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

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Abstract:

Based on an asset pricing model this paper shows that traditional growth accounting exercises attribute too much weight to capital deepening and suggests a method to filter out TFP-induced capital-deepening from the estimates. Using data for 16 industrialised countries, it is shown that labour productivity and capital deepening have been driven by total factor productivity and reductions in the required stock returns over the past 137 years. Furthermore, it is shown that TFP precedes the *K-L* ratio and not the other way around.

JEL classification: E0, E2, O47.

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

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1 Introduction

Growth accounting is often used to examine sources of economic growth (see for example Bosworth and Collins, 2008). Broadly, the sources of growth are of capital deepening and total factor productivity (TFP) growth. Growth accounting exercises have particularly been popular for countries that have experienced growth spurts such as the Asian Tigers, India, China and Germany and Japan in the 1950 and 1960s. In an influential article Young (1995) found that only a fraction of the impressive growth rates among the Asian Tigers was a result of TFP. Consequently, their growth rates were not as miraculous as often thought and growth rates would converge to ordinary growth rates as experienced in other countries as soon as the investment-induced growth effects ceased.

Unfortunately, growth accounting exercises run into a 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 Aghion and Howitt (2007), Barro (1999), Helpman (2004), Klenow and Rodriguez-Clare (1997), Prescott (1998), and Barro and Sala-i-Martin (1995). However, the literature has not shown whether an endogeneity bias prevails empirically and has not given intuitive explanations for the endogeneity bias. It is generally just mentioned that all growth is a result of technological progress along a balanced growth path. An exception is Klenow and Rodriguez-Clare (1997) who argue that productivity advances increase the marginal productivity of capital; thus, stimulating investment and capital accumulation.

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, it highlights factors that are responsible for the advances in labour productivity quite independently of TFP changes.

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 to capital deepening. Panel cointegration estimates are undertaken to test for cointegrating relationships between labour productivity or the capital-labour ratio and TFP. 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/L* ratio. These results support the predictions of economic growth models that capital deepening is a result of technological progress along the balanced growth path. Furthermore, the estimates show that most of the adjustment of capital stock to TFP-innovations occurs within a decade. This result implies that the endogeneity issue is serious even in growth accounting exercises that cover a relatively short period.

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 required stock returns for 16 industrialised countries over the past 137 years. Section 4 examines the quality of the data by comparing the data with that available from other sources at 10-year intervals. Section 5 tests whether the endogeneity prediction of economic growth models holds. The empirical estimates are used to account for growth in labour productivity in the industrialised countries over the past 137 years and are compared to the results from traditional growth accounting exercises in Section 6.

2 The endogeneity bias in growth accounting

To show the endogeneity problem associated with growth accounting exercises formally and intuitively, a Tobin's *q* model is used 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:

$$\max \Pi = \int_{t=0}^{\infty} e^{-\int_{v=0}^{t} r_v dv} \left[(1-\tau)_t \{ F(A_t, L_t, K_t) - L_t W_t - I_t \phi(I_t / K_t) \} - I_t \right] dt$$

st.

$$\dot{K}_{t+1} = I_t - \delta K_t ,$$

where Π is real profits, K is capital stock, I is gross investment, W is the real wage, L is labour services, r is the required returns to equity, $I_t \phi(I_t / K_t)$ is convex adjustment cost of investment, δ is the rate of capital depreciation, τ 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:

$$(1 - \tau_t)MP_{K,t} = (r_t + \delta)q_t - \dot{q}_t , \tag{1}$$
$$1 + \phi'(I_t)(1 - \tau_t) = q_t \tag{2}$$
$$\lim_{t \to \infty} e^{-\int_{v=0}^{t} r_v dv} q_t K_t = 0 ,$$

where q is the shadow price of capital or Tobin's q, MP_K is the marginal productivity of capital, 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 (2) is the equilibrium condition in the market for fixed investment. For a given required return to equity and employment, eqs (1) and (2) determine capital stock and stock prices.

Consumers. The representative consumer has preferences ordered by:

$$maxU = \int_{t=0}^{\infty} \frac{C_t^{1-\theta} - 1}{1 - \theta} e^{-\rho_t t} dt ,$$

subject to the budget constraint:

$$\dot{a}_t = W_t + r_t a_t - C_t$$

where U is utility, a is per capita assets, ρ is a subjective discount rate, θ is the coefficient of relative risk aversion and C is per capita consumption.

A necessary and sufficient condition for an interior solution is:

$$\frac{\dot{C}_t}{C_t} = \frac{1}{\theta}(r_t - \rho_t - \dot{\rho}t).$$ (3)

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:

$$F(A_t, K_t, L_t) = C_t + I_t/(1-\tau_t) + I_t\phi(I_t/K_t).$$ (4)

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

$$\dot{q}_t = (r_t + \delta)q_t - (1-\tau_t)MP_{K,t},$$ (5)

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

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

where $h = (\phi')^{-1}$. 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:

$$(1-\tau_t)\partial F(A_t, K_t, 1)/\partial K_t - \delta = (1-\tau)MP_K - \delta = \rho_t.$$ (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 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:

$$Y_t = A_t L_t^{\alpha_t} K_t^{1-\alpha_t} . \tag{9}$$

Solving (8) and (9) and differentiating yields capital deepening as a function of exogenous variables:

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

where the depreciation rate is set to zero. In this equation, the K/L ratio is determined by 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 in response 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):

$$\Delta \ln(Y_t / L_t) = \Delta \ln A_t + (1-\alpha_t)\Delta \ln(K_t / L_t) , \tag{11}$$

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

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

This equation has the same implications as the traditional Ramsey/Solow model, where economies are only growing in steady state due to technological progress. Since ρ and τ 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 α may or may not be constant outside steady state.

A key element in (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 given by (5), which, in steady state, can be written as the following dividend-discount model:

$$q_t = \frac{(1-\tau)MP_{K,t} - \delta}{\rho_t}.$$

This model is probably the most used stock valuation model in finance (see, for instance, Fama and French, 2002)[‡], 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 and initiates a capital deepening process, because the expected earnings per unit of capital exceed the required stock returns, ρ. The capital deepening terminates when after-tax 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 137 years in 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 Heaton and Lucas, 1999). Heaton and Lucas (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 system (5)-(7) to a two-equation system consisting of eqs (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 eqs (5), (6) and (9) yields the following simultaneous first-order differential system:

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

[‡] 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 $\dot{Q}_t = 0$ curve slopes downwards due to diminishing returns to capital.

The position of the $\dot{K} = 0$ line is unaffected by any exogenous shock in this model. For example, consider an unexpected reduction in required stock returns. This shifts the $\dot{q} = 0$ curve to the right. The stock market jumps to the 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_1, 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 the 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, ρ and τ, and that the stock market is the transmitter. Thus, capital accumulation in the private sector must be explained by one of these variables.[§] This is important for growth accounting exercises because it shows that one cannot treat capital deepening as an independent process.

Figure 1. Dynamics of *q* and *K*

[§] For an extension of the model, which allows for investment tax credits and depreciation for tax purposes, see Summers (1981).
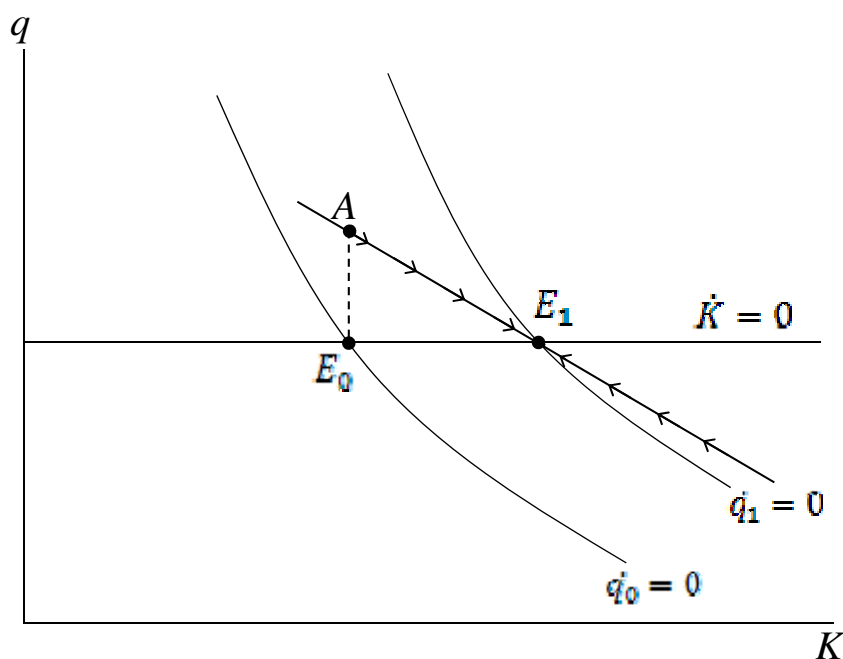
3 The historical path of TFP, ρ and Y/L

In this section, estimates of A and ρ are presented and compared to labour productivity growth for 16 industrialized countries over the past 137 years (1870-2006).

