Estimating UK capital adjustment costs

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Abstract

This paper estimates UK capital adjustment costs, using a data set for 34 industries spanning the whole UK economy for the period 1970-2000. The results show that it is costly to install new capital, and that it has been more costly to adjust the level of non-ICT capital (plant, machinery, buildings and vehicles) compared to the level of ICT capital (computers, software and telecommunications). The results are applied to an analysis of total factor productivity (TFP) growth. That analysis is focused on the 1990s - a period when the growth rate of the standard measure of TFP fell in the United Kingdom, while rising sharply in the United States. The estimates suggest that capital adjustment costs accounted for around two thirds of the observed slowdown in UK TFP growth. However, the adjustment is not large enough to reverse the finding that UK TFP growth declines in the second half of the 1990s, unlike the US experience of rising TFP growth.

Key words: Capital adjustment costs, investment, total factor productivity.

JEL classification: D24, D92, O47.

Summary

The aim of monetary policy is to keep inflation low and stable, in accordance with the target set by the Chancellor. A key influence on inflationary pressure is the balance between the demand for, and the economy's capacity to supply, goods and services. This capacity depends both on the quantities and qualities of the primary inputs into the production process - capital and labour - but also on the efficiency with which they are combined. The latter concept is often referred to as total factor productivity (TFP). A good knowledge of current and past productivity growth is therefore important for understanding aggregate supply activity, and so is relevant for the conduct of monetary policy.

To obtain a good measure of TFP growth, it is important to measure output and factor inputs correctly. There are a number of issues that need to be addressed. For example, the composition of aggregate inputs changes over time, and it is important to recognise and adjust for this. Also, the level of utilisation of the inputs may vary over the business cycle, which needs to be taken into account. It may also be costly to change the level of factor inputs, and adjusting for these costs may be important to better understand fluctuations in measured TFP growth.

The purpose of this paper is to get a better understanding of the costs associated with changing the level of capital; capital adjustment costs. The motivation for considering these types of costs is that when firms are investing in capital, they may need to divert resources to installing new capital rather than producing marketable output. This means that in periods of rapid investment growth, firms could be producing two types of products: the final product sold in the market and the services used within the firm to install capital. Marketable output may therefore be lower in periods of high investment growth, and this would cause a downward bias in estimates of measured productivity growth.

Simple plots of the standard measure of TFP growth (the Solow residual) and investment growth suggest a negative relationship between these series: TFP growth has fallen in periods of high investment growth, such as the late 1980s and the second half of the 1990s.

There are a number of studies that estimate capital adjustment costs for US data, but little is known about the importance of these costs for the United Kingdom. The main purpose of this paper is therefore to provide estimates of UK capital adjustment costs, using a newly constructed industry data set for 34 UK manufacturing and services industries, for the period 1970-2000.

The results are applied to an analysis of the second half of the 1990s: a period when TFP growth fell relative to the first half of the 1990s in the United Kingdom, while rising sharply in the United States. This period exhibits high growth in investment in information and communications technology (ICT). Separate estimates of adjustment costs are therefore provided for ICT and non-ICT capital. The results suggest that there exist significant adjustment costs for traditional non-ICT assets (plant and machinery, buildings, vehicle and intangibles). By contrast, there is less support for costly adjustment of ICT capital (computers, software, telecommunications equipment). We find some evidence that UK adjustment costs for non-ICT capital are larger than comparable estimates for the United States, while the cost of installing new ICT equipment appears to have been lower than those facing US firms.

The data set includes data for services industries, such as finance and business services. The output share of these industries has grown rapidly over time, and services industries also exhibited strong investment growth during the 1990s. Sectoral results suggest that it may be more costly to install capital in fast-growing services industries, than in more traditional manufacturing industries.

Finally, we find that capital adjustment costs accounted for around two thirds of the observed slowdown in UK TFP growth in the second half of the 1990s. However, the adjustment is not large enough to reverse the finding that UK TFP growth declined in the second half of the 1990s, unlike the US experience of rising TFP growth.

1 Introduction

In the late 1990s, labour and total factor productivity (TFP) accelerated in the United States, while decelerating in the United Kingdom.(1) This divergence is somewhat puzzling since the overall macroeconomic environment is similar in the two countries during this period; output growth rose, investment surged and unemployment fell to low levels. Yet, in terms of measured productivity performance, the United Kingdom lagged behind the United States.

One suggested explanation for the poor relative performance in the United Kingdom is that disruption costs associated with investment - adjustment costs - have been large. The idea is that when firms are investing in new capital, they may need to divert productive resources to installing the new capital rather than producing marketable output.(2) This means that firms are essentially producing two types of products: the final product sold in the market, and the services used internally to install new capital. Marketable output may therefore be lower during periods of high investment growth, and this would cause a downwards bias in estimates of measured productivity growth.

Previous studies provide evidence of sizable costs to adjusting the level of capital, supporting the hypothesis that standard measures of total factor productivity underestimate actual productivity growth in periods of rapid investment growth (Chirinko (1993) and Hammermesh and Pfann (1996) survey the adjustment cost literature, Basu, Fernald and Shapiro (2001) apply the results on US productivity growth using the adjustment cost estimates obtained by Shapiro (1986)). However, previous studies have mainly used US manufacturing data, and little is known about the importance of capital adjustment costs for the United Kingdom.(3) The main purpose of this paper is therefore to provide an estimate of the size of capital adjustment costs for the United Kingdom, using a newly constructed industry data set for 34 UK manufacturing and services industries, covering the period 1970-2000.

We quantify adjustment costs by estimating a system of structural equations, including the

(1) Annual TFP growth in the United States rose from around 0.6% in the first half of the 1990s, to around 1.1% in the second half of the 1990s. In the United Kingdom, TFP growth decelerated from around 1.7% to around 0.8% over the same period. The UK and US performances are discussed in detail in Basu, Fernald, Oulton and Srinivasan (2004).

(2) Examples of capital adjustment costs are implementation costs, the learning of new technologies and the fact that production may be temporarily interrupted.

(3) Exceptions to this are for example Nadiri (1992), who estimate adjustment costs using a cross-country sample including the United Kingdom, Palm and Pfann (1993) and Palm and Pfann (1997) who estimate asymmetric adjustment costs for UK manufacturing firms and Bloom, Bond and van Reenen (2001) who consider UK plant level investment.

investment Euler equation, using industry data for manufacturing and services industries. The benchmark estimation is carried out under the assumption of a constant elasticity of substitution production technology and convex capital adjustment costs. We use a set of exogenous instruments to identify the adjustment cost parameter, following recent work by Hall (2004). In a sensitivity analysis, alternative functional forms are considered and we conclude that the results appear to be robust across the different specifications considered. The estimates imply that a percentage increase in aggregate investment reduces aggregate value added by around 0.06%. Alternatively, after a shock to the user cost of capital, capital returns to its long-run equilibrium after around twelve years.

Most studies that estimate adjustment costs have quantified these for aggregate capital.[(4)] By contrast, the latest investment boom was driven, to a large extent, by high growth rates of investment in information and communications technology (ICT).[(5)] If adjustment costs differ across assets - it may be more costly to install a new iron mill than a fleet of vehicles - it may be important to account for changes in the composition of investment when assessing the impact of adjustment costs at the aggregate level. This paper also provides separate estimates of the adjustment cost parameters for ICT and non-ICT capital. The results suggest that there exist significant costs of adjustment for traditional non-ICT assets. By contrast, there is less support for costly adjustment of ICT capital.

The adjustment cost estimates are obtained using data for the manufacturing as well as services industries, whereas earlier studies have focused on manufacturing industries only. The inclusion of services is important, both because their share in the economy is growing rapidly over time, and also because these industries exhibited strong investment growth during the 1990s. The sectoral results also suggest that it may be more costly to install capital in fast-growing services industries, than in more traditional manufacturing industries.

The estimation results are used to estimate adjusted TFP growth at the industry level, and the industry results are aggregated to obtained a measure of aggregate TFP growth. We find that the estimated impact of capital adjustment costs was substantial during the second half of the 1990s, when they accounted for around two thirds of the observed slowdown in productivity growth. However, the adjustment is not large enough to reverse the finding that UK TFP growth declined in the 1990s, and does not close the gap relative to the United States.

