Investment-specific technological progress in the United Kingdom[1]

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Abstract

This paper adapts the dynamic general equilibrium model of Greenwood et al (1997, 2000) to decompose labour productivity growth along the balanced growth path for the UK economy into investment-specific technological progress and sector neutral technological progress. We find that investment-specific technological progress in information and communication technology (ICT) assets might account for around 20-30% of labour productivity growth along the balanced growth path. But this conclusion depends crucially on how ICT prices are measured. We show that shocks to investment-specific technological progress can have very different macroeconomic implications from a "neutral shock" that applies to production of all goods. We demonstrate that a permanent increase in the growth rate of ICT-specific technological progress will increase the investment expenditure share but lower the aggregate depreciation rate, while an increase in the return to investment in ICT capital will increase both the expenditure share and the depreciation rate.

1. Introduction

A broad consensus appears to have emerged amongst academics and policymakers alike that there was some improvement in (at least medium-term) US trend productivity growth in the second half of the 1990s. Recent attempts to decompose US labour productivity growth into its main determinants report that information and communication technology (ICT) has made significant contributions through increases in both capital deepening and total factor productivity (TFP) growth over this period. Notable examples include the work by Oliner and Sichel (2000), Gordon (2000), Jorgenson and Stiroh (2000) and Whelan (2000). Kneller and Young (2000) and Oulton (2000) perform similar decompositions for the United Kingdom, though the data constraints are greater in this case.[3] In this paper, this approach is labelled "historical growth accounting". A separate literature using dynamic general equilibrium (DGE) models distinguishes between technological progress that is specific to production of capital goods and technological progress that is "neutral" in the sense that it applies to production of all goods (TFP).[4] The main reference here is Greenwood et al (1997), with Greenwood et al (2000) and Pakko (2000) being recent examples of application. These models do not attempt historical decompositions of labour productivity growth, but instead decompose productivity along the balanced growth path of the economy into investment-specific technological progress and neutral

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3 One of the issues for these papers is that it is not at all clear that there has yet been any increase in trend productivity growth in the United Kingdom, despite strong increases in ICT investment. That is not of course to rule out the possibility that such productivity improvements might be on the horizon.

4 This relates directly to the Solow (1960) and Jorgenson (1966) debate on whether technological progress is "embodied" or "disembodied". Hercowitz (1998) argues that this language is imprecise and instead uses the distinction "sector-specific" and "neutral" technological progress that we also use in this paper.

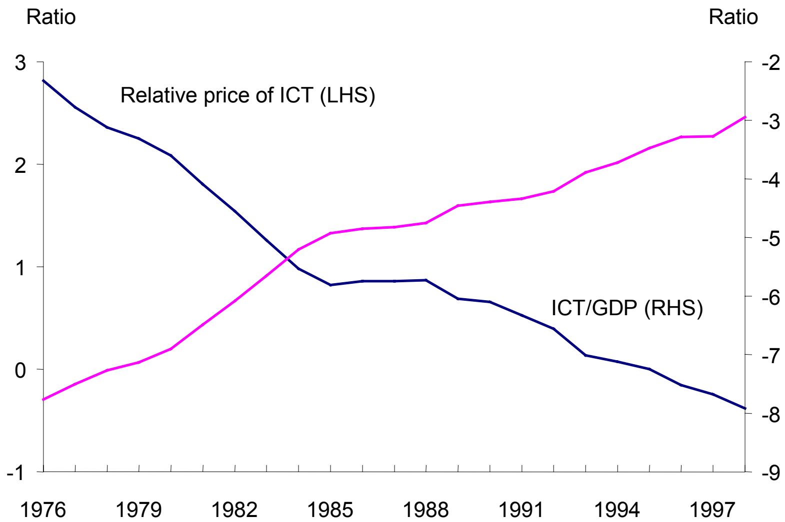
technological progress. This approach emphasises the importance of substitution effects: rapid technological progress in production of capital goods leads to declining prices and hence to increasing capital intensity.