3.1 The time preference

Like the Ramsey/Solow model, the model in this paper has only one discount rate since uncertainty is ruled out in the model specification. 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.[**]

    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

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[**] 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.

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 equal the required stock returns.

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

$$\rho_{it} = (1 - \alpha_{it})(1 - \tau_{it})(Y_{it} / K_{it}) - \delta_{it}, \tag{13}$$

where subscript i signifies country i. Here, capital stock is measured as non-residential capital stock. All the variables and parameters in (13) are allowed to vary across countries and over time. The corporate tax rate is measured as corporate taxes divided by net operating surplus. 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. Labour's share of total income, α_{it}, is estimated as the ratio of compensation to employees divided by nominal GDP for manufacturing. The reason for this is discussed in Section 3.4.

The data used to estimate (13) are collected from various national and international sources for the following 16 industrialized 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. The quality of the data is analyzed in the next section. 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:

$$\delta_{it} = \delta^M \frac{K_{it}^M}{K_{it}^M + K_{it}^B} + \delta^B \frac{K_{it}^B}{K_{it}^M + K_{it}^B}, \tag{14}$$

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, has 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 *et al*. (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 realized returns equal the required stock returns (see Madsen and Davis, 2006). The *ex post* stock returns adjustment is undertaken because $(1-\tau)$, *Y/K* and consequently, ρ, are biased upward. This is 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*, as measured in this paper, does not include residential capital stock.

Figure 2 displays estimates of ρ for the G6 countries and the G16 economies on average. Common to all the countries, including the countries that are not displayed in Figure 2, is that ρ has declined during the past 137 years from 14% to 5% on average. The decline in ρ is particularly pronounced in the periods from 1870 to 1913 and from 1955 to 1975. These periods were characterized by high economic growth and macroeconomic stability. Not surprisingly, the decline in ρ coincided with a marked increase in investment activity, which suggests that ρ-induced capital deepening may have played an important role for labour productivity growth in these two periods. Remarkably, for France the required returns have fluctuated around a relatively constant level of approximately 7% and only lately recorded its first market decline to approximately 5%.

Figure 2. Required Stock Returns, G16
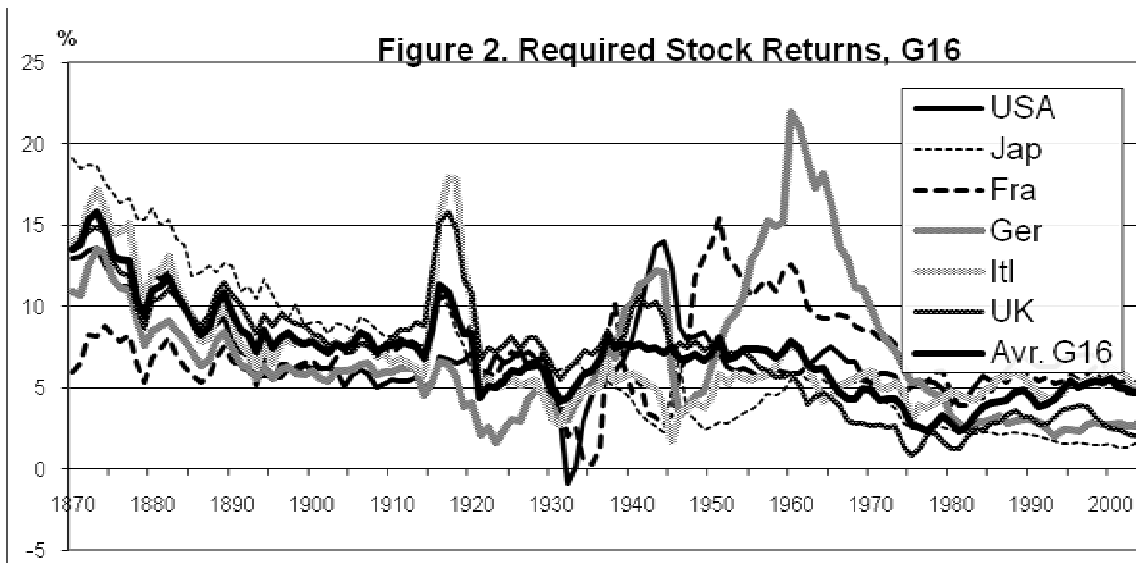
Note. The estimates are based on (13). The data are adjusted to an average of 7% in the entire period for all countries. The average required returns are an unweighted average

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). The decline is likely to be associated with the economic development of the OECD countries over the past 137 years. Since the Y/K ratio tends to be high for low-income countries (Mankiw *et al*., 1992) and tends to decline as the economy develops, as shown, for example, by Hsieh (2002) for the Asian Tigers, ρ is likely to depend on the stage of development of the economy.

3.2 TFP

The construction of the TFP data is based on homogenous Cobb-Douglas technology, where factors shares are allowed to vary over time and across countries based on the Divisia-Tornqvist index as follows:

$$TFP_{it} = \frac{Y_{it}}{L_{it}^{\alpha_{i,t-1}} K_{it}^{(1-\alpha_{i,t-1})}}$$

where *Y* is real GDP, *L* is labour inputs measured as annual hours worked per worker times economy-wide employment, *K* is non-residential capital stock, and α_{it} is the average of labour's income share at time *t* for the US and country *i*, following Wolf (1991). Output and capital are measured in purchasing power parities (Geary-Khamis dollars). Annual hours worked cover the non-agricultural sectors of the economy. The post WWII data are based on labour market surveys. The pre-WWII data are from estimates of number of weeks worked and hours per week, as discussed below.

Figure 3. TFP
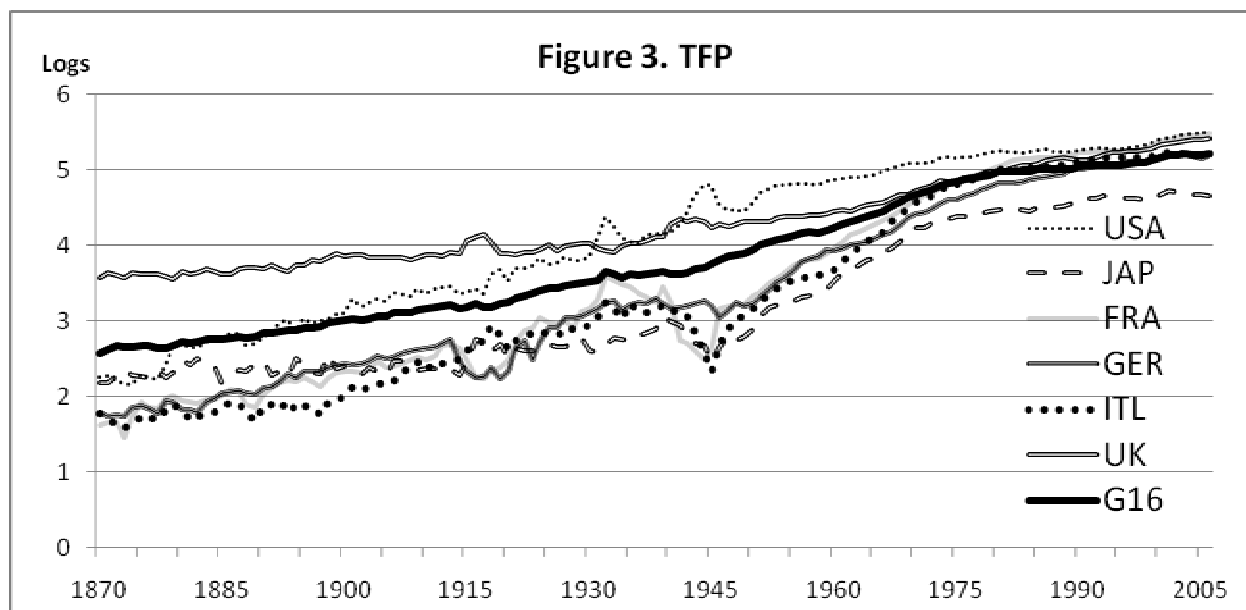
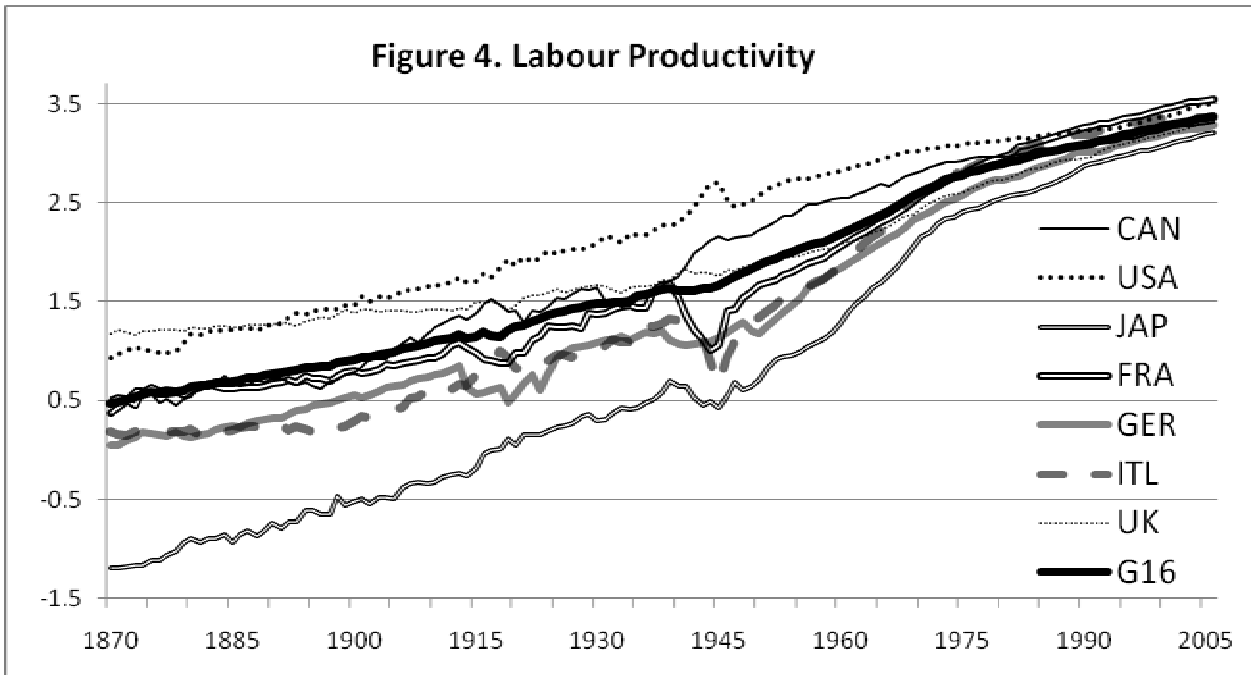**Note**. G16 is an unweighted average for the G16 countries.

