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中 文 摘 要： 本文首先建構了一理論模型，理論結果發現經濟成長率與一國之資訊通信科技水準之間有直接且內生的正向關係。接著，本文建構了 17 個高所得 OECD 國家之追蹤資料數據庫，樣本年間為 1980－2004（依國家不同而有樣本期間的變動），用以分析資訊通信科技（ICT）資本存量對這些高所得國家，在樣本年間生產力的貢獻。本篇論文的模型主軸參考 R&ouml；eller and Waverman（2001）所估計之總體生產力方程式，配合數個個體模型修正迴歸變數內生性之問題。與 R&ouml；eller and Waverman（2001）不同的是，本篇論文所考慮的主要解釋變數不只是他們所使用的電信基礎建設（telecommunication infrastructure），而是將 ICT 資本存量切割為三個部門：通訊設備部門、硬體部門與軟體部門，並配合通訊產品（市內電話與行動電話）及電腦普及率，來估計這些變數對高所得國家長期生產力的貢獻。本篇論文目前的實證結果顯示，除了行動電話普及率之外，這些 ICT 資本存量以及市內電話與電腦普及率，均對高所得國家有正面的生產力貢獻。此外，一旦這些國家達到一定數位化的門檻後，電腦普及率對生產力的貢獻將非線性地增加。這些實證上的結果，均與本文所建構之理論模型之預測一致。

中文關鍵詞： 訊通信科技、生產力成長、高所得國家

英 文 摘 要： This paper constructs an unbalanced panel dataset based on a varying sample period of 1980－2004 for 17 OECD countries to analyse the impact of information and communication technology (ICT) on productivity growth. This paper divides ICT capital stock into three categories, namely communication equipment, IT equipment (hardware), and software, and uses them together with telecommunication demand and personal computer (PC) penetration rate as productivity-related explanatory variables. It then estimates a macro production function using micro models for ICT investment, telecommunication demand, and PC penetration. The estimation results suggest that the three categories of ICT capital stock, together with telephone and PC penetration rates, positively and significantly influence productivity growth in the selected high-income economies. Moreover, once the level of digitalisation reaches 20%, it also provides a networked contribution to productivity growth.

英文關鍵詞： Information and Communication Technology； ICT；

Productivity Growth

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How ICT Penetration Influences Productivity Growth: Evidence from 17 OECD Countries*

Yi-Chia Wang†

Abstract

This paper constructs an unbalanced panel dataset based on a varying sample period of 1980–2004 for 17 OECD countries to analyse the impact of information and communication technology (ICT) on productivity growth. This paper divides ICT capital stock into three categories, namely communication equipment, IT equipment (hardware), and software, and uses them together with telecommunication demand and personal computer (PC) penetration rate as productivity-related explanatory variables. It then estimates a macro production function using micro models for ICT investment, telecommunication demand, and PC penetration. The estimation results suggest that the three categories of ICT capital stock, together with telephone and PC penetration rates, positively and significantly influence productivity growth in the selected high-income economies. Moreover, once the level of digitalisation reaches 20%, it also provides a networked contribution to productivity growth.

Keywords: Information and Communication Technology; ICT; Productivity Growth

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Introduction

Productivity[1] is the long-term driver of income growth and the prosperity of nations. Productivity depends on the quantity and quality of the factors of production available to a country and the social framework[2] in which they operate. Most western economies began to experience a productivity slowdown from 1973. In the US, measured growth in economy-wide productivity (labour productivity and total factor productivity (TFP)), averaged just 1.5% in the period 1973–1995, well below the averages of the preceding decades. Similarly, Australia's productivity growth showed its weakest rate in the 1980s, with labour productivity averaging 1.7% a year and the rate of TFP growth being just 0.7% a year.

This was of special concern given the large capital investments being made into IT and the increases in labour skills accompanying the spread of new computer technology. Nobel Prize Laureate in Economics Robert Solow indeed commented in 1987 that 'one saw computers everywhere but in the productivity statistics'. However, from around 1995 both labour productivity and TFP began to surge in the US. However, because of the lags in data availability and analyses, it was not until the landmark study of Jorgenson and Stiroh in 2000 that economists recognised that something unusual had begun to occur in US economy-wide productivity in the mid-1990s.

It is now widely agreed that advances in information and communication technology (ICT) have led to large direct and indirect benefits to economic growth and productivity. Jorgenson (2005) summarised the ICT productivity growth literature for the US as follows:

> *The vaulting contribution of capital input since 1995 has boosted growth by close to a percentage point (in the US). The contribution of investment in IT accounts for more than half of this increase. Computers have been the predominant impetus to faster growth, but communications equipment and software have made important contributions as well.*

The importance of the communication part of ICT is further recognized in the following quote by Alan Greenspan[3]:

> *Until the mid-1990's, the billions of dollars that businesses had poured into information technology seemed to leave little imprint on the overall economy. The investment in the new technology arguably had not yet cumulated to a sizable part of the U.S. capital stock, and computers were still being used largely on a stand-alone basis. The full value of computing power could be realized only after ways had been devised to link computers into large-scale networks…*

Further, it is not simply the spread of computers that generates productivity increases but also the ability to interconnect computers via modern communication systems. In essence, the ‘productivity miracle’[4] is a result of not just the computer itself but also of the ‘networked computer’.

There are a number of reasons to think that this ‘networking’ aspect is important. First, productivity did not slowly increase from year to year but seemed to explode from the early to mid-1990s, possibly because networked computers influenced growth and productivity. Second, significant advances in communications networks, such as the digitalisation of exchanges and the spread of fibre optic transmission, made it possible and economical to transmit huge data among firms, offices, and locations. However, these advances in communications networks must be modelled for what they are — network effects — and not summarised in a static framework.

The remainder of this paper is organised as follows. Section 2 proposes an endogenous growth framework that models the causal link between ICT and economic growth and describes the relevant empirical ICT studies as well as the gaps that this paper aims to fill. Section 3 illustrates a macro production function with micro models for ICT investment, telecommunication demand, and PC penetration. Section 4 describes the data sources of the sample, how the regression variables are constructed, and some sample statistics. Section 5 shows the empirical estimation results of the models proposed in Section 3 with some intuitive discussion. Section 6 concludes.

1. Theoretical and empirical background

Since Solow (1956), technological progress had long been regarded as an engine of productivity growth, even though its definition only briefly included the improvement in the human factor. From the early 1990s, however, growth theories started to incorporate technology in the production process. In the competitive equilibrium, the quantity and quality of technology innovation can be endogenously determined. The factor input of capital stock can be regarded as an integration of intermediate goods innovated by an R&D sector. Because the R&D sector in an economy includes ICT-producing sectors, ICT capital stock represents parts of the variety (and quality) of intermediate goods to be devoted to the final goods production sector. From this line of thought, the model built by Romer (1990) is capable of providing a theoretical foundation for this paper.