In this paper, we adapt the model of Greenwood et al (1997) to quantify the contribution of ICT-specific technological progress to productivity growth along the balanced growth path for the UK economy, drawing heavily on the efforts of our colleague Nick Oulton at the Bank of England to derive ICT investment data for the United Kingdom. Like Greenwood et al (1997), our motivation is the observation that rapid declines in the relative price of ICT goods have been accompanied by an increase in the ratio of real ICT investment, measured in units of ICT, to (non-housing) output (see Figure 1).[5] We identify technological progress in production of ICT goods as inversely related to the relative price of ICT goods. Using this information and the model's balanced growth path relations, we can calculate the contribution of ICT-specific technological progress to labour productivity growth along the balanced growth path. We find that despite the fact that ICT is a relatively small component of the overall capital stock, ICT-specific technological progress contributes significantly to labour productivity growth along the balanced growth path for the UK economy, accounting for around 20-30% of labour productivity growth.

The key advantage of the DGE approach over the growth accounting is that it permits forward-looking analysis: the short-run macroeconomic implications of a shock to investment-specific technological progress or TFP can be simulated, even if such shocks have not yet hit the economy. This is a particularly useful tool in our context, as it provides a macroeconomic guide for policymakers who wish to incorporate such shocks into their forecasts. We present impulse responses for temporary shocks to both ICT-specific technological progress and neutral technological progress. Shocks to ICT-specific technological progress have very different implications for investment, depreciation, the capital stock and labour productivity than shocks to neutral technological progress. The main driver of these differences is that where an increase in sector neutral technological progress has an immediate “free lunch” effect on final output - final output increases for a given level of factor inputs - technical progress that is specific to production of ICT investment goods requires that investment is undertaken. We describe these effects using a simple baseline model, but also consider extensions and variations that arguably bring the model closer into line with certain empirical regularities. In particular, we consider modifications to the labour supply specification, capital adjustment costs, variable utilisation of capital, and also modify the specification of the stochastic processes driving the shocks.

Figure 1

Relative price of ICT goods and the ICT-output ratio



Note: (1) All series are in logs; (2) ICT is measured in real quantities.

5 The details of how these series are derived are discussed at length in Section 3.1.

The main disadvantage of this approach is that it necessarily loses some of the empirical richness of the historical growth accounts. In particular, the balanced growth decompositions of Greenwood et al (1997) ignore the contribution that ICT makes to labour productivity through the direct effect of TFP improvements in the ICT-producing sector on economy-wide TFP. As such, this would understate ICT's contribution to long-run growth. Against this though, Hercowitz (1998) notes that the treatment of investment-specific technological progress in Greenwood et al (1997) implicitly assumes there are no resource costs to the economy when enjoying investment-specific technological progress. This is likely to overstate the contribution of ICT to long-run economic growth. In the following, we spell out in more detail the relation between the two approaches to growth accounting.

1.1 Balanced growth and "historical" growth accounting

The balanced growth accounting exercise differs from "historical" growth accounting by focusing on the long-run, or steady state, growth path. Growth accounting is about attributing growth at a particular point in time to growth in factor inputs and total factor productivity, taking prices and quantities as given. Take a typical but stylised growth accounting equation:

$$\Delta \ln Y_t = \alpha_t \Delta \ln K_t + (1 - \alpha_t)(\Delta \ln N_t + \Delta \ln H_t) + \Delta \ln TFP_t, \text{ or} \tag{1}$$

$$\Delta \ln Y_t - (\Delta \ln N_t + \Delta \ln H_t) = \alpha_t (\Delta \ln K_t - \Delta \ln N_t - \Delta \ln H_t) + \Delta \ln TFP_t \tag{2}$$

In (1), output growth $\Delta \ln Y_t$ is attributed to growth in capital inputs $\Delta \ln K_t$, labour inputs in heads and hours ($\Delta \ln N_t + \Delta \ln H_t$), weighted by their (possibly time-varying) income shares, and to growth in total factor productivity, $\Delta \ln TFP_t$. (2) is a simple rearrangement that attributes growth in labour productivity, measured per hour, to capital deepening, that is an increase in the capital-labour ratio, and to total factor productivity. Ignoring statistical issues, this is an accounting identity: indeed, total factor productivity growth is calculated to make these equations hold with equality.