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(4) Some recent papers consider heterogenous capital. For example, Mun (2002) estimate adjustment costs for ICT and non-ICT capital. Bloom *et al* (2001) and Cooper and Haltiwanger (2000) look at aggregation across assets and plant-level investment in studies of uncertainty and investment.

(5) See Basu *et al* (2004) for a discussion of UK ICT investment during the 1990s.

In Section 2 below, a simple model of investment is laid out. The capital stock is subject to convex costs of adjustment, and duality theory is applied to represent the problem of the firm from the cost side. The model is parameterised, and a system of equations to be estimated is derived. Section 3 discusses the estimation method, the data, and the empirical results. An adjusted measure of aggregate TFP growth is derived in Section 4 and Section 5 concludes.

2 Modelling investment

A model which specifies the firm's optimal choice of capital is detailed below. The model is parameterised and a set of equations describing the firm's optimal choice of variable inputs, capital and output are derived.

2.1 The firm's problem

Consider a representative firm with a production function for gross output, $Y_t,$ of the following form,

$$Y_t = F\left(L_t, M_t, K_t, I_t, Z_t\right) \qquad \textbf{(1)}$$

where L_t denotes labour input in period t, M_t material inputs, K_t capital, I_t investment, and where variable Z_t indexes technology, defined as any input that affects productivity but is not compensated for by the firm. The firm faces internal adjustment costs, and investment therefore enters as an argument in the production function.(6) This means that the firm faces a trade-off between producing output and diverting some factors of production away from current production in order to install new capital.(7)

The production technology in a given period can be represented by the short-run variable cost function: conditional on capital input K_t and output $Y_t,$ and for a given flow of investment I_t, the minimum of the real variable cost, $C_t,$ is given by

$$C_t = C\left(W_t, P_t^m, Y_t, K_t, I_t, T\right) \qquad \textbf{(2)}$$

where W_t is the price of labour relative to the price of aggregate output, P_t^m is the price of material inputs relative to the price of aggregate output and T is time, included to capture changes in productivity over time.

(6) Alternatively, one could consider external adjustment costs that are incurred when the firm outsources the installation of capital. For a discussion about internal and external adjustment costs, see Hammermesh and Pfann (1996).

(7) Labour is here considered a variable input. There is mixed evidence for the importance of labour adjustment costs. Shapiro (1986) and Hall (2004) find little evidence for adjustment costs in labour, while Merz and Yashiv (2004) argue that these costs play an important role, and that considering gross, rather than net, flows is important in the analysis of labour adjustment costs. For UK manufacturing firms, Palm and Pfann (1993) and Burgess (1988) find some evidence of costly adjustment for labour.

The short-run variable cost function is defined for a given level of output and capital input. The optimal path for capital is chosen by minimising the expected discounted value of future costs, given by

$$\mathrm{E}_t\left[\sum_{\tau=0}^{\infty}\frac{1}{1+r_{t,t+\tau}}\left(C_{t+\tau}+P^I_{t+\tau}I_{t+\tau}\right)\right] \quad \textbf{(3)}$$

subject to **(2)** and to the capital accumulation identity,

$$K_{t+1}=I_t+(1-\delta)\,K_t \quad \textbf{(4)}$$

where $\mathrm{E}_t\left[\cdot\right]$ denotes expectations, conditional on the information available in period t, $r_{t,t+\tau}$ is the relevant real discount factor for costs accrued in period $t+\tau$, P^I_t the price of investment relative to output and where δ denotes the rate of depreciation. The first-order condition for the optimal choice of capital is given by

$$\mathrm{E}_t\left[P^K_t+(1+r_t)\frac{\partial C_t}{\partial I_t}+\frac{\partial C_{t+1}}{\partial K_{t+1}}-(1-\delta)\frac{\partial C_{t+1}}{\partial I_{t+1}}\right]=0 \quad \textbf{(5)}$$

where P^K_t is the user cost of capital, defined by

$$P^K_t\equiv P^I_t\left[r_t+\delta-(1-\delta)\,\pi^I_t\right] \quad \textbf{(6)}$$

where $\pi^I_t\equiv\left(P^I_{t+1}-P^I_t\right)/P^I_t$.[8] Condition **(5)** states that the marginal cost of an additional unit of capital equals the expected discounted return to capital, where the marginal cost consists of the user cost and an adjustment cost, and where the return to capital is made up of a variable cost reduction and a saving in future adjustment costs.

In each period, the firm also chooses output to maximise profits. In a non-competitive market environment, the condition that the marginal cost equals marginal revenue can be expressed as

$$P_t=(1+\mu_t)\frac{\partial C_t}{\partial Y_t} \quad \textbf{(7)}$$

where P_t is the relative price of industry output and $1+\mu_t$ is the markup of the price over the marginal cost. In a monopolistic market, the markup will be determined by the inverse of the demand elasticity.

2.2 Empirical specification

The cost function is approximated by the translog cost function, which is a second-order approximation to a general cost function, dual to an arbitrary production function.[9] Let

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[8] One would generally include various tax adjustments in the measure of the user cost. This is done in the empirical work, but omitted here for simplicity.

[9] See Christensen, Jorgenson and Lau (1973) for the translog functional form.

C^v denote the short-run variable cost function, excluding adjustment costs, given by,

$$\begin{aligned}
\log C^v \quad = \quad & \alpha_0 + \alpha_w \log W + \alpha_p \log P^m + \alpha_y \log Y + \alpha_k \log K + \alpha_t T + \\
& \frac{\beta_{ww}}{2} (\log W)^2 + \frac{\beta_{pp}}{2} (\log P^m)^2 + \frac{\beta_{yy}}{2} (\log Y)^2 + \frac{\beta_{kk}}{2} (\log K)^2 + \frac{\beta_{tt}}{2} T^2 + \\
& \beta_{wp} \log W \log P^m + \beta_{wy} \log W \log Y + \beta_{wk} \log W \log K + \beta_{wt} T \log W + \\
& \beta_{py} \log P^m \log Y + \beta_{pk} \log P^m \log K + \beta_{pt} T \log P^m + \\
& \beta_{yk} \log Y \log K + \beta_{yt} T \log Y + \beta_{kt} T \log K
\end{aligned} \qquad \textbf{(8)}$$

where parameter restrictions have been imposed to make the cost function symmetric. For the adjustment cost function, the following convex form is considered,

$$\psi\left(I_t, K_t\right) = \frac{\beta_{dk}}{2} \left(\frac{I_t}{K_t} - \theta \right)^2 \qquad \textbf{(9)}$$

where β_{dk} and θ are parameters. Recent work by Cooper and Haltiwanger (2000) and Cooper, Haltiwanger and Power (1999) give empirical support to the use of a convex adjustment cost function. Although non-convexities matter at the plant or the firm level, they have little role for understanding fluctuations at the industry or the aggregate level, and a convex formulation is therefore appropriate for that analysis. In the benchmark case, θ is assumed to be zero, implying that both replacement investment (δK_t) and investment in new capital ($K_{t+1} - K_t$) incur adjustment costs. Under the assumption that replacement investment is more routine and therefore less costly than other types of investment, one could consider an alternative specification where only investment in new capital incurs adjustment costs. However, we argue that there is no clear distinction between replacement and other investment, as machines are rarely replaced at a one-for-one basis. Moreover, in an environment of rapid technological progress, new technology is embodied in new capital goods.[10] To evaluate the sensitivity of the estimates to this assumption, we also consider a more general specification where θ is estimated, but cannot reject the null hypothesis that it is equal to zero, suggesting that adjustment costs depend on gross investment. This means that factor adjustments have both steady-state and cyclical effects and this turns out to be important when considering the impact of capital adjustment costs on productivity growth, as the impact will be non-zero, even when the economy is close to its long-run equilibrium.

The adjustment cost function is assumed to enter linearly into the translog cost function,

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(10) See for example Kiley (1999) and Mun (2002) for a discussion about the adoption of new technology, as embodied in capital goods, and the impact on adjustment costs and measured productivity growth.

net of adjustment costs. The variable cost function can therefore be expressed as

$$C = C^v e^{\psi(I,K)} \qquad \textbf{(10)}$$

subject to **(8)** and **(9)**.[11] Alternatively, one could approximate equation **(2)** to the second order, to provide a fully microfounded approximation of the cost function, including adjustment costs, as in Morrison (1988a,b). The disadvantage of using this more rigorous approach is that substantially more parameters need to be estimated.