We assume that an aggregate production function follows the following Cobb–Douglas form:

$$Y = AH^{\alpha}K^{1-\alpha}, \text{ where } \quad 0 < \alpha < 1 \tag{1}$$

and where Y is the aggregate output of ICT-using sectors, A is the time-invariant factor, H is the input of human capital, and K is the aggregate quantity of intermediates created in the ICT-producing sectors, which is

$$K = \left[\int_0^N x(j)^{1-\alpha}\, dj\right]^{\frac{1}{1-\alpha}} . \tag{2}$$

In equation (2), $x(j)$ represents the purchase of intermediate type j and N is the number of varieties of intermediate ICT inputs which determines the level of ICT technology in this economy. All intermediate goods $x(j)$ are produced by monopolistic firms in ICT-producing sectors. $x(j)$ is demanded by competitive ICT users to produce final goods and services. Therefore, ICT users take the price of $x(j)$ and $p(j)$ as given. The profit-maximising strategy in ICT-using sectors is to employ $x(j)$ and equate its marginal product $MP_{x(j)}$ with its factor price $p(j)$. In other words

$$MP_{x(j)} = \frac{\partial Y}{\partial x(j)} = A(1-\alpha)H^{\alpha}x(j)^{-\alpha} = p(j). \tag{3}$$

Equation (3) can further help us derive the following factor demand function of the intermediate $x(j)$ in ICT-using sectors:

$$x(j) = H\left[\frac{A(1-\alpha)}{P(j)}\right]^{\frac{1}{\alpha}}. \tag{4}$$

It is assumed that the marginal (and average) cost of innovating a new $x(j)$ by ICT-producing firms is constant and normalised to one. In addition, the inventor of good $x(j)$ has to consider the start-up cost, F. The start-up cost of inventing a new intermediate $x(j)$ depends on the number of varieties previously created; thus, F is assumed to be a monotonically decreasing function of the existing level of ICT technology, represented by the number of varieties, N. Therefore, $F'(N) < 0$ describes this consideration. Given the above assumptions, the present value of the profit from discovering the jth intermediate ICT good is given by

$$\pi(j) = -F(N) + \int_0^{\infty}[p(j) - 1]x(j)e^{-rt}\, dt, \text{ where } r \text{ is the real interest rate.} \tag{5}$$

The optimal pricing rule for monopolistic ICT-producing firms to maximise $\pi(j)$, taking into account the factor demand from final goods producers (equation (4)), can be derived from equation (5) as

$$p(j) = \frac{1}{1-\alpha} > 1. \tag{6}$$

A lower share of aggregate intermediate inputs, K,l in ICT-using sectors leads to a higher markup price $p(j)$, as shown in equation (6). By symmetry, this markup pricing is identical to all intermediate ICT goods $x(j)$. In the long run, each monopolistic inventor has zero profit because of the free-entry condition, and thus we can combine equations (4), (5), and (6) to obtain the real interest rate in this system:

$$r = \frac{H}{F(N)} A^{\frac{1}{\alpha}} \alpha (1-\alpha)^{\frac{2-\alpha}{\alpha}}. \tag{7}$$

Next, a representative household maximises its lifetime utility given by

$$\int_0^\infty \left(\frac{C^{1-\theta}}{1-\theta}\right) e^{-\rho t} dt, \tag{8}$$

where ρ represents a constant rate of time preference and θ is the inverse of the constant intertemporal elasticity of the substitution of the consumption of ICT goods, c. The first-order conditions of the Hamiltonian function solve the growth rate of the consumption of ICT goods[5] in the economy as:

$$\gamma_c = \frac{\dot{C}}{C} = \frac{1}{\theta}(r-\rho). \tag{9}$$

Equation (9) includes the real interest rate, r, that has been previously determined in ICT-producing sectors. Therefore, combining equations (7) and (9) yields the full representation of the growth rate in this economy:

$$\gamma_c = \frac{1}{\theta}\left[\frac{H}{F(N)} A^{\frac{1}{\alpha}} \alpha (1-\alpha)^{\frac{2-\alpha}{\alpha}} - \rho\right]. \tag{10}$$

In equation (10), a lower rate of time preference or higher intertemporal elasticity of substitution increases the economic growth rate in this system. The intuition of the changes of these exogenous parameters is consistent with traditional Ramsey-type theorems. In addition, two scale effects are embedded in equation (10). First, when an economy is equipped with a higher stock of human capital, H, its growth rate will be directly boosted. Second, when an economy is experiencing a rapid expansion in the number of varieties, N, it reduces the fixed ICT start-up cost of innovating a new intermediate, which indirectly increases the economic growth rate.

Most studies of the role of ICT in productivity and economic growth are growth accounting exercises. In other words, they are accounting identities with output (GDP) changes being accounted for by the changes in the underlying variables that make up GDP — essentially labour and capital. The standard growth accounting framework of Jorgenson and Griliches (1967) suggests that growth in annual labour productivity consists of four factors: changes in labour quality, increases in non-ICT capital, increases in ICT capital, and the Solow residual after accounting for changes in capital and labour (i.e. TFP).

Empirical ICT studies have used data from a wide range of advanced economies to several industries and firms in an economy.[6] Firm-level data provide a great number of degrees of freedom, which improves estimation efficiency. For instance, Crépon and Heckel (2002) collected data from 300,000 French firms for their growth accounting exercise and found that the production of ICT and capital deepening contributed to productivity by 0.4% and 0.3%, respectively. Oulton and Srinivasan (2005) selected 34 UK industries in their TFP and labour productivity regressions over the 1970–2000 period and found that ICT deepening was a major source of productivity growth in the 1990s.

Further, the aggregate measures of macroeconomic variables such as ICT and non-ICT capital stock make cross-country estimation possible. Previous cross-country studies have focused on collecting data from developed countries that have mature ICT markets. Gust and Marquez (2004), for instance, used 13 OECD countries from 1993 to 2000 in a growth accounting regression and found that IT production and expenditure are positive contributors to labour productivity. Röeller and Waverman (2001) studied how telecommunications infrastructure affects economic growth using evidence from 21 OECD countries over a 20-year period. Their study jointly estimated a micro model for telecommunications investment with a macro production function and found evidence of a significant causal link, especially when a critical mass of telecommunications infrastructure is present. In general, no matter which levels of data those empirical ICT studies chose to analyse, most concluded that ICT is productive and some even expected a much larger impact of ICT on productivity growth than would be expected from using a standard neoclassical model.

The growth accounting approach has been widely applied in empirical ICT studies. Calculations from growth accounting studies are essentially static, however, which makes it difficult to relate unexpected breaks in behaviour to their underlying causes. By contrast, this paper uses an econometric model that estimates statistically the relationships that drive GDP and productivity in order to analyse the sources of productivity advances and to isolate contributions from a series of factors as well as their interactions.

This paper advances the empirical ICT literature in several ways. First, the endogenous growth theory outlined in this section describes and explains the strong causal relationship between changes in inputs, such as ICT capital stock, and growth in labour productivity. Second, a summary of the cross-country ICT studies by Draca, Sadun, and Reenen (2006) suggested that, compared with the acceleration of productivity growth in the US since 1995, there has been no such acceleration of productivity growth in the EU, mainly because of the performances of ICT-using sectors. However, by including influential regressors such telecommunication and digitalisation, this paper can correct for the possible downward bias of the contribution of ICT capital stock to labour productivity growth. Third, instead of industry-level ICT investment, this paper considers how PC penetration and its interaction with the level of digitalisation affect productivity growth in advanced countries. Finally, the data sources used in this paper make it possible for us to separately identify the contribution of each of the components in the stock of ICT capital, including the stock of hardware, software, and communication equipment. Such a task has rarely been carried out in previous country-level ICT studies.

