GROWTH AND CAPITAL DEEPENING SINCE 1870: IS IT ALL TECHNOLOGICAL PROGRESS?

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Abstract. Growth accounting exercises are used to decompose the growth in labour productivity into capital deepening and technological progress. Based on the Abel-Blanchard (1983) Tobin’s $q$ model it is shown that capital deepening is a function of technological progress, required stock returns and taxes. Using data for 16 industrialised countries, this paper shows that capital deepening is heavily endogenous, total factor productivity explains most of the advances in labour productivity and reductions in the required stock returns have been influential for capital deepening and advances in labour productivity during the past 135 years.

JEL classification: E0, E2, O47.

Key words: Growth accounting, TFP growth, required stock returns, endogeneity

1 Introduction
A well-known finding in economic growth models is that all growth in labour productivity in the very long run is caused by advances in total factor productivity (TFP). Thus, if an economy is in a steady state, it would not be useful to undertake growth accounting exercises provided the discount rate is constant. However, if the discount rate is not constant and the country is outside its steady state, growth accounting may be a worthwhile exercise, particularly for economies at their take-off stage. The purpose of growth accounting, according to Jones (1997), is to gauge the effects of capital-deepening and TFP in periods of exceptionally high labour productivity growth.

Unfortunately, growth accounting exercises run into a nasty dilemma. A problem associated with the traditional growth accounting framework is that it does not give any information about factors that are responsible for capital deepening. Thus, a mechanical growth accounting exercise would neglect the TFP-induced capital deepening and attribute TFP only to its direct effect on labour productivity growth. This difficulty has been pointed out by Barro (1999), Barro and Sala-I-Martin (2001), Helpman (2004),
Klenow and Rodriguez-Clare (1997) and Prescott (1998). However, the literature has not given an explicit account of the endogeneity problem and the mechanism by which TFP shocks are transmitted to capital. Moreover, the literature in particular has not shown whether an endogeneity bias prevails empirically. The hypothesis that labour productivity is TFP-induced in the long run is an empirical issue that has not been validated empirically thus far.

Why is capital deepening a positive function of TFP? In the Solow model, labour-augmenting technological progress leads to capital deepening because it enhances the marginal productivity of capital. However, the mechanism by which this is brought about is not clearly spelled out in standard expositions, because the asset market is not an explicit part of the model. This paper presents a modified version of Abel and Blanchard’s (1983) Tobin’s $q$ model to illustrate how TFP innovations and changes in the required stock returns explicitly transmit to capital and, therefore, labour productivity. In the Abel-Blanchard model, a technological innovation increases the expected returns to capital stock and brings $q$ above its steady state level of one, which, consequently, leads to capital-deepening because the expected returns from an addition unit of capital exceeds the expected stock returns. The model also explicitly shows how reductions in the expected stock returns and tax rates lead to capital deepening and, therefore, highlights factors that are responsible for the advances in labour productivity quite independently of TFP changes.

In the Tobin’s $q$ model in this paper, variations in capital-output ratios, $K/Y$, are the result of variations in required stock returns and corporate tax rates. With constant factor shares and homogenous production technology, changes in the required stock returns lead to proportional changes in the $Y/K$ ratio, because stockholders establish the required stock returns and firms invest until the after-tax returns of the last investment projects equal the required returns. In the empirical part of the paper, this result is used to identify the required stock returns.

Mankiw, Weil and Romer (1992) and Mankiw (1995), among others, have shown, indirectly, that there is a positive correlation between per capita output and the capital-output ratio ($K/Y$). Moreover, they use this result as evidence in favour of the Solow model, where variations in the $K/Y$ ratio reflect variations in the savings propensity. In the Tobin’s $q$ model, variations in $K/Y$ ratios are the result of variations in required stock returns and corporate tax rates. Using data for 16 industrialised countries, from the past 135 years, this paper shows that a reduction in the expected stock returns played a pivotal role for growth in the 19th century and in the first two decades following WWII.

The empirical implications of the Abel-Blanchard model are tested in this paper. For this model to be a valid description of labour productivity growth, capital deepening must be explained by TFP-
innovations and changes in the required returns. Furthermore, TFP-innovations must lead capital
deepening. Panel cointegration estimates are undertaken to test for cointegrating relationships between
labour productivity or the capital-labour ratio and TFP, and after-tax required returns and Granger
causality tests are used to test whether TFP leads the capital-labour ratio, $K/L$, or vice versa. The tests
show that there is a strong long-run relationship between the $Y/K$ ratio, TFP and after-tax expected stock
returns and that TFP significantly leads the $Y/K$ ratio, thus supporting the predictions of economic growth
models. The empirical estimates are used to account for growth in labour productivity in the
industrialised countries over the past 135 years and compared to the results from traditional growth
accounting exercises.

Although the primary contribution of the paper is empirical, the next section briefly shows that
the much neglected Abel and Blanchard (1983) model is a valuable tool for analysing the endogeneity of
capital in growth, because it explicitly shows how innovations in TFP or required stock returns transmit
to capital deepening by Tobin’s $q$. Section 3 shows the path of TFP, $Y/L$ and the required stock returns for
the 16 industrialised countries over the past 135 years and Section 4 tests whether the endogeneity
prediction of economic growth models holds. In Section 5, the coefficient estimates are used to account
for growth since 1870.

2 The endogeneity bias in growth accounting
To show the endogeneity problem associated with growth accounting formally and intuitively, a Tobin’s
$q$ model is used explicitly to illustrate which exogenous factors are responsible for capital deepening and
the adjustment path towards steady state. The model is based on a modified version of the Abel and
Blanchard (1983) model. The model consists of firms, the stock market and consumers.