Figure 3 shows the natural log of TFP over the past 137 years for the G16 countries, as an unweighted average, and for the G6 countries individually. The average growth rate was higher in the period 1945-1973 than in the surrounding years and has since stabilized at the rate that prevailed before WWII. The figure confirms the well-known fact that the USA took over from the UK as the world leader in the beginning of the 20th century. A significant convergence has taken place over the time-span considered and several countries have today caught up to the US TFP level, notably the UK, and France, which according to Madsen (2007, 2008) has largely been a result of technology spillovers between countries. Another interesting feature that can be seen in the figure is that Japan does not appear to be the growth miracle it is supposed to be. Its exceptionally high TFP growth path has been comparable with that of Germany and Italy up to 1970. Since 1970 Japan's TFP growth rate has been below the average growth rate in the G16 countries.

The reduction in TFP during WWI and WWII for France and Germany and Italy and Japan during WWII is not likely to be a result of technological regress. It is more likely to be a result of measurement errors and fluctuations in capacity utilization during, and immediately after, the world wars. Some of the data are not available in some years for some countries during the war periods and interpolated in the primary source (see for example Maddison, 1995). Furthermore, the capital stock in several European countries has been adjusted for war damages as noted in the data appendix. Since the precise amount of damage is impossible to assess, the estimates of capital stock for the countries that were involved in the wars are likely to be biased in the years surrounding the end of the world wars. Finally, the TFP estimates

are influenced by variations in capacity utilization during and after the world wars noting that TFP is estimated under the assumption of fully utilized factors of production. The surge in TFP in the US over the period from 1942 to 1945, for example, is likely to be a result of an overheated economy during the same period. Conversely, France, Germany and Italy were likely to have underutilize their factors of production; thus, artificially reducing TFP during the later part of the wars and immediately after the wars.

3.3 Labour productivity

Figure 4 shows the well-known fact that labour productivity has been trending upwards over the past 137 years and has tended to converge across countries. It is notable that France has recently taken over from the US as the world leader. This outcome is likely to have been influenced by the level and the change in annual hours worked. In 2006 the average French worker worked 1555 hours a year while the number was 1887 for the US. Furthermore, the annual hours worked declined by 27% in France over the period from 1969 to 2006, while they were almost unaltered in the US during the same period.

Note. G16 is an unweighted average for the G16 countries.

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. This 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 1950 in Japan may have accounted for the discrepancy between TFP and labour productivity growth in the same period. Similarly, TFP in the UK was stagnant over the period from 1900 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 1870-2006, the required returns have only declined modestly in France, but decreased from 14% to 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 137 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.

3.4 Labour's income share

Data for the manufacturing sector is used to estimate factor shares because the data go further back in time than aggregate income shares and because manufacturing income share data are of much better quality than data for the other sectors of the economy. There are several problems associated with economy-wide data for factor shares. First, economy-wide operating surplus includes interest on government bonds and all earnings of self employed labour. Neither of these reflect the returns to tangible and intangible capital. Furthermore, since inflation lowers the real value of debt, inflation exaggerates the returns to capital and, therefore, capital's income share, in inflationary periods. The problem associated with self-employment is that self employers' own labour is not recorded as compensation to employees but as capital income. The usual way to deal with this problem is to impute labour costs by assuming the same average earnings for self employed and employees. However, historical data regarding the number of self-employed is not available for most countries. Although this is also a problem for labour's share in manufacturing, the number of self-employed in manufacturing is substantially lower than that in agriculture and trade (Chan-Lee and Sutch, 1985). Second, returns to government expenses, such as infrastructure and investment in public schools and universities, do not earn operating surplus; thus, understating returns to capital. Third, operating surplus in the financial and the real estate sectors are imputed and, therefore, may not give a correct indication of the returns to

capital in these sectors. These considerations suggest that factor shares in manufacturing are much less subject to measurement errors than factor shares in other sectors of the economy.

Figure 5. Labour's Income Share in Manufacturing, G16
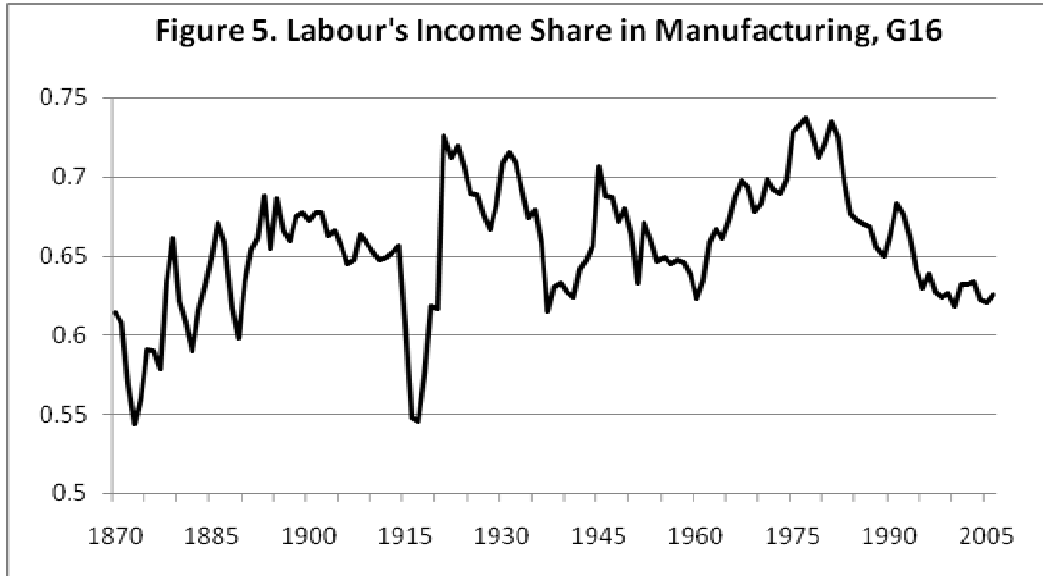
Note. G16 is an unweighted average for the G16 countries.

Labour's income share in manufacturing over the past 137 years is shown in Figure 5 for G16, where the share is computed as compensation to employees divided by GDP in the manufacturing sector. Only the G16 average of factor shares is shown in the figure because the cycles in labour's share tend to coincide across countries. The figure shows that factor shares have fluctuated around a constant level over the past 137 years, which is consistent with the predictions of standard growth models. The only deviation from this pattern appears to be the increasing labour share over the period from 1870 to 1900. However, earlier data for Sweden shows that labour's income share was at a low in 1870 (Edvinsson, 2005). This low could well have been a worldwide phenomenon since factor shares tend to co-vary across nations. The peaks in labour's share in the beginning of the 1920s and the 1970s are associated with strong wage pushiness and large-scale strikes (see Madsen, 1998, 2004). Conversely, the reduction in labour's share during and immediately after WWI was associated with high inflation combined with nominal wage rigidity (Madsen, 2004).