2. Empirical model

The empirical structure in this paper is similar to that proposed by Röeller and Waverman (2001), which included both micro models and a macro production function. However, this paper extends their model in a number of directions. First, it includes ICT as a source of economic growth. Second, it develops a hedonic version of the aggregate production function in order to estimate the impact of investment in ICT capital as well as the characteristics of that capital. Third, it separately estimates the contribution to productivity growth by hardware, software, and communication equipment. Fourth, it interacts PC penetration with the degree of the digitalisation of the telecom network, a measure of the extent of network modernisation. This fourth extension allows us to analyse how networked computers influence economic activity.

The system in the model consists of a production function (output equation) and six additional equations that represent the ICT market demand and supply sides. The use of an equation system aims to account for the fact that ICT capital and its characteristics are regarded as endogenously determined variables. Therefore, this paper uses a two-stage least squares approach to estimate the production equation using selected instrumental variables.

3.1 Production function

The economy-wide production function relates output to labour, non-ICT capital, ICT capital, and the characteristics of ICT capital. For country i at time t, the production function is assumed to be a Cobb–Douglas functional form:

$$Y_{i.t} = A_i H_{i,t}^{a_H} (KNICT)_{i,t}^{a_{KNICT}} G(*)_{i,t} exp(a_T t), \quad (11)$$

where the notations and definitions of the variables and parameters are summarised in Table 1.

“Table 1 about here”

It is assumed that the ‘effective’ ICT real capital stock, $G(*)$, is a function of the actual measure of the stock and the stock’s characteristics. Therefore, the hedonic function $G(*)$ can be written in terms of (natural) logarithms as

$$\begin{aligned} \log G(*)_{i,t} &= a_{COM} \log(KCOM)_{i,t} + a_{HARD} \log(KHARD)_{i,t} + a_{SOFT} \log(KSOFT)_{i,t} \\ &+ a_{MLPEN} MLPEN_{i,t} + a_{MBPEN} MBPEN_{i,t} + a_{PCI} PCI_{i,t} \\ &+ a_{MED}\left(PCI_{i,t} \times DIG\_MED_{i,t}\right) + a_{HIGH}\left(PCI_{i,t} \times DIG\_HIGH_{i,t}\right) \end{aligned} \quad , \quad (12)$$

where the notations and definitions of the variables and parameters are summarised in Table 2. The functional form (12) has a number of advantages. The production function specified in (11) does not impose constant returns to scale. The effective ICT stock function thus allows us to estimate the impact of not just the level of ICT capital but also its characteristics. The use of penetration rates allows us to explore and identify the importance of the network effects associated with ICT on productivity.

“Table 2 about here”

The specification of the output equation allows us to choose a model either with or without fixed effects. Röeller and Waverman (2001) presented the result of a model without fixed effects and the results of two further models with fixed effects included in the output equation. They showed that the impact of telecom penetration on economic growth is significantly reduced when fixed effects are introduced. The fixed-effect model, on one hand, is one way of controlling for the impact of unobservable heterogeneities across countries and of reducing the problem of spurious correlations (i.e. the fact that the coefficient on telecom penetration actually reflects the impact of a number of other growth-promoting variables that are not included in the regression). On the other hand, the random-effect model deals with the case where there are no country-specific fixed effects but where cross-country heterogeneities exist. Section 5 describes the fixed-effect and random-effect estimations for the following log-linearised production function, which can be derived from equations (11) and (12):

$$
\begin{aligned}
\log\left(\tfrac{Y}{H}\right)_{i,t} &= a_{0,i} + a_T t + (a_H + a_{KNICT} + a_{COM} + a_{HARD} + a_{SOFT} - 1)\log H_{i,t} \\
&+ a_{KNICT}\log\left(\tfrac{KNICT}{H}\right)_{i,t} + a_{COM}\log\left(\tfrac{KCOM}{H}\right)_{i,t} + a_{HARD}\log\left(\tfrac{KHARD}{H}\right)_{i,t} \\
&+ a_{SOFT}\log\left(\tfrac{KSOFT}{H}\right)_{i,t} + a_{MLPEN}MLPEN_{i,t} + a_{MBPEN}MBPEN_{i,t} + a_{PCI}PCI_{i,t} \\
&+ a_{MED}\left(PCI_{i,t} \times DIG\_MED_{i,t}\right) + a_{HIGH}\left(PCI_{i,t} \times DIG\_HIGH_{i,t}\right) + u_{GDP,i,t}
\end{aligned}
\quad , \qquad (13)
$$

where a_0 is the country-specific fixed-effect constant and u_{GDP} is the regression residual of equation (13).

There are some important differences between the present specification of the output equation and the Röeller–Waverman specification. First, the dependent variable is level of productivity, measured by GDP per hour worked, whereas the dependent variable used by Röeller and Waverman (2001) was simply GDP. Second, equation (13) includes ICT capital in the regression, whereas Röeller and Waverman (2001) excluded telecom capital stock in their regression. Third, the present output equation incorporates the impact of scale (hours worked) on productivity in order to capture any scale economies in the economy-wide production process.

3.2 Telecommunication and computer penetration (demand) equations

In addition to Röeller and Waverman's (2001) estimation of a demand equation for the penetration of mainline telephone, this paper further includes the demand equation of mobile phone penetration in the system. These two equations together form the demand for telecommunications as follows:

Mainline phone penetration rate (*MLPEN*)

$$MLPEN_{i.t} + WL_{i.t} = b_{0ML} + b_{GDPML}\log\left(\frac{Y}{POP}\right)_{i,t} + b_{MLP}\log(MLP)_{i,t} + u_{ML,i,t}; \qquad (14)$$

Mobile phone penetration rate (*MBPEN*)

$$MBPEN_{i.t} = b_{0MB} + b_{GDPMB}\log\left(\frac{Y}{POP}\right)_{i,t} + b_{MBP}\log(MBP)_{i,t} + u_{MB,i,t}, \qquad (15)$$

where the notations and definitions of the variables and parameters are summarised in Table 3.

"Table 3 about here"

The following is the third demand equation in the system:

Penetration rate of personal computer (*PCI*)

$$PCI_{i.t} = c_{PCI} + c_{GDP}\log\left(\frac{Y}{POP}\right)_{i,t} + c_{HARDP}\log(HARDP)_{i,t} + u_{PCI,i,t}, \qquad (16)$$

where $HARDP$ denotes the price of hardware (IT equipment), u_{PCI} is the regression residual in equation (16), and c_{PCI}, c_{GDP}, and c_{HARDP} are regression parameters.

Equations (14) to (16) are extensions of the micro model for telecommunications demand from Röeller and Waverman (2001). These equations are estimated in this paper using fixed-effect and random-effect techniques. Hausman (1978) tests are then performed to confirm which of the estimation techniques best fits the data.

3.3 ICT investment (supply) equations

In Röeller and Waverman (2001), the stock of telecommunication infrastructure (*TELECOM*) was assumed to be a direct input in the production process. However, this paper considers not only *TELECOM* input but also aggregate ICT capital stock and investment. ICT investment forms its capital stock that is required in the production process. Furthermore, ICT capital stock can be divided into the following three components (in order to separately identify their respective contributions to productivity in equation (13)):

Investment into communication equipment (*INVCOM*)

$$\begin{aligned} INVCOM_{i.t} &= d_{0COM} + d_{GACOM}\log(GA)_i + d_{GBCOM}GB_{i,t} + d_{COMP}\log(COMP)_{i,t} \\ &+ d_{TCOM}t + u_{INVCOM,i,t} \end{aligned}; \quad (17)$$

Investment into IT equipment (*INVHARD*)

$$\begin{aligned} INVHARD_{i.t} &= d_{0HARD} + d_{GAHARD}\log(GA)_i + d_{GBHARD}GB_{i,t} \\ &+ d_{HARDP}\log(HARDP)_{i,t} + d_{THARD}t + u_{INVHARD,i,t} \end{aligned}; \quad (18)$$

Investment into software (*INVSOFT*)

$$\begin{aligned} INVSOFT_{i.t} &= d_{0SOFT} + d_{GASOFT}\log(GA)_i + d_{GBSOFT}GB_{i,t} \\ &+ d_{SOFTP}\log(SOFTP)_{i,t} + d_{TSOFT}t + u_{INVSOFT,i,t} \end{aligned}, \quad (19)$$

where the notations and definitions of the variables and parameters are summarised in Table 4.

