The Long-Run Impact of ICT

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Abstract

This paper examines the growth impact of digital capital in the US and EU-15 countries from a long-run perspective. It estimates output elasticity to ICT assets within an aggregate production function framework by means of a panel cointegration analysis.

It is found that Europe is lagging behind the US in terms of ICT utilisation, especially due to the dismal performance of the largest countries. On the other side, there is a core of small dynamic EU economies whose growth pattern has been positively influenced by ICT over the last quarter of century.

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1. Introduction

In a recent paper Jorgenson and Vu (2005) have shown that capital input accumulation has been the primary source of the world's output growth between the end of the twentieth century and the beginning of the current one. Since 1995 the acceleration in the growth rate of output and labour productivity can be traced for a large fraction to advances in Information and Communication Technology (ICT). The impressive improvement in the price-performance ratio of microelectronic components has fuelled the rise in technical efficiency of ICT producing industries and the rapid adoption of computers, software and communication equipment by firms and households, as a consequence of price decline (Jorgenson, 2001).

The growth impact of ICT has been particularly sizeable in the US as well as in most countries of the OECD area (Finland, Korea and Australia) and such developing economies as China and India. Aside from few episodes, instead, Europe seems to have lost momentum and, for this reason, recently the EU institutions have renewed with great emphasis their medium-term initiative towards the construction of a common information-based economic space (i-2010; see EC, 2005).

Thus far, the relevance of ICT for national performance has been mainly investigated through growth accounts, decomposing output growth into the income share-weighted rise of factor inputs. On the other hand, econometric literature has focussed principally on short-run effects of ICT equipment, sometimes comparing countries on the basis of industry data. After a decade from the advent of the often-called *Information Age* and, not secondarily, over a quarter of century from the first wave of investments in office machinery, it seems useful to investigate the growth effects of ICT from a long-run perspective, through a panel cointegration analysis. Given the nature of general purpose technology, in fact, the productive impact of digital capital is likely to fully materialize only in a long-term horizon, especially at the most aggregate level of analysis; by applying the usual methods of estimation on short-differences, there may be the risk that a part of its contribution remains neglected.

This paper aims at gauging the impact of ICT capital on GDP levels for the US and the EU-15 countries over the period 1980-2004. It employs two newly available procedures which represent the dynamic extension of panel ordinary least squares and seemingly unrelated regression (PDOLS and DSUR). The latter will be shown to be more suited for our analysis, as it is able to more powerfully account for cross-country dependence, yielding non-trivial differences in the results.

The remainder is organized as follows. Section 2 surveys the empirical literature on the role of ICT capital in aggregate performance. Section 3 presents the analytical framework at the basis of the work, briefly describing the properties of PDOLS and DSUR. A short statistical analysis is reported in Section 4 where output growth is decomposed into the factor inputs' contributions. Section 5 lays out the econometric findings; initially, it analyses the trend stationary properties of our variables (par. 5.1), and then quantifies the long-run impact of ICT by estimating an aggregate production function (par. 5.2).

It is documented that ICT has played a substantial role for economic growth in the US, but less in Europe. In line with the sound of growth accounts studies, the leading economies of the European Union (as well as Greece and Portugal) are found to lag in exploiting the growth potential of information technology. On the other side, there is a core of small dynamic economies whose growth pattern has been positively influenced by the deployment of these new technologies. There are two points of the analysis that are worthwhile remarking. First, the significance of ICT variables arises only when we properly account for cross-country dependence using dynamic SUR estimator. Second, the results are demonstrated to be robust to the omission of human capital by integrating our main data set with two additional (external) sources. Finally, Section 6 summarizes and makes some concluding remarks.

2. ICT and economic growth

The impact of ICT investment on economic performance has been scrutinized from more than one perspective. There is a large international evidence that computer use exerts a positive effect on firms' productivity. Dedrick et al. (2003), Pilat (2004) and, more recently, Draca et al. (2006) have surveyed this large body of studies. In summary, to be profitable IT equipment requires complementary investments in communication equipment and software, together with some other collaborating inputs such as human capital and organizational factors. Moreover, ICT capital acts as enabler of further innovations in many business activities, with a clear advantage for companies undertaking R&D projects.

Yet, as pointed out by Pilat (2004), the benefits gained at the firm-level may be not appearing in aggregate statistics as the poor performance of less productive businesses may obscure the growth of the most innovative ones. This aspect is more accentuated in presence of strong market rigidities that prevent successful firms from emerging, thereby reducing the incentives to high-tech investment. According to Bassanini and Scarpetta (2002), such institutional factors make Europe a scarcely dynamic economic space, in part explaining why ICT has contributed to economic growth to a smaller extent than in the US. In particular, IT investment has been doomed by labour market's restrictions, which hamper firms to adjust their workforce to the new technological paradigm (Gust and Marquez, 2004).

The prominence of information technology for the US aggregate economy was initially stressed by Jorgenson and Stiroh (2000) and Oliner and Sichel (2000). At the beginning, however, it was believed that productivity gains were confined to IT production sectors (Gordon, 2000).[1] Nowadays, instead, there is a broad consensus on the pervasiveness of growth effects of these new technologies. The formidable fall in semiconductors' price has fuelled both TFP growth in ICT-producing sectors and ICT capital deepening in the rest of the economy,

[1] Investigating the localization of productivity acceleration within the US, Daveri and Mascotto (2006) find that the states where labour productivity grew at a faster rate present an IT specialisation above the national mean. A coherent evidence is provided by O'Mahony and van Ark (2003) for the EU-15 member states.

accounting for the full one-percent acceleration in US labour productivity occurred after 1995 (Jorgenson et al., 2003).[2]

Both a lower high-tech specialization and a smaller usage of ICT equipment are considered the main determinants of the slower economic growth experienced by Europe (Timmer et al., 2003).[3] Nevertheless, a low degree of ICT specialisation is not necessarily bad for growth as stressed by the performance of Australia, Canada and Mexico (Pilat and Wolfl, 2004). In terms of welfare, then, huge benefits from technical advances in ICT production also accrue to using countries, as a consequence of price decline (Bayoumi and Haacker, 2002).