**Firms.** Investment and stock prices are determined jointly from the following optimisation problem of
the representative firm, where the discount rate is a given:

$$
\max \Pi = \int_0^\infty e^{-\delta t} \left[ (1 - \tau_r) (A_t, L_t, K_t) - L_t W_t - \phi(I_t) \right] \Pi dt
$$

st.

$$
K_{t+1} = I_t - \delta K_t,
$$

where $\Pi$ is real profits, $K$ is capital stock, $I$ is net investment, $W$ is the real wage, $L$ is labour services, $r$ is
the required returns to equity, $\phi(I)$ is convex adjustment cost of investment, $\phi'(I) > 0$, $\phi''(I) > 0$, $\delta$ is
the rate of capital depreciation, \( \tau \) is the corporate tax rate and \( A \) is the technology level. Furthermore, \( F_K' > 0, F_K' < 0, F_A' > 0, \) and \( F_A' < 0 \). The firm is an all equity firm and all earnings are paid out.

Solving this optimisation problem yields the following first order conditions for optimum, under the assumption of perfect competition:

\[
(1 - \tau_i)MP_{K,t} = (r_t + \delta)q_t - \dot{q}_t, \tag{1}
\]

\[
1 + \phi'(I_t)(1 - \tau) = q_t, \tag{2}
\]

\[
\lim_{t \to \infty} e^{-\tau} q_t K_t = 0,
\]

where \( q \) is the shadow price of capital or Tobin’s \( q \) and a dot over a variable signifies first differences. The last equation is the transversality condition, which states that the discounted value of the market capitalisation of the company is zero as time goes towards infinity. Equation (1) is the asset market equilibrium condition and Equation (2) is the equilibrium condition in the market for fixed investment. For a given required returns to equity and employment, Equations (1) and (2) determine capital stock and stock prices.

**Consumers.** The representative consumer has preferences ordered by:

\[
\max U = \int_{t=0}^{\infty} \frac{C_t^{1-\theta} - 1}{1-\theta} e^{-\rho t} dt,
\]

subject to the budget constraint:

\[
\dot{a}_t = W_t L_t + r_t a_t - C_t,
\]

where \( U \) is utility, \( a \) is per capita assets, \( \rho \) is a subjective discount rate, \( \theta \) is the coefficient of relative risk aversion and \( C \) is consumption.

A necessary and sufficient condition for an interior solution is:

\[
\frac{\dot{C}_t}{C_t} = \frac{1}{\theta} (r_t - \rho_t). \tag{4}
\]

This equation states that consumption growth is positive if the rate of return on any asset exceeds the subjective discount rate, because relatively high returns give the consumer an incentive to save now and consume later.
2.1 General equilibrium

The condition for equilibrium in the goods market is given by:

\[ F(A_t, K_t, L_t) = C_t + I_t + \phi(I_t). \]  \hfill (4)

Solving out consumption from Equation (3) using Equation (4), we arrive at the following simultaneous first-order differential equation systems, with the \((K, q, r)\)-vector of endogenous variables:

\[ \dot{q}_t = (r_t + \delta)q_t - (1 - \tau_t)\text{MP}_{K}, \]  \hfill (5)

\[ \dot{K}_t = h[(q_t - 1)/(1 - \tau_t)], \]  \hfill (6)

\[ \dot{C}_t = (r_t - \rho_t)(F(A_t, K_t) - h[(q_t - 1)/(1 - \tau_t)]) - \phi(h[(q_t - 1)/(1 - \tau_t)])) / \theta, \]  \hfill (7)

where labour is normalised to one following Abel and Blanchard (1983) and \( h = (\phi')^{-1} \). The model can be easily extended to allow for endogenous labour supply, as shown by Kiley (2004); however, this extension does not influence the steady-state properties of the model.

2.2 Endogeneity bias in growth accounting frameworks

Solving (5)-(7) in steady state yields the following key equation from which the \(K/L\) ratio can be recovered:

\[ (1 - \tau_t)\partial F(A_t, K_t, L_t) / \partial K_t - \delta = (1 - \tau_t)\text{MP}_K - \delta = \rho_t. \]  \hfill (8)

This equation has a very intuitive interpretation. Firms invest until the after-tax returns to capital are equal to the returns required by investors following a shock to the marginal productivity of capital or the required stock returns. A technology innovation, for example, increases the marginal productivity of capital. Since the returns to investment exceed the returns required by investors, a capital deepening process will be initiated. Thus, although the increase in \(Y/L\) is initiated by the technology in this example, a standard growth accounting exercise would erroneously attribute some of the TFP-induced growth effects to capital deepening.

To find a closed-form solution, consider the homogeneous Cobb-Douglas production function with Hicks’ neutral technological progress:

\[ Y_t = A_t L_t^\alpha K_t^{1-\alpha_t}. \]  \hfill (9)
Solving (8) and (9) and differentiating yields capital deepening as a function of exogenous variables:

\[
\Delta \ln \frac{K_t}{L_t} = \frac{\Delta \ln (1 - \alpha_t)}{\alpha_t} + \frac{\Delta \ln (1 - \tau_t)}{\alpha_t} + \frac{\Delta \ln A_t}{\alpha_t} - \frac{\Delta \ln \rho_t}{\alpha_t} - \ln \frac{K_t}{L_t} \Delta \alpha_t, \tag{10}
\]

where the depreciation rate is set to zero. In this equation, changes in the \(K/L\) ratio are determined by changes in technology, the discount rate, corporate taxes and factor shares. Thus, the model shows explicitly which exogenous factors are responsible for capital deepening. The dynamic adjustment of the \(K/L\) ratio to shifts in these factors is analysed in the next subsection.

Examining the implications of (10) for growth accounting, consider the rewritten total differential of the Cobb-Douglas production function given by (9):

\[
\Delta \ln \frac{Y_t}{L_t} = \Delta \ln A_t + (1 - \alpha_t) \Delta \ln \frac{K_t}{L_t}, \tag{11}
\]

which is the traditional growth accounting model without human capital and land inputs. Combining (10) and (11) yields labour productivity as a function of exogenous variables under the assumption of a constant \(\alpha\):

\[
\Delta \ln \frac{Y_t}{L_t} = \frac{1 - \alpha}{\alpha} \Delta \ln (1 - \tau_t) + \frac{\Delta \ln A_t}{\alpha} - \frac{1 - \alpha}{\alpha} \Delta \ln \rho_t. \tag{12}
\]

This equation has the same implications as the traditional Ramsey/Solow model, where economies are only growing in steady states due to technological progress, persistent changes in savings rates, as reflected in \(\rho\), and persistent changes in corporate tax rates. Since \(\rho\) and \(\tau\) cannot permanently change in one direction, it follows that steady state growth that is not related to technological progress can only last for a limited period of time. The technology parameter \(\alpha\) may or may not be constant outside steady states. However, if the productivity and price neutrality conditions in the natural rate of unemployment framework are adapted, labour’s income share is constant in a steady state and \(\alpha\) can be treated as a constant.