4 The quality of the data

The reliability of the results generated in this paper relies on the quality of the data. Particularly, the parameter estimates in the empirical section below may be biased if the dependent and the independent

variables are measured by errors. Thus, it is important for the results in this paper that the data are of good quality. While most of the GDP data has been scrutinized by other researchers, the data for hours worked, employment and capital stock have, to a large extent, not. To assess the quality of the data one needs to benchmark the data against a secondary source. Ideally, it would be best to compare the data in this paper against an alternative international data source in which the data go far back in history.[††]

Baier *et al*. (2006) and Huberman and Minns (2007) have generated long historical data for employment, capital stock and annual hours worked. The data are approximately decadal and cover most of the countries and periods used in this paper. Like in this study, Baier *et al*. (2006) base their estimates of the capital stock on the perpetual inventory method. Baier *et al*. (2006) use Summers and Heston's real investment rates and Mitchell's nominal investment rates. Their capital stock data include non-residential as well as residential investment. Residential investment data are not used in this study because residential capital does not belong to the production function.

This section compares the reliability of the data in this paper (primary source) with the data of Baier *et al*. (2006) and Huberman and Minns (2007) (secondary source). If one treats the primary and the secondary data sources as independent estimates of hours worked, employment, and capital stock, the method suggested by Griliches (1986) can be used to test for the reliability of the data. The method is simply to regress one set of data against the other set of data in a bivariate regression. The slope coefficients reflect the reliability ratios of the data.

More formally, consider a variable x that has two different components: The signal reflecting the true information about the variable, x^*, and a noise term due to measurement error, e. Two different data sets with different measurement errors are given by:

$$x_{pr} = x^* + e_{pr}, \tag{15}$$

$$x_{se} = x^* + e_{se}, \tag{16}$$

where the sub-scripts 'pr' and 'se' stand for primary and secondary data source, where the primary data source is the one used in this paper and the secondary source is either Baier *et al*. (2006) or Huberman and Minns (2007). It is assumed that x^* and e and e_{pr} and e_{se} are uncorrelated. It is, however, likely that

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[††] OECD's *Stocks and Flow of Capital* contains cross-country data for capital stock that go back to the 1950s or 1960s. A problem associated with their capital stock data is that they are estimated by statistical agencies and, as such, are not comparable across countries. The countries use different depreciation rates and not all countries allow for depreciation of old capital such as Japan, for example.

the measurement errors in the two data sets are positively correlated because they, in some instances, rely on the same data sources. Therefore, the reliability of the data sources, as estimated below, probably represent the upper limit of their reliability. Huberman (2004) is, for example, used as source for hours worked before 1913 for most of the countries considered in this paper and by Huberman and Minns (2007).

The *reliability ratio*, R_{pr}, of x_{pr} can be estimated as:

$$R_{pr} = \frac{\text{cov}(x_{pr}, x_{se})}{\text{var}(x_{pr})},$$
(17)

where R_{pr} has the probability limit $\text{var}(x^*)/[\text{var}(x^*) + \text{var}(e_{pr})]$. Thus, the lower is the variance of the measurement error of the primary data the closer R_{pr} is to one and, consequently, the more reliable is the primary source data. If the error terms are corrected the reliability index may exceed one.

If the serial correlation of the signal is higher than that of the noise, which is often the case, the reliability of the data in first differences will be lower than that in levels. More formally the probability limit for the reliability ratio when the variables are measured in first differences is given by (Griliches and Hausman, 1986):

$$p \lim R_{pr}^{\Delta} = \frac{\text{var}(x^*)}{\text{var}(x^*) + \text{var}(e_{pr})(1 - \rho_{pr})/(1 - \rho_{x^*})},$$

where ρ_{pr} is the serial correlation of the errors of the primary source and ρ_{x^*} is the serial correlation of x^*. The reliability ratio is one in this expression if the variance of the measurement error is zero. The higher is the variance of the error term the lower is the reliability ratio. Furthermore, the reliability ratio is lower the more serial correlated is x^* relative to the serial correlation of the measurement errors in the primary data source provided that the variance of the error term is non-zero.

The results of estimating eqs (15) and (16) are presented in Table 1. First consider the reliability of the hours worked data in the first four rows, where the secondary data source is the estimates of Huberman and Minns (2007). The data cover the G16 countries except Finland, Japan, and Norway, which are not covered in the data set of Huberman and Minns (2007). The estimated coefficients in the regressions in the first two rows are all highly significant and the coefficient estimates are close to one. This suggests that measurement errors are insignificant in either of the data source. The reliability index is about 8% higher for the primary source than the secondary sources. The estimates are not very

sensitive to whether or not the variables are measured in logs. The reliability indexes for both data sources remain high in the first difference estimates (rows 3 and 4). The reliability indexes are close to 0.7, which reinforces the finding from the level estimates that both data sources are reliable. The reliability index is slightly higher for the primary than the secondary source; however the difference is not sufficiently significant to strongly prefer one source over the other. The difference may well reflect that the measure errors in the primary and the secondary data source are correlated and not that the quality of the primary source is higher than the quality of the secondary source. Overall, these results suggest that any of the data for annual hours worked are reliable and that the primary source data may be slightly more reliable than the data from Huberman and Minns (2007).

Table 1. Reliability ratio's.

Row	Data	Levels(L) Diff(D)	Fixed Effects	Logs	R_{pr}	R_{se}
1	Hours	L	No	No	1.022(65.0)	0.941(65.0)
2	Hours	L	No	Yes	1.017(63.9)	0.945(63.9)
3	Hours	D	No	Yes	0.778(12.0)	0.651(12.0)
4	Hours	D	No	No	0.746(12.3)	0.692(12.3)
5	Capital/pop	L	Yes	Yes	1.068(36.1)	0.817(36.1)
6	Capital	L	Yes	Yes	1.070(53.5)	0.877(53.5)
7	Capital/pop	D	No	Yes	0.412(5.16)	0.303(5.16)
8	Capital	D	No	Yes	0.319(1.44)	0.034(1.44)
9	Emp	L	Yes	Yes	0.934(41.5)	0.962(41.5)
10	Emp	L	No	Yes	0.966(106.5)	1.017(106.5)
11	Emp/pop	L	Yes	Yes	0.398(4.47)	0.234(4.47)
12	Emp	D	Yes	Yes	0.484(3.72)	0.175(3.72)
13	Emp	D	No	Yes	0.747(7.85)	0.364(7.85)
14	Emp/pop	D	No	Yes	0.471(3.75)	0.167(3.75)

Notes. The figures in parentheses are *t*-statistics. The following data periods are used. Hours: 1870, 1880, 1890, 1900, 1913, 1929, 1938, 1950, 1960, 1973, 1980, 1990, and 2000. The data set covers the G16 countries except Finland, Japan, and Norway. Capital stock: 1870, 1880, 1890, 1900, 1910, 1920, 1930, 1947, 1961, 1970, 1980, 1990, and 2000 (some of the countries start one or two decades after 1870, see Baier *et al*., 2006, for details on data availability). Employment: 1870, 1880, 1890, 1900, 1910, 1920, 1930, 1947, 1961, 1970, 1980, 1990, and 2000 (some of the countries start one or two decades after 1870, see Baier *et al*., 2006, for details on data availability). The *primary data* source is the data used in this paper and the *secondary data* source is the data used by either Baier et al. (2006) (employment and capital stock) or Huberman and Minns (2007) (annual hours worked).

Rows 5-8 show the reliability index for capital stock. The level regressions in rows 5 and 6 indicate that the reliability of the primary source is high. R_{pr} is 1.07 for both regressions while R_{se} is, on average, 0.85. This difference may, to some extent, reflect that the secondary source includes residential capital stock. The reliability ratios for the primary and the secondary source decline to 0.36 and 0.18 on average, respectively, when the data are measured in first differences. While the reliability of the primary source

remains at an acceptable level in the first difference estimates, the reliability of the secondary source data is at a critically low level. Overall, the tests suggest that the data on capital stock used in this paper are significantly more reliable than the data of Baier *et al.* (2006).

Turning to the reliability of the employment data, both data sets are of high quality in rows 9 and 10. However, the reliability ratio of the secondary source drops to 0.23 when employment is normalized by the population (row 11). The reliability ratios decline when employment is normalized by the population because the normalization removes a strong trend element from the data. As such, the normalized data are much more revealing about the quality of the data than the data that are not normalized. The reliability ratios remain high in the first difference estimates for the primary source (rows 12 and 13); however, the ratio for the secondary source is only about half the size of that of the primary data source. The reliability of the primary data source remains relatively high when employment is normalized by the population while the reliability indexes again fall to critically low levels for the secondary data source (row 14).