Searching for the industry sources of US resurgence, Stiroh (2002b) and Nordhaus (2005) observe that it entirely originated in those sectors that produce and intensively use ICT capital. Relative to the US, O'Mahony and van Ark (2003) point out that the EU is severely lagging in some ICT-using service sectors like finance, wholesale and detail trade, where in the US new asset types facilitated radical business re-organisations in the last decade (McGuckin et al., 2004).

Econometric evidence on the nexus between ICT capital deepening and industry labour productivity growth is still mixed. According to Stiroh (2002a), US manufacturing sectors have not taken a particular advantage from digital assets, apart from ICT producing firms. On the other hand, O'Mahony and Vecchi (2005) find a positive effect for all US market industries, but not for the UK. For the latter country, however, a favourable indication comes from Oulton and Srinivasan (2005).

At the highest level of aggregation, the scarce availability of comparable statistics have enormously limited econometric studies across countries. Moreover, it should be pointed out that findings do considerably vary in relation to the nature of the data employed, time-frame, country coverage and estimation technique. Relying upon a private source (until 1993), Dewan

[2] Cette et al. (2005) argue that if the decline in relative prices did persist, the potential output growth could be enhanced in the US by over two percent points per year. Recent works have described the sharp acceleration in TFP of ICT using industries occurred after the dot-com crash of 2000; nevertheless, it is still unclear which forces lie behind such a performance (see, respectively, Jorgenson et al. 2006 and Stiroh, 2006).

[3] Earlier works investigating the growth contributions of ICT in the OECD and/or EU countries include Colecchia and Schreyer (2002), Daveri (2002), Vijselaar and Albers (2002) and van Ark et al. (2002).

and Kraemer (2000) find a significant ICT contribution to output only for developed countries. Park and Shin (2004) 'update' that kind of study to a more recent period (1992-2000), employing the World Development Indicators by the World Bank. A positive effect can be identified either both richer and less industrialised nations, proportionally to their endowment of IT assets.[4] Furthermore, there emerges an indirect external effect of digital capital on productivity growth.

A less orthodox attempt of assessing the existence of ICT spillovers is carried out by Dutta and Otsuka (2004), using patents application data for a small group of nations. Given that the flow of new knowledge (applications) is strongly and positively correlated to the stock of patents applied by high-tech industries, ICT patents are used as a proxy of knowledge inputs within a production function framework. Nevertheless, in contrast to the prescriptions of new growth theories, GDP is not affected by knowledge, perhaps due to the short time-span considered in this study.[5]

Similar in the spirit is the work by Becchetti and Adriani (2005) who regard ICT as enabler of knowledge diffusion. By estimating a growth regression à la Mankiw-Romer-Weil, they find that the uptake of new technologies is a crucial additional factor to explaining income differentials across countries.

Fuss and Waverman (2005) evaluate instead whether ICT engender networking effects, building a system of simultaneous equations where TFP is supposed to depend on the penetration rate (and digitalisation) of telecom infrastructures. The underlying idea is that advanced communication equipment puts in connection the stock of computers, fuelling the social value of ICT capital over private return; moreover, disentangling TFP growth into various sources (scale economies, time trend and spillovers) shows that ICT externality was the main contributor to productivity for most OECD countries in the late 1990s.

[4] This is consistent with findings provided by Belorgey et al. (2006).

[5] Likewise, Aiginger and Falk (2005) observe that technological specialisation, measured by the share of high-tech exports and EPO ICT patent application, does not add much information to R&D intensity as a source of growth for OECD countries.

Following this line of discussion, ICT spillover might be even higher than estimated in Fuss and Waverman (2005), as they do not consider the benefits stemming from the connection with IT capital of trading partner countries. To a broad extent, this is the goal pursued by Lee and Guo (2004). These authors explicit foreign ICT investment as a determinant of national TFP growth, reporting a robust evidence in favour of spillovers going from richer to less developed countries. According to Gholami et al. (2005), however, the relation between ICT and international trade is double-sense. On one hand, digital capital enhances the outflow of foreign direct investment from industrialized economies, since it facilitates access to information on new markets and co-ordination with headquarters. On the other hand, the inflow of FDI stimulates the dissemination of new technologies in developing countries.

3. Analytic framework

After 1995 there has been a valuable research effort to assess the fraction of output growth traceable to the deployment of ICT capital. Aside from few exceptions, econometric studies have adopted techniques more suited for the short-run, being based on first-differenced variables. This has the advantage of working with stationary series and using traditional inference to test the results' robustness. As known, however, it happens at the cost of losing some useful information when there exists a long-run stationary (cointegration) relation between dependent variable and regressors.

Real investment in ICT equipment has accelerated enormously in the last decade, growing annually at double-digit rates. Nevertheless, the installed capacity was already relatively high before the mid-1990s, and hence at least partly the current earnings may originate from the past.[6] Given the nature of general purpose technology, ICT needs a long time to yield positive returns, since its introduction is usually accompanied by business re-organizations, complementary investment, and more generally adjustment costs. According to Brynjolfsson and Hitt (2003) and Oulton and Srinivasan (2005), it is due to these additional factors that ICT capital

[6] See Gordon (2004) for a discussion on the delayed growth effects of ICT.

exhibits a larger coefficient when estimated on long differences than on annual growth rates.[7] Basu et al. (2004) provide corroborative evidence for the US industries, but not for the UK for which ICT turns out to be insignificant. van Ark and Inklaar (2005) specifically identify an U-inverted relation between the timing of ICT capital contribution and TFP growth: 'early normal returns' are ascribed to the direct productivity gains of ICT-production and -investment (*hard savings*), while the following 'negative spillover' to the delayed effects of complementary investments (*soft savings*).