Several restrictions could be imposed on the cost function to reduce the numbers of free parameters. A well-behaved cost function is homogenous of degree one in prices.

$$\alpha_w + \alpha_p = 1 \qquad \textbf{(11)}$$

$$\beta_{wp} + \beta_{pp} = \beta_{ww} + \beta_{wp} = \beta_{wy} + \beta_{py} = \beta_{wk} + \beta_{pk} = \beta_{wt} + \beta_{pt} = 0 \qquad \textbf{(12)}$$

The assumption that the variable cost function is homogenous of a constant degree α_y in output further implies the following parameter restrictions.

$$\beta_{wy} = \beta_{py} = \beta_{yy} = \beta_{yk} = \beta_{yt} = 0 \qquad \textbf{(13)}$$[12]

There are some additional curvature conditions that also need to be fulfilled: the variable cost function should to be increasing and concave in input prices, decreasing and convex in capital, and convex in investment, and these conditions need to be satisfied at each observation.

By using the variable cost function **(8)** and **(9)** and given the restrictions in **(11)**, **(12)** and **(13)**, and by normalising all input prices by the price of materials, the variable cost function can be rewritten as

$$\begin{aligned} \log \tilde{C}_t \;=\;& \alpha + \alpha_w \log \tilde{W}_t + \alpha_y \log Y_t + \alpha_k \log K_t + \alpha_t T + \\ & \frac{\beta_{ww}}{2}\left(\log \tilde{W}_t\right)^2 + \frac{\beta_{kk}}{2}\left(\log K_t\right)^2 + \frac{\beta_{tt}}{2}T^2 + \\ & \beta_{wk} \log K_t \log \tilde{W}_t + \beta_{wt} T \log \tilde{W}_t + \beta_{kt} T \log K_t + \frac{\beta_{dk}}{2}\left(\frac{I_t}{K_t} - \theta\right)^2 \end{aligned} \qquad \textbf{(14)}$$

where $\tilde{C}_t \equiv C_t / P_t^m$ and $\tilde{W}_t \equiv W_t / P_t^m$. By applying Shephard's lemma on **(8)**, using the restrictions in **(11)**, **(12)** and **(13)**, the optimal cost-minimising input demand equations,

[11] This approach is common in the adjustment cost literature, see Pindyck and Rotemberg (1983), Shapiro (1986), Bernstein and Nadiri (1991), Nadiri (1992) and Mun (2002).

[12] This assumption means that the ratios of the cost-minimising input demands do not depend on the level of output. This may be a restrictive assumption since it limits the amount of substitutability with respect to capital that the model can pick up. However, relaxation of this assumption means that the system needs to be estimated using non-linear GMM and substantially more parameters also need to be estimated.

normalised by the price of material inputs, are obtained,

$$S_{L,t} = \alpha_w + \beta_{ww} \log \tilde{W}_t + \beta_{wk} \log K_t + \beta_{wt} T \quad \textbf{(15)}$$

$$S_{M,t} = 1 - \alpha_w - \beta_{ww} \log \tilde{W}_t - \beta_{wk} \log K_t - \beta_{wt} T \quad \textbf{(16)}$$

where $S_{L,t}$ and $S_{M,t}$ denote the shares of labour and materials in variable costs, respectively. The system does not have full rank since the share equations sum to one. When estimating the model, the share equation for material inputs is therefore dropped.

Finally, by using **(8)** and **(9)**, and by multiplying through by K_{t+1}/C_{t+1}, the Euler equation **(5)** can be expressed as,

$$\mathrm{E}_t \left[\frac{P_t^K K_{t+1}}{C_{t+1}} + S_{K,t+1} + \beta_{dk} \Gamma_{t+1} \right] = 0 \quad \textbf{(17)}$$

where $S_{K,t+1}$ is the elasticity of C_{t+1}^v (the variable cost function net of capital adjustment costs) with respect to capital, satisfying

$$S_{K,t+1} = \alpha_k + \beta_{kk} \log K_{t+1} + \beta_{wk} \log \tilde{W}_{t+1} + \beta_{kt} T \quad \textbf{(18)}$$

and where

$$\Gamma_{t+1} = (1 + r_t) \left(\frac{I_t}{K_t} - \theta \right) \frac{\Delta K_{t+1}}{\Delta C_{t+1}} - \left(\frac{I_{t+1}}{K_{t+1}} - \theta \right) \Delta K_{t+2} \quad \textbf{(19)}$$

where $\Delta X_t = X_t / X_{t-1}$ for any variable X_t. The Euler equation implies that variations in factor intensities may not only reflect relative movements in factor prices, but also costs to adjusting the level of capital.

Under the assumption that the elasticity of demand is constant and exogenously given, the markup equation can be expressed as

$$P_t = \alpha_p \frac{C_t}{Y_t} \quad \textbf{(20)}$$

where we have combined **(7)** and **(8)** and where $\alpha_p \equiv (1 + \mu)\alpha_y$ is the markup of prices over average variable costs. By taking the logarithm of each sides, we obtain

$$p_t = a_p + a_m (c_t - y_t) \quad \textbf{(21)}$$

where $a_p \equiv \log \alpha_p$, $c_t \equiv \log C_t$, $y_t \equiv \log Y_t$ and where $a_m = 1$. As discussed in the section below, the data set is constructed under the assumption that economic profits are zero. However, this does not imply that the markup over marginal costs is zero. As discussed by Basu and Fernald (2000), when free entry drives profits to zero in equilibrium, the markup parameter is non-zero as long as the firm faces non-constant returns to scale in the production of output.

For simplicity, the model is laid out under the assumption that there exists only one capital asset. It can be extended easily to allow for multiple assets, as shown in Appendix A, in which case the system of equations includes one Euler equation for each asset. We further assume that adjustment costs for different types of assets are separable.

3 Estimation, data and results

The system of equations consisting of the variable cost function **(14)**, the share equation for labour **(15)**, one Euler condition **(17)** for each asset j and the markup equation **(21)** are estimated jointly using the general method of moments (GMM). Below, we discuss the data, the estimation method and the choice of instruments and thereafter go through the results. The section ends with a discussion about the robustness of the results.

3.1 The data

To estimate the model, industry data from the Bank of England industry data set are used. This is a newly constructed data set which contains data for 34 industries, from 1970 to 2000 (for a more detailed overview, see Oulton and Srinivasan (2003)).[13] For each industry, there are data on gross output, value added and inputs of capital services, labour services and intermediates, in real and nominal terms. The capital services data is a quality-adjusted measure of capital that takes into account the composition capital. In practice, this is done by weighting different assets together by their rental prices, covering four types of non-ICT assets (structures, plant and machinery, vehicles, and intangibles) and three types of ICT assets (software, computers and telecommunications equipment). Labour services are measured as hours worked, including an adjustment for quality, described in Groth, Gutierrez-Domenech and Srinivasan (2004). The real intermediate index is a weighted average of purchases from other industries and from imports.

To estimate the user cost of capital, economic profits are assumed to be zero. The share of capital is in this case a residual, from which the price of capital can be obtained.[14] This also gives an implied rate of return, equal to the realised, post-tax rate of return. Alternatively, the user cost of capital could be estimated without imposing the zero-profit constraint, but this would require an estimate of the required rate of return, r_t. Moreover, studies using US data (Basu and Fernald (2000), Rotemberg and Woodford (1995) and Morrison (1990)) provide evidence that profit rates are close to zero.

Earlier studies that estimate adjustment costs use an asset-price weighted stock of capital. It is in this case straightforward to derive a measure of aggregate investment, using a Thornqvist index to aggregate different types of assets. Here we apply a different aggregation method, that is consistent with the rental-price weighted index of capital, as

[13] The original data set includes data for 1969 to 2000. However, one of the variables (investment) that we use here is only available for the period 1970 to 2000.
[14] The rental price shares were volatile between 1974 and 1980 and have therefore been smoothed over this period.

discussed in Appendix B.

