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Information and Communication Technologies in a Multi-Sector Endogenous Growth Model

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Abstract
This paper investigates the impact of Information and Communication Technologies (ICT) on growth in an economy, consisting of three sectors, ICT-producing, ICT-using and non-ICT-using. The benefits from ICT come from the falling prices of the ICT-using sector's good, which is used for the production of intermediate goods. Their falling prices provide incentives for investment for sectors using them, so the non-ICT-using sector experiences sustained growth driven by capital accumulation. Rates of growth across the three sectors differ, but the aggregate economy is on a balanced growth path with constant labour shares across sectors. US evidence confirms the model's predictions.

JEL Classification: O40, O41
Keywords: multi-sector economy, endogenous growth, balanced growth path, Information and Communication Technologies

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This fall has generated incentives to invest in these goods, by driving down the production cost for ICT-using industries. The resulting falling prices of the goods produced by the ICT-using industries give rise to investment opportunities for the industries that use the ICT-using sector's goods. Through this mechanism, the gains from the fall in costs are transmitted to the entire economy. In order to develop intuition for the impact of price declines of ICT goods on aggregate productivity, we may consider the following example: Say an ICT-producing industry develops a new microprocessor. This chip can be used in the production of general-purpose machinery that is of higher quality and can be made available at a lower price[1]. The air-conditioners that will be part of this production will become available to financial institutions, as well as to hairdressers. So, despite the fact that the hairdressers do not use directly ICT, they benefit from its advances because it lowers their costs.

Figure 1 shows the employment shares in the three sectors (excluding government) that this paper studies for the United States over the period 1979-2001. There are two interesting features in these data. First, the share of the ICT-producing sector is very small (4%), and the share of the ICT sector (the aggregate of ICT-using and ICT-producing sectors) is much smaller compared to that of the non-ICT sector. Second, the employment shares appear constant over time.

The theoretical framework presented in this paper can account for the two facts present in Figure 1, and for the findings of the growth accounting exercises. In the model, the ICT-producing sector is the technology producing sector; by construction, it is the engine of growth. The sector that directly benefits from the advances in ICT production is the one using ICT capital, the "ICT-using" sector. As long as this sector is producing capital goods that are used throughout the economy, by both the ICT-using and the non-ICT-using sectors, the ICT-production growth is transmitted to the entire economy. This is because the falling costs for the ICT-using sector allow for falling prices of its output and therefore falling capital prices. Thus, growth is driven by capital accumulation, of both ICT-capital and non-ICT-capital

[1] Among the most intensive ICT users in the United States economy are industries producing predominently business services and equipment. See discussion in Section 4.

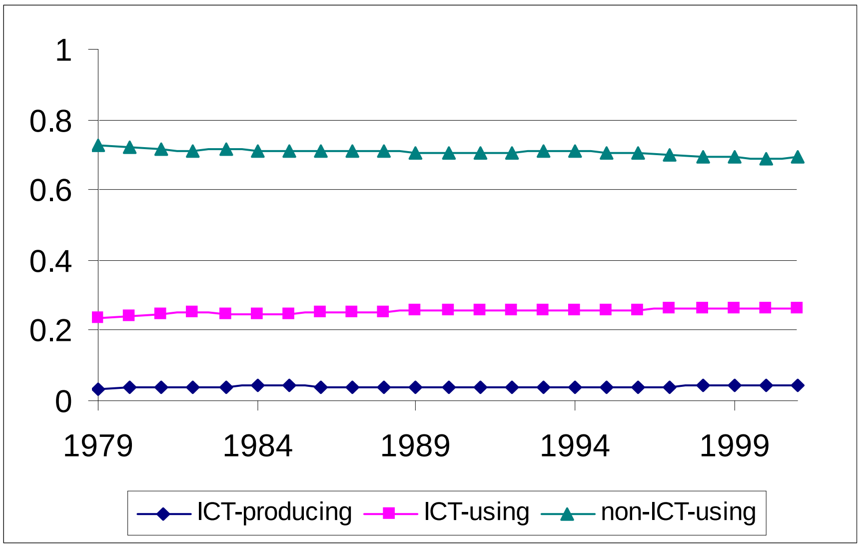

Figure 1: Shares out of total hours worked.

goods. The ICT-using sector, however, will be growing faster compared to the non-ICT-using sector, as it grows because of both positive TFP growth and capital accumulation. Under some restrictions on preferences the aggregate economy is on a constant growth path with constant employment shares.

The paper is closely related to the endogenous growth literature that focuses on R&D (Romer, 1990, Grossman and Helpman, 1991). It introduces into a Romer (1990)-type model the non-ICT-using sector that is using only technologically obsolete intermediate capital goods. The aim is to account for the fact that for a long period after the introduction of new large scale technologies, some productive industries do not make use of them.

Another strand of literature related to this paper is the recent theoretical literature that deals with the impact of ICT upon growth. Following the "paradox" of the low productivity growth of the 1970s and 1980s (Quah, 2001), the recovery of productivity growth in the United States economy in the 1990s has been explained in the context of General Purpose Technologies (GPT) (Helpman and Trajtenberg, 1998)[2]. Several empirical studies find

[2]Economic historians were the first to draw the analogy between ICT and great inven-

supportive evidence for the hypothesis that ICT is a GPT, i.e. that the use of ICT goods involves important externalities for the ICT intensive industries (Jorgenson et al., 2004, Oliner and Sichel, 2002, Triplett and Bosworth, 2002, Basu et al., 2003). While motivated by the idea of a GPT, the model of this paper does not aim to explain the cycle involved in the introduction and adoption of a new large scale technology. Instead, it shows how unbalanced growth at the disaggregate level, caused by the lack of adoption of a new essential technology, can still be consistent with balanced growth at the aggregate level.

Making use of United States data at the three-digit ISIC level, this paper provides some supportive evidence for the predictions of the model. Industries reported in the original database are grouped into the three sectors according to whether they produce ICT and their ICT usage and their properties are compared to the model's predictions. The data support the model's prediction that growth across the different sectors is different, with the ICT-using sector growing faster than the non-ICT-using sector. They also support that any output growth differences among the final goods sectors are cancelled out by changes in relative prices. The data show no reallocation of labour across these sectors. In addition, the model's multi-sector structure provides an explanation for how a small TFP growth rate at the aggregate level is compatible with the high productivity of the ICT-producing sector.

This paper is organized as follows: Section 2 presents the model. Section 3 analyses the conditions for the existence of a unique steady-state and explores its properties and the implied comparative statics. Section 4 presents some supportive evidence by analyzing US data over the period 1979-2001. Section 5 concludes.

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tions of the past, such as the combustion engine, electricity and railways, that pioneered the first and second industrial revolutions (David, 1991, David and Wright, 1999). The features of a GPT, as given by Lipsey, Bekar, Carlaw (1998), are: "wide scope for improvement and elaboration; applicability across a wide range of uses; potential for use in a wide variety of products and processes; strong complementarities with existing or potential new technologies".

2 The Model

2.1 Production Side

The model examines a three-sector economy. There are two final goods sectors in the economy, one using ICT-capital and one not using it. The third sector is the ICT-producing sector, which performs R&D and discovers new ICT goods. In what follows, the numeraire is the output of the non-ICT-using sector.

2.1.1 ICT-producing Sector

The ICT-producing sector employs a fraction u_N of aggregate labour stock, L, and produces new ICT "ideas", $\dot{N}$. The production exhibits economies of scale that constitute the engine of growth. The motivation for the production externalities is that there is learning-by-doing: as the production size increases, more new production ideas and practices become available. The exogenous productivity is given by parameter λ. In order to have sufficient incentives to innovate, this sector operates as a monopoly.

$$\dot{N} = \lambda(u_N L)N \tag{1}$$

2.1.2 ICT-using Sector

The ICT-using sector absorbs a fraction u_1 of labour and employs N intermediate ICT-capital goods, $\{x_1(j)\}_{j\in[0,N]}$, in order to produce output, Y_1. The number of intermediate goods varieties is expanding over time. This sector is perfectly competitive[3].

$$Y_1 = (u_1 L)^{1-\alpha} \int_0^N x_1^\alpha(j)dj \tag{2}$$

The final good is used either for consumption, c_1, or the production of ICT-capital, K_1, and non-ICT-capital, K_0. For simplicity, both forms of

[3] Allowing both sectors to use both ICT and non-ICT-capital at different intensities, would not change the main features of the equilibrium.

capital fully depreciate within the period.

$$Y_1 = c_1 + K_0 + K_1 \tag{3}$$

2.1.3 non-ICT-using Sector

The non-ICT-using sector employs a fraction u_0 of labour and combines it with the sector-specific capital varieties, $\{x_0(i)\}_{i\in[0,A]}$, to produce final good, Y_0. This sector is not using ICT-capital. Instead, it uses non-ICT capital, which has a fixed number of varieties over time, A, that have already been discovered. This stands for the assumption that the non-ICT-using sector does not benefit directly from ICT, as it only makes use of obsolete technologies. This sector is perfectly competitive[4].

$$Y_0 = (u_0 L)^{1-\alpha} \int_0^A x_0^\alpha(i)di \tag{4}$$

The final good is used only for consumption c_0 purposes.

$$Y_0 = c_0 \tag{5}$$

2.1.4 Intermediate Capital Varieties Market

There is a fixed number, A, of firms that produce intermediate capital varieties that are used only by the non-ICT-using sector. There is also an expanding number, N, of firms that produce intermediate capital varieties that are exclusively used by the ICT-using sector. In both cases, the only input is a unit of the final output of the ICT-using sector. Every firm in this "sector" has infinite-horizon monopolistic rights that come from exploiting a patent. The price of the patent equals the present discounted value of the firm's stream of profits. The firms operate under monopolistic competition.