In addition to these issues, both direct effects and productivity spillovers of ICT are likely to fully materialize only in the long-run at an economy-wide level *because of* that compensation working among firms, industries and/or sectors ('aggregation of relations'). For the US, this kind of bias has been econometrically investigated by McGuckin and Stiroh (2002), who show how both statistical and economic relevance of ICT capital increasingly reduces moving to higher levels of analysis.[8]

In light of this discussion a cross-country analysis employing at a long-term horizon appears to be the most suited to properly assess the *aggregate* impact of information technology. This paper estimates a *long-run* production function for the US and EU-15 member states over the period 1980-2004. To this aim, it utilises two new techniques of panel cointegration estimation, PDOLS and DSUR; the former is the dynamic version of panel OLS estimator (Mark and Sul, 2003), the latter consists of the time series extension of seemingly unrelated regression (Mark et al., 2005).[9]

[7] To be reminded is that O'Mahony and Vecchi (2005) find a significantly positive impact of digital capital on the output growth of the US (market) industries by looking at a long-term horizon; this contrasts with several previous studies, which were mainly based on short-run techniques.

[8] A further source of concern in this kind of regressions is potential bias deriving from aggregation of heterogeneous inputs ('aggregation of variables'); for ICT assets, this problem is found to progressively vanish rising the level of data aggregation (McGuckin and Stiroh, 2002). See Stiroh (2004) for a sensitivity study on the choice of specification model, estimation technique and variables' aggregation in quantifying the output elasticity to IT capital.

[9] Among others, Bottazzi and Peri (2007) employ PDOLS to study the quantitative impact of international knowledge on technological innovation of the OECD countries. Cointegration estimators based on the SUR approach have also been developed by Moon and Perron (2005) and Westerlund (2005). See Breitung and Pesaran (2005) for recent developments in panel time-series econometrics.

Let us assume a log-linear Cobb-Douglas production function. GDP (Y) is expressed as dependent on hours worked (H), non-ICT capital and ICT assets (K_N and K_{ICT}):[10]

$$\ln Y_{it} = \alpha_{0i} + \alpha_{1i} t + \beta_1 \ln H_{it} + \beta_2 \ln K_{N,it} + \beta_3 \ln K_{ICT,it} + u_{it}; \qquad (1)$$

i=1,...,N denotes the cross-sectional units (N=16), t=1,...,T time dimension (T=25), whilst the deterministic part of the specification includes an individual intercept, a time trend, and also common time dummies when running PDOLS (in form of working on cross-sectionally demeaned variables).

It is evident that, within this framework, the equilibrium error u_{it} is affected by endogeneity with own-equation regressors and cross-dependence with the disturbances of the other equations. If first-differenced variables are stationary, they behave as correlated random walks ($\Delta x_{it} = e_{it}$), and hence the long-run covariance of the equations' system errors (u_{it}, e_{it}) can be modelled as a partitioned matrix; this displays the covariance (sub)matrices of single error terms on the diagonal blocks ($\Omega_{u'u}$ and $\Omega_{e'e}$), and the ones of their cross-product out of the diagonal ($\Omega_{e'u}$ and $\Omega_{u'e}$). $\Omega_{u'u}$ describes the degree of correlation existing among equations; non-null values of off-diagonal parameters determine the inefficiency of least squares estimator, leading to adopt seemingly unrelated regression. $\Omega_{e'e}$ regulates instead the cross-equation dependence of regressors, explaining why some efficiency gains can be obtained by a system estimator with respect to the ones based on single equations. Finally, $\Omega_{e'u}$ models the endogeneity between error term and regressors that, within each equation, is source of simultaneity bias for the static estimation techniques.

Panel dynamic OLS and dynamic SUR eliminate these biases by adding *p* lags and leads of own first-differenced regressors (Δx_{it}) to each country-equation so as to purge the

[10] The Cobb-Douglas technology is the most utilised specification in productivity literature, especially when dealing with heterogeneous inputs and in presence of data limitations (cross-sectional or time-series). The hypothesis that such a technology is valid for the entire sample is obviously debatable. For instance, Antràs (2004) reports evidence against this assumption for the US, while it seems to hold for Finland only on a very long time horizon (Jalava et al., 2006). However, there is cross-country evidence that adopting this kind of technology yields factor inputs' elasticities lying close to those obtained with less parsimonious specifications like a translog; see Kumbhakar and Wang (2005).

equilibrium error u_{it} from the effect of reverse causality, and by including the ones of the other panel units (Δx_{jt}) to remove cross-sectional dependence. Both estimators can be implemented through a feasible two-step procedure. As a first step, any individual dependent variable and each element of the explanatory variables' matrix are regressed on the vector of p lags and leads. Then, the cointegration vector is computed by means of either the estimator of least squares or seemingly unrelated regression on the stacked residuals of such auxiliary regressions. The former estimator pools equations together, while the latter estimates the system by pre-multiplying the residuals with the inverse matrix of the lower triangular Cholesky decomposition of the long-run error covariance ($\Omega_{u'u}$ =LL').

It is important to point out that the general (*unrestricted*) version of the dynamic SUR estimator devised by Mark et al. (2005) computes one cointegrating vector for each single equation, verifying whether they can be considered statistically identical within the system through a Wald test. Unfortunately, this test is oversized when time dimension is not sufficiently long, leading to reject systematically the null hypothesis of homogeneity. This forces us to *assume* that a common cointegration vector is valid for all the panel units, and thus in the regression analysis below we employ the *restricted* version of DSUR estimator.