Table 1 shows the classification of the 34 industries and maps these into broader sectors of the economy. Table 2 shows the investment to capital ratios for the different sectors, for ICT and non-ICT investment, for the whole time period and for the two subperiods 1970-95 and 1995-2000. Non-ICT capital appears to be close to its long-run equilibrium, with an investment to capital ratio of around 10% to 15%, and with a small increase between the first and the second period.[15] The exceptions are transportation industries (driven by road and air transport) and other business services, which all exhibit high investment ratios. The investment to capital ratios for ICT capital, on the other hand, are high across all industries, on average around 50%, which suggests that investment in ICT assets is above its long-run equilibrium.[16]

The model is estimated using data for the non-farm private economy (excluding agriculture and the government sectors), but where we also exclude the two industries oil and gas and coal and mining.[17] The inclusion of services industries may be problematic, as real output may be poorly measured for some of these industries (see eg Griliches (1994)). Therefore, results are included where the model is estimated separately for the subgroups manufacturing and services industries.

3.2 Estimation method and the choice of instruments

To estimate the model, the conditional expectations in the Euler condition are replaced with actual values and a vector of error terms is introduced. If the equations are correctly specified, the error vector consists of a forecast error for the Euler condition while the other terms are zero. Under rational expectations, the expectation error in the Euler condition is uncorrelated with any information known at the decision date. Under this identifying assumption, any period t variable can be used as an instrument. However, as discussed by Garber and King (1983), Chirinko (1993) and more recently by Hall (2004), the Euler equation approach relies on the assumption that the model is exactly specified and that all relevant variables that would shift the model variables can be observed. When the Euler equation involves some unobservable forcing variables, it is generally not

(15) The investment to capital ratio is equal to the depreciation rate in the long-run equilibrium. For non-ICT capital, the asset depreciation rates vary between 2.5% (buildings), 13% (plant and intangibles) and 25% (vehicles).
(16) For ICT capital, the depreciation rates varies between 11% (telecommunications equipment) to 31.5% (computers and software).
(17) The fit of the Euler equation is very bad for these industries, and we have chosen therefore not to include them. This may reflect the fact that large structural changes have taken place over the period considered.

possible to achieve identification by using period t variables as instruments.

Under a more general representation that allows for specification (as well as measurement and optimisation) errors in the Euler equation, identification requires some additional assumptions about the error terms. Under the identifying assumption that they follow a first-order moving average process, variables known in period $t-1$ could be used as instruments.[18] When the error term is serially correlated, however, lagged values of endogenous variables may be correlated with the error term in the Euler equation. Strongly exogenous variables, that are uncorrelated both with the expectation error but also with the unobserved forcing variables, should in this case be used as instruments.

There is evidence that it is not appropriate to model the residual in the Euler equation as a moving average process. Hall (2004) argues that movements in factor shares are too slow to be the result of adjustment costs, and previous studies that use lagged endogenous variables for identification typically find strong evidence against the overidentifying restrictions, reflecting either model misspecification or invalid instruments.

In a dynamic general equilibrium, few exogenous variables exists. Hall (2004) uses a measure of federal defence spending and a dummy variable for years where there were oil price shocks, as instruments. The overidentifying restrictions cannot be rejected, but the correlation between the instruments and model variables appears to be rather low, particularly for the defence spending instrument. The precision of some of the estimates is also low, possibly reflecting this fact.[19] We use a similar approach to Hall (2004). In the baseline regressions, we use an instrument set consisting of lagged values of the growth rates of two exogenous variables; the price of oil and exogenous demand, and a constant. The demand instrument is industry specific and created as an attempt to increase the correlation between the exogenous variables and the model variables.[20]

To be able to use these instruments, additional restrictions need to be imposed on the translog cost function, to reduce the number of parameter to be estimated. The restrictions, which are discussed in further detail below, imply a constant elasticity of substitution technology. As an extension, the translog cost function is also estimated. The instrument set in this case also includes lagged endogenous variables: the variable costs, the user cost

[18] This is the identifying assumption made by Shapiro (1986). Similar assumptions are common in the investment Euler equation literature, as discussed by Whited (1998).

[19] This is discussed by Shea (1997), who shows that valid instruments need to be adequately correlated with the model variables.

[20] As shown in Appendix C, the demand instrument is calculated as the weighted growth rate of demand from the rest of the economy. If unobserved shocks are correlated across industries however, the demand instrument may also be correlated with the error term in the Euler equation.

of capital, investment and capital.

Another issue is the choice of capital, which due to planning and installation lags is likely to be correlated with period $t-1$ variables. For this reason, instruments dated in year $t-2$ are used.

The model is estimated by pooling yearly industry data for the period 1970 to 2000. To allow for industry-fixed effects in the variable cost function, the error term in this equation is specified as $e_{it} = \nu_i + \eta_t$, where subscript i denotes industry and subscript t time. Also, to control for industry-specific markups, we allow the parameter a_p in **(21)** to vary across industries. The variables in the variable cost function **(14)** and the markup equation **(21)** are expressed in terms of deviations from the industry-specific mean before estimating the system of equations, thus eliminating the fixed effects.[21]

3.3 Basic results

The basic results are obtained under the assumption of a constant elasticity of substitution technology. This implies that the following additional restrictions on the variable cost function **(14)**.

$$\beta_{ww} = \beta_{kk} = \beta_{tt} = \beta_{wk} = \beta_{wt} = \beta_{kt} = 0$$

The results from the baseline regression for aggregate capital are reported in regression (1) in Table 3. The elasticity of the variable cost function with respect to output ($1 + \alpha_y$) is not significantly different from one, so the production function exhibits short-run constant returns to scale. The estimated labour share in variable costs (α_w) is around 0.35 and the estimated coefficient on capital (α_k) is negative, as expected. The adjustment cost parameter (β_{dk}) is positive and significantly different from zero. Regression (2) reports the the same regression, but allowing for separate coefficients on ICT and non-ICT capital (where subscript ict and non denote ICT and non-ICT capital, respectively). The estimate of the adjustment cost parameter for non-ICT capital is positive and significant and higher than that on aggregate capital. By contrast, the estimated adjustment cost parameter is small and imprecisely measured for ICT capital. There is little evidence against the overidentifying restrictions in these regressions, with a p-value of around 0.2. Serial correlation in the Euler equation residual is slightly positive, with a Durbin-Watson test statistics of around 1.6. The fit of the Euler equations, in terms of the correlation between the predicted and the actual values of the ratio of fixed to variable costs is around 0.28 for aggregate and non-ICT capital. The correlation is lower for ICT capital, at around 0.14.

[21] We find that, although theory implies that the parameter a_m in **(21)** is equal to one, the fit of the model is improved substantially when this parameter is estimated freely. This may reflect the fact that, as is discussed in the data section, some smoothing of the data has taken place.

We also re-estimate the system excluding the markup equation, as reported by regression (3) and (4) in Table 3. As shown in the table, the results are robust across the two specifications.

To quantify the impact of adjustment costs on the dynamics of capital, the Euler equation is log-linearised around steady state to obtain an equation that, in any period t, relates capital to current and future expected variable costs and rates of return. Some additional assumptions about the environment are made to obtain an explicit expression for the Euler equation. The firm is assumed to be a price taker, and wages, material prices, and the required rate of return are held constant. In this case, the linearised rule for the representative firm can be expressed as

$$k_{t+1} = \mu_1 k_t - A\mu_1 \sum_{\tau=0}^{\infty} \mu_2^{-\tau} p_{t+\tau}^K \tag{22}$$

where μ_1 and μ_2 are the two roots of the Euler equation, A is a function of the underlying parameters, and where a stable equilibrium is obtained for $\mu_1 < 1 < \mu_2$. Based on the parameter estimates reported in regression (1) in Table 3, the two roots satisfy $\mu_1 = 0.72$, $\mu_2 = 1.48$ and $A = 0.11$, which implies that after a shock to the rental price of capital, capital returns to its long-run equilibrium after around twelve years. The speed of adjustment is lower than that reported by Shapiro (1986), who obtains a root to the Euler equation of 0.75. With quarterly data, this implies a convergence time of around four years. However, the adjustment process is faster than that typically found in the q literature; as discussed by Chirinko (1993), one of the most important criticisms of the q model is that estimated adjustment costs are unreasonably high, partly reflecting the fact that stock market data on equity prices are much more volatile than investment. To account for this, adjustment costs need to be very high.[22]

To evaluate the impact of adjustment costs on measured productivity, we need an estimate of the elasticity of variable costs with respect to investment, φ^c. By using **(9)** and **(10)**, we obtain the following expression.

$$\varphi^c = \beta_{dk} \left(\frac{I}{K} \right)^2 \tag{23}$$

Table 4 reports investment elasticities for aggregate and for ICT and non-ICT capital for the different sectors. At the aggregate level, a percentage increase in investment raises variable costs by 0.028%, reflecting higher elasticities for non-ICT capital than for ICT capital.[23] At the sectoral level, the elasticities are large in business services and in

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(22) For example, Summers (1981) finds that after 20 years only half of the adjustment to a shock in the rate of return would have taken place. Similar or slower convergence times are reported in other studies using the q approach.