In particular, a firm that produces the non-ICT-using capital variety i,

[4] Allowing for a different capital intensity in this sector would not affect the features of the equilibrium, while complicating the analytical expressions. The simplifying assumption of setting it equal to that of the ICT-using sector is used to highlight the differences across the two sectors that stem from the type of the capital used.

has a market value at time t, $V_0^t(i)$, which equals the present discounted value of its future stream of profits. The discount factor depends on the market interest rate, $r(t)$. The unit cost of production equals the price, p_1, of the ICT-using final good. Given its market power, the firm selects its price $\hat{p}_0(i)$, by taking into account the demand it faces from the non-ICT-using good producers.

$$V_0^t(i) = \int_t^{\infty} e^{-\int_0^t r(\tau)d\tau} \left(\hat{p}_0(i)x_0(i) - p_1 x_0(i)\right) dt \qquad (6)$$

A firm that produces the ICT-using capital variety j, has a market value at time t, $V_1^t(j)$. The output will be priced at $\hat{p}_1(j)$ taking into account the demand from the ICT-using final good producers. The unit cost of production is p_1.

$$V_1^t(j) = \int_t^{\infty} e^{-\int_0^t r(\tau)d\tau} \left(\hat{p}_1(j)x_1(j) - p_1 x_1(j)\right) dt \qquad (7)$$

In equilibrium, the markets of the two types of capital varieties should clear.

$$K_0 = \int_0^A x_0(i)di \qquad (8)$$

$$K_1 = \int_0^N x_1(j)dj \qquad (9)$$

2.1.5 Labour Market

The labour stock is fixed over time. The labour market is perfectly competitive. The market clearing condition requires that all resources are allocated across all three sectors that use labour.

$$1 = u_0 + u_1 + u_N \qquad (10)$$

2.2 Consumer Side

2.2.1 Households

There is a continuum of identical households of size one. The representative household gains utility from its consumption of ICT-using and non-ICT-using goods. A general framework of joint CES and CRRA preferences allows both intertemporal and intratemporal substitution to come into play (the intratemporal and intertemporal elasticities of substitution are constant over time and equal to $\frac{1}{1-\epsilon}$, and $\frac{1}{\sigma}$ respectively).

$$u(c_0, c_1) = \frac{\left([\theta c_0^{\epsilon} + (1-\theta)c_1^{\epsilon}]^{\frac{1}{\epsilon}}\right)^{1-\sigma} - 1}{1-\sigma}; \theta \in (0,1), \epsilon < 1, \sigma > 0 \tag{11}$$

The labour stock is uniformly distributed across all agents in the economy, so that each of them offers L. In every period, the households' income comes from the wage, w_L, they earn from supplying their labour and the interest rate, r, they receive on their total asset holdings, S. The only means of savings available are the assets of the intermediate capital varieties producing firms. Their budget constraint takes the form:

$$\dot{S} = rS + w_L L - c_0 - p_1 c_1 \tag{12a}$$

3 Steady-State Analysis

3.1 Existence of Steady-State

A Constant Growth Path (CGP) is a steady-state equilibrium path along which the ICT-production stock, N, the aggregate output, $Y = Y_0 + p_1 Y_1$, capital, $K = p_1 K_0 + p_1 K_1$, and consumption, $C = c_0 + p_1 c_1$, grow at a constant rate. The conditions that allow for the existence of such an equilibrium path will be investigated under the framework of the social planner's problem as it allows for an insight on what drives them. All proofs are given in Appendix A.

Proposition 1 *The necessary and sufficient condition for the existence a CGP with N, Y, C and K growing at constant rates is that the preferences exhibit unit intratemporal elasticity of substitution, i.e.* $\epsilon = 0$. *For an interior solution, the sufficient conditions are that* $\sigma > \bar{\sigma}(\theta, \alpha, \lambda, \rho; L)$ *and* $L > \bar{L}(\theta, \alpha, \lambda, \rho)$. *Along the unique CGP there is no reallocation of labour,* $\dot{u}_0 = \dot{u}_1 = \dot{u}_N = 0$.

The most important restriction required for Proposition 1 to hold, is the unit intratemporal elasticity of substitution[5]. Along the CGP the economy needs to satisfy static efficiency, i.e. the marginal rate of substitution needs to equal the marginal rate of transformation, and the resource constraints should be satisfied within every period and over time. This is feasible as long as the substitution patterns in consumption that are driven by relative consumption goods prices are matched by the substitution patterns of factors.

In the case of an intratemporal elasticity which is greater than one, the consumers substitute the non-ICT-using good for the cheaper ICT-using good. That puts demand pressure on the production of the ICT-using sector and requires this sector to attract more labour from the non-ICT-using sector. Yet, with these substitution patterns, the market clearing conditions are not met over time, unless the consumers are indifferent about the timing of their consumption (i.e. they have zero time preference rate). Any degree of impatience regarding the timing of consumption reinforces the substitution patterns within every period of time. The unit intratemporal elasticity of substitution is the only case that the consumption substitution patterns

[5]The conditions for a CGP here, are similar to the ones in the structural change literature, e.g. Ngai and Pissarides (2004), Kongsamut, Rebelo and Xie (2001). Their aim is to explain labour reallocations, across manufacturing and services industries. In the former, these shifts are explained through different exogenous TFP growth rates of sectors and an elasticity of intratemporal substitution less than one in the production side, while in the latter through different income elasticities. As noted in the introduction, such labour reallocations are not present in the ICT context.

match the production substitution patterns. It implies constant expenditure shares, and therefore through the static efficiency conditions implies constant labour allocations for the two final good sectors.

It should be noted that for constant growth rate in ICT-production, aggregate output and capital the only requirement is that the labour allocation in the ICT-producing sector is constant. The growth of the final goods sectors is driven by labour, capital accumulation and TFP growth. The growth of capital for the ICT-using and the non-ICT-using sectors is exactly the same. This is because the prices of both the ICT and non-ICT capital goods fall at the rate of the ICT-production growth. Only the ICT-using sector experiences TFP growth, which is driven by the use of the expanding variety of the ICT-capital. However, this TFP growth is offset at the aggregate output level by the falling price of the ICT-using good. Any reallocation of labour between the two final goods sectors also cancels out given the condition on constant allocation for the ICT-producing sector. Therefore, aggregate output growth only reflects capital accumulation and is a constant fraction of the ICT-production growth. The same reasoning works for aggregate capital.

In order for the CGP to satisfy also efficiency in the limit, i.e. the transversality condition, two more restrictions are required. One is standard: the size of the labour stock should be sufficiently large, in order for the economy to have incentives to direct part of its resources into R&D. The second one comes from the multi-sector feature of the economy: for incentives to exist in keeping resources into the final good sectors, the intertemporal elasticity of substitution should not be too high. The consumers would substitute current consumption with future one depending on the gap between the real interest rate in consumption units and their subjective discount rate. The means of savings in this economy drives resources into the ICT-producing sector, so as to enhance future production possibilities for the final goods sectors. However, very high intertemporal elasticity of substitution would not allow dynamic efficiency, as it would drain the final good sectors from production resources.

3.2 Features of the Steady-State

In what follows, the decentralized equilibrium steady-state is analyzed. Given Proposition 1, the steady-state of the decentralized equilibrium is derived by imposing unit intratemporal elasticity of substitution and constant labour shares on the model. The details are given in Proposition 2. The most interesting static equilibrium results are:

$$p_1 = \left(\frac{A}{N}\right)^{1-\alpha} \tag{13}$$

$$\hat{p}_0 = \hat{p}_1 = \frac{p_1}{\alpha} \tag{14}$$

$$\frac{u_0}{u_1} = \frac{(1-\alpha^2)\theta}{1-(1-\alpha^2)\theta} \tag{15}$$

Condition (13) shows that the relative price of the ICT-using good is falling over time at a rate which is proportional to the rate of expansion of the ICT-capital. The factor of proportionality is equal to the labour share in final goods production, given the labour augmenting nature of the technology. As condition (14) shows, the prices of all capital varieties fall at the same rate as the price of the final ICT-using good. Therefore, the productivity gain of the non-ICT-using sector comes only indirectly. This sector is using a fixed number of capital varieties, but these varieties become cheaper and cheaper relative to the non-ICT-using final good. The falling prices generate increased demand for the existing capital varieties. Capital deepening is the only source of growth in this sector. At the same time, the ICT-using sector benefits from more varieties of capital becoming available. The benefits from more varieties complement those from cheaper varieties delivering faster growth for this sector relative to the non-ICT-using sector.

Condition (15) comes from equating the marginal rate of substitution to the marginal rate of transformation and using the market clearing conditions. It gives an expression for the ratio of the relative labour shares in the two final goods sectors. This ratio depends on the expenditure share of the non-ICT-using good, θ, as long as it affects the marginal utility of consumption.

It also depends on the output elasticity of capital, α, since that affects the capital-labour substitution. The same parameter also specifies the size of the mark-up, $\frac{1-\alpha}{\alpha}$, that the capital producers enjoy.

The following Proposition summarizes the dynamic equilibrium results.

Proposition 2 *For preferences that satisfy: $\sigma > \bar{\sigma}$ and $\epsilon = 0$, along the CGP the following are true*[6]*:*

The growth rate of every sector and of the aggregate economy is proportional to the endogenous growth rate of the ICT-producing sector, g_N^d:

$$\frac{\dot{Y}_0}{Y_0} = \frac{\dot{c}_0}{c_0} = \frac{\dot{C}}{C} = \frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = \alpha g_N^d$$

$$\frac{\dot{Y}_1}{Y_1} = \frac{\dot{c}_1}{c_1} = \frac{\dot{K}_1}{K_1} = \frac{\dot{K}_0}{K_0} = g_N^d$$

The labour allocations are constant and depend on all parameters of the model and the aggregate labour stock:

$$u_z^d = u_z^d(\theta, \rho, \sigma, \alpha, \lambda; L); z = \{0, 1, N\}$$

Given the static optimization conditions described above, the features of the dynamic optimization conditions follow immediately. In particular, the ICT-using sector is growing at the same rate as the ICT-producing sector, since this sector fully benefits from any advances in the ICT-production, both in terms of capital deepening and in terms of TFP increase. In contrast, the non-ICT-using sector grows only because of capital deepening, which is driven by the fact that non-ICT-capital is becoming cheaper over time. Therefore, the growth rate for the non-ICT-using sector is only a fraction of the economy's full potential, g_N^d, with the fraction being equal to the capital share in final good production.

[6] The conditions for an interior solution are an endogenously determined lower bound for labour stock, $\bar{L}(\theta, \alpha, \lambda, \rho)$, and an upper bound for the intertemporal elasticity of substitution, $\frac{1}{\bar{\sigma}(\theta,\alpha,\lambda,\rho;H)}$.

At the aggregate level, the effects of differential output growth are completely cancelled out by the growth rate of relative prices. The economy is along a balanced growth path, where the consumption to output and capital to output ratios are constant within every sector, but different across sectors. The growth rate of the economy is a function of the preference and production parameters and the available labour stock.