4. Data characteristics and some descriptive results

Our study employs the GGDC Total Economy Growth Accounting database that has been developed at the University of Groningen (Netherlands).[11] It includes the US and all the European Union member states before the enlargement (EU-15), and refers to the period 1980-2004. As a measure of output, it considers real GDP net of rentals paid for residential buildings so to avoid any distortion related to measurement differences across countries. Hours worked (in million thousands) are adopted as a proxy of labour input and, as a result, the contribution

[11] http://www.ggdc.net/dseries/growth-accounting.html, release June 2005. See Timmer et al. (2003) for details and the underlying growth accounting methodology. All monetary variables have been converted from national currencies into US constant dollars of 2000.

of labour quality is embedded into the residual (TFP). Capital investment is disentangled into three kinds of ICT asset (computer and office machinery, communication equipment and software) and three non-ICT related types (non-IT equipment, transport equipment and non-residential buildings); for ICT investment, a qualitative adjustment based on the US hedonic deflators is made to treat homogeneously their technical characteristics (price harmonisation). The flow of capital services is estimated through the permanent inventory method with asset-specific geometric deprecation rates, converting series to mid-year values, $K_{i,t}=(S_{i,t}+S_{i,t-1})/2$.

As for descriptive analysis, in Table 1 output growth is decomposed into factor inputs' contribution. When one considers Europe and United States as a whole, it is possible to see how the share-weighted growth of ICT capital has been as high as that of non-ICT assets over the period 1980-2004. In average, it amounts to 0.6%-points per year, reflecting an annual average growth of 14% and an income share of 0.04. ICT accounts thus for one seventh of total capital services.

Comparing the two Atlantic sides highlights that the contribution of digital capital has been considerably higher in the US (0.78 against 0.44 of Europe); by contrast, the dynamics of non-ICT capital is much closer (0.55 vs 0.66). Another remarkable discrepancy can be identified in the role played by hours worked (0.06 vs 0.93), because of the negative contribution displayed by some EU-15 member states. Europe exhibits a larger impact of TFP over the long run due to technological convergence (0.96 vs 0.89 of the US); nevertheless, it is important to pinpoint that there has been a sharp change in the last years. Indeed, productivity growth presents an inexorable downward trend in the EU since the mid-1990s, while experiencing a striking acceleration in the US, especially after 2001.

"Table 1 about here"

Country-specific data show wide heterogeneity within Europe in the ICT contribution to output, which ranges from 0.22 percentage points in Greece to 0.70-0.74 in Belgium and Luxembourg. The overall figure of ICT hides a substantially different dynamics in high-tech expenditure (office machinery, communication equipment and software). A large proportion of the European lag can be ascribed to the small contribution of computers and software, especially in major continental economies. Figures comparable to the US are exhibited only by Belgium and Luxembourg for computers, the Scandinavian countries for software and, finally, Finland and Italy for communication equipment.

Looking at the other sources of growth, TFP arises as the main driver of output for most countries except for Austria, Greece, Italy, Luxembourg and Spain. Non-ICT capital accounted for a sizeable part of GDP growth in several catching-up economies as well as in France and Italy; in these two countries its contribution exceeds that of digital assets, contrarily to what happens for Germany.

In Europe, only those states that have intensively liberalised their labour markets during the 1990s have substantially benefited from the contribution of hours worked (Ireland, Luxembourg, Netherlands and Spain). On the other hand, although most countries have increased the employment rate, this has not been sufficient to offset the secular downward trend in hours worked per employed, and consequently they show negative values for hours worked (McGuckin and van Ark, 2005).

As illustrated by Jorgenson and Vu (2005), human capital has been another key factor for development, but this cannot be seen in our data as its impact is incorporated into the Solow's residual. However, a rough indication can be obtained integrating the GGDC series with the average level of education estimated by Barro and Lee (2000) for people aged 25 and over. The last columns of Table 1 reports the measure of labour input obtained multiplying hours worked with the average years of schooling, which will be used in the following to check our estimates' robustness. From columns II and VII it is easy to see how the rise in the level of human capital outweighed the long-lasting decline in the amount of hours worked. Human capital-adjusted labour eventually provides a positive contribution to GDP growth for all countries but Germany; the largest labour contribution are now shown by those countries starting from a relatively low level of development (Greece, Portugal and Spain).[12] Cleaning TFP from the

[12] Barro and Lee (2000) estimate the average years of schooling at five-year intervals up to 2000. Intermediate years have been geometrically interpolated, while the growth rate of 1995-2000 has been used to estimate the levels after 2000. Because of the lack of data, the average level of neighbouring countries has been attributed to

contribution of human capital remarkably reduces its annual growth rate, becoming even negative for some EU states.

5. Econometric results

5.1 Panel unit roots and cointegration analysis

This section is devoted to demonstrate that the macro-economies series employed in our study are trend stationary and there exists a relation of cointegration among them. As a first step, we need to show that log-level variables are not stationary, but they do if considered in first differences. To check the order of integration of the series we employ the t-bar statistics developed by Im, Pesaran and Shin (2003) (in so forth IPS), that consists in an average of ADF tests carried out on each country equation. The IPS test assumes a null hypothesis of non-stationary, and diverges to a negative infinite under the alternative one allowing for heterogeneity in short-run dynamics. Contemporaneous interdependence is removed by subtracting out the cross-sectional mean (time demeaning), since it is equivalent to work with common time dummies.

Im et al. (2003) have shown that t-bar is more powerful than the previous generation of unit roots tests, based on the alternative hypothesis of homogeneity, as the one proposed by Levin and Lin (1993) (hereinafter LL). Table 2 reports both kinds of tests where the optimal number of ADF lags is chosen by a step-down procedure minimizing an information criterion. Along with country-specific intercepts, a time trend is included in the log-levels specification, but not in that using annual growth rates. The acceptance of the null hypothesis in the first regression (levels), and contemporaneously the rejection in the second one (growth rates), means that our series are trend stationary. Unequivocally, this is the conclusion indicated by inference based on IPS test. Moreover, the log-levels specification shows the relatively large

Luxembourg. Using the level of education for people aged 15 and over (rather than aged 25) we obtain substantially smaller contributions of labour input (and hence higher TFP growth) for Greece, Italy and Spain. Further insights on the role of human capital and skill composition for economic growth can be obtained for a sub-group of our countries looking at the measure of labour quality computed by O' Mahony and van Ark (2003). This index of labour quality is employed to build an alternative measure of labour input to use in the sensitivity analysis below.