"Table 4 about here"

Equations (17) to (19) are similar to equation (3') in Röeller and Waverman (2001, page 916), which includes the country's geographic area (GA), real government budget balance (GB)[7], and the costs of associated investment. Röeller and Waverman (2001) used the price of telephone services to explain *TELECOM* investment; however, in this paper the price deflators of ICT investment are considered to be alternative proxies. Equations (17) to (19) are also estimated using fixed-effect and random-effect techniques. Hausman (1978) tests are again performed to confirm which of the estimation techniques best fits the data.

3. Data description and construction

In order to estimate the model described in Section 3, data were gathered from the following public sources: the OECD, the International Telecommunication Union (ITU), and the datasets constructed by the Groningen Growth and Development Centre (GGDC). The latter data are based on national accounts as compiled by individual national statistical agencies and the OECD. Purchasing power parities (PPPs) and relative price levels across countries rely on the OECD's published estimates of PPP exchange rates.

4.1 Sample selection

The availability of relevant data drove the selection of sample countries. While sources such as the OECD's PPP tables cover the major macroeconomic series for virtually all nations, far less detailed information is available for capital stocks estimated at the sector level. Since the models described in the previous sections of this paper require estimates of ICT capital stock as well as overall capital stock, we need either to construct these capital stock series ourselves or to rely on existing efforts to estimate them. Estimating capital stock is, in theory, possible if one has an initial starting value for the capital stock as well as estimates of gross fixed capital formation (for which annual series are more widely available than are estimates of stocks), and can make some reasonable assumptions about depreciation. However, in practice, it is difficult to find data on initial capital stocks and to make reasonable conjectures about what these starting values should be.

The sample in this paper comprises the 15 nations covered by the GGDC's Total Economy Growth Accounting Database (Timmer, Ypma, & van Ark, 2003). This contains (among other variables) estimates of capital stocks in the following areas: (1) IT equipment, (2) Software, (3) Communications Equipment, (4) Non-ICT Equipment, and (5) Non-Residential Structures. The GGDC has collected these data for 14 EU nations[8] and the US from 1980 to 2004. It also provides detailed information on how these estimates were constructed — primarily from national accounts data — on their website at www.ggdc.net.

In addition to the 14 EU nations and the US, ICT investment data were further supplemented from Canada, based upon Statistics Canada and from Australia based on data from the Australian Bureau of Statistics.[9] The major difficulty was updating the ICT capital stocks. This updating was accomplished by applying the perpetual inventory method (PIM), utilizing the various ICT investment series that were available. For each asset category, a starting capital stock selected led to a result consistent with the growth in capital stocks.[10]

Therefore, the final sample in this paper covers 17 OECD countries (14 EU nations, the US, Canada, and Australia) from 1980 to 2004. All data were converted into US dollars using the PPP data from the OECD, based to the year 2000.

4.2 Capital stock and price indices

Differences in national accounting practices for measuring ICT capital, especially differences in the capitalisation of software in national accounts and construction of constant-quality price indices for computers, software, and communications equipment, pose a major problem for studies on this topic. The GGDC capital stock measures use the OECD's price index harmonisation method proposed by Schreyer (2002). This harmonisation method uses US constant-quality price indices for ICT equipment as the starting point and then accounts for country-specific inflationary factors. For example, the ratio of the US IT price index to the US GDP deflator is used to control for IT inflation relative to general inflation, and then this ratio is applied to the particular country's GDP deflator index to calculate the country-specific IT goods deflator. Such an approach seems intuitively appealing, since IT goods are widely traded with most countries being net importers of IT equipment. Therefore, the rapid declines in the constant-quality prices of computers, semiconductors, and the like reported by the US are also being experienced in other OECD countries. The cross-sectional average of the price indices of IT equipment, communication equipment, and software are presented in Table 5.

"Table 5 about here"

Given that 2000 is the sample base year, the average of the earliest IT deflator in 1980 is 8.41. This figure means that the value of a computer produced in 2000 was 8.41 times more valuable compared with one produced in 1980. This confirms the widely held view that the price of IT equipment has dropped considerably over the past three decades because of the rapid development of computer technology, whereas the price deflators of communication equipment and software have been relatively stable.

Similar to the selection of Röeller and Waverman (2001), who used the price of telephone services to proxy for *TELECOM* investment, this paper uses price indices for fixed mainline telephone and mobile phone services based on the revenue per telephone user and revenue per mobile user. This information is available from the ITU dataset.

As mentioned before, this paper updates the ICT investment series by applying the PIM and by using the various ICT investment series available. To implement this method for generating ICT capital stock series from ICT investment for Canada and Australia, we make the following two assumptions:

1) IT equipment, communication equipment, and software depreciate at rates of 31.5%, 11.5%, and 31.5%, respectively. These depreciation rates were estimated by Jorgenson and Stiroh (2000).

2) Adopting the GGDC methodology, the starting stock values were set so that the growth rate of stock is equal in the first two periods, namely $\frac{K_1-K_0}{K_0}=\frac{K_2-K_1}{K_1}$, where K_t denotes capital stock at time t.

Based on these two assumptions, we can derive the initial capital stock value: $K_0=\frac{I_0^2}{I_1^2-(1-d)I_0}$, where d is the depreciation rate and I_0 and I_1 are gross fixed capital formation (investment) series at time 0 and 1, respectively. The PIM generates the capital stock series of IT equipment, software, and communication equipment in our sample period for Canada and Australia.

4.3 Sample statistics of the major variables

Table 6 lists and describes the variables used in this paper. Tables 7 to 9 show the levels of regression variables in two representative years (according to the country that has available data points) and the compound annual growth rates (CAGRs) during this period. Displaying these CAGRs is similar to the data shown in Table 1 in Röeller and Waverman (2001, page 914).

"Table 6 about here"

Tables 7 to 9 present some observable findings for sample countries. First, on average, ICT capital stock grows faster than non-ICT capital stock from 1980 to 2004. Second, of the three categories of ICT capital stock, IT equipment displays the highest growth (approximately 20% per annum), compared with 10–15% for software and 5–10% for communication equipment. Third, mainline telephone penetration grows at a stable rate similar to productivity growth, whereas mobile penetration grows at an extremely high rate in the final decade of the sample period. In the early 1980s, fewer than 10 people per 100 inhabitants possessed mobile phones, whereas this figure was more than 10 times bigger in 2004. Finally, PC penetration grows at a stable rate of approximately 10% per annum.

"Tables 7 to 9 about here"

4. Regression results and discussion

Although most of the variables listed in Tables 7 to 9 are available during the sample period 1980–2004, data on mobile and PC penetration are missing in the earlier sample years for most countries. As a result, the regressions conducted in this section are based on the available data points for each country. The estimation techniques used are fixed-effect and random-effect estimations. Hausman (1978) tests are also performed to confirm which of the estimation techniques best fits the data. We first discuss the regression outputs for the three penetration equations (ICT demand equations) summarised in Table 10.

