Journal of International Economics,* 51, 49-78.

[7] Fukao, K. and Miyagawa, T. (2007): Productivity in Japan, the US, and the mayor EU economies: Is Japan falling behind? *RIETI Discussion Paper Series* 07-E-046.

[8] Gollin, D. (2002): Getting Income Shares Right. *Journal of Political Economy*, 110, pp. 458-474.

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

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

[11] Hayashi, F. and Prescott, E. (2002): The 1990s in Japan: A lost decade, *Review of Economic Dynamics*, 5, 206-235.

[12] Inklaar, R., McGuckin, R. and van Ark, B. (2003): ICT and productivity in Europe and the United States: Where do the differences come from? *Economics Program Working Paper Series*, n. 03-05, The Conference Board, New York.

[13] Inklaar, R., Timmer, and van Ark, B. (2005): ICT and productivity in Europe and the United States. Where the differences come from?, *The Conference Board EPWP* 03-05.

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

[15] Jorgenson, D. (2002): *Economic growth in the information age.* MIT Press, Cambridge.

[16] Jorgenson, D. and Motohashi, K. (2005): Information technology and the Japanese economy. *Journal of the Japanese and International Economies*, 19, 460-481.

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

[18] Martínez, D., J. Rodríguez and Torres, J.L. (2008a): The productivity paradox and the new economy: The Spanish case. Forthcoming in *The Journal of Macroeconomics*, 30, 1169-1186.

[19] Martínez, D., J. Rodríguez and Torres, J.L. (2008b): Productivity growth and technological change in Europe and the US, Mimeo.

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

[21] Miyagawa, T., Ito, Y., and Harada, N. (2004): The IT revolution and productivity growth in Japan. *Journal of the Japanese and International Economies*, 18, 362-389.

[22] Miyagawa, T., Sakuragawa, Y., and Takizawa, M. (2006): The impact of technology shocks on the Japanese business cycle- An empirical analysis based on the industry data, *Japan and the World Economy*, 18, 401-417.

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

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

[25] Shinjo, K. and Zhang, X. (2003): Productivity analysis of IT capital stock: The USA-Japan comparison. *Journal of the Japanese and International Economies*, 17, 81-100.

[26] Sonobe, T. and Otsuka, K. (2001): A new decomposition approach to growth accounting: derivation of the formula and its application to prewar Japan. *Japan and the World Economy*, 12, 1-14.

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

[28] Tokui, J., Inui, T. and Kim. Y. (2008): Embodied technological progress and productivity slowdown in Japan, *RIETI Discussion Paper Series* 08-E-017.

[29] Vijselaar, F. W. and Albers, R. M. (2002): New Technologies and Productivity Growth in the Euro Area, *ECB Working Papers* No. 122.

Table 1: 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
v	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_{str}	0.9917	1.0017	1.0017
η_{nict}	1.0073	1.0043	1.0046
η_{ict}	1.0674	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)	2.13	2.13	2.13	2.12
Neutral change (a)	1.63	1.68	1.71	1.75
Implicit change (b)=(b1)+(b2)+(b3)	0.50	0.45	0.41	0.38
Structures (b1)	-0.19	-0.20	-0.21	-0.22
NICT equipment (b2)	0.19	0.18	0.18	0.17
ICT equipment (b3)	0.49	0.47	0.45	0.43
Discount factor, β	0.9906	0.9811	0.9719	0.9628
Investment rate	20.08	18.29	16.79	15.52
Cost shares				
Structures, α_{str}	0.1461	0.1551	0.1626	0.1690
NICT equipment, α_{nict}	0.1660	0.1600	0.1550	0.1507
ICT equipment, α_{ict}	0.0492	0.0462	0.0438	0.0417
Decomposition of technological change				
Neutral	76.53	78.76	80.63	82.23
Implicit	23.47	21.24	19.37	17.77

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)	1.11	1.13	1.15	1.16
Neutral change (a)	0.32	0.38	0.42	0.47
Implicit change (b)=(b1)+(b2)+(b3)	0.79	0.75	0.72	0.70
Structures (b1)	0.03	0.03	0.03	0.03
NICT equipment (b2)	0.06	0.05	0.05	0.05
ICT equipment (b3)	0.70	0.67	0.64	0.61
Discount factor, β	0.9754	0.9661	0.9570	0.9481
Investment rate	14.19	13.02	12.02	11.17
Cost shares				
Structures, α_{str}	0.1190	0.1249	0.1299	0.1342
NICT equipment, α_{nict}	0.0978	0.0949	0.0925	0.0904
ICT equipment, α_{ict}	0.0584	0.0554	0.0528	0.0506
Decomposition of technological change				
Neutral	28.98	33.49	37.18	40.27
Implicit	71.01	66.51	62.81	59.72