A key element in equation (12) is that technological progress has an impact of \(1/\alpha\), or about 1.5 times as much, on labour productivity growth as it does in the traditional growth accounting framework because of the TFP-induced capital deepening process. An unexpected increase in TFP leads to an increase in the capitalised profits per unit of capital and, therefore, to higher stock prices as reflected in Tobin’s \(q\), as can be seen from the asset market equilibrium condition (5), which, in steady state, can be written as the following dividend-discount model:
\[ q_t = \frac{(1 - \tau_t)MP_{K,t} - \delta}{\rho_t}. \]

This model is probably the most used stock valuation model in finance (see, for instance, Fama and French, 2002)\(^1\), which is surprising given that the numerator is endogenous and automatically adjusts until it equals the denominator: an increase in TFP brings \( q \) above its steady state value of 1 and initiates a capital deepening process, because the expected earnings per unit of capital exceed the required stock returns, \( \rho \). The capital deepening terminates when the earnings of an additional unit of capital approaches the required stock returns.

Since the subjective discount factor is assumed constant and taxes are usually excluded from the Ramsey/Solow model, it follows that all growth is due to TFP growth in steady state. However, it is unlikely that the required stock returns have been constant over the past 135 years in the industrialised countries. The finance literature theoretically and empirically finds the required stock returns to be time-varying (see, for example, Blanchard, 1993, Cochrane, 2001, Fama and French, 2002, and Lucas and Heaton, 1999). Lucas and Heaton (1999) show theoretically that expected returns depend on market participation and Campbell and Cochrane (1999) show that expected stock returns are countercyclical because of habit formation in consumption. Empirically, Fama and French (2002) argue that expected stock returns decreased substantially during the 20th century, and thus were a factor that contributed to the capital-deepening in the same period.

### 2.3 Diagrammatic exposition

To illustrate in a phase diagram the dynamic adjustment of the \( K/L \) ratio to changes in the exogenous factors given by (10), it is necessary to reduce the dynamic systems (5)-(7) to a two-equation system consisting of (5) and (6). In other words, the required returns are assumed to be equal to the subjective discount rate in the transition towards the steady state. Solving (5), (6) and (9) yields the following simultaneous first-order differential systems:

\[ \dot{q}_t = \rho_t q_t - (1 - \tau_t)(1 - \alpha)A_t(L_t / K_t)^a, \]

\[ \dot{K}_t = h[(q_t - 1)/(1 - \tau_t)], \]

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\(^1\) The numerator is after-tax earnings per share and \( q \) is measured as the stock price in traditional stock valuation models. Thus, Tobin’s \( q \) model is a dividend-discount model that is normalised by capital stock.
where the depreciation rate is set equal to zero and the required stock return is equal to the subjective discount rate. The dynamics of the system are displayed in Figure 1. The \( \dot{Q} = 0 \) curve slopes downwards due to diminishing returns to capital.

**Figure 1. Dynamics of \( q \) and \( K \)**

The position of the \( \dot{K} = 0 \) line is unaffected by any exogenous shock in this model. For example, consider a reduction in required stock returns. This shifts the \( \dot{q} = 0 \) curve to the right. The stock market jumps to point \( A \), because profits are discounted at a lower rate. The higher stock prices initiate a capital deepening process and the economy moves along the stable manifold until a new steady state is reached at point \( E' \), where the after-tax returns to capital equal the required stock returns. Similarly, a TFP-induced increase in expected earnings per unit of capital, or a reduction of the corporate tax rate, shifts the \( \dot{q} = 0 \) curve to the right and stock prices jump to point \( A \) to capitalise on higher expected earnings and follow the new stable manifold towards a new steady state. The key issue here is that the \( K/L \) ratio is determined entirely by \( A, \rho \) and \( \tau \), and that the stock market is the transmitter. Thus, capital accumulation in the private sector must be explained by one of these variables. \(^2\)

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\(^2\) For an extension of the model, which allows for investment tax credits and depreciation for tax purposes, see Summers (1981).
3 The historical path of TFP, \( \rho \) and \( Y/L \)

In this section, estimates of \( A \) and \( \rho \) are presented and compared to labour productivity growth for 16 industrialised countries over the past 135 years.

3.1 The required stock returns

Like the Ramsey/Solow model, the model in this paper has only one discount rate since uncertainty is ruled out in the specification of the utility function. In the absence of uncertainty, there is no distinction between assets of different risk classes. However, in the model in this paper, the relevant discount rate is the required stock returns, because exogenous shocks are transmitted to capital by the stock market and the bond market plays no role. In the new finance theory, returns to an asset are determined by idiosyncratic factors and the interaction between stock returns and consumption growth following the consumption capital asset pricing model CCAPM. Unlike the traditional CAPM, returns to other assets are irrelevant for stock returns in the CCAPM (see, for example, Cochrane, 2001). Thus, the discount rate on bonds is irrelevant in the present context.\(^3\)

Unfortunately, expected stock returns cannot be directly measured. A common approach for recovering expected stock returns is to use Gordon’s growth model, or its dynamic counterpart, where the expected or required share returns are equal to the expected dividend price ratio plus the expected growth in dividends or earnings per share, as shown in the previous section (Blanchard, 1993, Fama and French, 2002). Fama and French (2002) use average historical growth in dividends as the relevant measure of expected dividend growth, whereas Blanchard (1993) uses the conditional forecast of dividend growth to recover the expected returns to equity. There are several problems associated with these approaches: publicised composite stock indices cover only a subset of the economy, long historical data are not available for many countries, and identifying assumptions about information sets used by investors when they form expectations are required. To overcome the difficulties that are associated with estimation of expected growth in dividends, this paper uses the principle that stock holders set the required returns and firms, working in the interests of stockholders, invest until the after-tax returns to capital equals the required stock returns, to identify expected returns.