“Table 10 about here”

The following discussion is based on the estimation outputs from the fixed-effect models with the support of Hausman test statistics. Telephones, mobile phones, and computers are all normal goods. The estimation of income elasticity in Table 10 suggests that in the sample OECD countries, people have a relatively inelastic demand for telephones and PCs when their incomes increase, whereas mobile phones are likely to be considered luxury goods, as the estimated income elasticity of demand for mobile phones is greater than one. Overall, a one percentage point increase in per capita GDP leads to a 0.52%, 2.16%, and 0.07% increase in the penetration rates of telephones, mobile phones, and PCs, respectively. These fixed-effect estimates make economic sense.

In terms of the price elasticity of ICT demand, the fixed-effect estimates are in a reasonable range for mobile phones and PCs. Based on this estimation, the demand for these two goods is inelastic: a one percentage point increase in their own price only leads to a 0.13% and 0.17% reduction in the penetration rates of mobile phones and PCs, respectively. However, the elasticity of demand for mainline telephones is positively estimated. This can be explained by the fact that a mainline telephone is considered to be necessary for every household and business; thus, this service grows even when the mainline price (measured by the ratio of total mainline revenue to the number of mainline users) increases. Therefore, a one percentage point increase in the mainline price leads to a 0.02% increase in the penetration rate of mainline telephones.

Next, the regression results for investment into ICT goods (ICT supply equations) are presented in Table 11. The following discussion is based on the estimation outputs from the fixed-effect models with the support of Hausman test statistics. Table 11 shows that investment (per labour working hour) into the three ICT goods reduces as a country grows in geographic area. This is intuitive because, taking into account the scale effects, H, ICT investment in smaller countries is expected to have higher returns, more efficient network connections, and lower maintenance costs for ICT equipment compared with that in larger countries. This finding contradicts the result found by Röeller and Waverman (2001) that investment into telecommunication infrastructure increases as a country grows in geographic area; however, the omitted consideration of scale effects may have misled their estimation.

"Table 11 about here"

We also find that the government's budget surplus only motivates the level of investment into hardware. This is consistent with the finding by Röeller and Waverman (2001). There is no significant relationship between investment into other ICT goods (communication equipment and software) and the government's budget surplus.

The impact of price indices on IT goods investment is also worthy of discussion. The negative estimate of log(*HARDP*) in Table 11 suggests that investment into IT equipment is expected to increase as the price of IT equipment falls (as shown in Table 5). Compared with hardware investment, software investment is motivated by an increase in its price index. Finally, there is no statistically significant relationship between investment into communication equipment and its price index.

Lastly, we shift our focus to the key regression results for the log-linearised production function in Table 12. To estimate the log-linearised production function, this paper performs an estimation using the two-stage least squares approach with (assumed) exogenous variables from the ICT demand and supply equations as instruments. This approach is consistent with the method carried out by Röeller and Waverman (2001), who estimated a micro model for telecommunication investment using a macro production function.

"Table 12 about here"

With the support of Hausman test statistics, Table 12 presents the results from the fixed-effect model, showing no significant time trend in the regression output for equation (13). This estimation result is different from Röeller and Waverman (2001), whose work suggested that GDP per person displays a negative time trend. The either negative or non-significant time trend suggests that instead of exogenous growth factors, the sample of high-income OECD countries may rely on endogenous growth engines such as ICT and non-ICT capital.

The three ICT capital stock series are found to make a positive and significant (at the 1% level) contribution to labour productivity. Compared with the negative estimate of non-ICT capital stock (–16%), the joint contribution of ICT capital stock to labour productivity is estimated to be 21%. Of the three ICT capital stock categories, communication equipment has the highest productivity share (9.41%), with the shares of IT equipment and software approximately half of this.

The estimates in Table 12 imply that $\hat{a}_H = 1 - 0.2688 - (\hat{a}_{KNICT} + \hat{a}_{COM} + \hat{a}_{HARD} + \hat{a}_{SOFT}) = 1.23$ in production equation (11). This estimate may not be that conventional; however, the domination of scale effects implies the existence of increasing returns to scale among all factor inputs. With no exogenous time trend, the growth among sample OECD countries is strictly endogenous.

The characteristics of ICT capital include the penetration rates of mainline telephones, mobile phones, and PCs. The mainline telephone penetration rate increases productivity by 0.2%. This emphasises the importance of telecommunication infrastructure during the process of economic development. We also note that mobile phone penetration does not statistically significantly explain productivity growth.

A positive and non-linear network effect is also found. PC penetration contributes to labour productivity only when certain levels of digitalisation (more than 20%) are achieved. When a country reaches a digitalisation level between 20% and 80%, a one percentage point increase in PC penetration leads to a 0.0053% increase in labour productivity. Moreover, when a country's digitalisation level grows above 80%, the contribution of PC penetration to productivity rises to 0.3711%.

5. Conclusion

This paper divided ICT capital stock into three categories: IT equipment, communication equipment, and software. We found that these capital stock series positively and statistically significantly affect productivity growth. These effects individually influence productivity growth, while non-ICT capital is found to be counterproductive. Telephone penetration also emphasises the importance of telecommunication infrastructure on productivity growth. However, mobile phone penetration does not significantly influence productivity growth during economic development. We also found that PC penetration contributes to productivity growth only when the digitalisation level in a country is higher than 20%.

The empirical evidence presented in this paper leads to two main conclusions. First, the resources devoted to physical capital accumulation are more beneficial to productivity growth if they are diverted towards the improvement of the quality and quantity of ICT capital stock. Second, the levels of digitalisation and the extension of mainline telephone services create positive externalities in boosting labour productivity in advanced OECD countries. This may help explain cross-country differences in labour productivity, especially between developed and developing economies.

In this paper, telephone and PC penetration rates were found to influence the productivity value created by ICT, but the mobile phone penetration rate was surprisingly unproductive. This may be because of the limited time span of the data used in this paper, namely between 1980 and 2004.

Nowadays, people do not only sit in front of a desktop to access the Internet; rather, many use portable devices with connections to 3G mobile phones that send and receive data wirelessly. By using more recent data, we might reasonably find that the penetration rates of mobile phones and portable devices, the level of accessibility to the Internet, and the cost of using the Internet also influence the value created by ICT. We also expect the efficient deployment of technology along business value chains and the altitude of users to be beneficial to the value created by ICT. The present paper thus opens up this line of thought as a future research direction.

Tables

Table 1: Definition of the endogenous variables and exogenous parameters in equation (11)

Variable category	Definition
System variables	
Y	aggregate output (to be measured by real GDP)
A	country specific constant (exogenous time-invariant factor)
H	labour input (to be measured by the total hours worked)
$KNICT$	country's real capital stock net of the ICT capital stock (non-ICT capital stock)
$G(*)$	"effective" ICT real capital stock (described below)
Exogenous parameters	
a_H	the share of labour input that contributes to real GDP
a_{KNICT}	the share of non-ICT real capital stock that contributes to productivity
a_T	the coefficient of the time trend representing autonomous technical change

Table 2: Definition of the regression variables and parameters in equation (12)

Variable category	Definition
System variables	
$KCOM$	a country's actual measure of real capital stock of communication equipment
$KHARD$	a country's actual measure of real capital stock of IT equipment (hardware)
$KSOFT$	a country's actual measure of real capital stock of software
$MLPEN$	the penetration rate of fixed mainline (telephone)
$MBPEN$	the penetration rate of mobile phone
PCI	the penetration rate of personal computers
DIG_MED	A dummy variable that equals one when a country's digitalisation level is greater than 20% but less than or equal to 80%
DIG_HIGH	A dummy variable that equals one when a country's digitalisation level is above 80%
a_{COM}, a_{HARD}, a_{SOFT}, a_{MLPEN}, a_{MBPEN}, a_{PCI}, a_{MED}, and a_{HIGH} are all regression parameters.	