power of such a test that, in contrast to LL, points to non-stationary of both capital series. This outcome signals the presence of a considerable degree of cross-sectional heterogeneity for these two variables.[13]

"Table 2 about here"

Next we verify whether macro-economic series are cointegrated, i.e. whether there is a long-run production function. In so doing, we rely upon the ADF-type statistics proposed by Pedroni (1999, 2004). They belong to a set of seven tests built on the residuals of least squares regression of the potentially cointegrated relation (eq. 1); all these tests are shown to be robust to double-sense causality. They can be distinguished into two types (panel and group mean tests), both sharing the null hypothesis of no cointegration but diverging for the alternative one. Being computed on pooled annual data, panel ADF tests assume a common cointegrating vector while the group mean ADF tests, which consist in between-averages of the individual statistics, admit heterogeneity in parameters. In light of such properties, the panel ADF statistics can be regarded as the closest to the unit roots test proposed by Levin and Lin (1993), while the group mean ADF statistics to the test devised by Im et al. (2003).

Controlling for heterogeneity is of great importance in short sample where the null hypothesis of no cointegration may be accepted for the entire panel only because of few cases; nevertheless, in our study it is always rejected, indicating the existence of a long-run relation among output and factor inputs (Table 2).[14]

5.2 Long-run production function estimation

[13] According to Pesaran (2006), the IPS test is not robust in presence of high levels of cross-sectional dependence, as this is only partly removed by time demeaning; in this case, the coefficient of the lagged level of the dependent variable is downward biased and the null hypothesis of non-stationary is over-rejected by t-bar. Among our variables, this risk is potentially high for ICT capital due to the use of a common deflator for investment expenditure; yet, this series results trend stationary at a normal level of confidence (5%). Results of Table 2 are largely confirmed when using the CIPS test robust to the cross-sectional dependence proposed by Pesaran (2006). All unreported findings cited hereinafter are available on request from the author.

[14] These statistics are one sided tests which are distributed as standard normal, diverging to a negative infinite under the alternative hypothesis (cointegration).

The estimation of the long-run production function is carried out initially by panel DOLS.[15] The first section of Table 3 considers the overall sample (columns I-IV), whilst the last column focuses on the European countries only. For sake of completeness, columns I-II also display the estimates obtained without trend, even though in the discussion below attention will be paid only to the trend stationary case.

It should be noticed from the first two columns that the elasticity of factor inputs are slightly different from the income shares reported in Section 4. Indeed, the coefficients of labour and non-ICT capital are approximately a fifth smaller than the corresponding income shares, while that of ICT capital is three times larger. In line with a large international evidence, there is indication of slightly decreasing returns (around 0.90).

"Table 3 about here"

The inclusion of time trend reduces remarkably the size of coefficients (col. III-IV). Since macro-economic series grow uniformly over time, a large fraction of their variance can be explained deterministically. This occurs in particular for non-ICT assets that are no longer significant. On the other side, when one does not control for the effect of contemporaneous shocks, the coefficient of hours worked decreases from 0.52 to 0.32, whilst that of ICT capital passes from 0.14 to 0.09. Introducing time dummies, there is a reduction only in the output elasticity to labour, because of the pronounced cyclical nature of this variable. Surprisingly, from the last column it can be seen that these findings remain practically unchanged when the United States are excluded from the analysis.

At this point we estimate the model by means of dynamic SUR. This estimator allows for a more powerful control of cross-country correlation than common time dummies, which notoriously are effective only for low levels of interdependence. Specifically, as discussed above, we adopt the *restricted* version of DSUR developed by Mark et al. (2005). This assumes a common (homogenous) cointegrating vector among the panel units, confining thus cross-country heterogeneity to individual fixed-effects, time trend and short-run dynamics. The

[15] Both in PDOLS and DSUR estimation, the maximum value for the step-down procedure selecting the optimal number of lags (and leads) of first differenced regressors is fixed to one. Standard errors are corrected with the pre-whitening method in PDOLS, parametrically in DSUR.

implementation of DSUR requires the calculation of a larger amount of parameters with respect to panel DOLS. As a result, with relatively short time series at hand, one must divide the panel units into various sub-groups, with the consequence of lowering the estimates' precision in comparison with a full system regression.[16] In light of these reasons, the production function is estimated below splitting the sample into three sub-groups on the basis of the countries' size.[17] This type of classification rests on the assumption that there exists a positive relation between scale and production technology and, empirically, appears to be justified by the contemporaneous correlation among PDOLS residuals (col. V, Table 3).

Table 4 reports both PDOLS and DSUR findings for comparative aims. The former estimation presents some interesting points. Firstly, labour elasticity is higher for the largest countries by a three times factor with respect to the other states (around 0.62-0.67 against 0.21-0.25). Secondly, non-ICT capital is uninformative for explaining output levels only for the first group of countries, while it enters with a negative sign for the medium-sized ones; note that the same happens in DSUR for the smallest members of the EU.[18] Last but not least, digital capital exhibits a positive and significant coefficient only for the group of small countries (0.094), that is made up by some notorious ICT-intensive users like Denmark, Finland, Ireland and Luxembourg.

As apparent from the right section of Table 4, relevant efficiency gains come from using dynamic seemingly unrelated regression in place of PDOLS. Also, coefficients show some remarkable changes. The growth effect of hours worked is now slightly smaller for the entire group of big countries (col. V), but it rises when the US are left out (col. VI). A comparable coefficient is presented by the smallest economies, but not by the medium-sized ones which instead display a rather downsized elasticity.

[16] Mark et al. (2005) stress that the panel units should be at least a twelfth of the time dimension to make unrestricted DSUR feasible and with all desirable properties. Recently, Westerlund (2006) has proposed a more computationally convenient estimator (*bias adjusted*) that removes the long-run cross-sectional dependence by calculating common factors among individuals in place of estimating all their covariances.