Solving (8) and (9) yields the steady-state required stock returns as follows:

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\(^3\) This result can be generated by the model above by allowing for a stochastic discount factor in the utility function. However, since the focus of this paper is not on the returns to various assets, the deterministic model is adopted.
\[ \rho_i = (1 - \alpha_i)(1 - \tau_i)(Y_i / K_i) - \delta_i, \]  
\[ \tag{13} \]

where subscript \( i \) signifies country \( i \). Here the depreciation rate is allowed to vary over time and across countries and factor shares are allowed to vary across countries but are fixed over time. The depreciation rate is fixed for each category of capital stock, but is allowed to vary as the composition of capital stock changes, as detailed below. The principle behind this equation is that firms invest in fixed capital until the after-tax earnings per unit of capital are equal to the returns required by stockholders. Thus, provided that firms follow Tobin’s \( q \) in their investment decisions, the after-tax expected returns of new investment projects are determined entirely by the returns required by stockholders.

The data used to estimate (13) are collected from various national and international sources for the following 16 industrialised nations, for which the data needed to compute TFP are available since 1870: Canada, the USA, Japan, Australia, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland and the UK. These countries henceforth are referred to as the G16 countries. The data construction and data sources are detailed in the data appendix. Labour’s share of total income, \( \alpha_i \), is estimated as the ratio of compensation to employees divided by nominal GDP for each country averaged over the period in which data are available back in history. The wage income of the self-employed is imputed into the estimates to allow for the fact that labour of the self-employed is recorded as profit income in national accounts. Income is measured as the economy-wide GDP. The corporate tax rate is measured as corporate taxes divided by net operating surplus. The stock of fixed capital is measured as the sum of machinery and equipment capital and non-residential building and structures capital stock using the perpetual inventory method, with depreciation rates of 17.6% and 3%, respectively.

The time-varying aggregated depreciation rate is computed as:

\[ \delta_i = \delta^M \frac{K^M_i}{K^M_i + K^B_i} + \delta^B \frac{K^B_i}{K^M_i + K^B_i}, \]  
\[ \tag{14} \]

where the superscripts \( M \) and \( B \) refer to machinery and equipment capital and non-residential building and structures, respectively. This time-varying depreciation rate acknowledges that the ratio between machinery and equipment capital and total non-residential capital stock has increased substantially since 1870 and, consequently, driven up the composite depreciation rate.

Finally, the required returns are adjusted to an average of 7% for each individual country, following the estimates of average real stock returns over the past century by Dimson, Elroy, Marsh and
Staunton (2004). The stock returns are assumed constant across countries, since Dimson et al. (2004) found them to vary little across countries. Note that *ex post* stock returns can be used for *ex ante* stock returns in the long run since, in the $q$ model, firms adjust the capital stock to a level where the realised returns equal the required stock returns. The *ex post* stock returns adjustment is undertaken because $(1-\alpha)$, $(1-\tau)$ and $Y/K$, and consequently $\rho$, are biased upward. The adjustment is important because the share of income going to capital in national accounts includes interest payments on bonds, which are not relevant for stock returns, and because $Y$ includes imputed housing rent, whereas $K$ does not include residential capital stock.

![Figure 2. Required Stock Returns, G16](image)

**Note.** The estimates are based on (13). The data are adjusted to an average of 7% in the entire period for all countries. The average required returns are an unweighted average.

Figure 2 displays estimates of $\rho$ for each G6 country and for the G16 economies on average. Common to all the countries, including the countries that are not displayed in Figure 2, is that $\rho$ has declined during the past 135 years. The decline in $\rho$ is particularly pronounced during the periods from 1870 to 1913 and from 1955 to 1975, during which $\rho$ declined by more than a third. Not surprisingly, the decline in $\rho$ coincided with a marked increase in investment activity, which suggests that $\rho$-induced capital deepening may have played an important role for labour productivity growth in these two periods.

The long decline in the required stock returns has also been noted in the financial literature (see, for example, Blanchard, 1993, and Fama and French, 2002). It is not entirely clear, however, which factors were responsible for the decline. Since $Y/K$ tends to be high for low-income countries (Mankiw, Romer and Weil, 1992, Mankiw, 1995) and declines as the economy develops, as shown, for example, by Hsieh (2002) for the Asian Tigers, $\rho$ is likely to depend on the stage of development of the economy.
The indexes of total factor productivity relative to the USA in 1950 are constructed as:

\[
\frac{TFP_{i,1950,US}}{TFP_{1950,US}} = \frac{Y_{i,1950,US}}{Y_{1950,US}} \left( \frac{K_{i,1950,US}}{K_{1950,US}} \right)^{\alpha_i} \left( \frac{L_{i,1950,US}}{L_{1950,US}} \right)^{\alpha_0}, \quad i = 1, 2, \ldots, 16
\]

where \( \alpha_i \) is the average of labour’s income share in the USA and country \( i \). Labour inputs are measured as total employment multiplied by annual hours worked per worker. Since the annual hours worked have almost halved for most of the countries over the past century, the hours adjustment is crucial. Output and capital are measured in purchasing power parities (Geary-Khamis dollars).

Figure 3 shows the log of TFP over the past 135 years for the G16, as an unweighted average, and for the G6 countries individually. Three periods in which the average TFP growth trend differs can be distinguished: 1870-1950, 1950-1973 and 1973-2004. The figure confirms the well-known fact that the USA took over for the UK as the world leader in the beginning of the 20th century. What is a less well-known fact is that Germany and France took over as world leaders around 1990, strongly influenced by reduced working hours in Europe and increasing number of people in the working age on public transfer payments. Another interesting feature that can be seen in the figure is that Japan does not appear to be the growth miracle it, until recently, was supposed to be. Its exceptionally high TFP growth during the period...
from 1915 to 1970 was rather a catch-up from extraordinarily poor growth performance in the 1870-1915 period, and growth since 1970 has been below the average growth rate of the G16 countries. Japan today is the country with the lowest level of TFP among the G16 countries. In 2004, it was 37% below the world leader (France) and 15% below Australia, which was the second lowest in the G16 sample.