Table 3: Definition of the regression variables and parameters in equations (14) and (15)

Variable category	Definition
System variables	
WL	a country's waiting list (per hundred population) of mainline telephones
POP	a country's total population
MLP	the price of mainline telephone calls
MBP	the price of mobile calls
b_{0ML}, b_{GDPML}, b_{MLP}, b_{0MB}, b_{GDPMB}, and b_{MBP} are all regression parameters.	
u_{ML}, and u_{MB} are regression residuals in equations (14) and (15), respectively.	

Table 4: Definition of the regression variables and parameters in equations (17) to (19)

Variable category	Definition
System variables	
GA	geographic area of a country
GB	government's real budget surplus of a country
$COMP$	the price of communication equipment
$HARDP$	the price of hardware (IT equipment)
$SOFTP$	the price of software
d_{0COM}, d_{GACOM}, d_{GBCOM}, d_{COMP}, d_{TCOM}, d_{0HARD}, d_{GAHARD}, d_{GBHARD}, d_{HARDP}, d_{THARD}, d_{0SOFT}, d_{GASOFT}, d_{GBSOFT}, d_{SOFT}, and d_{TSOFT} are all regression parameters.	
u_{INVCOM}, $u_{INVHARD}$, and $u_{INVSOFT}$ are regressions in equations (17), (18), and (19), respectively.	

Table 5: Average price deflators for ICT goods

Year	Deflator of IT equipment	Deflator of Communication equipment	Deflator of Software
1980	8.41	0.77	0.96
1981	8.99	0.84	1.04
1982	8.85	0.91	1.11
1983	7.92	0.98	1.17
1984	7.13	1.03	1.19
1985	6.58	1.06	1.20
1986	6.03	1.10	1.20
1987	5.65	1.13	1.21
1988	5.32	1.15	1.21
1989	5.10	1.16	1.17
1990	4.78	1.16	1.15
1991	4.40	1.17	1.13
1992	4.00	1.17	1.06
1993	3.64	1.18	1.06
1994	3.29	1.16	1.03
1995	2.90	1.14	1.02
1996	2.28	1.12	1.00
1997	1.85	1.12	0.98
1998	1.44	1.07	0.96
1999	1.13	1.03	0.97
2000	1.00	1.00	1.00
2001	0.83	0.97	1.01
2002	0.72	0.96	0.99
2003	0.63	0.93	0.97
2004	0.58	0.92	0.95

Table 6: Description of regression variables

Variable	Description
GDP	Real GDP in 2000 US$ at PPP (millions)
H	Total working hours (millions)
POP	Total population
KNICT	Non-ICT Capital in 2000 US$ at PPP (millions)
INVHARD	Investment of IT equipment in 2000 US$ at PPP (millions)
INVCOM	Investment of Communication equipment in2000 US$ at PPP (millions)
INVSOFT	Investment of Software equipment in 2000 US$ at PPP (millions)
KCOM	Capital stock of Communication equipment in 2000 US$ at PPP (millions)
KHARD	Capital stock of IT equipment in 2000 US$ at PPP (millions)
KSOFT	Capital stock of Software equipment in 2000 US$ at PPP (millions)
HARDP	A deflator that represents the price of IT equipment
COMP	A deflator that represents the price of communication equipment.
SOFTP	A deflator that represents the price of software
MLPEN	Percentage of mainline (telephone) users in population
MBPEN	Percentage of mobile users in population
WL	Waiting list for mainlines
PCI	Percentage of personal computer users in population
DIGITAL	Level of digitalisation (%)
DIG_MED	DIG_MED=1 if 20% < Digital ≤ 80%
DIG_HIGH	DIG_HIGH=1 if Digital > 80%
MLP	Mainline Retail Price: Total mainline revenues / Number of mainline users
MBP	Mobile Phone Retail Price: Total mobile phone revenues / Number of mobile phone users
GB	Government Surplus in 2000 US$ at PPP (millions)
GA	Geographic Area (square kilometres)

Table 7: The CAGRs of GDP per working hour, GDP per capita and non-ICT capital stock per working hour for OECD countries

	GDP per hour worked (in 2000 US$)		CAGR 1980–2004	GDP per capita (in 2000 US$)		CAGR 1980–2004	Non-ICT capital per hour worked (in 2000 US$)		CAGR 1980–2004
	1980	2004		1980	2004		1980	2004	
Austria	25.25	39.68	1.90%	18,024	27,391	1.76%	43.30	78.85	2.53%
Australia	21.66	31.62	1.59%	16,962	27,017	1.96%	50.06	60.22	0.77%
Belgium	25.61	41.40	2.02%	16,508	25,057	1.75%	56.63	77.78	1.33%
Canada*	23.09	30.46	1.33%	17,793	27,131	2.03%	47.44	53.41	0.57%
Germany	21.99	37.60	2.26%	16,394	23,535	1.52%	53.56	68.33	1.02%
Denmark	22.05	37.00	2.18%	17,988	27,209	1.74%	36.95	70.62	2.74%
Spain	18.43	27.90	1.74%	11,635	20,748	2.44%	28.73	60.77	3.17%
Finland	18.12	34.82	2.76%	15,434	24,882	2.01%	38.79	63.19	2.05%
France	25.42	43.83	2.30%	17,160	24,610	1.51%	40.27	89.19	3.37%
Greece	17.97	23.65	1.15%	12,540	17,425	1.38%	31.19	49.89	1.98%
Ireland	15.29	42.17	4.32%	10,026	30,618	4.76%	25.91	51.42	2.90%
Italy	24.73	34.95	1.45%	16,151	23,687	1.61%	35.79	59.79	2.16%
Netherlands	28.11	38.95	1.37%	17,208	25,584	1.67%	64.04	78.28	0.84%
Portugal	12.29	20.24	2.10%	10,258	17,175	2.17%	16.54	31.92	2.78%
Sweden	21.49	34.46	1.99%	16,422	25,630	1.87%	39.59	59.29	1.70%
UK	18.83	33.07	2.37%	14,504	25,456	2.37%	26.97	46.08	2.26%
US	24.68	38.30	1.85%	19,958	32,642	2.07%	42.77	54.67	1.03%

* Instead of 1980, the initial year for Canada is 1983 based on the available dataset.