[17] Big countries: US, Germany, France, UK and Italy. Medium-sized countries: Spain, Netherlands, Belgium, Sweden and Austria. Small countries: Greece, Portugal, Denmark, Finland, Ireland and Luxembourg.

[18] Unreported single-equation estimates point to Finland and Sweden as sources of noise for such results. These countries were characterized by a regime shift in capital accumulation in the early 1990s, as discussed by Daveri and Silva (2004) and Lindbeck (2000).

Non-ICT capital is significant (at a 10% level) only for all the largest economies, showing a coefficient of 0.074; however, when the focus is restricted on the EU states the estimated elasticity jumps up to nearly 0.19 and reaches a very high level of significance.

It is surely in the estimation of ICT impact that DSUR outperforms panel dynamic OLS. Digital capital emerges now as a driver of growth for most countries except for the EU big states. Its coefficient ranges from 0.054 for the medium-sized group to 0.171 of smaller economies, whereas evidently the value reported in column V (0.124) reflects the inclusion of the US.[19] This result is consistent with growth accounts evidence. In Europe the major continental economies have not been able to exploit the growth potential of ICT equipment because of more general problems of competitiveness. Despite relatively higher investment rates in technologically advanced capital, the performance of the United Kingdom is also downsized if compared to the US, confirming to a broad extent the findings reported by Basu et al. (2004) and O'Mahony and Vecchi (2005). Also, at both an industry and firm-level, our outcomes align with Matteucci et al. (2005), who demonstrate how UK, Italy and Germany have benefited from ICT considerably less than the United States, with a negligible contribution in service sectors.

Sensitivity analysis of parameters

One of the key outcomes of the foregoing analysis is that the size of ICT elasticity exceeds the income share when significant. Several arguments have been advanced to explain a similar result, all pointing to the inadequacy of neoclassic assumptions at the basis of the income shares' calculation (perfect competition and full output exhaustion).

Our evidence seems to exclude increasing returns while, at least for ICT investment, the risk of large error measurements across countries should be eliminated by the usage of harmonised deflators. Furthermore, it is difficult to believe that the market of digital assets behaves less competitively than that of non-ICT equipment. Thus, only two explanations

[19] It is interesting to underline that factor inputs' elasticity are aligned to income shares only for France, Germany, Italy and UK.

remain valid to justify our findings (see Stiroh, 2002a). On one hand, the size of ICT coefficient might reflect the presence of external effects caused by networking or productivity spillovers that push up the social value of ICT capital over private return. On the other hand, it might be upward biased because of the omission in econometric specification of such relevant variable as human capital or labour quality. Increasing levels of firms' spending in ICT have been accompanied over time by complementary investments in high-skilled or -educated employees, which further enhance the returns of high-tech equipment. The mutual reinforcing effect between these factors is stressed by Brynjolfsson and Hitt (2003) who underline the difficulty of disentangling the two components in absence of accurate data. Caselli and Coleman (2001) observe in a large panel of countries that there is a positive correlation between computer uptake and level of human capital since the early stages of diffusion. Sometimes however, as reported by O'Mahony and Vecchi (2005), ICT elasticity shows small variation between using quality-adjusted or raw labour data.

Therefore, now we conduct a sensitivity analysis to check the robustness of the output elasticity to ICT capital. As a first step, we employ the measure of labour input obtained multiplying the amount of hours worked by the average level of education (*human capital-adjusted labour*), described above in Section 4. Yet, this indicator may fail to *fully* grasp the growth contribution of labour as accounting for only one determinant of workers' productivity, while missing such additional factors as skill composition or workforce's experience. Hence, as a second step, we carry out a regression analysis for a group of countries (France, Germany, Netherlands, UK -labelled EU-4, and US) for which labour quality series are available from a consistent source (O'Mahony and van Ark, 2003). Under the neoclassic assumption that workers are paid to marginal productivity, labour quality is inferred weighting the contribution of each workers' category with the wage bill, after identifying groups on the basis of education, gender, age. Thus, the alternative measure of labour input has been obtained multiplying hours worked by this index of labour quality (*quality-adjusted labour*).[20]

[20] This index has been obtained by applying the labour quality growth reported in O' Mahony and van Ark (2003) to the levels estimated by Jorgenson and Vu (2005) for 1995. O' Mahony and van Ark (2003)'s estimates are obtained at an industry level and then aggregated for the overall (market) economy.

Correcting labour services for the average level of education broadly confirms PDOLS and DSUR results (Table 5). In comparison to the regression based on hours worked, now we find in both kinds of estimation a larger labour elasticity for the major countries, and a lower one for the medium- and small-sized economies. Anomalously, there emerges a negative sign for ICT capital for the largest EU countries in PDOLS regression. On the other side, DSUR findings appear to be clearly more robust, indicating a positively significant effect of ICT capital on the economic growth of our sample of countries, with the exception of Germany, France, Italy and the UK.

At this point it seems useful to make a step forward and verify whether the productive impact of ICT is uniform within the group of small-sized economies. This is composed of countries characterized by a different degree of ICT utilisation (see Table 1), along with for attitude towards innovative and knowledge-intensive activities. The suspect is that the output elasticity to digital assets above found hides substantially different growth impacts. Indeed, distinguishing between low-tech and high-tech countries (Greece and Portugal on one hand, and the remaining states on the other) ICT capital turns out to be significant only for the most technologically advanced countries (Denmark, Finland, Ireland and Luxembourg). With regard to the other factor inputs, there arises a large discrepancy in traditional assets, whilst the labour elasticity is much closer.

Next we check the estimates' robustness for EU-4 and US, using the measure of quality-adjusted labour. It has been possible to build this variable only up to 2000; thus, for comparative aims, Table 6 also reports the results relative to the period 1980-2004 based on hours worked. As shown from the first two columns, ICT coefficient changes remarkably if including or not the United States; it amounts to 0.092 in the former case and rises to 0.140 in the latter one. In light of the outcomes of the previous section, the significance of digital capital for the EU countries is clearly attributable to the good performance of the Netherlands.