These equations are obviously useful tools for providing a historical account of output or productivity growth. But they are less useful as a tool for forward-looking analysis: by taking factor inputs as given, growth accounting does not provide us with a tool for making projections for future growth, because it is conditional on the behaviour of factor demand. The DGE approach differs by characterising a steady state balanced growth path of a dynamic general equilibrium model that imposes constraints on factor inputs. Specifically, the steady state balanced growth path is characterised by constant growth rates. Growth in capital inputs is related to growth in its economic determinants, neutral technological progress and investment-specific technological progress. Employment grows at a constant rate, that is the rate of population, and hours per worker are constant. Income shares are constant. In other words, along the balanced growth path:

$$\Delta \ln Y = \alpha (\Delta \ln Y + \Delta \ln Q) + (1 - \alpha)(\Delta \ln N) + \Delta \ln TFP. \tag{3}$$

where no subscript indicate that the variable is time-invariant. Here, capital growth is characterised as the growth in production of final goods $\Delta \ln Y$ (as this is a homogeneous good model) and the growth that is specific to production of investment goods, $\Delta \ln Q$. This equation is useful because, unlike (1) and (2), it characterises the long run.[6] In the following, we describe Q as sector-specific while TFP is described as sector neutral technological progress; notation-wise, we use the term Z to describe TFP.

Greenwood et al (1997) offer two alternative interpretations of the index, Q. First, in this homogeneous good model, Q can be seen as denoting the amount of capital that can be purchased in efficiency units for one unit of final output. This increases over time with investment-specific technological progress. A second interpretation is that Q represents the vintage of a capital good: each period a new vintage is produced that is successively more productive - of "higher quality" - than the previous one. The empirical counterpart of Q is identical in both interpretations: it equals the inverse of the price of investment goods, adjusted for quality, relative to some measure of the price of the homogeneous good (this must be a consumption deflator as the homogeneous good enters agents' utility functions).

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[6] As mentioned, the disadvantage of this framework is that it is necessarily less rich than a growth accounting framework a la Jorgenson: in this example, and in our balanced growth accounting, we do not take account of factors such as labour quality that are obviously important in providing an account of economic growth.

In the growth accounting literature, the expenditure measure of GDP growth includes a measure of investment that allows for the "quality" of capital goods having improved over time. The empirical implication is that left hand side of (3) should be deflated by a quality-adjusted deflator to reflect the quality improvement in the investment component of aggregate demand. In the homogeneous good framework of Greenwood et al (1997), no such allowance is made. In this literature, output is expressed in units of the homogeneous good and so the empirical counterpart is that output should be deflated by a consumption deflator.[7] Hercowitz (1998) sets out a framework that he argues nests the positions of both these traditions. In particular, he shows that the homogenous good model embedded in Greenwood et al (1997) assumes there are no resource costs to the economy from investment-specific technological progress, while arguing, following Hulten (1992), that quality-adjusting the left hand side of (3) is a way of incorporating such resource costs: an increase in quality requires a reduction in another expenditure component for a given level of aggregate output. In a one-sector model, this has undesirable implications; in particular, the relative price of investment goods is constant, inconsistent with the empirical evidence, and the difference between investment-specific and sector neutral progress can no longer be identified. Hercowitz's (1998) essay implies that a more general model that allows for *some* form of resource cost would be superior. In the absence of such a model, we follow Greenwood et al (1997, 2000), implicitly assuming there are no resource costs of investment-specific technological progress.[8]