Table 8: The CAGRs of ICT capital stock per working hour for OECD countries

	IT capital per hour worked (in 2000 US$)		CAGR 1980–2004	Communication capital per hour worked (in 2000 US$)		CAGR 1980–2004	Software capital per hour worked (in 2000 US$)		CAGR 1980–2004
	1980	2004		1980	2004		1980	2004	
Austria	0.014	1.425	21.31%	0.64	2.16	5.19%	0.02	0.86	17.68%
Australia	0.019	3.460	24.31%	0.57	1.64	4.50%	0.04	2.21	18.66%
Belgium	0.041	3.191	19.95%	0.28	2.17	8.90%	0.06	0.87	12.02%
Canada*	0.034	2.111	21.66%	0.62	1.44	4.05%	0.10	1.20	12.61%
Germany	0.020	1.389	19.31%	0.65	1.76	4.22%	0.05	0.84	12.75%
Denmark	0.034	2.324	19.32%	0.23	0.63	4.27%	0.06	1.66	14.83%
Spain	0.017	0.657	16.31%	0.38	1.11	4.52%	0.07	0.61	9.34%
Finland	0.014	0.391	15.02%	0.16	3.82	14.03%	0.16	1.59	10.02%
France	0.007	0.872	22.22%	0.29	1.66	7.60%	0.05	0.99	13.58%
Greece	0.026	0.799	15.42%	2.58	1.59	-1.98%	0.03	0.21	9.27%
Ireland	0.012	1.045	20.31%	0.11	1.04	9.70%	0.07	0.26	5.83%
Italy	0.022	0.992	17.19%	0.92	2.50	4.24%	0.07	0.63	9.48%
Netherlands	0.015	1.755	22.09%	0.21	0.50	3.80%	0.12	1.40	10.85%
Portugal	0.086	0.713	9.23%	0.71	1.21	2.22%	0.05	0.10	2.64%
Sweden	0.032	1.771	18.27%	0.63	1.49	3.64%	0.09	1.71	12.80%
UK	0.016	1.616	21.21%	0.23	1.30	7.50%	0.03	1.03	15.90%
US	0.032	2.056	18.95%	0.70	2.97	6.23%	0.09	1.70	13.03%

* Instead of 1980, the initial year for Canada is 1983 based on the available dataset.

Table 9: The CAGRs of telephone and PC penetration for OECD countries

	Mainline penetration (per 100 inhabitants)		CAGR 1980–2003	Mobile phone penetration (per 100 inhabitants)		CAGR 1993–2004	Personal computer per 100 inhabitants		CAGR 1991–2004
	1980	2003		1993	2004		1991	2004	
Austria	29.02	47.68	2.18%	2.79	97.36	38.10%	7.74	41.67	13.83%
Australia	32.27	55.15	2.36%	3.91	82.60	31.97%	16.06	68.90	11.85%
Belgium	24.80	47.00	2.82%	0.67	88.32	55.76%	9.97	35.08	10.16%
Canada	40.58	63.21	1.95%	4.78	47.21	23.15%	12.82	70.54	14.01%
Germany	33.19	65.96	3.03%	2.18	86.42	39.72%	9.80	56.10	14.36%
Denmark	43.43	66.94	1.90%	6.89	96.10	27.07%	13.41	65.92	13.03%
Spain	19.34	41.60	3.39%	0.66	93.91	56.98%	3.34	26.64	17.31%
Finland	36.40	49.20	1.32%	9.63	95.63	23.20%	11.33	48.22	11.78%
France	29.51	56.44	2.86%	1.00	73.72	47.90%	7.37	48.66	15.62%
Greece	23.55	45.39	2.89%	0.46	100.61	63.12%	1.95	8.98	12.47%
Ireland	14.20	49.13	5.54%	1.71	94.52	43.99%	10.21	50.29	13.05%
Italy	23.07	45.94	3.04%	2.12	108.19	43.00%	4.58	31.29	15.93%
Netherlands	34.57	48.18	1.45%	1.41	91.34	46.07%	11.28	68.47	14.88%
Portugal	10.67	40.33	5.95%	1.02	102.26	51.97%	3.04	13.92	12.41%
Sweden	58.00	76.57	1.22%	8.86	103.22	25.01%	12.73	76.14	14.75%
UK	32.24	59.52	2.70%	3.90	102.81	34.65%	12.45	60.39	12.91%
US	41.40	62.94	1.84%	6.20	60.97	23.09%	23.43	74.06	9.26%

Note: The selection of the time span in this table is based on the available data points.

Table 10: The regression results for the penetration of mainline telephones, mobile phones, and PCs

equation (14): Mainline telephone penetration	Random Effect		Fixed Effect	
Dependent Variable: *MLPEN*+(*WL*/*POP*)	Obs.=351		Obs.=351	
Explanatory Variables	Estimate	Std. Error	Estimate	Std. Error
Constant	2.3851***	0.1170	2.4063***	0.1172
log(*GDP*/*PO*P)	0.5137***	0.0187	0.5176***	0.0191
log(*MLP*)	0.0191**	0.0075	0.0185**	0.0076
Hausman test statistic	$\chi^2(2) = 5.02$			

equation (15): Mobile phone penetration	Random Effect		Fixed Effect	
Dependent Variable: *MBPEN*	Obs.=230		Obs.=230	
Explanatory Variables	Estimate	Std. Error	Estimate	Std. Error
Constant	5.8189***	0.3077	9.4391***	0.4513
log(*GDP*/*POP*)	0.9824***	0.0905	2.1555***	0.1416
log(*MBP*)	–0.2648***	0.0178	–0.1290***	0.0226
Hausman test statistic	$\chi^2(2) = 128.28$			

equation (16): PC penetration	Random Effect		Fixed Effect	
Dependent Variable: *PCI*	Obs.=338		Obs.=338	
Explanatory Variables	Estimate	Std. Error	Estimate	Std. Error
Constant***	1.0155***	0.1392	0.6222***	0.1601
log(*GDP*/*POP*)**	0.1768***	0.0366	0.0709*	0.0425
log(*HARDP*)***	–0.1509***	0.0065	–0.1674***	0.0073
Hausman test statistic	$\chi^2(2) = 25.86$			

Note: The above regressions report ordinary standard errors and covariances. ***, **, and * denote the level of significance at 1%, 5%, and 10%, respectively. The Hausman test statistics are in favour of the fixed-effect estimation for the *MLPEN* regression at the 10% level and 1% level for the *MBPEN* and *PCI* regressions, respectively.

Table 11: The regression results for ICT investment

equation (17): Investment of communication equipment	Random Effect		Fixed Effect	
Dependent Variable: log(*INVCOM*/*H*)	Obs.=423		Obs.=423	
Explanatory Variables	Estimate	Std. Error	Estimate	Std. Error
Constant	–4.5065***	0.6843	19.3399***	5.1054
log(*GA*)	0.1156**	0.0537	–1.7769***	0.4052
GB	5.61E–07	3.83E–07	5.20E–07	3.88E–07
t	0.0691***	0.0024	0.0718***	0.0025
log(*COMP*)	0.0996	0.0721	0.0591	0.0731
Hausman test statistic	$\chi^2(4) = 25.59$			

equation (18): Investment of IT equipment (hardware)	Random Effect		Fixed Effect	
Dependent Variable: log(*INVHARD*/*H*)	Obs.=423		Obs.=423	
Explanatory Variables	Estimate	Std. Error	Estimate	Std. Error
Constant	–4.7167***	0.7765	13.5021***	4.4065
log(*GA*)	0.0163	0.0603	–1.4259**	0.3492
GB	9.29E–07***	3.36E-07	8.61E–07***	3.39E–07
t	0.1567***	0.0055	0.1564***	0.0055
log(*HARDP*)	–0.2415***	0.0463	–0.2603***	0.0465
Hausman test statistic	$\chi^2(4) = 28.78$			

equation (19): Investment of software	Random Effect		Fixed Effect	
Dependent Variable: log(*INVSOFT*/*H*)	Obs.=423		Obs.=423	
Explanatory Variables	Estimate	Std. Error	Estimate	Std. Error
Constant	–4.7222***	0.8768	5.0008	4.3699
log(*GA*)	0.0843	0.0688	–0.6872**	0.3468
GB	2.40E–07	3.27E–07	2.10E–07	3.30E–07
t	0.1212***	0.0020	0.1222***	0.0021
log(*SOFTP*)	0.3335***	0.0667	0.2853***	0.0678
Hausman test statistic	$\chi^2(4) = 21.16$			

Note: The above regressions report ordinary standard errors and covariances. ***, **, and * denote the level of significance at 1%, 5%, and 10%, respectively. The Hausman test statistics are in favour of the fixed-effect estimation for the three regressions at the 1% level.