Further on the features of the steady state of the model economy, the current framework does not allow for transition dynamics. The proof is provided for the social planner's equilibrium under Corollary 1 in Appendix A. The reason for that is the existence of a unique state stock variable, which has constant rate of return along the CGP. The latter is due to the type of externalities present in the production function of this sector. As a result, following a structural change in one of the key parameters, this economy will only exhibit discrete shifts from the original CGP to the new one, without an intermediate phase of smooth transition path[7].

3.3 Comparative Statics

Proposition 3 *The growth rate of the economy is higher and the labour shares in the two final goods' sectors are lower, the more patient the agents in the economy are (the lower ρ is) and the more productive the ICT-producing sector is (the higher λ is). The effect of a higher output elasticity of capital (α), or of the expenditure share of the non-ICT-using good (θ) is ambiguous and depends on the values of different parameters of the model.*

Patient agents would be more willing to substitute current consumption with future consumption. The additional savings direct resources to the ICT-producing sector. This is because as asset holdings increase, they drive interest rates down and patent prices up. This enables higher growth in the long run, since it provides incentives for higher ICT-production growth.

[7] Transition dynamics can be delivered by a slowly depreciating physical capital. That would make the model highly nonlinear and requires the use of numerical solution methods. This case has been explored and its results are available by the author upon request.

An increased productivity in the ICT-producing sector would have the same effect. It would increase the marginal product of the labour in this sector, and thus would attract more labour. The incentives to produce more ICT would come from higher patent prices, that would result both from the increased productivity and the reduced interest rate.

The comparative statics following an increased preference towards the non-ICT-using consumption good is more complex. On the one hand, since the marginal utility of consumption goes up in this sector, there are forces to increase resources in its production. On the other hand, reducing the resources from the ICT-producing sector implies that the rate of growth of the economy falls. Hence, the rate at which the price of the non-ICT-using good increases relative to the ICT-good falls as well. This implies that there would be a force that reduces consumption growth in the non-ICT-using sector, since it reduces the gap between the interest rate in consumption units and the subjective discount rate. For unit intertemporal elasticity of substitution, this second effect is eliminated because the market interest rate coincides with the interest rate in consumption units. Hence, stronger preference for non-ICT-using goods implies lower growth rate and a diversion of resources out of the ICT-using and producing sector and into the non-ICT-using sector.

The same reasoning applies to the case of higher output elasticity of capital. On the one hand, this reduces the mark-up that the capital producers enjoy, and thus increases the production of capital and output. The effect of capital accumulation upon growth becomes stronger. On the other hand, since the labour share in output falls, this reduces the incentive for growth as it mitigates the gap between the interest rate in consumption units and the subjective discount rate. Again, for unit intertemporal elasticity of substitution, the second effect is eliminated and thus the result of higher output elasticity of capital is an increase in the labour share in the ICT-producing sector and a decrease of the labour share in the final goods' sectors.

4 Supportive Evidence

According to the model, the ICT-using sector is the sector fueling the economy with intermediate capital varieties, while the non-ICT-using sector is mainly producing a consumption good. In order to check whether the resulting grouping of sectors supports this, the Bureau of Economic Analysis (BEA) "Use Table" of the "Benchmark 1997 Input-Output Table" was used to calculate the use shares of the commodities of the ICT-producing, ICT-using and non-ICT-using sector. The uses considered are "total intermediates" and "personal consumption". The results are shown in Table 1, where the shares are also reported separately for the manufacturing and services industries within each of the three sectors. The ICT-producing sector turns out as a clearly capital/intermediate producing sector, followed by the ICT-using sector.

Table 1

Shares of commodities' use		Intermediates	Consumption
ICT-producing	MAN	84.1	15.9
	SER	55.2	44.8
	TOTAL	81.5	18.5
ICT-using	MAN	84.0	16.0
	SER	59.7	40.3
	TOTAL	63.8	36.2
non-ICT-using	MAN	69.2	30.8
	SER	49.9	50.1
	TOTAL	58.7	41.3

Source: BEA, Benchmark Input Output Table, 1997.

As in the theoretical model, the industries are grouped into three major sectors: ICT-producing, ICT-using and non-ICT-using. See Appendix B for precise sources and definitions of the data and details regarding the industries in each major sector and the aggregation method used. Figure 1, in the introduction of the paper, presents the hours shares of the three sectors over the period 1979-2001. These shares show virtually no change during this period. The share of the ICT-producing sector is around 4%, that of ICT-using changes from a minimum of 24% to a maximum of 26% and that of non-ICT-using changes from 73% to 71%[8]. The reason that the focus is on the period before 1995, is that the empirical literature suggests that in 1995 there has been a structural break in most of the series of interest.

Figure 2 gives the value added at current prices of the three sectors over the same period. The rates of growth are roughly the same. The same picture is derived from Figure 3, where the displayed series are the annual (exponential) growth rates, without any filtering. The non-ICT-using sector supplies on average 71% of total value added over the period 1979-1995. The ICT-using and the ICT-producing supply on average 24% and 4% respectively.

Given the implications of the model, the share of value added of the non-ICT-using sector out of the two final good sectors should be equal to the share of this sector in hours used in the two final good sectors. This value added share of the non-ICT-using sector is equal to 75% on average over the period 1979-1995. The hours share is equal to 74%. Another implication, according to the static optimization condition (15), is that the value added share of the non-ICT-using sector out of total final good sectors' value added is equal to $\theta(1-\alpha^2)$. Also, the preference parameter θ is equal to the expenditure share for the non-ICT-using good. According to the BEA data on private consumption expenditures, the average expenditure share of the non-ICT-using good is 87% over the 1979-1995 period. Given the value added share of 75% and expenditure share of 87% the optimization condition implies an output elasticity of capital, α, equal to 0.37. This is in accordance to the estimates of an output elasticity equal to 0.33 by the growth literature.

[8] For the decomposition of the aggregate private economy favoured by the structural change literature (e.g. Ngai and Pissarides, 2004), the data reveal striking trends. Over the period 1979-1995, the share of Agriculture (ISIC:01-05) in total hours worked is relatively constant around 4%, while that of Services (ISIC: 50-95) increases from 54% to 63% and Manufacturing (ISIC: 10-45) falls from 41% to 33%. This employment share for Manufacturing is considerably higher than what is usually reported. The difference comes from excluding government activities and using a measure of total employment in terms of hours worked, rather than in terms of number of persons engaged in production.

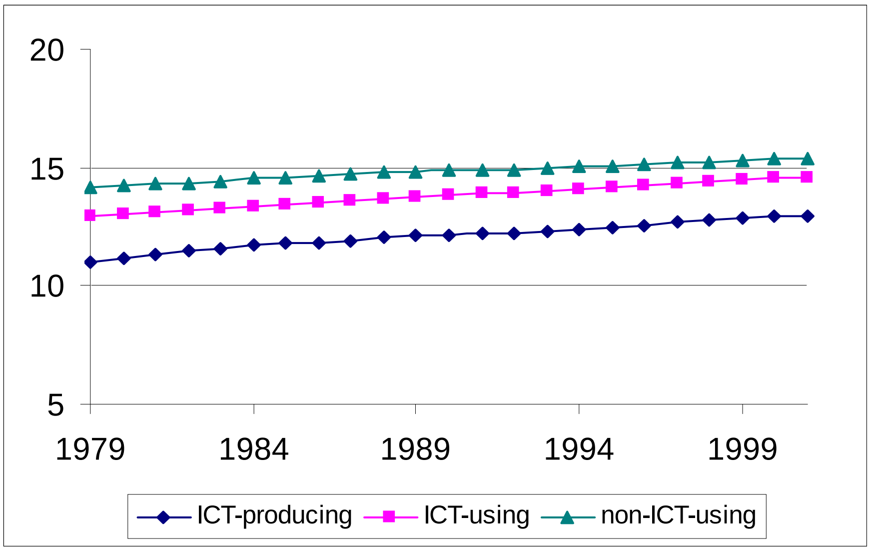

Figure 2: Value added at current prices (units in logs, millions of $US).

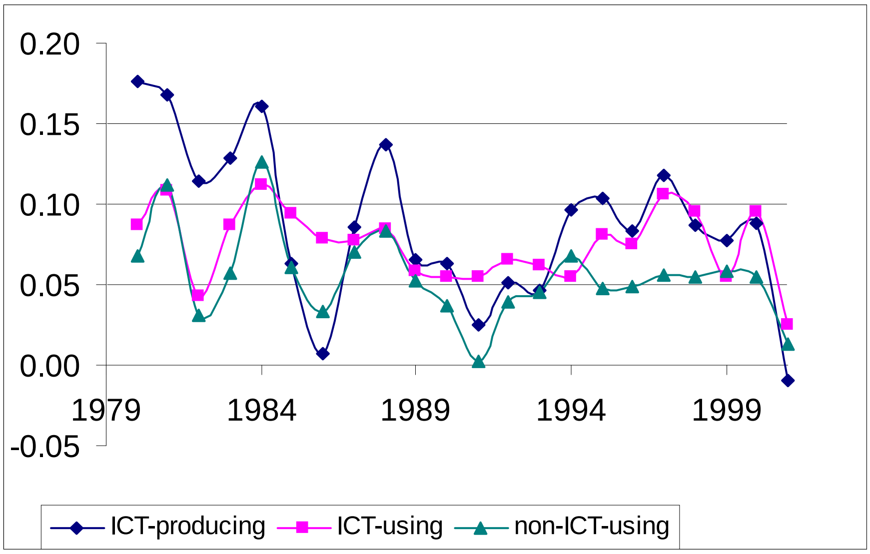

Figure 3: Growth rate in value added (current prices).

Figure 4 gives the value added at constant prices. In contrast to Figure 2 growth is stronger in the ICT-producing sector, followed by the two final good sectors. Growth in the ICT-using sector is picking up during the sample period, especially after 1995. The same picture is derived by contrasting Figures 3 and 5.