(23) Note that due to the non-linear form of the elasticity, the elasticity for aggregate capital does not simply equal the sum of that of non-ICT and ICT capital.

transportation, reflecting high investment to capital ratios in fast-growing industries such as finance, communication and business services and in air transportation.

Basu *et al* (2004) report a value of the elasticity of *aggregate value added* with respect to aggregate investment of -0.035, based on adjustment cost estimates by Shapiro (1986). The elasticity of variable costs with respect to investment is related to the elasticity of gross output with respect to investment, φ^y, in the following way:

$$\varphi^y = -(1 + \alpha_y)^{-1}\varphi^c \qquad \textbf{(24)}$$

To convert the output elasticity to value added terms, we divide φ^y by one minus the material share, before aggregating across industries. From this, an elasticity of aggregate value added with respect to investment of around -0.055 is obtained, around 0.2 percentage points higher than that reported by Basu *et al* (2004) for US data.

3.4 Sensitivity and robustness

This section discusses the sensitivity of the estimates, both across different specifications of the model, and across different subgroups.

Table 5 shows the stability of the results across the two subgroups services and manufacturing industries. The results for aggregate capital are reported in regressions (1) and (2), and regressions (3) and (4) allow for separate coefficients on ICT and non-ICT capital. The estimated coefficients differ somewhat between the groups; the labour share is higher in services than in manufacturing industries, and so is the elasticity of variable costs with respect to capital. The estimated adjustment cost parameter for aggregate capital is larger for services than for manufacturing industries, where it is imprecisely measured. We find that there is stronger evidence against the overidentifying restrictions at the sectoral level (p-values between 1% and 3%), but there is little evidence of serial correlation in the Euler equation residual (with Durbin-Watson statistics for the Euler conditions close to 2.0). The fit of the Euler equations, in terms of the correlation between the predicted and the actual values of the ratio of fixed to variable costs, is notably better for manufacturing than for services industries (with correlation coefficients 0.2 and 0.08, respectively).

In the basic regressions, the assumption that it is costly to install both new and replacement capital is imposed. Regressions (1) and (2) in Table 6 show the regression results when the parameter θ in **(9)** is estimated using non-linear GMM. The estimation procedure is less robust than linear GMM, and some of the parameter estimates are sensitive to the starting values. We also find that a regression equation where only exogenous variables are included as instruments do not perform well, in terms of the fit of the equations. A larger instrument set that contains some endogenous variables (discussed in the section on instruments) is therefore used. The estimate of θ is positive but not significantly different from zero, as shown in regression (1). Regression (2) shows that the same holds for θ_{non} and θ_{ict}. The remaining parameter estimates are similar to those reported in the baseline regressions, although the adjustment cost parameter is larger.

To control for potential non-stationarity in the variables included in the variable cost function, regressions (3) and (4) in Table 6 show the regression results when the cost function is estimated in first difference. The results are similar to those obtained in the baseline case, with the main difference being that the estimate of the adjustment cost parameter is larger. The Durbin-Watson statistics for the Euler equation is similar to that for the baseline case, but the fit of the Euler equations is worse, with a correlation coefficient of 0.07 for aggregate capital.

So far, the assumption of constant elasticities of substitution has been imposed. This limits the amount of substitutability with respect to capital that the model can pick up, and this may bias the adjustment cost estimates. Table 7 gives the estimation results for the translog cost function, using the larger set of instruments. Regression (1) shows the results for aggregate capital. The adjustment cost estimate is positive and larger than that obtained for the CES case. The correlation between the capital share and its predicted value is 0.38, higher than in the baseline CES case. However, there is evidence against the overidentifying restrictions, with a p-value close to zero.

Regression (2) shows the same results, allowing for two types of capital. Some of the second-order terms do not enter significantly, and these are dropped in the final regression.[24] The results are similar to those reported in the baseline regressions: the adjustment cost parameter for non-ICT capital is significant and greater than that on aggregate capital, while that on non-ICT does not enter significantly. The fit of the Euler equation for ICT capital is improved substantially compared to the CES case. However, the overidentifying restrictions are now strongly rejected.

The adjustment cost estimates are larger under the translog specification compared to the CES case. This partly reflects the fact that the estimated elasticity of variable costs with respect to capital (given by S_K in **(17)**) is constant in the case of a CES technology, whereas the translog specification estimates a large increase over the period considered. The ratio of fixed to variable costs has risen over time, but not by as much as the estimated increase in capital's shadow price. The difference motivates the larger adjustment cost

[24] Excluded parameters are $\beta_{kk,non}$, $\beta_{kk,ict}$ and $\beta_{non,ict}$.

estimates obtained in the case of a translog cost function.

3.5 Discussion

To sum up, the results give support for significant adjustment costs in aggregate and non-ICT capital. For ICT capital, there is less support for these types of costs. These results appear to be robust across different specifications of the model, although the benchmark estimation gives the smallest estimate of the adjustment cost parameter. We also find evidence of substantially larger adjustment costs in services industries than in more traditional manufacturing industries.

The finding of small, and imprecisely measured, adjustment costs in ICT capital is surprising: Mun (2002) finds that marginal adjustment costs for ICT capital have been substantial in the United States over the period 1983-98.(25) In a study by Kiley (1999), it is argued that computer adjustment costs may even exceed the investment expenditure.(26) The small and imprecise estimates obtained here may reflect mismeasurement: as discussed by Oulton and Srinivasan (2003) there is uncertainty about the level of UK software investment and ICT prices. Also, industry ICT capital data for the 1970s and the 1980s are not that reliable.(27) Taken at face value, however, the results indicate that UK firms have not spent as much resources on installing ICT capital as US firms. In Basu *et al* (2004), it is argued that to benefit from ICT investment, in terms of higher productivity growth, firms need to undertake costly co-investment in complementary capital, and that the process of building up this capital may take time. They find that the US evidence is consistent with the notion that firms have undertaken this type of co-investment in the past, and that contemporaneous investment is correlated with diverted resources towards unmeasured complementary investment (ie adjustment costs). By contrast, they find that some complementary investment was going on in the late 1990s in the United Kingdom, but this effect is not large enough to have a substantial impact on measured productivity growth. Thus, there is some corroborative evidence that UK firms have spent less resources on installing ICT capital than their US counterparts.

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(25) On average, one dollar spent on non-computer capital incurs about 9 cents of internal adjustment costs. For computer capital, adjustment costs are higher and vary between 35 and 60 cents.
(26) Kiley (1999) uses available data on the total cost for installing new computer systems, which shows that about 20% to 40% of total IT spending is system spending (hardware), while the remainder is allocated to training, support, and software. These, he argues, represents adjustment costs for installing new computers. However, some of these costs are treated here as investment (software) and some would show up as external adjustment costs. The estimates by Kiley (1999) are therefore not directly comparable to the estimates in this study.
(27) There are no published industry data for UK ICT investment for the period prior to 1989. Over this period, ICT investment is constructed by distributing whole-economy investment across industries using the expenditure shares for 1989. Also, aggregate ICT data is not available on a yearly basis for the period prior to 1989, and an interpolation method has therefore been used.

4 Adjustment costs and aggregate TFP growth

One interesting application of our work is the impact of capital adjustment costs on measured TFP growth, and we now proceed to evaluating this. To do so, we first need to estimate TFP growth at the industry level, and thereafter aggregate over the economy to obtain an economy-wide measure of TFP growth.