Figure 6. Annual Hours Worked
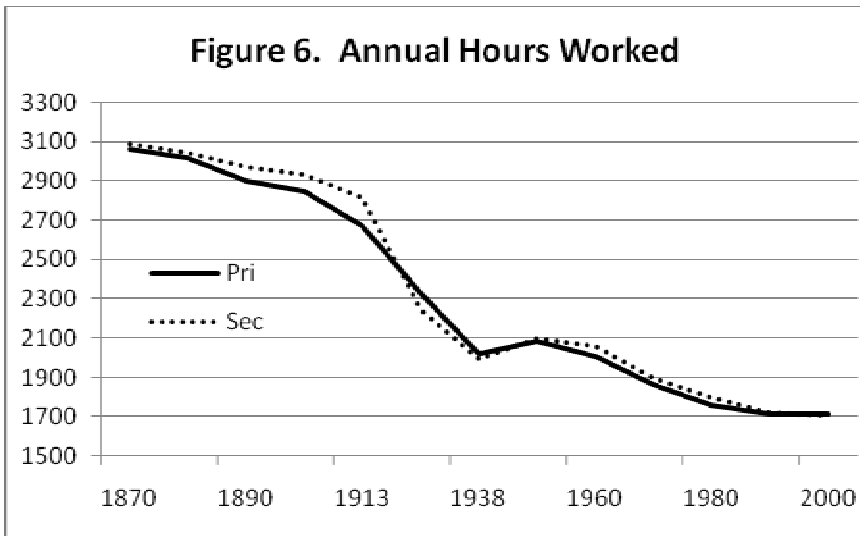
Notes. Weighted average of the countries considered in Table 1. See, for country sample, the notes to Table 1. The size of the population is used as weights. The primary source is the data used in this paper and the secondary data source is Huberman and Minns (2007).

Figure 6 compares a weighted average of the data used in this paper and the data of Huberman and Mins (2007) (see notes to Table 1 for country sample). Population sizes are used as weights. The curves move closely together. Both curves show a substantial decline in the number of working hours over the past century. Annual working hours were reduced by almost a third during the first four decades of the 19th century. A further 15% decline took place in the post-WWII period.

Turning to per capita capital stock in Figure 7, the discrepancy between the primary and the secondary source is more pronounced than that of hours worked. While the relationship between the two curves is reasonably tight in levels, it is not in first differences, which is also reflected in the reliability tests in Table 1. The growth rate is much stronger in the secondary source than the primary source over the period from 1870 to 1900, while the opposite holds true during the period from 1950 to 1990. Furthermore, per capita capital stock decreases in the primary source over the period from 1940 to 1950, while it increases in the secondary source.
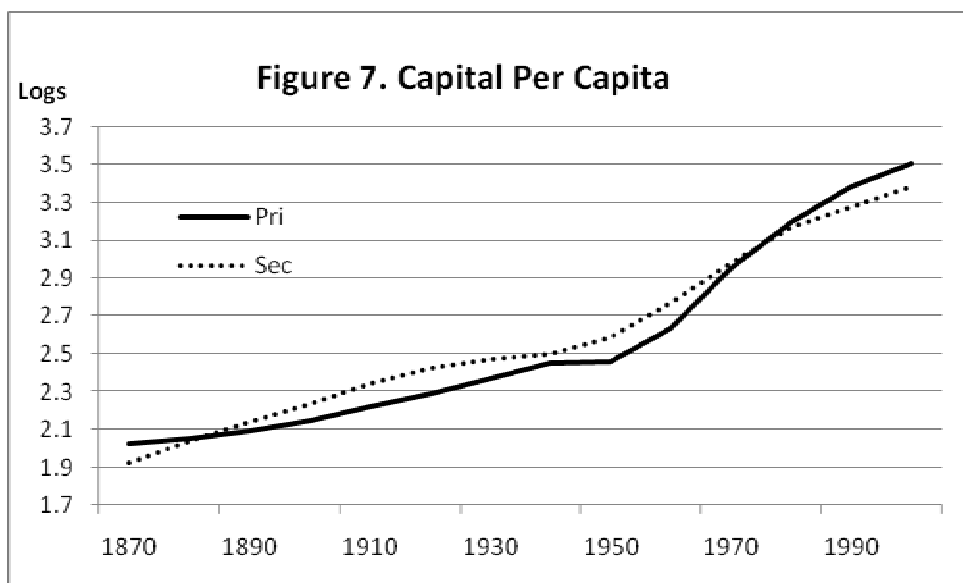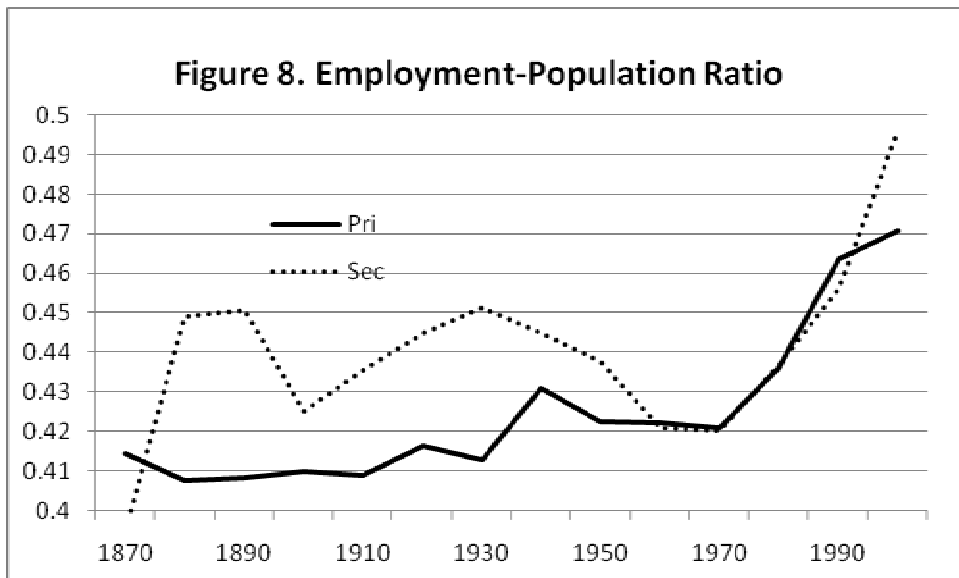

Note. See notes to Figure 5. The primary source is the data used in this paper while the secondary source is Baier *et al*. (2006).

The difference between the two data sources is likely to reflect that the primary source includes only non-residential capital stock, the treatment of war damages in the two data sources, and the different paths in particular countries across the two data sources. Since the ratio of residential investment in total investment is in the vicinity of 30% and varies substantially over time, the trend in per capita total capital stock will be sensitive to whether or not residential investment is included in the estimates. The large destruction of the capital stock during WWI and, particularly, during WWII for Germany, Belgium, the UK, France, Japan, and the Netherlands, is allowed for in the primary source but not in the secondary source. This explains, to a large degree, why per capita capital stock in the primary source decreases over the period from 1940 to 1950, while it increases in the secondary source during the same period. This further implies a much stronger growth in the capital-population ratio over the period from 1950 to 1970 in the primary source compared to the secondary source. The extraordinarily strong growth in the ratio of

capital to population, in the primary source data, over the period from 1950 to 1970 relative to other periods is consistent with the extraordinarily high per capita output growth during this period.

The ratio of employment to population ("labour force participation rate") is displayed in Figure 8. Note that the wild swings in the data, to some extent, reflect that the vertical axis is narrowed down to the range between 0.4 and 0.5. The primary source shows that the labour force participation rate was relatively stable up to WWI and increased thereafter. The dip in 1930 is associated with the Great Depression and the increase in 1940 reflects the increasing number of employed people used to support the war economy. The "labour force participation rate" in the secondary data source (Baier *et al.*, 2006) has been fluctuating around a relatively constant level up to around 1980 and increased thereafter. The abrupt shifts in the secondary data source reflect some implausible shifts in the "labour force participation rate" for some countries. The ratio plummeted from 0.94 to 0.47 in Denmark over the period from 1890 to 1900, which is also visible in the data source of Baier et al. (2006) (Mitchell). For Belgium the rate is reduced from 0.46 to 0.20 from 1930 to 1940. For Finland the rate increases from 0.23 to 0.55 over the period from 1870 to 1940. Finally, the rate drops from 0.56 to 0.34 in the period 1920 to 1990 and increases to 0.45 in 2000 in France. These erratic shifts are not present in the primary source and suggest that some adjustment of the data in the secondary source may be warranted.

Figure 8. Employment-Population Ratio

Note. See notes to Figure 5. The primary source is the data used in this paper while the secondary source is Baier *et al*. (2006).

Overall, the reliability check of the data suggests that the data used in this paper are highly reliable, have plausible paths, and compares well with the data of Huberman and Minns (2007) and, particularly, the

data of Baier *et al.* (2006). Since the data in this paper has the additional advantage of being annual they are likely to provide reliable information in the regression analysis below.

5 Empirical estimates

The theoretical section raised three issues 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 137 years. The second question is whether the K/L ratio can be explained by TFP and ρ. The third question is whether there is any causal relationship between K/L and TFP. The theoretical analysis showed that capital deepening was a result of changes in investor's required returns and changes in TFP, while there was no feed-back effects from capital deepening to TFP. This begs the question as to whether changes in TFP are quantitatively important for capital deepening and whether the analysis misses out feed-back effects from capital to TFP. It cannot be ruled out that a strong demand for capital stock gives innovative incentives. Granger 'causality' analysis is undertaken to investigate this issue.