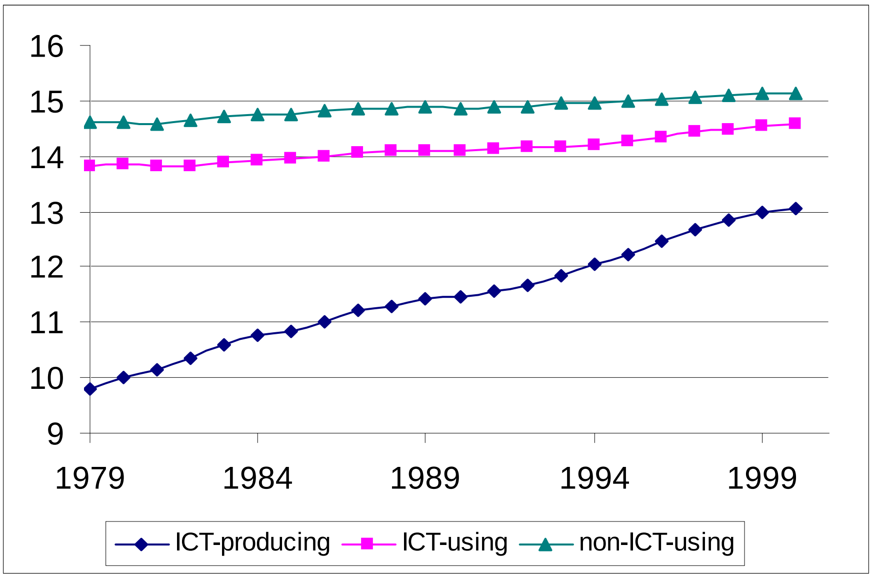

Figure 4: Value added at constant prices (quantity index, 1995=100).

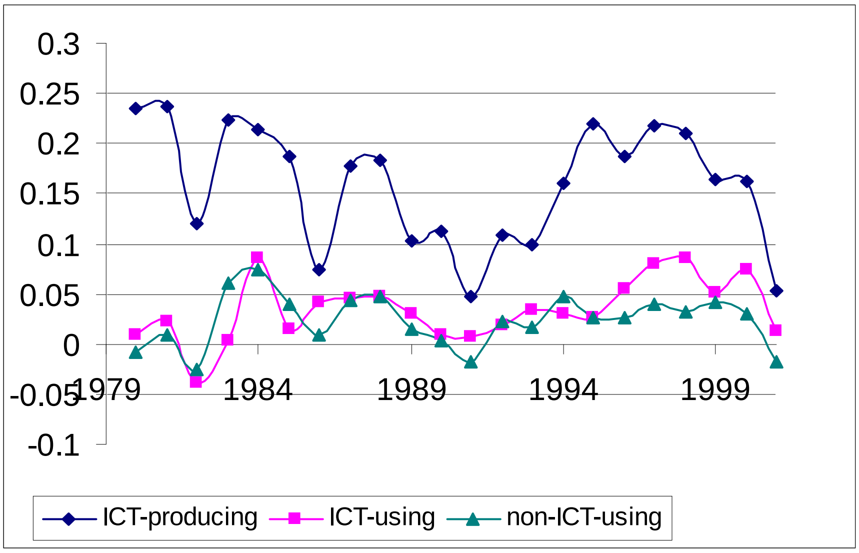

Figure 5: Growth rate in value added (constant prices).

Moreover, according to the model, when evaluating the growth rate of the final good in terms of the non-ICT-using good, the aggregation should give the growth rate of output of the non-ICT-using good. This is because the negative price effect upon the growth rate of the value of the ICT-using good cancels out the positive output effect in that sector. Figure 6 shows together the output and price effects. Over the period 1980-1995 these two effects move in the opposite direction and have approximately the same size. The hypothesis of a zero mean for the series that comes from their aggregation cannot be rejected at the 1% significance level. After 1995 though, the negative correlation of these two effects becomes weaker and not statistically significant. This implies that the aggregate output growth is higher than the output growth of the non-ICT-using sector[9].

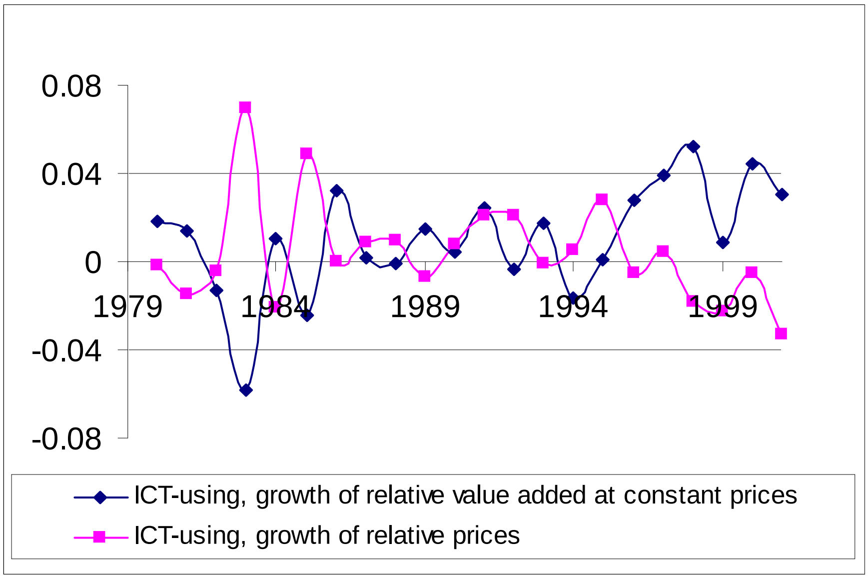

Figure 6: Quantity vs. price effect (relative to the non-ICT-using sector).

Finally, the model has an implication about the TFP growth rate for the aggregate economy. Using the production functions for the two final goods sectors and the predictions of the decentralized equilibrium of the model, the aggregate Solow residual is equal to $(1-\alpha)\frac{p_{Y_1}Y_1}{p_{Y_0}Y_0+p_{Y_1}Y_1}g_N^d$[10]. This means that TFP growth rate is only a fraction of the growth of the ICT-producing sector and this fraction depends on the output elasticity of labour and the value

[9]Within the context of the model of this paper, the evolution of the United States economy after 1995 is interpreted as transition dynamics of the economy following an increase in the exogenous productivity of the ICT-producing sector. The extension of the model for transition dynamics together with a calibration exercise of the United States economy over the period 1985-2001 is available by the author.

[10]If real GDP, $\tilde{Y}$, aggregates the final good production, then its implied growth rate is: $\frac{\dot{\tilde{Y}}}{\tilde{Y}} = \frac{p_{Y_0}Y_0}{p_{Y_0}Y_0+p_{Y_1}Y_1}\frac{\dot{Y}_0}{Y_0} + \left(1 - \frac{p_{Y_0}Y_0}{p_{Y_0}Y_0+p_{Y_1}Y_1}\right)\frac{\dot{Y}_1}{Y_1}$. Using the results under Proposition 2:

added share of the ICT-using sector. For a labour share of 70% and a 26% value added share of the ICT-using sector, only 18% of the growth of the production of ICT translates into TFP growth[11].

5 Conclusions

This paper has developed a theoretical framework that accounts for growth in ICT era. The source of growth are the externalities present in the ICT-production. It analyzes the mechanism through which growth is transmitted from the ICT-producing sector to the aggregate economy. The sector using ICT-capital goods fully benefits from the use of the new technologies, experiencing both capital deepening and TFP growth. This results in falling capital prices, because the ICT-using sector is also the capital-producing sector of the economy. The falling capital prices drive capital deepening in the sector that does not use ICT-capital. Therefore, despite the fact that only one sector is using ICT-capital goods, the benefits from their use spread throughout the economy.

At the same time the mechanism that drives growth in this model, i.e. the falling capital prices, may explain growth caused by any technologies that expand the production possibility frontier of the capital-producing industries in an economy. In that sense, the model is more general than its selected application in this paper (i.e. to account for growth in the ICT context). On more general grounds, this paper provides insight into how multiple sectors of different growth potentials interact within an economy in a way that allows for a CGP at the aggregate level, where growth is sustained endogenously.

$$\text{"Solow-Residual"} \equiv \frac{\dot{\tilde{Y}}}{\tilde{Y}} - \frac{p_{Y_0} Y_0}{p_{Y_0} Y_0 + p_{Y_1} Y_1} \left[(1-\alpha) \left(\frac{\dot{\overline{u_0 H}}}{u_0 H} \right) + \alpha \frac{\dot{K}_0}{K_0} \right]$$
$$- \left(1 - \frac{p_{Y_0} Y_0}{p_{Y_0} Y_0 + p_{Y_1} Y_1} \right) \left[(1-\alpha) \left(\frac{\dot{\overline{u_1 H}}}{u_1 H} \right) + \alpha \frac{\dot{K}_1}{K_1} \right]$$
$$= \frac{p_{Y_1} Y_1}{p_{Y_0} Y_0 + p_{Y_1} Y_1} (1-\alpha) \frac{\dot{N}}{N}$$

[11] Based on the implication of the model that the growth rate of the ICT-using sector reflects the ICT technology growth, the resulting estimate of the TFP growth is higher than that reported in Jorgenson et al. (2004).

In the steady-state growth path, there is no reallocation of labour across sectors. The growth of the ICT-using sector is the same as the rate of growth of the ICT-producing sector, because this sector uses capital varieties that follow the growth of the ICT-production stock. The rate of growth of the non-ICT-using sector is equal only to a fraction of the ICT-production growth that is equal to the output elasticity of capital. This is because this sector grows only due to capital deepening given that it uses obsolete technologies that are available at falling prices. At the aggregate level, due to constant returns-to-scale any TFP growth differences are absorbed by relative prices' growth. The aggregate growth rate is driven by the advances in the ICT-production. It is endogenously determined as a function of the preference and production parameters of the model and the size of the labour stock. The aggregate consumption to capital and output to capital ratios are constant over time. These ratios are also constant for the disaggregated sectors, but are different across sectors. The market interest rate, as well as the interest rate in consumption units are also constant over time.

Data from the United States economy, when mapped to the theoretical structure, reveal virtually constant hours shares for the three sectors. They support the claim that any differences in output growth are reflected in differences in prices' growth. They also support the claim that the volume of production of the ICT-using sector grows faster than the non-ICT-using one. The model is also used together with the data to show how the TFP growth at the aggregate level can reflect only a small fraction of the ICT-production TFP growth.