An adjusted measure of productivity growth at the industry level can be obtained from the cost side. It is shown in Appendix D that by totally differentiating the variable cost function, and dividing through by total costs, the following expression is obtained,

$$dz_j = -\gamma_j \frac{C_{T_j}}{TC_j} - \varphi_j^y di_j - \gamma_j \frac{(P_{K_j} - Z_{K_j})K_j}{TC_j} dk_j \qquad \textbf{(25)}$$

where C_T is the derivative of variable costs with respect to time, Z_K is the shadow price of capital, equal to $-C_K$, γ denotes the degree of returns to scale, and where subscript j denotes industry. The left-hand side of **(25)** is a measure of productivity growth obtained from the output side, under the assumption that the production function is homogenous of degree γ,

$$dz_j = dy_j - \gamma(s_{l_j} dl_j - s_{k_j} dk_j - s_{m_j} dm_j) \qquad \textbf{(26)}$$

where s_{l_j}, s_{k_j} and s_{m_j} are the shares of labour, capital and materials in gross output, respectively. This equals underlying technological progress, as measured by the reduction in variable costs over time, plus two terms which capture the impact of capital adjustment costs on measured TFP growth.[28] The standard measure of productivity growth will be biased downwards in periods of positive investment growth, as captured by the second term on the right-hand side in **(25)**. The third term reflects the disequilibrium effect arising from the fact that, in the presence of capital adjustment costs, the shadow price of capital may not equal the market prices of capital.

In a companion paper, discussed in Groth *et al* (2004), we analyse the impact of disequilibrium and scale effects on measured TFP growth. Here, we instead focus on evaluating the direct impact of capital adjustment costs on productivity growth. To do so, we set the scale and the disequilibrium effects to zero, and aggregate over the dual measure of TFP growth, given by $-\gamma C_T/TC$. Together with **(25)**, we obtain the following expression:

$$dz = \sum_j w_j \left(dz_j + \varphi_j^y di_j \right) \qquad \textbf{(27)}$$

where dz is the growth rate of aggregate TFP, dz_j the standard measure of TFP growth in industry j, given by **(26)**, and where w_j is the Domar weight of industry j, defined as the

[28] Caves, Christensen and Swanson (1981) show that $-\gamma C_T/TC$ is a dual measure of technological progress obtained from the cost side.

ratio of nominal gross output in industry j to aggregate nominal value added.[29]

Table 8 reports average values of TFP growth, adjusted TFP growth, and the impact of capital adjustment costs on TFP growth for the periods 1980-85, 1985-90, 1990-95 and 1995-2000, for the non-farm private economy, and for manufacturing and services industries. It also reports the average values over the four subperiods. The conventional measure of aggregate TFP has grown at a rate of around 1.1% over the period considered. Taking into account capital adjustment costs, we find that they add an additional 0.3 percentage points to aggregate TFP growth, and the impact is greatest during the expansion years 1985-90 and 1995-2000, when investment grew rapidly.[30] During the period 1995-2000, capital adjustment costs are estimated to contribute by around two thirds to the reduction in TFP growth, or by around 0.6 percentage points. As reported by Basu *et al* (2004), during the same period, capital adjustment costs are estimated to raise US TFP growth by around 0.2 percentage points.

Thus, in the late 1990s, the estimated impact on UK TFP growth is larger than that reported for the United States, both because the elasticities are larger, but also because the United Kingdom experienced higher investment growth than the United States. However, the adjustment is not large enough to reverse the finding that UK TFP growth declined in the second half of the 1990s, and does not close the gap with the United States.

The impact of adjustment costs on measured TFP growth is of course uncertain. To illustrate this, Chart A shows adjusted TFP growth together with the 95% confidence interval.[31] Unadjusted TFP growth coincides with the lower bound for the confidence interval, while the upper bound suggests an acceleration in UK TFP growth between the first and the second half of the 1990s.

5 Conclusions and suggestions for future work

This paper lays out a simple framework for estimating capital adjustment costs, and uses an industry data set for manufacturing and services industries to obtain UK estimates. The results supports the existence of significant convex costs of adjustment in aggregate

(29) The Domar weights used to aggregate over industries do not sum to one; aggregate nominal gross output is around twice as high as aggregate nominal value added. Thus, the impact of capital adjustment on aggregate TFP growth is around twice of that at the industry level.
(30) The adjusted measure of TFP growth has been calculated using the estimated adjustment cost parameter reported in regression (1), Table 3.
(31) The point estimate and the confidence intervals are based on the regression results reported in column 1, Table 3. Note that the confidence interval is very narrow in some years (1980, 1990, 1999) when investment growth was close to zero.

capital. This reflects sizable adjustment costs in non-ICT equipment. By contrast, estimated adjustment costs for ICT equipment are small and imprecisely measured. The sectoral results further suggest that it is more costly to install capital in the faster-growing services industries than in manufacturing industries.

Since GMM estimation of Euler equations suffers from a number of problems - most notably, that the overidentifying restrictions are typically rejected - the benchmark estimation uses a set of exogenous variables as instruments. We find that, in contrast to many previous studies, there is little evidence against the overidentifying restrictions.

The benchmark estimates suggest that, after a shock to the user cost of capital, it takes capital around twelve years to return to its long-run equilibrium. Elasticities of variable costs with respect to investment are derived, and the elasticity of aggregate value added with respect to investment is somewhat higher than comparable estimates for the United States.

The analysis suggests that the estimate of TFP growth at the aggregate level is biased. In particular, by taking into account capital adjustment costs, the deceleration in TFP growth between the first and the second half of the 1990s is reduced by around two thirds, or 0.6 percentage points. This reflects large adjustment costs in services industries, whereas the impact on manufacturing industries is smaller. However, the adjustment is not large enough to reverse the finding that underlying UK TFP growth declined in the 1990s, and does not close the gap relative to the United States in terms of productivity performance.

As an extension, one could consider modelling labour and capital adjustment costs jointly, as previous work suggests that the interaction may be important to take into account. The structural model of the economy is also very stylised, and a richer framework that allows for financial market imperfections could for example be developed, to obtain more precise adjustment cost estimates.

Appendix A: Multiple assets

In a generalised framework which allows for multiple assets, the normalised variable cost function can be expressed as

$$
\begin{aligned}
\log \tilde{C}_t \;=\; & \alpha + \alpha_w \log \tilde{W}_t + \alpha_y \log Y_t + \sum_j \alpha^j \log K_t^j + \alpha_t T + \\
& \frac{\beta_{ww}}{2}\left(\log \tilde{W}_t\right)^2 + \sum_j \frac{\beta_{kk}^j}{2}\left(\log K_t^j\right)^2 + \frac{\beta_{tt}}{2} T^2 + \\
& \sum_j \beta_{wk}^j \log K_t^j \log \tilde{W}_t + \beta_{wt} T \log \tilde{W}_t + \sum_j \beta_{kt}^j T \log K_t^j + \\
& + \sum_i \left(\sum_{j \neq i} \beta_{kk}^{ij} \log K^i \log K^j \right) + \sum_j \frac{\beta_{dk}^j}{2}\left(\frac{I_t^j}{K_t^j} - \theta^j\right)^2
\end{aligned}
\qquad \textbf{(A-1)}
$$

where superscript j denotes asset type. This specification implies that adjustment costs for different assets are separable. The share equations for labour and materials now satisfy

$$S_{L,t} = \alpha_w + \beta_{ww} \log \tilde{W}_t + \sum_j \beta_{wk}^j \log K_t^j + \beta_{wt} T \qquad \textbf{(A-2)}$$

$$S_{M,t} = (1 - \alpha_w) - \beta_{ww} \log \tilde{W}_t - \sum_j \beta_{wk}^j \log K_t^j - \beta_{wt} T \qquad \textbf{(A-3)}$$

and for each asset j, there is one Euler equation satsifying

$$\mathrm{E}_t \left[\frac{P_t^{K,j} K_{t+1}^j}{C_{t+1}} + S_{K,t+1}^j + \Gamma_{t+1}^j \right] = 0 \qquad \textbf{(A-4)}$$

where $S_{K,t+1}^j$ is the elasticity of C_{t+1}^v with respect to asset j, satisfying

$$S_{K,t+1}^j = \alpha_k^j + \beta_{kk}^j \log K_{t+1}^j + \beta_{wk}^j \log \tilde{W}_{t+1} + \sum_{i \neq j} \beta_{kk}^{ij} \log K_{t+1}^i + \beta_{kt}^j T \qquad \textbf{(A-5)}$$

and where we have the following relation.