Most importantly, when we employ the measure of quality-adjusted labour, it is possible to see that there is scarce co-variation between the coefficient of this variable and that of ICT capital for this sample of countries (col. III and IV),[21] confirming thus our general outcomes. By contrast, we observe a fall in the coefficient of non-ICT assets, and as expected an increase in the labour elasticity.

6. Concluding remarks

Despite a global convergence in the uptake of digital technologies occurred after 1995, this work has shown that non-negligible differences persist within the EU-15 in the long-run growth effects of ICT. In line with the large body of growth accounts literature, there is a core of European countries that are sensibly lagging behind the US in terms of productive impact of new asset types. On the other hand, the recent development pattern of small dynamic economies in Europe has been favourably influenced by the deployment of information technology.

The dismal technological performance of largest EU member states is usually ascribed to the structural weakness of their economies, become particularly evident (and worrisome) in the last decade. A low specialization on innovative productions and a rigid regulation of internal markets are the roots of its fall in competitiveness. These factors have lessened the incentives to high-tech investment, depressing the global returns of ICT. It is known that digital capital makes firms more flexible, but at the same time requires a dynamic environment to yield the expected efficiency gains. In this connection, the renewed commitment of the EU institutions for creating a common digital platform (i-2010) and sustaining ICT usage goes towards the right direction. Yet, these interventions are unlikely to stimulate productivity until stronger policies for competition and innovation are not pursued by national institutions.

Another remarkable feature of the paper can be identified in the usage of panel cointegration techniques to estimate the sources of growth. At an economy-wide level of analysis, this is indispensable to assess the contribution of ICT, whose nature of general

[21] This finding is confirmed when the focus is restricted on the EU-4 countries, as the coefficient of ICT does modify only marginally.

purpose technology confines relevant productivity gains to the long-run. In this respect, dynamic seemingly unrelated regression arises as the most suited procedure of estimation, allowing to identify the wide discrepancies existing within Europe and between the EU and US.

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Table 1: **Contributions to GDP growth of EU-15 and US** (1980-2004)
annual average growth rates (% points)

	GDP	**TFP**	**Hours worked**	**Non-ICT capital**	**ICT capital**	***TFP corrected***	***Labour Input***
	I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Austria	2.09	0.73	0.14	0.79	0.43	*0.53*	*0.35*
Belgium	1.94	0.99	-0.05	0.31	0.70	*0.62*	*0.31*
Denmark	1.92	0.81	-0.18	0.64	0.66	*0.48*	*0.15*
Finland	2.35	1.82	-0.28	0.34	0.48	*1.18*	*0.36*
France	1.98	0.95	-0.21	0.95	0.29	*0.24*	*0.50*
Germany	1.75	1.39	-0.43	0.37	0.42	*1.05*	*-0.08*
Greece	1.91	0.49	0.58	0.62	0.22	*-0.48*	*1.56*
Ireland	5.33	3.01	0.62	1.38	0.32	*2.49*	*1.14*
Italy	1.71	0.42	0.15	0.76	0.38	*-0.47*	*1.04*
Luxembourg	4.69	1.27	1.41	1.26	0.74	*0.82*	*1.86*
Netherlands	2.22	0.73	0.58	0.47	0.45	*0.24*	*1.07*
Portugal	2.49	1.14	0.27	0.76	0.33	*-0.21*	*1.61*
Spain	2.81	0.84	0.67	0.97	0.33	*-0.40*	*1.91*
Sweden	2.19	0.96	0.14	0.49	0.60	*0.40*	*0.71*
United Kingdom	2.57	1.29	0.14	0.61	0.52	*0.83*	*0.61*
EU-15	2.12	0.96	0.06	0.66	0.44	*0.38*	*0.64*
United States	3.16	0.89	0.93	0.55	0.78	*0.80*	*1.03*
Overall sample	2.66	0.93	0.51	0.61	0.62	*0.54*	*0.89*
inputs' growth rate			*0.74*	*2.33*	*14.0*		*1.29*
inputs' income share			*0.70*	*0.26*	*0.04*		*0.70*

Source: Own elaborations on data from Timmer et. al (2003), updated June 2005. Contributions are income share-weighted growth rates. Labour input is given by hours worked multiplied by the average level of education (years of schooling for people aged 25 and over) extrapolated from Barro and Lee (2000).

Table 2: **Panel unit roots and cointegration analysis**

	UNIT ROOTS			
	Levels (incl. time dummies and trend)			
	GDP	**Hours worked**	**Non-ICT capital**	**ICT capital**
Levin-Lin (1993)	-0.33	-0.11	-1.57	-3.09°
IPS (2003)	-1.06	-0.79	-1.20	-1.45
	First differences (incl. time dummies)			
Levin-Lin (1993)	-2.45°	-5.45°	-1.46	-2.18°
IPS (2003)	-4.29°	-7.20°	-3.98°	-5.66°
	PANEL COINTEGRATION			
	Levels (incl. time dummies and trend)			
	Panel ADF		Group ADF	
Pedroni (1999)	-2.20°		-2.47°	

Notes: All statistics are distributed as standard normal, diverging to an infinite negative under the alternative hypothesis; a step down procedure is employed to select the optimal number of ADF lags for each equation. Variables are cross sectionally demeaned as equivalent to work with common time dummies; time trend is admitted only in log-levels specifications.

Panel unit roots tests assume the null hypothesis of non-stationary. Panel cointegration tests assume the null hypothesis of no cointegration.

° rejected at a 5% level of significance.