6 Appendix A: Analytical Proofs

Proof of Proposition 1

The social planner solves economy's dynamic optimization problem, having controls over: $\{c_0, c_1, x_1(i), x_0(j), u_0, u_1\}$, $\forall i \in [0, A]$, $\forall j \in [0, N]$. The unique state variable is:N.

$$\begin{aligned}
\mathcal{H} &= e^{-\rho t}\frac{\left(\left[\theta c_0^{\epsilon}+(1-\theta)c_1^{\epsilon}\right]^{1/\epsilon}\right)^{1-\sigma}-1}{1-\sigma} + \kappa\left[(u_0 L)^{1-\alpha}\int_0^A x_0^{\alpha}(i)di - c_0\right] \\
&\quad +\mu\left[(u_1 L)^{1-\alpha}\int_0^N x_1^{\alpha}(j)dj - \int_0^A x_0(i)di - \int_0^N x_1(j)dj - c_1\right] \\
&\quad +\nu\left[(1-u_0-u_1)\lambda L N\right]
\end{aligned} \tag{16}$$

The FOCs from the maximization problem (16) are the following[12]:

$$\frac{\partial \mathcal{H}}{\partial c_0} = 0 \Rightarrow e^{-\rho t}E^{1-\epsilon-\sigma}\theta c_0^{\epsilon-1} - \kappa = 0 \tag{17}$$

$$\frac{\partial \mathcal{H}}{\partial c_1} = 0 \Rightarrow e^{-\rho t}E^{1-\epsilon-\sigma}(1-\theta) c_1^{\epsilon-1} - \mu = 0 \tag{18}$$

$$\frac{\partial \mathcal{H}}{\partial x_0(i)} = 0, \forall i \Rightarrow \kappa\left[\alpha\left(u_0 L\right)^{1-\alpha} x_0^{\alpha-1}(i)\right] - \mu = 0, \forall i \tag{19}$$

$$\frac{\partial \mathcal{H}}{\partial x_1(j)} = 0, \forall j \Rightarrow \mu\left[\alpha\left(u_1 L\right)^{1-\alpha} x_1^{\alpha-1}(j) - 1\right] = 0, \forall j \tag{20}$$

$$\frac{\partial \mathcal{H}}{\partial u_0} = 0 \Rightarrow \kappa\left[(1-\alpha)\frac{Y_0}{u_0}\right] - \nu\lambda L N = 0 \tag{21}$$

$$\frac{\partial \mathcal{H}}{\partial u_1} = 0 \Rightarrow \mu\left[(1-\alpha)\frac{Y_1}{u_1}\right] - \nu\lambda L N = 0 \tag{22}$$

$$-\dot{\nu} = \frac{\partial \mathcal{H}}{\partial N} = \mu\left[(u_1 L)^{1-\alpha}x_1^{\alpha}(N) - x_1(N)\right] + \nu(1-u_1-u_0)\lambda L \tag{23}$$

The TVC is the following:

$$\lim_{T\to\infty}\left[\nu(T)N(T)\right] = 0 \tag{24}$$

[12] Let $E \equiv \left[\theta c_0^{\epsilon} + (1-\theta)c_1^{\epsilon}\right]^{1/\epsilon}$ be the composite index of consumption.

Equations (17) and (18) give[13]:

$$\frac{c_1}{c_0} = \left(\frac{1-\theta}{\theta}\frac{\kappa}{\mu}\right)^{\frac{1}{1-\epsilon}} \tag{25}$$

$$\frac{\dot{c}_0}{c_0} = \frac{1}{\sigma}\left[-\rho - (1-\psi(t))\frac{\dot{\kappa}}{\kappa} - \psi(t)\frac{\dot{\mu}}{\mu}\right] \tag{26}$$

Equations (19) and (20) give the each sector's demand function for intermediate goods. The model implies symmetry across each type of capital good:

$$x_0 = \left(\frac{\kappa}{\mu}\right)^{\frac{1}{1-\alpha}} \alpha^{\frac{1}{1-\alpha}} (u_0 L) \tag{27}$$

$$x_1 = \alpha^{\frac{1}{1-\alpha}} (u_1 L) \tag{28}$$

Equations (21) and (22) equate the value of marginal product of labour across all sectors:

$$\kappa\left[(1-\alpha)\frac{Y_0}{u_0}\right] = \nu\lambda L N \tag{29}$$

$$\mu\left[(1-\alpha)\frac{Y_1}{u_1}\right] = \nu\lambda L N \tag{30}$$

Using (29) and (30), equation (23) gives the growth rate of the shadow price of the state variable N:

$$-\frac{\dot{\nu}}{\nu} = \lambda L\,(1-u_0) \tag{31}$$

Inserting equations (27) and (28) back into the production functions gives the following implicit production functions:

$$Y_0 = \left(\frac{\kappa}{\mu}\right)^{\frac{\alpha}{1-\alpha}} \alpha^{\frac{\alpha}{1-\alpha}} A(u_0 L) \tag{32}$$

$$Y_1 = \alpha^{\frac{\alpha}{1-\alpha}} N(u_1 L) \tag{33}$$

Using these into (29) and (30) while dividing by parts, gives the relative shadow prices of the two final goods in (34).

[13] Let $\psi(t) \equiv \frac{(1-\beta(t))(1-\epsilon-\sigma)}{1-\epsilon}$, where $\beta(t) \equiv \frac{\theta c_0^{\epsilon}}{\theta c_0^{\epsilon}+(1-\theta)c_1^{\epsilon}}$.

$$\frac{\kappa}{\mu} = \left(\frac{N}{A}\right)^{1-\alpha} \tag{34}$$

Substituting (33) back into (30) and differentiating with respect to time implies equal rates of return for the ICT-producing and ICT-using sector, $\frac{\dot{\mu}}{\mu} = \frac{\dot{\nu}}{\nu}$.

By (25) it follows that $\beta(t) = \frac{\theta c_0^\epsilon}{\theta c_0^\epsilon + (1-\theta)c_1^\epsilon} = \frac{c_0}{c_0 + \frac{\mu}{\kappa} c_1}$. Using the resource constraints in each sector, together with the demand functions for capital varieties and the sectorial production functions, the static efficiency condition results in a relation between labour allocations and expenditure shares in the final good sectors:

$$\frac{u_0}{u_1} = \frac{(1-\alpha)\beta(t)}{1-(1-\alpha)\beta(t)} \tag{35}$$

A steady-state CGP is an equilibrium that satisfies the FOCs, the market clearing conditions and the TVC together with the CGP requirements. By the law of motion of the state variable N, the necessary and sufficient condition for constant g_N, is that $\dot{u}_N = 0$. Given the resource constraint: $1 = u_N + u_1 + u_0$, this condition can alternatively take the form[14]: $g_1 = -g_0 \frac{u_0}{u_1}$.

The next condition comes from the requirement that aggregate output grows at a constant rate. This condition coincides with the one for constant growth rate for the value of aggregate capital stock, since the latter is a fraction α of output in either sector. The growth rates for the production in the two sectors are derived from (32) and (33), together with (34):

$$\frac{\dot{Y}_0}{Y_0} = \alpha g_N + g_0 \tag{36}$$

$$\frac{\dot{Y}_1}{Y_1} = g_N + g_1 \tag{37}$$

These will be combined with (34) and (32), (33):

$$\frac{\dot{Y}}{Y} = \frac{Y_0}{Y}\frac{\dot{Y}_0}{Y_0} + \frac{\frac{\mu}{\kappa}Y_1}{Y}\left(\frac{\dot{Y}_1}{Y_1} + \frac{\dot{\mu}}{\mu} - \frac{\dot{\kappa}}{\kappa}\right) = \alpha g_N$$

The last equation is derived by using the steady-state condition $\dot{u}_N = 0$. Thus, this is a sufficient condition for a CGP for Y.

[14]Let $\frac{\dot{u}_s}{u_s} = g_s$ for $s = \{0, 1\}$

The growth rate of the aggregate consumption is:

$$\frac{\dot{C}}{C} = \frac{c_0}{C}\frac{\dot{c}_0}{c_0} + \frac{\frac{\mu}{\kappa}c_1}{C}\left(\frac{\dot{c}_1}{c_1} + \frac{\dot{\mu}}{\mu} - \frac{\dot{\kappa}}{\kappa}\right) = \frac{\dot{c}_0}{c_0} + (1-\beta(t))(1-\alpha)\frac{\epsilon}{1-\epsilon}g_N$$

Relations (26), (34)and (31) are used to get the last part of the equation. In order for $\frac{\dot{C}}{C}$ to be constant, g_0 needs to satisfy:

$$g_0 = (1-\sigma)(1-\alpha)^2\frac{\epsilon}{1-\epsilon}\beta(t)(1-\beta(t))\frac{u_N}{u_0}g_N \tag{38}$$

Equation (38) sets a condition on the evolution of the share of labour in the non-ICT sector over time[15]. The static optimization condition (35) together with the CGP condition for $\dot{u}_N = 0$ give another expression on g_0:

$$g_0 = \frac{\frac{d}{dt}(\beta(t))}{\beta(t)} = -\frac{\epsilon}{1-\epsilon}(1-\alpha)g_N(1-\beta(t)) \tag{39}$$

Conditions (38) and (39) should be jointly satisfied. Equating their LHSs and using that $u_N = 1 - \frac{u_0}{\beta(t)(1-\alpha)}$, gives an expression for the share of labour in the non-ICT-using sector: $u_0 = \frac{\sigma-1}{\sigma}(1-\alpha)\beta(t)$. Given the solution path for u_0, (35), (34) and (31) imply a growth rate for the consumption of the non-ICT-using good: $\frac{\dot{c}_0}{c_0} = \frac{1}{\sigma}\left[-\rho + \frac{\lambda L}{\sigma}(\alpha - (1-\sigma)(1-(1-\alpha)\beta(t))) + \frac{(1-\sigma-\epsilon)(1-\beta(t))}{1-\epsilon}(1-\alpha)g_N\right]$. This candidate solution should satisfy the market clearing conditions over time. Hence, it should be true that: $\frac{\dot{c}_0}{c_0} = \frac{\dot{Y}_0}{Y_0} = \alpha\frac{\lambda L}{\sigma} + g_0$. This implies a third expression on the evolution of the share of labour in the non-ICT-using sector:

$$g_0 = -\frac{\rho}{\sigma} - \frac{\epsilon}{1-\epsilon}\frac{\lambda L}{\sigma}(1-\alpha)(1-\beta(t)) \tag{40}$$

Equation (40) may only be reconciled with (39), if $\rho = 0$. This contradicts the original assumptions. Therefore, there is not any CGP for preferences with $\sigma > 0$ and $\epsilon < 1$ ($\sigma \neq 1$, $\epsilon \neq 1$).