5.1 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 model (the stochastic level counterpart of (12)) is regressed by pooling the data across the G16 countries:

$$\ln(Y/L)_{it} = \beta_0 + \beta_1 \ln TFP_{it} + \beta_2 \ln \rho_{it} + TD + CD + \varepsilon_{it,1}, \tag{18}$$

where TD represents time dummies, CD fixed effect dummies and ε is a stochastic error term. From the model given by (12), $\beta_1 = \alpha^{-1}$, or approximately 1.4, 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 (18) are estimated. Caution has to be exercised in the estimates where ρ is included as a regressor because the computations of ρ are based on the Y/K ratio. In the extreme case where τ, α, and δ are approximately constants, the identifying variations in ρ come from variations in Y/K. Consequently, β_2 will be biased towards $(\alpha - 1)/\alpha$.

Equation (18) is estimated using the dynamic least squares estimator of Stock and Watson (1993), where the first-differences of two-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. This is in contrast to the OLS estimator, which yields unbiased coefficient estimates in panels. 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 (18) are presented in Table 2. Labour's income share is allowed to vary in the TFP estimates in the first two columns, while it is fixed over time, but varies across countries, in the regressions in columns 3 and 4. The null hypothesis of a unit root in the residuals is rejected at conventional significance levels in all the regressions in the table, which suggests that that there is a long-run relationship between the variables included in the model. The estimated coefficients of TFP are statistically highly significant and have the sign and magnitude as predicted by the theory except for the estimates in the second column. The coefficient of TFP in the estimates in the second column has probably been driven down by the time-dummies because of a high correlation of TFP over time across countries. The estimated coefficients of ρ are significant and negative. However, the coefficients are less negative than the theory predicts, which may reflect that ρ is measured by a large error. The finding that the coefficients of TFP are generally well in excess of one gives support to 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.

Table 2. Restricted and unrestricted cointegration estimates (Equation (18)).

	1	2	3	4
TFP_t	1.50(28.4)	1.07(8.83)	1.59(31.2)	1.46(10.8)
ρ	-0.09(9.32)	-0.05(4.26)	-0.07(6.34)	-0.06(5.25)
$\bar{R}^2$	0.99	0.98	0.99	0.98
DF_λ	-8.01[0.00]	-31.9[0.00]	-2.00[0.02]	-4.35[0.00]
TD	No	Yes	No	Yes

Notes. The numbers in parentheses are absolute t-statistics. Estimation period: 1870-2006. The numbers in square brackets are p-values. $\bar{R}^2$ = adjusted 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.

Colums 1 and 2. Factor shares are allowed to vary over time and across countries.

Colums 3 and 4. Factor shares are fixed over time but vary across countries.

5.2 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 following stochastic counterpart of (10) is estimated using the same method and data as in the estimates above:

$$\ln(K/L)_{it} = \phi_0 + \phi_1 \ln TFP_{it} + \phi_2 \ln \rho_{it} + TD + CD + \varepsilon_{it,2}.$$ (19)

Following the predictions of the model given by (10), $\varphi_1 = \alpha^{-1}$, or approximately 1.4, and $\varphi_2 = -\alpha^{-1}$, or approximately -1.4.

Table 3. Restricted and unrestricted cointegration estimates of (19).

	1	2	3	4
TFP_t	1.67(21.1)	1.05(3.73)	1.79(23.0)	1.68(7.33)
ρ	-0.14(9.48)	-0.08(3.31)	-0.11(7.01)	-0.11(5.44)
$\bar{R}^2$	0.94	0.98	0.97	0.99
DF_λ	-6.02[0.00]	-17.9[0.00]	-0.02[0.49]	-0.37[0.35]
TD	No	Yes	No	Yes

Notes. See notes to Table 1.
Colums 1 and 2. Factor shares are allowed to vary over time and across countries.
Colums 3 and 4. Factor shares are fixed over time but vary across countries.

The regression results in Table 3 show that there is a cointegrated relationship between capital deepening, TFP and ρ in the regressions in which factor shares are allowed to vary over time. In the estimates in columns 1, 3, and 4 the estimated coefficients of TFP are slightly above the predictions of the model derived in the theoretical section while the opposite holds true for the regressions in the second column. Furthermore, since TFP is trending upwards over time coupled with a low coefficient of required returns, this implies that the bulk of capital deepening over the past 137 years has been a result of technological progress.

5.3 Sensitivity analysis

This section examines the stability of the parameter estimates and whether the results are affected by the inclusion of human capital in the TFP estimates. First the stability issue is addressed. The coefficient estimates in the previous two sections may not be stable over the entire period 1870 to 2006 because of structural changes in the economy, increasing tax rates and shifts in factor shares. To investigate the stability of the coefficient estimates, eqs (18) and (19) are estimated over the period from 1950 to 2006

and compared to the long estimates in Tables 2 and 3. The results are reported in Tables 4 and 5. Consider first the estimates in Table 4 in which labour productivity is explained by TFP and required returns. The variables are cointegrated in all regressions and the coefficient estimates of TFP are slightly below their counterparts in Table 2. The estimated coefficients of the required returns are significantly less negative than the estimates in Table 2. This may reflect that the trend in required returns has been relatively stable in the post WWII period and this has resulted in little identifying variation in the data. Furthermore, the strong temporary increase in the *K/Y* ratio in Germany in the 1950s was associated with a strong growth in per capita income during the same period.

Table 4. Restricted and unrestricted cointegration estimates (Equation (18)), 1950-2006.

	1	2	3	4
TFP_t	1.26(16.8)	0.72(4.63)	1.73(38.7)	1.38(11.1)
ρ	-0.03(2.05)	-0.01(0.61)	-0.04(6.92)	-0.03(4.53)
$\bar{R}^2$	0.98	0.98	1.00	1.00
DF_λ	-9.86[0.00]	-4.88[0.00]	-7.78[0.00]	-5.65[0.00]
TD	No	Yes	No	Yes

Notes. See notes to Table 1. Estimation period: 1950-2006.
Colums 1 and 2. Factor shares are allowed to vary over time and across countries.

Colums 3 and 4. Factor shares are fixed over time but vary across countries.

The regression results in Table 5 show the results of estimating (18) over the period from 1950 to 2006. The variables are cointegrated in all regressions, which suggests that the *K/L* ratio can adequately be explained by TFP and required returns. The estimated coefficients of TFP are, on average, close to the long estimates in the previous sub-section, while the estimated coefficients of required returns are slightly less negative than those produced by the regressions over the long time span.

Table 5. Restricted and unrestricted cointegration estimates of (19), 1950-2006.

	1	2	3	4
TFP_t	1.50(12.9)	0.95(4.57)	2.10(17.1)	1.64(5.77)
ρ	-0.06(2.94)	-0.04(2.00)	-0.08(4.68)	-0.07(3.25)
$\bar{R}^2$	0.94	0.98	0.97	0.99
DF_λ	-6.04[0.00]	-29.2[0.00]	-5.43[0.00]	-12.4[0.00]
TD	No	Yes	No	Yes

Notes. See notes to Table 1. Estimation period 1950-2006.
Colums 1 and 2. Factor shares are allowed to vary over time and across countries.

Colums 3 and 4. Factor shares are fixed over time but vary across countries.

Next human capital is allowed for in the TFP estimates. Allowing for human capital changes the TFP estimates as follows:

$$TFP_{it} = \frac{y_{it}}{(hL)_{it}^{\alpha_{i,t-1}} K_{it}^{(1-\alpha_{i,t-1})}},$$

where *h* is human capital, which is computed following the Mincerian approach:

$$h = \exp(\theta s),$$

where *s* is educational attainment, which is defined as the average years of schooling among the population of working age and θ is the returns to schooling, which is set to 0.07 following the standard in the literature. Educational attainment is obtained from Baier *et al*. (2006). Since their data are only available approximately every ten years and end in 2000 the data are geometrically interpolated berween the ten-year periods and extrapolated from 2000 to 2006.

Table 6. Restricted and unrestricted cointegration estimates of eqs (18) and (19), 1875-2006.

	1	2	3	4
TFP_t	1.93(17.4)	1.39(8.70)	2.18(18.8)	1.82(6.81)
ρ	-0.08(4.58)	-0.06(4.65)	-0.13(6.91)	-0.11(5.43)
$\bar{R}^2$	0.99	1.00	0.97	0.98
DF_λ	-0.50[0.31]	-2.98[0.00]	-0.42[0.34]	-4.49[0.00]
TD	No	Yes	No	Yes

Notes. See notes to Table 1. Estimation period 1875-2006.
Colums 1 and 2. Y/L is the dependent variable.

Colums 3 and 4. K/L is the dependent variable.