3.3 Labour productivity
Figures 2 and 3 suggest that TFP growth and reductions in required stock returns have contributed to labour productivity advances in the G16 countries. The question is whether the paths of TFP and $\rho$ are consistent with the $Y/L$ path. Figure 4 shows the well-known fact that labour productivity has been trending upwards over the past 135 years and has tended to converge across countries. As with TFP, the USA was the world leader for most of the last century, but recently was overtaken by France, particularly, and Germany. Considering the average labour productivity growth trend, the following periods can be distinguished: 1870-1950, 1950-1973 and 1973-2004.

For individual countries, the findings presented in Figures 3 are 4 are not always consistent with the prediction of economic growth models that labour productivity is TFP-induced in the long run, which suggests, at least in a first approximation, that factors other than TFP have influenced labour productivity growth. Consider, for example, Japan, which had a labour productivity growth above the G16 average prior to WWII and yet TFP only increased modestly during the same period. The marked decline in the
required stock returns during the period from 1870 to WWI in Japan may have accounted for the TFP/labour productivity growth discrepancy in the same period. Similarly, TFP growth in the UK was stagnant until the Great Depression and yet the UK experienced a steady increase in labour productivity during the same period, which, to some extent, can be attributed to declining required returns. Finally, labour productivity in France has followed the G16 average, whereas its TFP growth has been above the G16 average during the entire period. This is consistent with the path in the required returns for France relative to the G16 average. Considering the whole time-span 1870-2004, the required returns almost have not declined in France, but decreased from 12% to less than 5% for the average G16 country.

Overall, the figures indicate that TFP potentially explains the lion’s share of the labour productivity advances over the past 135 years, but the decline in required returns may have played a role, particularly during the latter part of the 19th century and the first two decades following WWII.

4 Empirical estimates

The theoretical section raised two questions that need to be addressed before growth accounting exercises can be carried out. The first is whether TFP alone, or jointly with after-tax returns to fixed capital, can explain labour productivity over the past 135 years. The second question is whether the $K/L$ ratio can be explained by TFP and $\rho$.

4.1 Is labour productivity explained entirely by TFP in the long run?

To investigate the factors that have been responsible for the long-run path in labour productivity, the following cointegration regressions (stochastic level counterpart of (12)) are estimated by pooling the data across the 16 countries considered in this paper:

$$\ln(Y/L) = \beta_0 + \beta_1 \ln TFP_n + \beta_2 \ln \rho_n + TD + CD + \epsilon_{\alpha,1},$$

where TD is time dummies, CD is fixed effect dummies and $\epsilon$ is a stochastic error term. This follows the model given by (12) $\beta_1 = \alpha^{-1}$, or approximately 1.5, and $\beta_2 = (\alpha - 1)/\alpha$, or approximately -1/3. Time-dummies are included in the estimates to allow for the influence of potentially important omitted variables that change at the same rate across countries. The required stock returns are estimated from (14). Restricted and unrestricted versions of (15) are estimated. Caution has to be exercised in the estimates where $\rho$ is included as a regressor because the computations of $\rho$ are based on the $Y/K$ ratio. In the extreme case where $\tau$ and $\delta$ are approximately constants, the identifying variance in $\rho$ comes
from the variance in $Y/K$ and, consequently, $\beta_2$ will be biased towards $(\alpha-1)/\alpha$ because an identity is being estimated approximately.

Equation (15) is estimated using the dynamic least squares estimator of Stock and Watson (1993), where the first-differences of one-period lags and leads and concurrent values of the explanatory variables are included as additional regressors to capture the dynamic path around the long-run equilibrium. The advantage of using this estimator over the OLS estimator is that it possesses an asymptotic normal distribution and, therefore, the associated standard errors allow for valid calculations of $t$-tests, and this, in contrast to the OLS estimator, yields unbiased coefficient estimates in panels (Kao and Chiang, 2000). The Dickey-Fuller test for panel cointegration, which is derived by Kao (1999), is used to test for cointegration.

The results of estimating restricted and unrestricted versions of (15) are presented in Table 1. First, consider the estimates in the first column, where $\rho$ and the time-dummies are excluded from the estimates to investigate whether labour productivity growth in the long run can be explained by TFP. The estimated coefficient of TFP is 1.71 or an implied labour income share of 0.58, which is only slightly below the average of 0.62 for the countries in the sample used here. However, the null hypothesis of unit root in the residuals cannot be rejected at any conventional significance level indicating that important variables are omitted from the estimates. Adding time-dummies to the estimates, as shown in the second column, renders it even more difficult to reject the null hypothesis of unit root. Furthermore, the estimated coefficient of TFP is reduced to 1.12, which is well below the predictions of the model and, therefore, suggests that important variables have been omitted from the estimates.

Including $\rho$ and TFP as regressors, but no time-dummies, yields the estimates in the third column in Table 1. The coefficients of TFP and $\rho$ are statistically highly significant and they have the sign and magnitude as predicted by the theory. Furthermore, the null hypothesis of unit root is strongly rejected at any conventional significance level, which suggests that there is a long-run relationship between labour productivity, $\rho$ and TFP. The results support the theory that TFP plays a more important role in the long run than implied by conventional growth accounting exercises where the coefficient of one is attached to TFP growth. Adding time-dummies to the model in column 3 yields the estimates in the last column. The null hypothesis of unit root is still strongly rejected. However, the absolute size of the coefficient estimates of TFP and $\rho$ were reduced by the inclusion of the time-dummies, which suggests omitted variables. The significance of the time-dummies is discussed in the next sub-section.
Table 1. Restricted and unrestricted cointegration estimates (Equation (15)).