For unit intertemporal elasticity of substitution ($\sigma = 1$, while $\epsilon \neq 0$), the instantaneous utility function is: $u(c_0, c_1) = \frac{1}{\epsilon}\ln\left[\theta c_0^\epsilon + (1-\theta)c_1^\epsilon\right]$. The above analysis remains the same and the FOCs will be those derived for the general case,

[15] Since an interior solution implies $\beta(t) \in (0,1)$, $u_s \in (0,1)$, $\forall s \in \{0,1,N\}$ and $1-\epsilon > 0$, then $sgn(g_0) = sgn(1-\sigma)$.

in the limit of $\sigma = 1$. The FOCs with respect to the consumption goods result in (25) and:

$$\frac{\dot{c}_0}{c_0} = -\rho - \frac{\dot{\kappa}}{\kappa}\left[1 + \frac{\epsilon}{1-\epsilon}(1-\beta(t))\right] + \frac{\dot{\mu}}{\mu}\frac{\epsilon}{1-\epsilon}(1-\beta(t))$$

The aggregate consumption growth rate is: $\frac{\dot{C}}{C} = -\rho - \frac{\dot{\kappa}}{\kappa}$. The CGP requirement boils down to $\frac{d}{dt}\left(-\frac{\dot{\kappa}}{\kappa}\right) = \frac{d}{dt}\left(-\frac{\dot{\nu}}{\nu}\right) = -\lambda L\dot{u}_0 = 0$. Thus no reallocation will exist along the CGP. Given condition (35), (39) implies $\frac{d}{dt}(\beta(t)) = -\frac{\epsilon}{1-\epsilon}(1-\alpha)\beta(t)(1-\beta(t))g_N = 0$. An interior solution requires $\beta(t) \in (0,1)$ and $g_N > 0$ in the steady-state. Hence, it is necessary that the preferences exhibit also unit intratemporal elasticity of substitution, i.e. $\epsilon = 0$. Unit intertemporal elasticity of substitution alone is not sufficient to allow for a CGP.

For unit intratemporal elasticity of substitution, along with a general intertemporal substitution pattern ($\epsilon = 0$ and $\sigma \neq 1$), the instantaneous utility function is: $u(c_0, c_1) = \frac{\left(c_0^{\theta}c_1^{1-\theta}\right)^{1-\sigma}-1}{1-\sigma}$. The FOCs with respect to the two consumption goods imply:

$$\frac{c_1}{c_0} = \frac{1-\theta}{\theta}\frac{\kappa}{\mu} \tag{41}$$

$$\frac{\dot{c}_0}{c_0} = \frac{1}{\sigma}\left[-\rho - \frac{\dot{\kappa}}{\kappa}(1-(1-\sigma)(1-\theta)) - \frac{\dot{\mu}}{\mu}(1-\sigma)(1-\theta)\right] \tag{42}$$

The aggregate consumption growth rate is:

$$\frac{\dot{C}}{C} = \frac{\dot{c}_0}{c_0} = \frac{1}{\sigma}\left[-\rho - \frac{\dot{\kappa}}{\kappa} + (1-\sigma)(1-\theta)(1-\alpha)g_N\right]$$

For the same reason as above, the condition for constant aggregate consumption growth rate excludes reallocation of resources along the steady-state. Condition (39) is automatically satisfied since $\beta(t) = \theta$. Condition (38) is satisfied because $\epsilon = 0$. Therefore, the only condition left in order to pin down the CGP is (40)[16].

In order to check that the solution path is indeed interior the model is solved for the labour allocations and the growth rate of the ICT stock. First, (34) and (31) are used into (42). Then the system of $\frac{\dot{c}_0}{c_0} = \alpha g_N$ and (35) is solved with respect

[16]Note finally that the limit case of $\sigma = 1$ and $\epsilon = 0$, which corresponds to instantaneous utility: $u(c_0, c_1) = \theta \ln c_0 + (1-\theta)\ln c_1$ is only a special case of the preferences with $\epsilon = 0$ and $\sigma > 0$, $\sigma \neq 1$. The same analysis applies.

to the labour allocations in the two final good sectors. The following equilibrium outcomes summarize the CGP for the social planner's economy:

$$u_1^* = \frac{\left[\frac{\rho}{\lambda L} - (1-\sigma)(1-\theta(1-\alpha))\right]}{\sigma} \tag{43}$$

$$u_0^* = \frac{\theta(1-\alpha)\left[\frac{\rho}{\lambda L} - (1-\sigma)(1-\theta(1-\alpha))\right]}{\sigma(1-\theta(1-\alpha))} \tag{44}$$

$$g_N^* = \lambda L \frac{1-\theta(1-\alpha) - \frac{\rho}{\lambda L}}{\sigma(1-\theta(1-\alpha))} \tag{45}$$

For an interior solution, it is sufficient to check that $u_1^* > 0$ and $g_N^* > 0$[17]. As long as $1-\theta(1-\alpha) > 0$, which is reasonable for a standard selection for the parameters, the condition for $g_N^* > 0$ is $1-\theta(1-\alpha) - \frac{\rho}{\lambda L} > 0$ and the condition for $u_1^* > 0$ is that $\frac{\rho}{\lambda L} - (1-\sigma)(1-\theta(1-\alpha)) > 0$. These combine to provide two necessary and sufficient conditions: $L > \frac{\rho}{\lambda(1-\theta(1-\alpha))}$ and $\sigma > \frac{1-\theta(1-\alpha)-\frac{\rho}{\lambda L}}{1-\theta(1-\alpha)}$. *Q.E.D.*

Proof of Proposition 2

Production side: The final good producers are price takers. Therefore, their demand for capital comes by equating the value of marginal product of every capital variety to its price:

$$\frac{\partial Y_0}{\partial x_0(i)} = \alpha(u_0 L)^{1-\alpha} x_0^\alpha(i) = \hat{p}_0(i), \forall i \tag{46}$$

$$p_1 \frac{\partial Y_1}{\partial x_1(j)} = \alpha(u_1 L)^{1-\alpha} x_1^\alpha(i) = \hat{p}_1(j), \forall j \tag{47}$$

The producers of the capital varieties are functioning under monopolistic competition. In the absence of dynamic decision variables, they maximize their profits by choosing their price and production in every period.

$$\pi_0 = \max_{\hat{p}_0(i), x_0(i)} \{\hat{p}_0(i)x_0(i) - p_1 x_0(i); s.t.(46)\}$$

$$\pi_1 = \max_{\hat{p}_1(i), x_1(i)} \{\hat{p}_1(i)x_1(i) - p_1 x_1(i); s.t.(47)\}$$

[17]Note that $u_1^* > 0$ iff $u_0^* > 0$ and $g_N^* > 0$ iff $u_N^* > 0$.

The solutions to these programs are:

$$x_0 = \alpha^{\frac{2}{1-\alpha}} \left(\frac{1}{p_1}\right)^{\frac{1}{1-\alpha}} (u_0 L) \tag{48}$$

$$x_1 = \alpha^{\frac{2}{1-\alpha}} (u_1 L) \tag{49}$$

$$\hat{p}_0 = \hat{p}_1 = \frac{p_1}{\alpha}$$

The model delivers symmetry among the varieties of each type of capital goods. The implied profit flows for every period is:

$$\pi_0 = \frac{1-\alpha}{\alpha} \alpha^{\frac{2}{1-\alpha}} \left(\frac{1}{p_1}\right)^{\frac{\alpha}{1-\alpha}} (u_0 L) \tag{50}$$

$$\pi_1 = p_1 \frac{1-\alpha}{\alpha} \alpha^{\frac{2}{1-\alpha}} (u_1 L) \tag{51}$$

These producers enter the market upon getting a "blueprint" that makes their products compatible with one of the old technologies, A, or one of the new ones, N. With well defined property rights, the cost that each producer needs to assume in order to acquire a blueprint is equal to the present discounted value of his entire stream of future profits. The guess is that along the steady-state the interest rate is constant. This is to be verified later. In this case, the value function of each type of firm becomes:

$$rV_0 = \pi_0 \tag{52}$$

$$rV_1 = \pi_1 \tag{53}$$

Since the labour market is perfectly competitive, there exists a wage,w_L, that clears out the market. This wage is equal to the value of marginal product of labour in all three sectors:

$$\frac{\partial Y_0}{\partial (u_0 L)} = (1-\alpha) \left(\frac{1}{p_1}\right)^{\frac{\alpha}{1-\alpha}} A \alpha^{\frac{2\alpha}{1-\alpha}} = w_L \tag{54}$$

$$p_1 \frac{\partial Y_1}{\partial (u_1 L)} = p_1 (1-\alpha) N \alpha^{\frac{2\alpha}{1-\alpha}} = w_L \tag{55}$$

$$p_N \frac{\partial \dot{N}}{\partial (u_N L)} = \frac{\pi_1}{r} \lambda N = \frac{1}{r} p_1 \frac{1-\alpha}{\alpha} \alpha^{\frac{2}{1-\alpha}} (u_1 H) \ \lambda N \ = w_L \tag{56}$$

In (56), the price of the output of the ICT-producing sector, p_N, is equal to

the market value of a firm that produces intermediate capital varieties which are compatible to ICT. The market value is given by (53) and (51).
Equating (54) and (55):

$$p_1 = \left(\frac{A}{N}\right)^{1-\alpha} \tag{57}$$

Equating (55) and (56):

$$r = \alpha\lambda u_1 L \tag{58}$$

Consumer side: The households solve the following dynamic problem by choosing $\{c_0, c_1\}$:

$$\mathcal{H} = e^{-\rho t}\frac{\left(c_0^{\theta}c_1^{1-\theta}\right)^{1-\sigma}-1}{1-\sigma} + \lambda\left[rS + w_L L - c_0 - p_1 c_1\right]$$

The solution to this problem gives the standard conditions:

$$\frac{c_1}{c_0} = \frac{1-\theta}{\theta}\frac{1}{p_1} \tag{59}$$

$$-\frac{\dot{\lambda}}{\lambda} = r \tag{60}$$

These imply:

$$\frac{\dot{c}_0}{c_0} = \frac{1}{\sigma}\left[r - \rho - (1-\sigma)(1-\theta)\frac{\dot{p}_1}{p_1}\right] \tag{61}$$

Searching for a CGP, the conditions are the same as under Proposition 1. Since $\frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = \alpha g_N$, the share of labour in the ICT-production sector needs to be constant for constant growth rates for N, Y , K. The requirement for CGP for consumption $\frac{\dot{C}}{C} = \frac{1}{\sigma}\left[r - \rho + (1-\sigma)(1-\theta)(1-\alpha)g_N\right]$, is that the interest rate is constant. This verifies the original guess. From (58), it follows that there exists no reallocation of real resources in the steady-state.