Table 5: Germany, 1977-2005

After tax return rate, $(g/\beta - 1) \times 100$	**4%**	**5%**	**6%**	**7%**
Observed productivity, g	2.37	2.37	2.37	2.37
Calibrated productivity, (a)+(b)	2.31	2.31	2.31	2.31
Neutral change (a)	1.80	1.82	1.84	1.86
Implicit change (b)=(b1)+(b2)+(b3)	0.51	0.48	0.47	0.45
Structures (b1)	0.02	0.02	0.02	0.03
NICT equipment (b2)	0.07	0.07	0.07	0.06
ICT equipment (b3)	0.41	0.39	0.37	0.36
Discount factor, β	0.9839	0.9745	0.9653	0.9563
Investment rate	16.70	15.34	14.19	13.19
Cost shares				
Structures, α_{str}	0.1084	0.1132	0.1174	0.1210
NICT equipment, α_{nict}	0.1153	0.1122	0.1095	0.1072
ICT equipment, α_{ict}	0.0351	0.0333	0.0319	0.0306
Decomposition of technological change				
Neutral	77.98	78.90	79.69	80.37
Implicit	22.01	21.09	20.30	19.63

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	2.68	2.28
Calibrated productivity, (a)+(b)	2.43	1.55	0.50	2.22	2.46	2.44
Neutral change (a)	2.06	1.17	-0.28	1.67	2.08	1.94
Implicit change (b=b1+b2+b3)	0.37	0.37	0.79	0.55	0.37	0.51
Structures (b1)	-0.27	-0.14	0.16	-0.20	-0.16	0.09
NICT equipment (b2)	0.21	0.10	0.01	0.13	0.20	0.04
ICT equipment (b3)	0.43	0.42	0.62	0.62	0.34	0.38
Percentage						
Neutral	0.85	0.76	-	0.75	0.85	0.79
Implicit	0.15	0.24	-	0.25	0.15	0.21

Table 7: Estimation of parameters

	Japan	**U.S.A.**	**Germany**
ρ_{str}	0.9030	0.9726	0.8419
σ_{str}	0.0195	0.0180	0.0096
ρ_{nict}	0.9461	0.9221	0.9495
σ_{nict}	0.0162	0.0104	0.0102
ρ_{ict}	0.9388	0.8472	0.3871
σ_{ict}	0.0478	0.0274	0.0186
ρ_{A}	0.8522	0.9478	0.7239
σ_{A}	0.0154	0.0142	0.0087

Table 8: Forecast error variance decomposition

	Japan				USA				Germany			
	ε_{str}	ε_{nict}	ε_{ict}	ε_A	ε_{str}	ε_{nict}	ε_{ict}	ε_A	ε_{str}	ε_{nict}	ε_{ict}	ε_A
Time					Productivity							
1	12.16	0.16	0.00	87.67	7.56	0.04	0.00	92.40	8.31	0.29	0.00	91.40
5	13.67	18.93	9.31	58.09	11.03	3.21	4.68	81.08	10.18	11.67	3.44	74.72
10	13.56	19.28	9.58	57.57	11.96	3.23	4.63	80.18	10.17	11.76	3.37	74.70
50	13.58	19.11	9.53	57.78	11.83	3.18	4.55	80.44	10.22	11.74	3.35	74.69
					Consumption							
1	83.79	1.13	0.00	15.08	77.95	0.38	0.01	21.66	74.26	2.58	0.04	23.12
5	67.95	8.80	3.33	19.91	65.78	1.59	1.27	31.36	65.05	8.73	1.00	22.22
10	66.47	9.91	3.98	19.63	65.67	1.68	1.30	31.35	67.14	9.20	0.98	22.68
50	65.85	9.87	4.04	20.24	64.75	1.66	1.28	32.30	66.82	9.18	0.97	23.02
					Structures investment							
1	65.08	27.34	2.55	5.02	82.21	8.12	2.16	7.51	67.77	23.02	1.50	7.71
5	61.64	32.03	3.57	2.76	80.37	11.14	3.72	4.77	63.86	28.24	2.91	4.99
10	61.62	32.03	3.57	2.79	80.33	11.13	3.72	4.82	63.85	28.24	2.91	5.01
50	61.61	32.03	3.57	2.79	80.32	11.13	3.72	4.83	63.85	28.24	2.91	5.01
					Non-ICT investment							
1	49.21	50.58	0.00	0.20	69.52	29.84	0.01	0.64	46.49	53.07	0.02	0.42
5	50.57	49.30	0.01	0.12	70.62	28.98	0.04	0.36	48.50	51.16	0.06	0.27
10	50.57	49.30	0.01	0.12	70.62	28.98	0.04	0.36	48.50	51.16	0.06	0.28
50	50.57	49.30	0.01	0.12	70.61	28.98	0.04	0.36	48.50	51.16	0.06	0.28
					ICT investment							
1	11.29	0.00	88.68	0.03	27.58	0.03	72.15	0.25	13.53	0.12	86.31	0.04
5	11.18	0.01	88.80	0.02	26.72	0.05	73.08	0.15	10.64	0.13	89.21	0.02
10	11.18	0.01	88.80	0.02	26.72	0.05	73.08	0.15	10.64	0.13	89.21	0.02
50	11.18	0.01	88.80	0.02	26.72	0.05	73.08	0.15	10.64	0.13	89.21	0.02
					Total investment							
1	39.32	0.59	0.00	60.09	50.76	0.29	0.01	48.94	39.61	1.55	0.02	58.81
5	49.17	9.88	5.73	35.21	56.78	1.68	3.28	38.26	44.86	4.96	2.47	47.41
10	48.91	9.90	5.73	35.46	56.58	1.70	3.29	38.44	44.77	5.00	2.46	47.76
50	48.89	9.91	5.73	35.47	56.56	1.70	3.28	38.46	44.77	5.01	2.46	47.76