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFP_t</td>
<td>1.71(25.1)</td>
<td>1.12(4.39)</td>
<td>1.59(114.0)</td>
<td>1.39(28.6)</td>
</tr>
<tr>
<td>ρ</td>
<td>-1.56(22.0)</td>
<td>-1.40(16.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{R}^2$</td>
<td>0.96</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>$DF_λ$</td>
<td>1.42[0.92]</td>
<td>3.01[1.00]</td>
<td>-48.6[0.00]</td>
<td>-41.9[0.00]</td>
</tr>
<tr>
<td>TD</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Notes. The numbers in parentheses are absolute t-statistics. The numbers in brackets are p-values. $\bar{R}^2$ = adjusted $R^2$ and TD = Time-dummies. The estimates are based on the dynamic OLS method, and the t-statistics are corrected for autocorrelation following the method suggested by Stock and Watson (1993). $DF_λ$ is Kao’s (1999) panel Dickey-Fuller test for cointegration, distributed as $N(0,1)$ under the null hypothesis of no cointegration. Constants and country-dummies are included in the regressions but are not shown. The models are estimated for the periods 1872-2002 for the G16 countries.

4.2 Is the $K/L$ ratio explained by TFP and $ρ$ in the long run?

To investigate the relationship between the $K/L$ ratio, TFP and $ρ$, the stochastic counterpart of (10) is estimated using the same method and data as in the estimates above:

$$\ln(K/L)_t = \phi_0 + \phi_1 \ln TFP_t + \phi_2 \ln ρ_t + TD + CD + \epsilon_{it,2},$$  \hspace{1cm} (16)

Following the model given by (10), $\phi_1 = \alpha^{-1}$, or approximately 1.5, and $\phi_2 = -\alpha^{-1}$, or approximately -1.5. The estimation results are presented in Table 2.

Table 2. Restricted and unrestricted cointegration estimates (Equation (16)).

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFP_t</td>
<td>1.61(55.1)</td>
<td>1.07(10.8)</td>
</tr>
<tr>
<td>ρ</td>
<td>-3.88(26.1)</td>
<td>-3.44(20.4)</td>
</tr>
<tr>
<td>$\bar{R}^2$</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>$DF_λ$</td>
<td>-55.4[0.00]</td>
<td>-48.7[0.00]</td>
</tr>
<tr>
<td>TD</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Notes. See notes to Table 1.

The results presented in Table 2 show that there is a strong cointegrating relationship between capital deepening, TFP and $ρ$, regardless of whether time-dummies are included in the estimates. The estimated
coefficients of TFP are close to the model predictions when time-dummies are excluded and below the model predictions when time-dummies are included in the estimates. The estimated coefficients of $\rho$ are substantially more negative than are the model predictions, regardless of whether time-dummies are included in the estimates.

The reduction in the estimated coefficient of TFP from 1.6 to 1.1 when time-dummies are included in the estimates suggests that important variables, which change at the same rate across countries, are omitted from the estimates. To investigate the significance of the time-dummies for capital deepening, Figure 5 displays the estimated coefficients of the time-dummies normalised to zero in 1872. The estimated coefficients of the time-dummies from the $Y/L$ estimates from the fourth column in Table 1 are also displayed in the figure. The time-dummies show a moderate increase up to circa 1950, but take an upward turn during the 1950-1980 period and increase slowly thereafter. The 1950-1980 upturn is particularly remarkable in the $K/L$ estimates, where the time-dummies contributed to an approximately 60% increase in the $K/L$ ratio. Since the $K/L$ ratio tripled in this period, it follows that the time-dummies accounted for almost a third of the increase in the $K/L$ ratio during this period. In the 130-year period during which the time-dummies span, they contribute to a 133% increase in the $K/L$ ratio, which is a marginal contribution when one considers that the $K/L$ ratio increased 52 times for the average G16 country during this period. The time-dummies contribute less than half of the magnitude of the increase in the $Y/L$ ratio in the entire time-span considered in Figure 5.

**Figure 5. Time-Dummy Estimates**

![Time-Dummy Estimates](image)

**Notes.** The estimated coefficients of the time-dummies are from the estimates in the fourth column in Table 1 and the second column in Table 2. The estimates are normalised to zero in 1872.
In sum, the estimates indicate that TFP and $\rho$ account for almost all of the increase in the $Y/L$ and $K/L$ ratios over the past 135 years. The increasing importance of the time-dummies during the 1950-1980 period suggests that important variables that increased at the same rate across countries have been omitted from the models. These omitted variables could be unmeasured technological advances or introductions of tax-laws that have made investment more attractive.

4.3 Granger causality

The cointegration estimates above do not reveal anything about causality and, in the most extreme case, that TFP has been driven by the $K/L$ ratio and not *vice versa*. Gordon (2000), for example, argues that investment contains new technology and, as such, advances the knowledge of the society. If sources other than advances in TFP have initially enhanced investment that has brought with it more advanced technological knowledge, it is the capital deepening that has been responsible for the increase in TFP, and not the other way around. To examine the causality issue, Granger causality tests are conducted in this section. Although Granger causality tests cannot reveal anything about causality, they can indicate whether TFP precedes the $K/L$ ratio as predicted by the model in the theoretical section, where TFP leads to capital deepening with an adjustment period that is predominantly determined by the shape of the adjustment cost function. If this adjustment is the route of adjustment, it should be reflected in the Granger causality tests.

The following equation is estimated for the G16 countries:

$$\Delta \ln y_{it} = \varphi_0 + \varphi_1 \sum_{j=1}^{5} \Delta \ln y_{i,t-j} + \varphi_2 \sum_{j=1}^{5} \Delta \ln x_{i,t-j} + \epsilon_{it,j}$$

where $\Delta$ is a five-year difference operator and $x$ and $y$ are TFP and $K/L$. The equation is estimated for the period from 1895 to 2004 since lags and five-year differences prevent longer estimation periods. Four-year differences are used for the last observation. The 1945 and 1950 observations are omitted from the estimates because of the extreme variations in the variables during these periods. Five-year differences are used to filter out influences from the business-cycle. The same approach and the same length of the first-differences have been used by Blomstrom, Lipsey and Zejan (1996) to examine “causality” between productivity growth and investment.