Along the CGP the market clearing conditions need to be satisfied at every point in time. Together with the FOCs, this implies constant consumption to output ratios in every sector. Equating (61) to $\frac{\dot{Y}_0}{Y_0} = \alpha g_N$ while using (58) and the ICT-production function:

$$u_1 = \frac{\frac{\rho}{\lambda L}+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)}{\alpha+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)} - \frac{\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)}{\alpha+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)}u_0 \tag{62}$$

Using the market clearing conditions, the demand functions for capital varieties and the final good production functions into the static efficiency condition imply that:

$$\frac{u_0}{u_1} = \frac{\theta(1-\alpha^2)}{1-\theta(1-\alpha^2)} \tag{63}$$

Solving the system of the last two equations:

$$u_1^d = \frac{(1-\theta(1-\alpha^2))\left[\frac{\rho}{\lambda L}+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)\right]}{\alpha(1-\theta(1-\alpha^2))+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)} \tag{64}$$

$$u_0^d = \frac{\theta(1-\alpha^2)\left[\frac{\rho}{\lambda L}+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)\right]}{\alpha(1-\theta(1-\alpha^2))+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)} \tag{65}$$

$$g_N^d = \lambda L\frac{\alpha(1-\theta(1-\alpha^2))-\frac{\rho}{\lambda L}}{\alpha(1-\theta(1-\alpha^2))+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha)} \tag{66}$$

In order to ensure that this is indeed an interior solution, it is sufficient to check that $u_1^d > 0$ and $g_N^d > 0$. The condition for $g_N^d > 0$ requires that $\alpha(1-\theta(1-\alpha^2)) - \frac{\rho}{\lambda L} > 0$ and $\alpha(1-\theta(1-\alpha^2)) + \sigma\alpha - (1-\sigma)(1-\theta)(1-\alpha) > 0$. The condition for $u_1^d > 0$ requires that $\frac{\rho}{\lambda L} + \sigma\alpha - (1-\sigma)(1-\theta)(1-\alpha) > 0$ and $\alpha(1-\theta(1-\alpha^2))+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha) > 0$. These combine to provide two necessary and sufficient conditions: $L > \frac{1}{\lambda\alpha(1-\theta(1-\alpha^2))}$ and $\sigma > \frac{(1-\theta)(1-\alpha)-\frac{\rho}{\lambda L}}{\alpha+(1-\theta)(1-\alpha)}$.

For the implied intertemporal elasticity of substitution is non-negative: $L > \frac{\rho}{\lambda(1-\alpha)(1-\theta)}$. If $\theta(1-\alpha)\left[1-\alpha(1+\alpha)\right] \leq 1-2\alpha$, then $\lambda L > \frac{1}{\alpha(1-\theta(1-\alpha^2))} \geq \frac{\rho}{(1-\alpha)(1-\theta)}$ and it is sufficient that $L > \frac{1}{\lambda\alpha(1-\theta(1-\alpha^2))}$. If instead $\theta(1-\alpha)\left[1-\alpha(1+\alpha)\right] > 1-2\alpha$, then it is sufficient that $\lambda L > \frac{\rho}{(1-\alpha)(1-\theta)}$.

Alternatively, the interior solution may be satisfied for $\alpha(1-\theta(1-\alpha^2))-\frac{\rho}{\lambda L} < 0$ and $\frac{\rho}{\lambda L}+\sigma\alpha-(1-\sigma)(1-\theta)(1-\alpha) < 0$. For reasonable parameterization this case is not relevant, while it generates perverse results for the comparative statics and the comparison to the first best from an economic point of view. *Q.E.D.*

Proof of Corollary 1

The system of the FOCs, the two resource constraints and the TVC of (16) is solved without imposing the steady-state CGP conditions.

Along any equilibrium path, the following are true: Since $c_0 = Y_0$, it follows that $\frac{\dot{c}_0}{c_0} = \frac{\dot{Y}_0}{Y_0} = \alpha g_N + g_0$. Since $c_1 = Y_1 - K_1 - K_0$, where $K_1 = \alpha Y_1$ and $K_0 = \alpha \left(\frac{N}{A}\right)^{1-\alpha} Y_0$, it follows that $\frac{\dot{c}_1}{c_1} = \frac{\dot{Y}_1}{Y_1} = g_N + g_0$. From the static optimization: $u_0 = \frac{\theta(1-\alpha)}{1-\theta(1-\alpha)} u_1$ it follows that $g_0 = g_1 = g$. Using the latter with the resource constraint: $1 = u_0 + u_1 + u_N$, it follows that: $\dot{u}_N = -g(1 - u_N)$.

Given that in the steady-state $\tilde{c}_0 = \frac{c_0}{N^\alpha}$ and $\tilde{c}_1 = \frac{c_1}{N}$ remain constant, it is useful to define the composite consumption index: $E \equiv \tilde{c}_0^\theta \tilde{c}_1^{1-\theta}$. Its growth rate is equal to:$\frac{\dot{E}}{E} = \theta \left(\frac{\dot{c}_0}{c_0} - \alpha g_N\right) + (1-\theta)\left(\frac{\dot{c}_1}{c_1} - g_N\right)$. Since $\frac{\dot{c}_1}{c_1} = \frac{\dot{c}_0}{c_0} - (1-\alpha) g_N$, it follows that $\frac{\dot{E}}{E} = \frac{\dot{c}_0}{c_0} - \alpha g_N$. Using the results above regarding the growth rate of consumption implied by the market clearing conditions:

$$\frac{\dot{E}}{E} = g \tag{67}$$

At the same time, using (42) together with (**??**), (31) and $\frac{u_0}{u_1} = \frac{\theta(1-\alpha)}{1-\theta(1-\alpha)}$:

$$\frac{\dot{E}}{E} = -\frac{\rho}{\sigma} + \frac{\lambda L}{\sigma} \left(1 - \theta(1-\alpha)\right)\left(1 - \sigma u_N\right) \tag{68}$$

Equating (67) and (68):$g = -\frac{\rho}{\sigma} + \frac{\lambda L}{\sigma} \left(1 - \theta(1-\alpha)\right)\left(1 - \sigma u_N\right)$. Therefore:

$$\dot{u}_N = (1 - u_N)\left[\frac{\rho}{\sigma} - \frac{\lambda L}{\sigma}\left(1 - \theta(1-\alpha)\right)\left(1 - \sigma u_N\right)\right] \tag{69}$$

This first order non-linear differential equation in the share of labour in the ICT-producing sector summarizes completely the dynamics of the economy. Its solution is[18]:

$$t - \int^{u_N(t)} \frac{1}{\frac{\lambda H}{\sigma}\left[\frac{\rho}{\lambda L} - (1-\sigma z)(1-\theta(1-\alpha))\right](1-z)} dz + \digamma = 0 \tag{70}$$

Solved for an initial condition: $u_N(0) = u_N^*$, i.e. starting from the steady-state, the solution is $u_N(t) = u_N^*$. This implies that $\dot{u}_N = g = 0$. In turn, this implies that there are no transition dynamics, as long as g_N, $\frac{c_0}{Y_0}$, $\frac{c_1}{Y_1}$, and $\frac{c_0}{p_1 K_0}$, $\frac{c_1}{K_1}$ always remain constant in and out of steady-state. Note also that (69) ,may be rewritten as:

$$\dot{u}_N = (1 - u_N)\left(1 - \theta(1-\alpha)\right)\left(u_N - u_N^*\right) \tag{71}$$

[18]The differential equation is a quadrature. Let $\digamma$ be some arbitrary constant of integration.

From (71), if the economy deviated from steady-state position then there would be no forces to restore the steady-state. The dynamics imply that (for $u_N < 1$ and $1 > \theta(1-\alpha)$) $u_N > u_N^* \Leftrightarrow \dot{u}_N > 0, \forall t$. *Q.E.D.*

Proof of Proposition 3

Let $\pi = \alpha\left(1-\theta(1-\alpha^2)\right) + \sigma\alpha - (1-\sigma)(1-\alpha)(1-\theta) > 0$.

Effect of a change in λ:

$$\begin{aligned}
\frac{\partial u_1^d}{\partial \lambda} &= \frac{\left(1-\theta(1-\alpha^2)\right)\frac{\rho}{L}}{\pi}\left(-\frac{1}{\lambda^2}\right) < 0 \\
\frac{\partial u_0^d}{\partial \lambda} &= \frac{\theta(1-\alpha^2)}{1-\theta(1-\alpha^2)}\frac{\partial u_1^c}{\partial \lambda} < 0 \\
\frac{\partial g_N^d}{\partial \lambda} &= \frac{\alpha\left(1-\theta(1-\alpha^2)\right)L}{\pi} > 0
\end{aligned}$$

Change in ρ:

$$\begin{aligned}
\frac{\partial u_1^d}{\partial \rho} &= \frac{\left(1-\theta(1-\alpha^2)\right)}{\pi}\frac{1}{\lambda L} > 0 \\
\frac{\partial u_0^d}{\partial \rho} &= \frac{\theta(1-\alpha^2)}{1-\theta(1-\alpha^2)}\frac{\partial u_0^c}{\partial \rho} > 0 \\
\frac{\partial g_N^d}{\partial \rho} &= -\frac{1}{\pi} < 0
\end{aligned}$$

Change in θ:

$$\begin{aligned}
\frac{\partial g_N^d}{\partial \theta} = \frac{\lambda L}{\pi^2}\Big\{&-\alpha(1-\alpha^2)\left[\frac{\rho}{\lambda L} + \sigma\alpha - (1-\sigma)(1-\alpha)(1-\theta)\right] \\
&-(1-\sigma)(1-\alpha)\left[\alpha\left(1-\theta(1-\alpha^2)\right) - \frac{\rho}{\lambda L}\right]\Big\}
\end{aligned}$$

Given the condition for interior solution, the first term is negative. The second term will be also negative iff $\sigma \leq 1$. Also:

$$\frac{\partial\left(\frac{u_0}{u_1}\right)}{\partial \theta} = \frac{1-\alpha^2}{\left[1-\theta(1-\alpha)\right]^2} > 0$$