The results of estimating eqs (18) and (19) are presented in Table 6. The regressions in columns 1 and 2 show that the estimated coefficients of TFP are around 1.6, which is consistent with the prediction of the model in the theoretical section and slightly higher than the regression results in Table 2. The estimated coefficients of required returns are on average -0.07, which is close to the estimates in Table 2. In the regressions in columns 3 and 4, in which *K/L* is the dependent variable, the estimated coefficient of TFP is on average 2 and highly significant. The elasticity is slightly above the estimates in Table 3. This result reinforces that TFP plays a major role in capital deepening. The estimated coefficients of required returns

are also highly significant and of the right sign. The estimated coefficients are comparable with the estimates in Table 3.

5.4 Granger causality tests

The theoretical model in this paper predicts that the *K*/*L* ratio is growing at the same rate as the growth in TFP along the balanced growth path and that capital deepening is caused by technological progress. There are no feedback effects from capital to TFP. However, Gordon (2000) argues that investment contains new technology and, thus, advances the knowledge of the society. Suppose that investment is enhanced by a positive demand shock. The higher investment, in turn, brings with it more advanced technological knowledge. In this case 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 do not say anything about causality, they can reveal whether TFP precedes changes in *K*/*L* or *vice versa*.

The following equation is estimated for the G16 countries:

$$\Delta \ln y_{it} = \varphi_0 + \varphi_1 \sum_{j=1}^{5} \Delta \ln y_{i,t-j} + \varphi_2 \sum_{j=1}^{5} \Delta \ln x_{i,t-j} + \varepsilon_{it,3} \,,$$

where Δ 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 2005, noting that the long lags prevent longer estimation periods. The same approach and the same length of the first-differences have been used by Blomstrom *et al.* (1996) to examine "causality" between productivity growth and investment. The model is also estimated with only one lag of the five-year differences.

The model is estimated by GLS in which correlation between the error-terms is allowed for. More precisely, the covariance matrix is weighted by the correlation of the disturbance terms using the following variance-covariance structure:

$$\begin{aligned}
E\{\varepsilon_{it}^2\} &= \sigma_i^2, & i = 1, 2,\ldots N, \\
E\{\varepsilon_{it}, \varepsilon_{jt}\} &= \sigma_{ij}, & i \neq j, \\
\varepsilon_{it} &= \phi_i \varepsilon_{i,t-1} + v_{it} \,,
\end{aligned}$$

where σ_i^2 = the variance of the disturbance terms for country *i* = 1, 2,... *N*, σ_{ij} = the covariance of the disturbance terms across countries *i* and *j*, and ε and *v* are disturbance terms. The variance σ_i^2 is assumed to be constant over time but to vary across countries. The error terms , σ_{ij}, are assumed to be mutually

correlated across countries as random shocks are likely to impact all countries at the same time. The parameters σ_i^2, σ_{ij} and ϕ are estimated using feasible generalized least squares.

Table 7. Granger causality tests.

Lags	Dep. var. (y_t)	Ind. var.(x_t)	$\sum x$	$\sum y$
5	TFP	K/L	-0.01(2.36)	0.64(23.0)
5	K/L	TFP	0.04(6.48)	0.99(939)
1	TFP	K/L	-0.01(0.68)	0.71(38.1)
1	K/L	TFP	0.04(8.34)	0.99(1060)

Notes. The numbers in parentheses are absolute *t*-statistics. Five lags are allowed for in the regressions in the first two rows while only one lag is included in the estimates in the last two rows. The coefficients in the first two rows are the sum of the coefficients of all lags, and the numbers in parentheses are their attached *t*-statistics. The models are estimated over the period from 1895 to 2005 in the estimates in the first two rows and from 1875 to 2005 in the regressions in the last two rows.

The results of the Granger causality tests are shown in Table 7. The regressions in the first and third row show that *K/L* does not influence TFP, whereas the regressions in the second and the fourth row show a significant positive link between the *K/L* ratio and past TFP-innovations. These results suggest there is an unambiguous, one-way relationship from TFP to *K/L*.

The results in Table 7 are also interesting from a growth accounting perspective, because the adjustment of capital stock to TFP-innovations is very short as revealed by the sum of estimated coefficients of lagged *K/L*, which are close to one. This suggests that the *K/L* ratio, to a large extent, has adjusted to TFP innovations within the 25-year lag period considered in the estimates recognizing 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.

6 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 ρ. 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 ρ. The following four periods are considered: 1870-1890, 1890-1950, 1950-1973 and 1973-2006. The 1870-1950 period is split into two periods, since ρ declined significantly during the 1870-1890 period and, thereafter, stabilized. In the estimates for which the endogeneity bias is corrected for, the coefficients of TFP and ρ are attached the values of 1.57 and -0.06, respectively, in the first four rows in Table 8, and factor shares are fixed over time. The computations in

the last four rows in Table 8 are based on coefficients of TFP and ρ of 1.37 and -0.09 and factors shares are allowed to vary over time.

The standard growth accounting decomposition is displayed in columns 2 and 3 in Table 8 ("A" section). In the growth accounting in section "B" (columns 4-6), productivity growth is decomposed into TFP growth, changes in required stock returns and a residual. The estimates are unweighted averages for the G16 countries. The calculations in the "A" section show that traditional growth accounting gives approximately the same weight to TFP and K/L as sources of growth over the considered period. From this, one would conclude that half of the growth in the G16 countries over the period from 1871 to 2006 is savings-induced capital accumulation. When the endogeneity of K/L is allowed for, TFP explains about ¾ and ρ about ¼ of labour productivity growth during the period 1871-2006. Furthermore, the ρ–induced labour productivity growth is predominantly limited to the period before 1890 during which required returns declined substantially. Since 1973 labour productivity growth has been driven entirely by technological progress.

Table 8. Growth decomposition for G16 on average.

		1	2	3	4	5	6
Row	Period	Actual Y/L	A TFP	A K/L	B TFP	B ρ	B Residual
1	1871-1890	2.29	1.35	0.94	2.11	0.45	-0.27
2	1890-1950	1.87	1.12	0.75	1.76	0.37	-0.27
3	1950-1973	4.12	2.54	1.57	4.00	0.58	-0.46
4	1973-2006	2.05	1.10	0.95	1.73	-0.12	0.44
5	1871-1890	1.58	0.13	1.45	0.19	1.79	-0.38
6	1890-1950	1.87	0.17	1.69	0.24	0.56	1.06
7	1950-1973	4.11	2.23	1.88	3.06	0.87	0.17
8	1973-2006	2.05	1.95	0.10	2.67	-0.09	-0.53

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. In the estimates in the first four rows the coefficient of TFP is set to 1.57 and the coefficient of ρ is set to -0.06. In the estimates in the last four rows the coefficient of TFP is set to 1.37 and the coefficient of ρ is set to -0.09. Factor shares are allowed to vary in the estimates in rows 5-8.

7 Concluding remarks

Using a Tobin's q model, this paper has shown that technological progress transmits directly and indirectly to labour productivity through the channel of capital deepening. An unexpected increase in TFP, for example, increases the marginal productivity of capital. Stock prices jump to the expected change in earnings and Tobin's q jumps above its steady state level. The q in excess of its steady state value triggers a capital deepening process that lasts until q returns to its equilibrium level. The indirect effect is neglected in standard growth accounting exercises and capital deepening is, consequently, considered as an independent factor influencing labour productivity.

Data over the period from 1870 to 2006 were used to test the predictions of the model. The estimates showed that the 23-fold increase in labour productivity in industrialised countries since 1870 has been driven by technological progress, predominantly, and a reduction in required stock returns. The regressions showed that labour productivity is cointegrated with TFP and the required stock returns. These results are important because they show that labour productivity in the long run is related to TFP and required stock returns. Furthermore, the regressions indicated that the K/L ratio is cointegrated with TFP and the required stock returns, which suggests that capital deepening is adequately explained by increasing TFP and decreasing required stock returns. Overall, the cointegration results give strong support to the predictions of economic growth models that labour productivity is driven by TFP in steady state and that changes in required stock returns have been influential for labour productivity growth in periods, particularly during the period from 1970 to 1890.

The cointegration estimates provide no information about causality and do not rule out a two-way relationship between TFP and the K/L ratio. However, the Granger causality tests gave strong support to the hypothesis that TFP precedes the K/L ratio and the absence of any feed-back 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 for which it can be assumed, with confidence, that the K/L ratio has not significantly adjusted to innovations in TFP.