$$\Gamma_{t+1}^j = (1 + r_t)\left(\frac{I_t^j}{K_t^j} - \theta^j\right)\frac{\Delta K_{t+1}^j}{\Delta C_{t+1}} - \left(\frac{I_{t+1}^j}{K_{t+1}^j} - \theta^j\right)\Delta K_{t+2}^j \qquad \textbf{(A-6)}$$

Appendix B: Aggregating investment data

Use that the growth rate of the real capital index can be expressed as a weighted average of the growth rates of the i individual assets available in the economy

$$\frac{K_{t+1} - K_t}{K_t} = \sum_i \omega_i \frac{K_{it+1} - K_{it}}{K_{it}} \qquad \textbf{(B-1)}$$

where K_t is the *flow of services* from aggregate capital in period t, K_{it} is the *stock of capital* in asset i at period t, and where the weight ω_i is given by

$$\omega_i = \frac{p_{it}^K K_{it}}{\sum_i p_{it}^K K_{it}} \qquad \textbf{(B-2)}$$

where p_{it}^K is the user cost of asset i in period t.[32]

The stock of capital in asset i satisfies

$$K_{it+1} = (1 - \delta_i) K_{it} + I_{it} \qquad \textbf{(B-3)}$$

where I_{it} is investment in the stock of asset i. Combining this with **(B-1)** gives the following equation.

$$K_{t+1} = \sum_i \frac{\omega_i K_t}{K_{it}} I_{it} + \sum_i \omega_i (1 - \delta_i) K_t \qquad \textbf{(B-4)}$$

The above equation can be expressed in aggregate terms.

$$K_{t+1} = I_t + (1 - \delta) K_t \qquad \textbf{(B-5)}$$

where aggregate investment is defined as a weighted index of investment in the different assets and where the aggregate depreciation rate is defined as a user-cost weighted index of the individual assets.

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[32] This equation holds approximately for the data set used. The reason for this is that capital services during period t are assumed to be derived from assets in the *middle* of period t. The *stock* of assets in the middle of period t is the geometric mean of the stocks at the beginning and the end of the period. There is thus not a linear mapping from assets in period t to the flow of capital services (Oulton and Srinivasan (2003)).

Appendix C: The demand-side instrument

For each industry i, the demand-side instrument is calculated according to

$$d_t^i = \sum_{j \neq i} w_j^i y_{jt} + w_c^i c_t + w_k^i k_t + w_x^i x_t$$

where d_t^i is the growth rate of demand for goods produced by industry i in period t, equal to a weighted sum of intermediate demand from all other industries, consumption demand, investment demand and exports. Variable y_{jt} is the growth rate of output in industry j, c_t the growth rate of aggregate consumption, k_t the growth rate of aggregate investment and x_t the growth rate of exports. The weights are calculated as follows:

$$w_j^i = \frac{\text{sales of intermediate goods from industry } i \text{ to industry } j}{Y_i}$$
$$w_c^i = \frac{\text{output from industry } i \text{ used for final consumption}}{Y_i}$$
$$w_c^i = \frac{\text{output from industry } i \text{ used for investment}}{Y_i}$$
$$w_c^i = \frac{\text{output from industry } i \text{ exported}}{Y_i}$$

where Y_i denotes gross output in industry i. The weights are calculated using data from the input-output tables for 1995 (Office for National Statistics (1995)). The data for output, consumption, investment and exports are consistent with the 2002 release (Office for National Statistics (2002)).

Appendix D: A measure of TFP growth obtained from the cost side

By taking a first-order approximation of the variable cost function around steady state, we obtain

$$\frac{C_Y Y}{C}\frac{C}{TC}dy + \frac{C_K K}{C}\frac{C}{TC}dk + \frac{C_I I}{C}\frac{C}{TC}di + \frac{C_T}{TC} = \frac{P_L L}{TC}dl + \frac{P_M M}{TC}dm \qquad \textbf{(D-1)}$$

where we have divided through with total costs, TC, where C_X denotes the derivative of the variable cost function with respect to any variable X and where dx is the log-deviation of variable X from steady state. Further manipulation gives

$$\frac{\alpha_y C}{TC}dy + \frac{(P_K - Z_K)K}{TC}dk + \frac{\varphi^c C}{TC}di + \frac{C_T}{TC} = \frac{P_L L}{TC}dl + \frac{P_M M}{TC}dm + \frac{P_K K}{TC}dk \qquad \textbf{(D-2)}$$

where Z_K is the shadow value of capital, defined as $-C_K$. Together with **(24)**, this can be rewritten as

$$dy + \frac{\gamma(P_K - Z_K)K}{TC}dk + \varphi^y di + \frac{\gamma C_T}{TC} = \gamma(\frac{P_L L}{TC}dl + \frac{P_M M}{TC}dm + \frac{P_K K}{TC}dk) \qquad \textbf{(D-3)}$$

where we have used that the degree of (long-run) returns to scale, γ, is given by $TC/((1+\alpha_y)C)$ when the economy is close to steady state, and where we have simplified by using that the benchmark estimate of α_y is zero.[33] Rewriting this expression gives

$$dz_t = -\frac{\gamma C_T}{TC} - \gamma\frac{(P_K - Z_K)K}{TC}dk - \varphi^y di \qquad \textbf{(D-4)}$$

where $-(\gamma C_T)/TC$ is the dual measure of TFP growth, obtained from the cost side, and where dz_t is the standard measure of productivity growth obtained from the output side when the production function is homogenous of degree γ in output. This can be expressed in terms of income shares,

$$dz_j = dy_j - \mu(s_{l_j}dl_j - s_{k_j}dk_j - s_{m_j}dm_j) \qquad \textbf{(D-5)}$$

where s_{l_j} is the share of labour in gross output, and so forth for the other variables, and where μ is the markup of prices over marginal costs, equal to γ in the case of zero economic profits.

[33] See Morrison (1985) and Caves *et al* (1981).

Appendix E: Tables

Table 1: Industry classification

no	Industry	SIC classification	Sector
1	Agriculture	01, 02, 05	Agriculture
2	Oil and gas	11, 12	Oil, gas & mining
3	Coal and mining	10, 13, 14	Manufacturing
4	Manufactured fuels	23	
5	Chemicals and pharmaceuticals	24	
6	Non-metallic mineral products	26	
7	Basic metals and metal goods	27, 28	
8	Mechanical engineering	29	
9	Electrical engineering and electronics	30, 31, 32, 33	
10	Vehicles	34, 35	
11	Food, drink and tobacco	15, 16	
12	Textiles, clothing and leather	17, 18, 19	
13	Paper, printing and publishing	21, 22	
14	Other manufacturing	20, 25, 36, 37	
15	Electrical supply	40.1	Utilities
16	Gas supply	40.2, 40.3	
17	Water supply	41	
18	Construction	45	Construction, hotels & distribution
19	Wholesale and vehicle sales	50, 51	
20	Retailing	52	
21	Hotels and catering	55	
22	Rail transport	60.1	Transportation
23	Road transport	60.2, 60.3	
24	Water tranport	61	
25	Air tranport	62	
26	Other transportation	63	
27	Communications	64	Other business services
28	Finance	6566	
29	Business services	67, 70, 71, 72, 73, 74	
30	Public administration and defence	75	Government sectors
31	Education	80	
32	Health and social work	85	
33	Waste treatment	90	
34	Miscellaneous services	91-99	Other business services

Table 2: Investment to capital ratios

	Non-ICT capital			ICT capital		
Sector	70-00	70-94	95-00	70-00	70-94	95-00
All industries	13.1	12.9	14.0	50.7	49.4	56.0
Oil, gas & mining	14.0	15.6	7.3	27.2	28.2	23.0
Manufacturing	11.3	11.3	11.4	53.2	53.4	52.6
Utilities	6.7	6.2	8.7	32.2	32.5	30.9
Construction, hotels & distribution	13.0	12.8	13.9	43.0	42.9	43.3
Transportation	21.6	20.8	24.8	28.3	30.3	20.3
Other business services	17.2	17.0	18.3	55.8	53.8	64.1