For $\sigma = 1$:

$$\begin{aligned}
\frac{\partial g_N^d}{\partial \theta} &= \frac{\lambda L}{\pi^2}\left[-\alpha(1-\alpha^2)\left(\frac{\rho}{\lambda L}+\alpha\right)\right] < 0 \\
\frac{\partial u_1^d}{\partial \theta} &= -\frac{\alpha(1-\alpha^2)}{\pi^2}\left(\frac{\rho}{\lambda L}+\alpha\right) < 0
\end{aligned}$$

Change in α:

$$\begin{aligned}
\frac{\partial g_N^d}{\partial \alpha} &= \frac{\lambda L}{\pi^2}\left\{\left[1-\theta(1-\alpha^2)+2\theta\alpha^2\right]\left[\frac{\rho}{\lambda L}+\sigma\alpha-(1-\sigma)(1-\alpha)(1-\theta)\right]\right. \\
&\quad \left. -(1-\theta(1-\sigma))\left[\alpha\left(1-\theta(1-\alpha^2)\right)-\frac{\rho}{\lambda L}\right]\right\}
\end{aligned}$$

The first term is positive. The second term is always negative. The final effect is ambiguous. Also:

$$\frac{\partial\left(\frac{u_0}{u_1}\right)}{\partial \alpha} = \frac{-2\theta\alpha}{[1-\theta(1-\alpha)]^2} < 0$$

For $\sigma = 1$:

$$\begin{aligned}
\frac{\partial g_N^d}{\partial \alpha} &= \frac{\lambda L}{\pi^2}\left[\frac{\rho}{\lambda L}\left(2-\theta(1-\alpha^2\right)+2\theta a^2)+2\alpha^3\theta\right] > 0 \\
\frac{\partial u_1^d}{\partial \alpha} &= -\theta\frac{2-\theta(1-\alpha^2)}{\pi}\left[\frac{\rho}{\lambda L}(1+\alpha^2)+2\alpha^3\right] < 0
\end{aligned}$$

Q.E.D.

7 Appendix B: Data Summary

Data Sources:

The data on employment, value added and value added deflators for 57 industries (at the three-digit ISIC Rev.3) of the United States economy are taken from the "60-Industry Database", which is constructed by the Groningen Growth and Development Centre (GGDC). The data cover the period 1979-2001 (version Oct. 2003). The dataset is constructed based on the information available in the OECD STructural ANalysis Database (STAN) and official United States Statistical Offices: the Bureau of Economic Analysis (BEA) and Bureau of Labour Statistics (BLS).

The data on ICT-capital intensity for 26 industries at the second-digit ISIC Rev. 3 are taken from the publication of GGDC: "ICT and Europe's Productivity Performance. "Industry-level Growth Account Comparisons with the United States". The correspondence of the "Industry Labour Productivity Database" and the "60-Industry Database" is based on the United Nations ISIC Rev. 3 classification.

The data on the use shares of the commodities are from the "Use Table" of the "Benchmark 1997 Input-Output Table" available from BEA. The 1997 benchmark I-O accounts use the classification system that is based on the North American Industry Classification System (NAICS). The correspondence between NAICS and ISIC Rev. 3 classification is based on matching the Bureau of Census NAICS and United Nations ISIC Rev. 3 classification. The matching is only approximate.

The data on "Personal Consumption Expenditures by Type of Expenditure" are taken from NIPA Table 2.5.5. available from BEA. The industry data are available on the NAICS basis. The correspondence to the ISIC Rev. 3 is the same as for the data from I-O accounts.

Variables:

Value added is current gross value added measured at producer prices or at basic prices, depending on the valuation used in the national accounts. It represents the contribution of each industry to total GDP.

Value added Deflator is the change in the value added deflator. It can be combined with current value added to derive quantity indices of real value added at industry level[19].

[19] The official data were readily adjusted into using a hedonic deflator system, so as to account better for the benefits arising from the ICT production and use. The deflators provided in the GGDC database come from official BEA data (harmonising of the deflators for other countries in the dataset does not affect USA data) and are based on the double deflation procedure for the ICT related industries. For an overview of the literature regarding hedonic deflators, see OECD "Handbook on Hedonic Indexes and Quality Adjustments in Price Indexes: Special Application to Information Technology Products", Triplett J. (2004).

Hours refers to average annual hours worked per employee or per person engaged.

Personal consumption expenditures are the goods and services purchased by persons[20].

Aggregation Method:

The private sector industries are grouped into three aggregate sectors: ICT-producing, ICT-using and non-ICT-using[21].

The Information and Communication Technology sector (ICT) is defined by the OECD in terms of the following ISIC Rev. 3.1 manufacturing classes: Office, accounting and computing machinery (3000), Insulated wire and cable (3130), Electronic valves and tubes and other electronic components (3210), Television and radio transmitters and apparatus for line telephony and line telegraphy (3220), Television and radio receivers, sound or video recording or reproducing apparatus, and associated goods (3230), Instruments and appliances for measuring, checking, testing, navigating and other purposes, except industrial process equipment (3312), Industrial process equipment (3313). The services class Computer and related activities (72), where software production takes place is the only services class that is included in the analysis here, following the lines of Jorgenson et al. (2004) in classifying the industries in the ICT-producing sector. The criterion used for classifying an industry as ICT using is its degree of ICT capital intensity. In particular, the average share of the ICT capital out of total capital compensation for an industry over the period 1979-2001 needs to exceed the average share that is observed in the aggregate economy over the same period. The data for the share of ICT capital in value added come from the GGDC's 2003 report for 26 industries for periods 1979-1995

[20] Persons. In the national income and product accounts (NIPAs), persons consist of individuals, nonprofit institutions that primarily serve individuals, private noninsured welfare funds, and private trust funds.

[21] The industries excluded from the analysis of the private sector economy sector are: Public administration and defence; compulsory social security (75), Education (80), Health and social work (85), Other community, social and personal services (90-93), Private households with employed persons (95), Extra-territorial organizations and bodies (99).

and 1995-2000[22][23]. Details on the industries in each aggregate sector are provided below[24].

The aggregation is straightforward for the hours and value added at current prices data. A Törnqvist index was applied to obtain value added deflators for each of the three sectors[25]. The aggregate value added deflator was then used to calculate value added at constant prices.

[22] Data are provided by GGDC for 26 industries. The appropriate mapping with the 57 industies was made following the ISIC Rev. 3 system.

[23] Alternative thresholds (e.g. the 60th, 70th, 80th percentile of the distribution) were also used and the results are essentially the same.

[24] ISIC codes, Rev.3, in the parentheses.

[25] The Törnqvist aggregation method is based on weighting each industry's exponential annual growth rate with a two-period average of its share in aggregate value added. After computing the growth rate, the implied quantity index was derived, with the normalization that it is equal to 100 in 1995.

Aggregate Sectors

ICT-producing sector:

Office machinery (30), Insulated wire (313), Electronic valves and tubes (321), Telecommunication equipment (322), Radio and television receivers (323), Computer and related activities (72), Scientific instruments (331)

ICT-using sector:

Other electrical machinery and apparatus nec (31-313), Other instruments (33-331), Mechanical engineering (29), Wholesale trade and commission trade, except of motor vehicles and motorcycles (51), Financial intermediation, except insurance and pension funding (65), Insurance and pension funding, except compulsory social security (66), Activities auxiliary to financial intermediation (67), Renting of machinery and equipment (71), Research and development (73), Communications (64), Other business activities (50%(741-3+749))

non-ICT-using:

Agriculture (01), Forestry (02), Fishing (05), Mining and quarrying (10-14), Food, drink & tobacco (15-16), Textiles (17), Clothing (18), Leather and footwear (19), Wood & products of wood and cork (20), Pulp, paper & paper products (21), Printing & publishing (22), Mineral oil refining, coke & nuclear fuel (23), Chemicals (24), Rubber & plastics (25), Non-metallic mineral products (26), Basic metals (27), Fabricated metal products (28), Motor vehicles (34), Building and repairing of ships and boats (351), Aircraft and spacecraft (353), Railroad equipment and transport equipment nec (352+359), Furniture, miscellaneous manufacturing; recycling (36-37), Electricity, gas and water supply (40-41), Construction (45), Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel (50), Retail trade, except of motor vehicles and motorcycles;repair of personal and household goods (52), Hotels & catering (55), Inland transport (60), Water transport (61), Air transport (62), Supporting and auxiliary transport activities; activities of travel agencies (63), Real estate activities (70), Private households with employed persons (95), Other business activities (50%(741-3+749))

Table B1

		Average			St Deviation		
series		1979-01	1979-95	1995-01	1979-01	1979-95	1995-01
share of total hours worked	ICT-producing	0.039	0.038	0.042	0.003	0.002	0.003
	non-ICT-using	0.708	0.712	0.698	0.009	0.006	0.005
	ICT-using	0.253	0.251	0.261	0.007	0.006	0.003
share of value added	ICT-producing	0.047	0.044	0.056	0.007	0.005	0.003
	non-ICT-using	0.697	0.712	0.659	0.031	0.020	0.014
	ICT-using	0.255	0.244	0.285	0.024	0.015	0.012
value added at current prices (in logs)	ICT-producing	12.109	11.866	12.752	0.564	0.436	0.176
	non-ICT-using	14.812	14.656	15.227	0.369	0.293	0.110
	ICT-using	13.804	13.582	14.390	0.504	0.379	0.172
value added at constant prices (in logs)	ICT-producing	11.467	11.002	12.612	0.978	0.680	0.379
	non-ICT-using	14.871	14.791	15.067	0.173	0.127	0.066
	ICT-using	14.122	14.004	14.404	0.235	0.135	0.139
value added deflator growth rate	ICT-producing	-0.071	-0.063	-0.095	0.031	0.031	0.022
	non-ICT-using	0.033	0.036	0.022	0.023	0.026	0.006
	ICT-using	0.037	0.047	0.015	0.025	0.020	0.017
labour productivity growth rate	ICT-producing	0.133	0.139	0.126	0.042	0.046	0.031
	non-ICT-using	0.017	0.017	0.018	0.015	0.015	0.014
	ICT-using	0.017	0.007	0.037	0.022	0.016	0.020
expenditure shares	non-ICT-using	0.864	0.869	0.849	0.013	0.011	0.005
	ICT-using	0.136	0.131	0.151	0.013	0.011	0.005

Source: All series from GGDC "60 Industry Database". Expenditure shares from the BEA NIPA Table on ""Personal Consumption Expenditures by Type of Expenditure", 2004.

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