The model is estimated by OLS or, more correctly, feasible GLS. To gain efficiency, the model is also estimated allowing for the correlation of the error-terms between countries. The covariance matrix is weighted by the correlation of the disturbance terms using the following variance-covariance structure:
\[ E\{\varepsilon_i^2\} = \sigma_i^2, \quad i = 1, 2, ..., N, \]
\[ E\{\varepsilon_i, \varepsilon_j\} = \sigma_{ij}, \quad i \neq j, \]
\[ \varepsilon_{it} = \phi \varepsilon_{i,t-1} + v_{it}, \]

where \( \sigma_i^2 \) is the variance of the disturbance terms for country \( i = 1, 2, ..., N \), \( \sigma_{ij} \) is the covariance of the disturbance terms across countries \( i \) and \( j \), and \( \varepsilon \) and \( v \) are disturbance terms. The variance \( \sigma_i^2 \) is assumed to be constant over time but to vary across countries and the error terms are assumed to be mutually correlated across countries, \( \sigma_{ij} \), as random shocks are likely to impact all countries at the same time. The parameters \( \sigma_i^2, \sigma_{ij} \) and \( \phi \) are estimated using feasible generalised least squares.

**Table 3.** Granger causality tests.

<table>
<thead>
<tr>
<th>Estimator</th>
<th>Dep. var. (( y_t ))</th>
<th>Ind. var. (( x_t ))</th>
<th>( \sum x )</th>
<th>( \sum y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>TFP</td>
<td>( K/L )</td>
<td>-0.01(1.33)</td>
<td>0.70(46.2)</td>
</tr>
<tr>
<td>System</td>
<td>( K/L )</td>
<td>TFP</td>
<td>0.05(13.3)</td>
<td>0.95(325)</td>
</tr>
<tr>
<td>OLS</td>
<td>TFP</td>
<td>( K/L )</td>
<td>-0.01(0.70)</td>
<td>0.72(23.3)</td>
</tr>
<tr>
<td>OLS</td>
<td>( K/L )</td>
<td>TFP</td>
<td>0.05(3.43)</td>
<td>0.95(89.5)</td>
</tr>
</tbody>
</table>

**Notes.** The numbers in parentheses are absolute \( t \)-statistics. The system estimator accounts for the mutual correlation between the disturbance terms, whereas the OLS estimator does not. Both estimators allow for first-order serial correlation and cross-country heteroscedasticity. The models are estimated for the period 1895-2004 (with 1945 and 1950 omitted) for the G16.

The results of the Granger causality tests are shown in Table 3. The estimates in the first row indicate that TFP is unaffected by past \( K/L \) ratios, whereas the estimates in the second row show a strong link between the \( K/L \) ratio and past TFP-innovations. The OLS estimates in the bottom two rows support the conclusion drawn from the system estimates, namely that there is, unambiguously, a one-way relationship from TFP to \( K/L \).

The results in Table 3 are also interesting from a growth accounting perspective, because the estimated long-run TFP elasticity of capital deepening is one, which suggests that the \( K/L \) ratio, to a large extent, has adjusted to TFP innovations within the 25-year time-span considered in the estimates, recognising that any contemporaneous influence of TFP on \( K/L \) has been ruled out by the tests. The practical implication of this result is that the contribution of capital deepening to economic growth in standard growth accounting exercises covering long time intervals is exaggerated.
5 Growth accounting

Estimates from a standard growth accounting exercise in this section are compared to growth accounting for which the $K/L$ ratio is assumed to have fully adjusted to innovations in TFP and $\rho$. These two exercises epitomise extremes in the sense that capital is assumed either to adjust instantaneously or not to adjust at all, to innovations in TFP and $\rho$. The following four periods are considered: 1870-1890, 1890-1950, 1950-1973 and 1973-2004. The 1870-1950 period is split into two periods, since $\rho$ declined significantly during the 1870-1890 period. In the estimates for which the endogeneity bias is allowed, the coefficients of TFP and $\rho$ are attached the values of 1.5 and -1.5, respectively, which are compromise estimates displayed in columns 3 and 4 in Table 1.

The growth accounting results are displayed in Table 4, where standard growth accounting decomposition is displayed in columns 2 and 3 ("A" section) and extended growth accounting, where productivity growth is decomposed to TFP growth, changes in required stock returns and a residual ("B" section, columns 4-6). Estimates are presented for the G6 countries individually, and G16 as an unweighted average, due to space limitations. The figures for G16, at the bottom of the table, on average show that traditional growth accounting gives only slightly more weight to TFP than it does to $K/L$ as sources of growth in all periods. From this, one would conclude that almost half of the growth in the G16 countries is savings-initiated capital accumulation. When the endogeneity of $K/L$ is allowed for, TFP explains about ¾ and $\rho$ about 1/8 of labour productivity growth during the 1871-2004 period. Less than 10% of the labour productivity growth remains unexplained.

Table 3. Growth decomposition.