Table 3: **Long-run estimation by PDOLS** (1980-2004), *levels*

	US and EU-15				EU-15
	I	*II*	*III*	*IV*	*V*
Hours worked	0.522*	0.505*	0.321*	0.293*	0.292*
	(0.079)	(0.079)	(0.031)	(0.050)	(0.036)
Non-ICT capital	0.235*	0.236*	0.021	0.028	0.026
	(0.096)	(0.087)	(0.043)	(0.043)	(0.043)
ICT capital	0.138*	0.138*	0.092*	0.094*	0.094*
	(0.018)	(0.016)	(0.010)	(0.011)	(0.011)
Obs. (N*T)	*400*	*400*	*400*	*400*	*375*
Intercept	*yes*	*yes*	*yes*	*yes*	*yes*
Time dummies	*no*	*yes*	*no*	*yes*	*yes*
Time trend	*no*	*no*	*yes*	*yes*	*yes*

Notes: GDP is the dependent variable. Estimates include country-specific intercepts (fixed effects) and, when specified, time trend; PDOLS utilises demeaned variables to control for common contemporaneous shocks as equivalent to working with time dummies. Standard errors in brackets. The maximum lag in the step-down procedure selecting the number of leads (and lags) is fixed to 1.
* significant at a 5% level.

Table 4: **Long-run estimation by groups**: **a comparison between PDOLS and DSUR** (1980-2004)

	PDOLS				DSUR			
	Big Countries	**EU Big Countries**	**Medium Countries**	**Small Countries**	**Big Countries**	**EU Big Countries**	**Medium Countries**	**Small Countries**
	I	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*
Hours worked	0.624* (0.137)	0.670* (0.149)	0.249* (0.045)	0.209* (0.113)	0.518* (0.041)	0.710* (0.060)	0.165* (0.012)	0.653* (0.012)
Non-ICT capital	0.150 (0.107)	0.072 (0.109)	-0.280* (0.093)	0.047* (0.045)	0.074 (0.042)	0.186* (0.054)	0.028 (0.033)	-0.076* (0.029)
ICT capital	0.030 (0.053)	-0.007 (0.059)	0.008 (0.033)	0.094* (0.017)	0.124* (0.014)	0.041 (0.029)	0.054* (0.006)	0.171* (0.007)
Obs. (N*T)	125	100	125	150	125	100	125	150
Intercept	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Time dummies	*yes*	*yes*	*yes*	*yes*	*no*	*no*	*no*	*no*
Time trend	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*

Notes: GDP is the dependent variable. All estimates include country-specific intercepts (fixed effects) and time trend; PDOLS utilises demeaned variables to control for common contemporaneous shocks as equivalent to working with time dummies. Standard errors in brackets. The maximum lag in the step-down procedure selecting the number of leads (and lags) is fixed to 1.
Big Countries: US, Germany, France, UK and Italy; *Medium Countries*: Spain, Netherlands, Belgium, Sweden and Austria; *Small Countries*: Greece, Portugal, Denmark, Finland, Ireland and Luxembourg.
* significant at a 5% level.

Table 5: **Robustness of PDOLS and DSUR estimates to human capital**

	PDOLS					
	Big Countries	**EU Big Countries**	**Medium Countries**	**Small Countries:**	*High-tech*	*Low-tech*
	I	*II*	*III*	*IV*	*V*	*VI*
Human-capital adjusted labour	0.654* (0.103)	0.710* (0.103)	0.197* (0.055)	0.050* (0.097)	0.109 (0.165)	-0.014 (0.181)
Non-ICT capital	0.165* (0.079)	0.114 (0.079)	-0.047 (0.133)	0.062 (0.056)	-0.018 (0.075)	0.223 (0.130)
ICT capital	-0.027 (0.034)	-0.072* (0.046)	0.040 (0.039)	0.110* (0.016)	0.111* (0.018)	0.208* (0.051)
Obs. (N*T)	125	100	125	150	100	50
	DSUR					
	Big Countries	**EU Big Countries**	**Medium Countries**	**Small Countries:**	*High-tech*	*Low-tech*
	I	*II*	*III*	*IV*	*V*	*VI*
Human-capital adjusted labour	0.558* (0.051)	0.899* (0.057)	0.120* (0.011)	0.581* (0.012)	0.787* (0.054)	0.740* (0.173)
Non-ICT capital	-0.007 (0.050)	0.228* (0.052)	0.163 (0.036)	-0.043 (0.022)	-0.336* (0.050)	0.408* (0.110)
ICT capital	0.114* (0.018)	0.003 (0.023)	0.051* (0.011)	0.181* (0.005)	0.181* (0.017)	0.003 (0.057)
Obs. (N*T)	125	100	125	150	100	50

Notes: GDP is the dependent variable. All estimates include country-specific intercepts (fixed effects) and time trend; PDOLS utilises de-meaned variables to control for common contemporaneous shock as equivalent to working with time dummies. Standard errors in brackets. The maximum lag in the step-down procedure selecting the number of leads (and lags) is fixed to 1.

Big Countries: US, Germany, France, UK and Italy; *Medium Countries*: Spain, Netherlands, Belgium, Sweden and Austria; *Small Countries*: Greece and Portugal (*Low-tech*), Denmark, Finland, Ireland and Luxembourg (*High-tech*).

* significant at a 5% level.

Table 6: **Robustness of DSUR estimates to labour quality for EU-4 and US**

	1980-2004		1980-2000	
	EU-4 and US *(hours worked)*	**EU-4** *(hours worked)*	**EU-4 and US** *(hours worked)*	**EU-4 and US** *(quality-adjusted labour)*
	I	*II*	*III*	*IV*
Quality-Adjusted Labour	0.308*	0.532*	0.020	0.121*
	(0.035)	(0.033)	(0.022)	(0.008)
Non-ICT capital	0.111*	0.086	0.311*	0.233*
	(0.040)	(0.059)	(0.038)	(0.030)
ICT capital	0.140*	0.092*	0.186*	0.183*
	(0.011)	(0.019)	(0.009)	(0.003)
Obs. (N*T)	125	100	105	105

Notes: GDP is the dependent variable. All estimates include country-specific intercepts (fixed effects) and time trend. Standard errors in brackets. The maximum lag in the step-down procedure selecting the number of leads (and lags) is fixed to 1.
EU-4: France, Germany, Netherlands and UK.
* significant at a 5% level.