Table 3: Basic regressions

	(1)	(2)	(3)	(4)
α_w	0.369 (0.006)**	0.369 (0.005)**	0.377 (0.007)**	0.376 (0.007)**
α_y	-0.081 (0.065)	-0.115 (0.057)*	-0.048 (0.070)	-0.090 (0.061)
α_k	-0.158 (0.005)**		-0.161 (0.007)**	
$\alpha_{k_{non}}$		-0.146 (0.005)**		-0.148 (0.005)**
$\alpha_{k_{ict}}$		-0.005 (0.000)**		-0.005 (0.000)**
β_{dk}	1.108 (0.633)*		1.147 (0.674)**	
$\beta_{dk_{non}}$		1.643 (0.796)**		1.687 (0.844)**
$\beta_{dk_{ict}}$		0.007 (0.007)		0.003 (0.008)
α_t	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
α_m	0.050 (0.009)**	0.049 (0.009)**		
Obs	729	729	729	729
Sargan	9.10	6.57	5.88	9.45
Significance	0.17	0.25	0.21	0.22

Notes: GMM estimation using pooled data allowing for fixed effects in the variable cost function and the markup equation. Regressions (1) and (2) estimate the full system, (3) and (4) exclude the markup equation. Instruments: constant, two-period lagged values of the growth rates of the oil price and exogenous demand. Standard errors in parenthesis. * denotes significant at the 10% level, ** denotes significant at the 5% level.

Table 4: Investment elasticities

	Aggregate capital	Non-ICT capital	ICT capital
	1980-00	1980-00	1980-00
All industries	0.028	0.021	0.002
Manufacturing	0.021	0.016	0.002
Utilities	0.005	0.004	0.001
Construction, hotels & distribution	0.026	0.022	0.001
Transportation	0.033	0.037	0.001
Other business services	0.065	0.050	0.002

Notes: Based on average investment to capital ratios for 1970 to 2000. Calculated using the adjustment cost estimates in regressions (1) and (2), Table 3. Industries weighted together using the gross output share.

Table 5: Stability of coefficients across sectors

	(1) Services	(2) Manufacturing	(3) Services	(4) Manufacturing
α_w	0.404 (0.007)**	0.321 (0.005)**	0.402 (0.007)**	0.321 (0.005)**
α_y	0.066 (0.053)	0.030 (0.150)	0.041 (0.058)	0.072 (0.155)
α_k	-0.205 (0.008)**	-0.113 (0.002)**		
$\alpha_{k_{non}}$			-0.189 (0.009)**	-0.104 (0.002)**
$\alpha_{k_{ict}}$			-0.006 (0.000)**	-0.004 (0.000)**
β_{dk}	1.593 (0.738)**	0.096 (0.206)		
$\beta_{dk_{non}}$			2.384 (1.201)**	0.255 (0.239)
$\beta_{dk_{ict}}$			-0.008 (1.206)	0.010 (0.004)**
α_t	0.002 (0.000)**	0.001 (0.001)	0.002 (0.000)*	0.001 (0.001)
α_m	0.062 (0.016)**	0.243 (0.004)**	0.053 (0.015)**	0.025 (0.004)**
Obs	432	297	432	297
Sargan	14.30	16.72	18.04	20.95
Significance	0.03	0.01	0.01	0.01

Notes: GMM estimation using pooled data allowing for fixed effects in the variable cost function and the markup equation. Instruments: constant, two-period lagged values of the growth rates of the oil price and exogenous demand. Standard errors in parenthesis. * denotes significant at the 10% level,
** denotes significant at the 5% level. Services include industry 15-29, 34. Manufacturing include industry 4-14.

Table 6: Alternative regression specifications

	(1)	(2)	(3)	(4)
α_w	0.370 (0.004)**	0.352 (0.003)**	0.368 (0.006)**	0.368 (0.006)**
α_y	-0.103 (0.030)	-0.007 (0.015)		
α_k	-0.152 (0.00)**		-0.158 (0.006)**	
$\alpha_{k_{non}}$		-0.151 (0.004)**		-0.146 (0.006)**
$\alpha_{k_{ict}}$		0.000 (0.000)		-0.005 (0.000)**
β_{dk}	3.654 (0.970)**		1.970 (0.730)**	
$\beta_{dk_{non}}$		1.619 (0.568)**		2.441 (1.032)**
$\beta_{dk_{ict}}$		-0.001 (0.022)		0.004 (0.008)
α_t	0.000 (0.000)	0.000 (0.000)	-0.007 (0.000)**	-0.008 (0.002)**
α_m	0.025 (0.001)**	0.001 (0.006)	0.044 (0.009)**	0.044 (0.009)**
θ	0.059 (0.048)			
θ_{non}		0.072 (0.061)		
θ_{ict}		0.000 (9.304)		
Obs	729	729	729	729
Sargan	77.97	107.13	13.77	13.93
Significance	0.00	0.00	0.06	0.08

Notes: GMM estimation using pooled data allowing for fixed effects in the variable cost function and the markup equation. Regressions (1) and (2) estimate θ, (3) and (4) estimate the cost function in the first difference. Instruments for (1) and (2): constant, two-period lagged values of the price of capital, capital, investment, the growth rate of the oil price and exogenous demand. Instruments for (3) and (4): constant, two-period lagged values of the growth rates of the oil price. Standard errors in parenthesis. * denotes significant at the 10% level, **denotes significant at the 5% level.

Table 7: The translog cost function

	(1)	(2)
α_w	0.399 (0.040)**	0.425 (0.027)**
α_k	0.057 (0.041)	
$\alpha_{k,non}$		-0.139 (0.006)**
$\alpha_{k,ict}$		-0.005 (0.000)**
α_y	0.266 (0.085)**	0.123 (0.044)**
α_t	0.00 (0.005)*	-0.002 (0.000)**
β_{ww}	0.099 (0.017)**	0.106 (0.013)**
β_{kk}	-0.025 (0.005)**	
$\beta_{kk,non}$		
$\beta_{kk,ict}$		
β_{tt}	0.000 (0.000)	0.000 (0.000)**
β_{wk}	0.002 (0.005)	
$\beta_{wk,non}$		0.000 (0.003)
$\beta_{wk,ict}$		-0.002 (0.000)**
β_{wt}	-0.004 (0.001)**	-0.005 (0.000)**
β_{kt}	-0.001 (0.000)*	
$\beta_{kt,non}$		0.000 (0.000)
$\beta_{kt,ict}$		0.000 (0.000)
$\beta_{k,ict,non}$		
β_{dk}	2.369 (0.693)**	
$\beta_{dk,non}$		2.572 (0.560)**
$\beta_{dk,ict}$		-0.001 (0.005)
α_p	0.035 (0.010)**	0.015 (0.006)**
Obs	729	729
Sargan	58.83	87.70
Significance	0.00	0.00

Notes: GMM estimation using pooled data allowing for fixed effects in the variable cost function and the markup equation. Instruments: constant, two-period lagged values of the growth rates of the oil price, exogenous demand, the price of capital, capital and investment. Standard errors in parenthesis. * denotes significant at the 10% level, **denotes significant at the 5% level.

Table 8: TFP growth, adjusted TFP growth with the adjustment to TFP growth, per cent per year

	Full sample			Services			Manufacturing		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
1980 – 85	1.45	1.39	-0.06	0.61	0.60	-0.01	3.00	2.86	-0.14
1985 – 90	0.64	1.22	0.58	-0.62	0.07	0.69	3.43	3.95	0.52
1990 – 95	1.66	1.57	-0.08	1.03	0.98	-0.06	1.96	1.79	-0.16
1995 – 00	0.71	1.24	0.53	0.51	1.17	0.65	0.80	1.04	0.24
Average	1.10	1.36	0.26	0.38	0.70	0.32	2.30	2.41	0.11

Notes: Column (1) gives the estimate of non-adjusted TFP growth, column (2) TFP growth adjusted for adjustment costs and column (3) the adjustment. Based on estimates in regression (1), Table 3.

Chart A : Adjusted TFP growth and the 95% confidence interval

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