<table>
<thead>
<tr>
<th>Country</th>
<th>Period</th>
<th>Actual $Y/L$</th>
<th>$\Delta$ TFP</th>
<th>$\Delta K/L$</th>
<th>$\Delta$ TFP</th>
<th>$\Delta$ $\rho$</th>
<th>$\Delta$ Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>1871-1890</td>
<td>1.64</td>
<td>0.46</td>
<td>1.18</td>
<td>0.69</td>
<td>0.53</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>1890-1950</td>
<td>2.24</td>
<td>1.66</td>
<td>0.58</td>
<td>2.49</td>
<td>-0.12</td>
<td>-0.12</td>
</tr>
<tr>
<td></td>
<td>1950-1973</td>
<td>2.46</td>
<td>1.27</td>
<td>1.19</td>
<td>1.91</td>
<td>0.32</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>1973-2004</td>
<td>1.56</td>
<td>0.76</td>
<td>0.81</td>
<td>1.13</td>
<td>0.24</td>
<td>0.18</td>
</tr>
<tr>
<td>Jap</td>
<td>1871-1890</td>
<td>1.62</td>
<td>-0.02</td>
<td>1.65</td>
<td>-0.04</td>
<td>2.83</td>
<td>-1.16</td>
</tr>
<tr>
<td></td>
<td>1890-1950</td>
<td>2.41</td>
<td>0.27</td>
<td>2.14</td>
<td>0.40</td>
<td>1.18</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>1950-1973</td>
<td>6.94</td>
<td>5.17</td>
<td>1.77</td>
<td>7.75</td>
<td>-0.15</td>
<td>-0.66</td>
</tr>
<tr>
<td></td>
<td>1973-2004</td>
<td>2.82</td>
<td>0.91</td>
<td>1.91</td>
<td>1.36</td>
<td>0.49</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Regardless of which accounting method is used, TFP explains the lion’s share of labour productivity growth in the 1950-1973 period for the G16 countries on average. Outside this high growth period, the contribution of TFP to labour productivity growth is sensitive to the chosen growth accounting method. For the individual countries, there is also a tendency for high labour productivity growth to be related to high TFP growth. Therefore, the high growth periods in modern history in the industrialised countries have been associated with strong TFP advances.

Japan is a remarkable case. Its exceptionally high labour productivity growth during the 1950-1973 period is predominantly TFP-induced according to traditional growth accounting and due entirely to TFP growth when the endogeneity of capital is accounted for. By contrast, TFP played a modest role for Japan before 1950. The average 1.62% labour productivity growth in the 1871-90 period was due to a significant capital deepening initiated by a marked reduction in the required stock returns and, as such, a result of increasing savings propensity. Discount rate induced capital deepening remained an important

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Fra</td>
<td>1.92</td>
<td>1.72</td>
<td>4.68</td>
<td>2.71</td>
</tr>
<tr>
<td></td>
<td>1.47</td>
<td>1.30</td>
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</tr>
<tr>
<td></td>
<td>0.45</td>
<td>0.42</td>
<td>2.03</td>
<td>1.23</td>
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<td></td>
<td>2.20</td>
<td>3.98</td>
<td>0.20</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>-0.18</td>
<td>-0.18</td>
<td>0.36</td>
<td>0.29</td>
</tr>
<tr>
<td>Ger</td>
<td>1.10</td>
<td>1.17</td>
<td>6.44</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>0.61</td>
<td>4.57</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>0.97</td>
<td>0.56</td>
<td>1.86</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>0.92</td>
<td>6.86</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>0.78</td>
<td>0.12</td>
<td>-0.45</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.12</td>
<td>0.03</td>
<td>0.50</td>
</tr>
<tr>
<td>Itl</td>
<td>0.59</td>
<td>2.05</td>
<td>5.28</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
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<td>1.10</td>
<td>3.10</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
<td>0.95</td>
<td>2.17</td>
<td>0.80</td>
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<td>1.66</td>
<td>4.66</td>
<td>1.90</td>
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<td></td>
<td>0.10</td>
<td>0.16</td>
<td>-0.27</td>
<td>0.13</td>
</tr>
<tr>
<td>UK</td>
<td>0.50</td>
<td>0.90</td>
<td>2.86</td>
<td>2.32</td>
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<td>0.40</td>
<td>0.95</td>
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</tr>
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<td></td>
<td>-0.09</td>
<td>0.61</td>
<td>1.43</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td>0.18</td>
<td>0.97</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>-0.13</td>
<td>0.46</td>
<td>0.46</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Notes. The A-columns are generated from standard growth accounting and the B-columns are created from endogenous growth accounting. The figures are annualised arithmetic means.
impetus to growth in the 1890-1950 period and TFP growth contributed only to 0.4% growth in labour productivity when instant adjustment in capital stock was allowed for.

6 Concluding remarks

Standard growth accounting exercises attribute capital-deepening to most of the 23-fold increase in labour productivity in industrialised countries since 1870, suggesting that capital investment has been an important impetus to the growth process. The empirical estimates in this paper challenge this conclusion and, to a large extent, confirm the predictions of growth theories that capital-deepening is driven by TFP, predominantly, and required stock returns. The estimates show the existence of significant cointegration relationships between labour productivity or capital deepening on the one hand, and TFP and required stock returns, on the other hand. These results are important because they show that labour productivity in the long run is related to TFP and required stock returns without any need to resort to the $K/L$ ratio. Furthermore, they show that the $K/L$ ratio is closely related to TFP and the required stock returns in the long run. The cointegration results give strong support to the predictions of economic growth models.

The cointegration estimates provide no information about causality and do not rule out the extreme case where advances in TFP are caused entirely by increases in the $K/L$ ratio and, therefore, that TFP has just acted as a proxy for the $K/L$ ratio in the regressions. Endogeneity of TFP was ruled out by Granger causality tests that give strong support to the hypothesis that TFP precedes the $K/L$ ratio and the absence of any feedback effects from the $K/L$ ratio to TFP. From these results it can be concluded that the $K/L$ ratio is endogenous and that standard growth accounting exercises can only be used for relatively limited time intervals and for which it can be assumed, with confidence, that the $K/L$ ratio has not significantly adjusted to innovations in TFP.
REFERENCES


DATA APPENDIX


Labour’s share. Is calculated as the economy-wide compensation to employees plus imputed compensation to self-employed divided by nominal GDP. The imputed compensation to employees is computed as the number of self-employed multiplied by economy-wide compensation to employees
divided by economy-wide employment. The output elasticities of inputs are computed from the average factor shares using data up to 2002. The following starting dates are used (in parentheses): Canada (1926), USA, (1899), Japan (1906), Australia (1870), Belgium (1950), Denmark (1900), Finland (1870), France (1920), Germany (1870), Italy (1950), Netherlands (1870), Norway (1930), Spain (1950), Sweden (1870), Switzerland (1950) and UK (1870). OECD National Accounts are used for the post-1950 data.