DATA APPENDIX

Capital stock of equipment and non-residential structures. The perpetual inventory method is used with the following depreciation rates: 17.6% for machinery and equipment, and 3% for non-residential buildings and structures. The stock of capital is initially set to the Solow model steady state value of $I_t/(\delta + g)$, where I is investment, δ is the depreciation rate and g is the growth in investment during the period from 1870 to 2004. The post 1960 data are from OECD, *National Accounts, Vol. II,* Paris*, (NA)*. Before 1950 the following sources are used for the countries for which historical data are available. Canada. 1870-1900: Both types of investment are assumed to follow total non-residential investment in nominal prices deflated by the CPI. 1901-1925: 5-year average disaggregated into 1-year intervals using total non-residential investment deflated by CPI. Source: F. H. Leacy (ed.), 1983, *Historical Statistics of Canada*, Statistics Canada: Ottawa. United States. Angus Maddison, 1995, *Explaining the Economic Performance of Nations*, Edward Elgar. Japan. 1885-1988: A. Maddison (1995) *op cit.*, Backdated to 1870 using the growth rate in total investment from Maddison (1995) *op cit*. 25.7% war damage to the 1945 capital stock is incorporated into the capital stock following Maddison (1995) *op cit*. Australia: 1863-1902: C. Clark, 1970, "Net Capital Stock," *Economic Record*, pp. 449-466. 1903-1950: M. W. Butlin, 1977, *A Preliminary Annual Database 1900/01 to 1973/74*, Research Discussion Paper 7701, Reserve Bank of Australia: Sydney. Belgium. M. van Meerten, 2003, *Capital Formation in Belgium, 1900-1995*, Leuven: Leuven University Press. Before 1900: The ratio of investment and GDP in 1900 multiplied by real GDP is used backdated to the data to 1870. War damage correction: WWI. 15.5% of 1913 GDP spread out evenly between the years 1914-1917. WWII 7.1% spread out evenly for the years 1943-45. The correction for war damage follows van Meerteen, 2003, (see his footnote no. 39). Denmark: 1870-1950: K. Bjerke and Nils Ussing, 1958, *Studier Over Danmarks Nationalprodukt 1870-1950*, G. E. C. Gads Forlag: Copenhagen. Finland. R. Hjerppe, 1989, *The Finnish Economy, 1860-1985*, Helsinki: Bank of Finland, Government Printing Centre. France. 1856-1895: Total investment deflated by industry prices. E. Chadeau, 1989, *l'Economie Nationale Aux XIX et XX Siecles*, Paris: Presses de l'Ecole normale Superieure. 1896-1914 and 1921-1938: J-J. Carre P. Dubois and E. Malinvaud, 1975, *French Economic Growth*, Stanford: Stanford University Press. 1914-1921 and 1939-1949: Crude steel production adjusted. Liesner *op. cit.* War damage of 2% is assumed each year over the periods 1914-17 and 1942-1945 following Maddison, 1995, *op cit*. Germany: W. Kirner, 1968, *Zeitreihen fur das Anlagevermogen der Wirtschaftsbereiche in der Bundesreplublik Deutschland*, Deutsches Institut fur Wirtschaftsforschung, Duncker & Humbolt: Berlin. The data are adjusted for war damage in the source. Non-residential buildings and structures 1850-1949. The following categories are added together: Land und Forstwirtschaft, Energiewirtschaft, Bergbau, Grundstoff- und Productionguter-industrie, Investeringsguterindustrie, Verbrauchenguterindustrie, Nahrings- und Genussmittel-industrie, Industrie Kleinbetr. und Handwerk, Baugewerbe, Handel, Eisenbahnen, Schifffahrt, Ubringer Verkehr, Nachr. ubermittlg, Kreditintitutionen und Vers. gew., Wohnungsvermietung, Sonst. Dienstleist., Strassen und Brukken, Wasser strassen und Hafen, and Ubrige staatl. Bereiche. Machinery and equipment 1926-1949. The same categories are added together as for investment in non-residential buildings and structures. 1870-1925: Scaled investment in machinery and equipment for Denmark, using the average over the period 1926-1930 as scaling factor. Italy. Instituto Centrale di Statistica, 1976, *Statistiche Storiche Dell'Italia 1861-1975*. Residential building investment is included in investment in buildings. Only 10-year averages are available before 1945. The data are uniformly distributed within the 10-year intervals. Netherlands. 1800-1913: J-P. Smits, E. Horlings, and J. L. van Zanden, 2000, *Dutch GNP and its Components, 1800-1913*, Groningen, http://www.eco.rug.nl/ggdc/PUB/dutchgnp.pdf. The general investment deflator is used as deflator. 1913-60: Central Bureau voor de Statistiek, 2001, *Tweehondred Jaar Statistiek in Tijdreeksen, 1800-1999*, Centraal Bureau voor de Statistiek, Voorburg. 10% war damage is evenly spread out over the years 1943-1945. Norway. Statistisk Sentralbyraa, 1968, *Nasjonalregnskap*, Oslo. 1865-1930: The investment data are derived from capital stock and official depreciation rates using the following formulae for buildings and equipment, respectively: $I_t^{eq} = K_t^{eq} - K_{t-1}^{eq}(1-0.15)$ and $I_t^{st} = K_t^{st} - K_{t-1}^{st}(1-0.02)$. 1930-1949: The data are interpolated from 1940 to 1945 using the algorithm suggested by V. Gomez and A. Maravall, 1994, "Estimation Prediction and Interpolation for Nonstationary Series with the Kalman Filter," *Journal of the American Statistical Association*, 89, 611-624. The general investment price deflator is used to adjust the *pre*-1940 data, which are in 1938 prices, whereas the *post*-1945 data are in 1955 prices. Spain. A. Carrearas (ed.), 1989, Estsdisticas Historicas De Espana, Madrid:

Fundacion Banco Exterior. 1850-1960: The growth rate in total investment is used to backdate investment in structures and machinery, respectively. Sweden. 1861-1949: O. Krantz and C. A. Nilsson, 1975, *Swedish National Product 1861-1970*, C. W. K. Gleerup. Investment in buildings includes residential investment. Switzerland. Ritzmann-Blickenstorfer, 1996, *Historical Statistics of Switzerland*, Zurich: Chronos. The growth rate in total investment is used to backdate the data from 1922. UK. Maddison, 1995, *op cit*. An annual 3.5% war damage is corrected for in the estimates during the 1943-45 period.

Economy-wide real GDP. The data are from OECD, *National Accounts*, after 1950. Before 1950: A. Maddison, 1995, *Monitoring the World Economy 1820-1992*, OECD, except for the following countries. Australia. B. Haig, 2001, "New Estimates of Australian GDP 1861-1948/49," *Australian Economic History Review*, 41, 1-34. From 1939 onwards, Maddison (1995) *op cit*. Finland. Hjerppe (1989) *op cit*. Italy. C. Bardini, A. Carreras, and P. Lains, 1995, "The National Accounts for Italy, Spain and Portugal," *Scandinavian Economic History Review* XLII, 115-146. Netherlands. Central Bureau voor de Statistiek, 2001, *op cit*. Norway. O. H. Grytten, 2004, "The Gross Domestic Product for Norway 1830-2003," in Chapter 6 in Ø Eitrheim, J. T. Klovland and J. F. Qvigstad (eds.) *Historical Monetary Statistics for Norway 1819-2003*, Norges Bank Occasional Papers No 35, Oslo, 241-288. Spain. C. Bardini *et al.*, 1995, *op cit*. Sweden. O. Johansson, 1967, *The Gross Domestic Product of Sweden and its Composition 1861-1955*, Stockholm: Almquist and Wiksell. Switzerland. Ritzmann-Blickenstorfer, 1996, *op cit*. C. H. Feinstein, 1976, *Statistical Tables of National Income, Expenditure and Output of the UK* 1855-1965, Cambridge: Cambridge University Press.

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Total employment. Includes all economically active, with full-time equivalents. 1950-2004: OECD, *Labour Force Statistics*. 1870-1949. The following sources are used. The algorithm suggested by V. Gomez and A. Maravall *op. cit.* is used to interpolate between the benchmark years as indicated for the individual countries. Canada. 1921-1959. F. H. Leacy (ed.), 1983, *Historical Statistics of Canada*, Statistics Canada: Ottawa. 1870, 1890, and 1913, and A. Maddison, 1991, *Dynamic Forces in Capitalist Development*, Oxford University Press: Oxford. The USA. 1900-1949. T. Liesner, 1989, *One Hundred Years of Economic Statistics*, Oxford: The Economist, 1870, 1890, and 1893: Maddison, 1991, *op. cit*. Japan. Ohkawa, M. Shinchara and L. Meissner, 1979, *Patterns of Japanese Economic Development: A Quantitative Appraisal*, New Haven: Yale University Press. Australia. 1901-1949. M. W. Butlin, 1977, *A Preliminary Annual Database 1900/01 to 1973/74*, Research Discussion Paper 7701, Reserve Bank of Australia: Sydney. Maddison, 1991, *op. cit*. Belgium. 1927-35 and 1945-1949. van Meerteen, 2003, *op cit*. Backdated from 1927 using population of working age (15-64) assuming a constant labour force participation rate, B. R. Mitchell, 1975, *European Historical Statistics 1750-1975*, Macmillan: London. Denmark. 1870-1949. S. A. Hansen, 1976, *Økonomisk Vækst I Danmark*, Copenhagen: Akademisk Forlag. Finland. 1870-1959. R. Hjerppe, 1989, *op. cit*. Germany. 1870-1872, 1874-1914, 1924-1940, and 1949. W. G. Hoffmann, F. Grumbach, and H. Hesse, 1965, *Das Wachstum der Deutschen Wirtschaft seit der mitte des 19. Jahrhunderts*, Springer-Verlag:

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