Table 12: The regression results for the log-linearised production function

equation (13): Production equation	Random Effect		Fixed Effect	
Dependent Variable: log(*GDP*/*H*)	Obs.=224		Obs.=224	
Explanatory Variables	Estimate	Std. Error	Estimate	Std. Error
Constant	3.7863***	0.2540	6.7071***	0.6175
t	–0.0068***	0.0021	–0.0028	0.0024
log(*KNICT*/*H*)	0.0100	0.0312	–0.1632***	0.0418
log(*KCOM*/*H*)	0.1102***	0.0089	0.0941***	0.0099
log(*KHARD*/*H*)	0.0417***	0.0106	0.0551***	0.0111
log(*KSOFT*/*H*)	0.0708***	0.0131	0.0578***	0.0143
log(*H*)	–0.0329*	0.0179	–0.2688***	0.0514
MLPEN	0.1997***	0.0662	0.1950***	0.0691
MBPEN	–0.0110	0.0150	–0.0147	0.0152
PCI	–0.2453*	0.1345	–0.3131**	0.1359
*DIG_MED*PCI*	0.2349**	0.1180	0.3184***	0.1196
*DIG_HIGH*PCI*	0.2908**	0.1262	0.3658***	0.1277
Hausman test statistics	$\chi^2(11) = 75.38$			

In additional to the above regressors, the following variables are employed in the set of instrumental variables: log(*MLP*) log(*MBP*) log(*HARDP*) log(*COMP*) log(*SOFTP*) log(*GDP*/*POP*) *GB*.

Note: The above regressions report ordinary standard errors and covariances. ***, **, and * denote the level of significance at 1%, 5%, and 10%, respectively. The Hausman test statistic is in favour of the fixed-effect estimation at the 1% level.

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[1] Productivity is generally measured in two main ways: output per hour worked called labour productivity and output per total input (i.e. labour and capital) called TFP.

[2] That framework includes basic property rights, rule of law, openness, and sector-specific issues such as regulation.

[3] Remarks by Alan Greenspan, 'Technology Innovation and its Economic Impact' before the National Technology Forum, St. Louis MO, April 7, 2000, emphasis added.

[4] Jorgenson, Ho, and Stiroh (2004) stated that 'communication technology is crucial for the rapid deployment and diffusion of the Internet, perhaps the most striking manifestation of information technology in the American economy'. This paper aims to determine whether the spread of modern telecom in conjunction with computers helps explain the productivity puzzle by including three kinds of capital in the economy-wide production function: computer and software capital, telecom capital, and other non-ICT capital. Both computer and telecom capital stocks have associated characteristics such as memory (computers) and digitalisation (telecom) which are (potentially) determined endogenously.

[5] The growth rate of the consumption of ICT goods can be generally regarded as the growth rate in this economy if the consumption of ICT goods is proportional to final output.

[6] See the survey by Draca et al. (2006).

[7] Röeller and Waverman (2001) employed GD as the government's real budget 'deficit' of a country, while this paper uses GB to represent a country's real budget 'surplus' in the later empirical analyses.

[8] These 14 EU countries are Austria, Belgium, Denmark, France, Finland, Germany, Greece, Ireland, Italy, the Netherlands, Portugal, Spain, Sweden, and the UK.

[9] The process of generating the ICT capital stock series from ICT investment for Canada and Australia is discussed in subsection 4.2.

[10] Some sensitivity tests on the Australian data were conducted. Owing to depreciation, it was found that the choice of starting capital stock had little impact on the productive capital stock. For example, for non-residential structures (the asset with the lowest depreciation rate) a doubling of the initial estimate of stock led to only a 6% increase in the 2003 estimate. A detailed description of how the capital stocks for Australia were constructed is available upon request.

國科會補助計畫衍生研發成果推廣資料表

日期:2012/09/29

國科會補助計畫	計畫名稱: 資訊通信科技資本對高所得國家生產力之貢獻
	計畫主持人: 王宜甲
	計畫編號: 100-2410-H-029-052- 學門領域: 經濟發展、技術變動與成長

無研發成果推廣資料

100 年度專題研究計畫研究成果彙整表

計畫主持人：王宜甲	計畫編號：100-2410-H-029-052-
計畫名稱：資訊通信科技資本對高所得國家生產力之貢獻	

成果項目			量化：實際已達成數（被接受或已發表）	量化：預期總達成數(含實際已達成數)	量化：本計畫實際貢獻百分比	單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
國內	論文著作	期刊論文	0	0	100%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	0	0	100%		
		專書	0	0	100%		
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（本國籍）	碩士生	2	2	100%	人次	本計畫雇用兩位東海大學碩士班二年級的兼任助理，蔡弘毅與謝雨真，月支新台幣 8000 元，共支 12 個月。
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
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國外	論文著作	期刊論文	1	1	100%	篇	本篇論文以英文撰寫，並且以於 Economic Development Quarterly 所接受，將於近期內刊登。
		研究報告/技術報告	0	0	100%		
		研討會論文	1	1	100%		本篇論文之初稿受到西南財經大學所舉辦之「International Conference on Economic and Financial Challenges in Asia Pacific

							而由於本計畫並無國外差旅費的補助，因此無法前往發表。
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（外國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)		無					

	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□未達成目標（請說明，以 100 字為限）

□實驗失敗

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說明：

2. 研究成果在學術期刊發表或申請專利等情形：

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本篇論文以英文撰寫，並且以於 Economic Development Quarterly 所接受，將於近期內刊登。

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

本文首先建構了一理論模型，理論結果發現經濟成長率與一國之資訊通信科技水準之間有直接且內生的正向關係。接著，本文建構了 17 個高所得 OECD 國家之追蹤資料數據庫，樣本年間為 1980－2004（依國家不同而有樣本期間的變動），用以分析資訊通信科技（ICT）資本存量對這些高所得國家，在樣本年間生產力的貢獻。本篇論文的模型主軸參考 R&ouml；eller and Waverman（2001）所估計之總體生產力方程式，配合數個個體模型修正迴歸變數內生性之問題。與 R&ouml；eller and Waverman（2001）不同的是，本篇論文所考慮的主要解釋變數不只是他們所使用的電信基礎建設（telecommunication infrastructure），而是將 ICT 資本存量切割為三個部門：通訊設備部門、硬體部門與軟體部門，並配合通訊產品（市內電話與行動電話）及電腦普及率，來估計這些變數對高所得國家長期生產力的貢獻。本篇論文目前的實證結果顯示，除了行動電話普及率之外，這些 ICT 資本存量以及市內電話與電腦普及率，均對高所得國家有正面的生產力貢獻。此外，一旦這些國家達到一定數位化的門檻後，電腦普及率對生產力的貢獻將非線性地增加。這些實證上的結果，均與本文所建構之理論模型之預測一致。