The remainder of the paper is organised as follows. In Section 2 we set out the baseline model, characterising the equilibrium of our dynamic economy and its balanced growth path. In Section 3, we calibrate the baseline model to the UK economy and decompose labour productivity growth along the balanced growth path into investment-specific technological progress and neutral technological progress. Section 4 presents the dynamic analysis of the baseline model, drawing out the key differences in the macroeconomic effects of investment-specific shocks and neutral shocks to technological progress. Section 5 presents extensions of the baseline model. We choose those extensions from the existing theoretical literature as these address some obvious shortcomings of the baseline model. Section 6 considers some "scenarios for structural change": more specifically, we consider the dynamic implications of permanent rather than temporary shocks to the level of technology, and draw out some implications of changing the growth rate of technological progress and the return to investment in some comparative statistics exercises. Finally, Section 7 concludes.

2. The baseline model

In the following, we describe the baseline model and characterise equilibrium and the balanced growth path. The model follows Greenwood et al (1997) closely, with the main differences being that we split the capital stock into ICT (indexed by *e* for exciting) and non-ICT (indexed *d* for dull) capital rather than equipment and structures, and we allow for investment-specific technological growth in both types of capital.[9] This latter distinction makes the analysis more relevant to the current UK policy debate. But

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7 This assumes that the economy is closed. In an open economy the empirical counterpart should, strictly speaking, be the domestically produced component of the consumption deflator. This is consistent with the homogeneous good assumption if we assume that countries specialise in production and that all imports are final goods.

8 Jorgenson and Stiroh (2000) further argue that the investment-specific technological progress identified by Greenwood et al (1997) as accounting for the major component of postwar US economic growth in fact reflects disembodied technological progress in the production of semiconductors used as intermediate inputs. We do not comment on this, except to note that in our homogeneous good model such a distinction cannot be made.

9 The non-stationarity of the quality-adjusted equipment investment-to-GDP ratio and the stationarity of the structures investment-to-GDP ratio in the United States is used by Greenwood et al (1997) to motivate their assumption that there is sector-specific technological progress in equipment but not in structures. But the structures investment data are not quality-adjusted in the same way as the equipment data in the United States: certainly no hedonic adjustments are made. Even with sector-specific technological progress in structures, the ratio of non-quality adjusted structures to GDP would be stationary along the balanced growth path. So this is not in fact a good motivation for their assumption of no sector-specific technological progress in structures. Our series for the quality-adjusted ICT ratio with respect to GDP is non-stationary in the United Kingdom too, so we assume that investment-specific technological progress occurs in that sector. As with the structures data in the United States, however, our non-ICT data are not hedonically adjusted. In the absence of such data for non-ICT investment, we follow Greenwood et al (1997) and use the stationarity properties of the non-quality adjusted data to justify our characterisation of sector-specific technological progress in the non-ICT sector. In particular, we allow for

recognising the particularly severe data constraints we face for quality-adjusted non-ICT prices in the United Kingdom, we also present balanced growth accounting estimates where it is assumed that only ICT is subject to investment-specific technological progress.

The key characteristic that distinguishes this model from a standard one-sector growth model is the capital accumulation equation. In the current model, the stock of capital of type $i = d, e$ at time $t + 1$, K^i_{t+1}, is related to the stock of capital and investment at time t, K^i_t through:

$$K^i_{t+1} = (1-\delta_i)K^i_t + Q^i_t X^i_t, \tag{4}$$

where δ_i is a parametric depreciation rate.[10]

The factor Q^i_t determines the amount of capital of type i that can be purchased for one unit of final output; in the standard neoclassical growth model $Q^i_t \equiv 1$ but here we allow Q to increase over time. Notice that investment X^i_t is measured in units of final goods, so aggregate investment X_t is given by $X_t = \Sigma X^i_t$. Here, we interpret Q^i_t as a measure of technological change specific to the production of investment good i: a rise in Q_t lowers the marginal cost of producing investment goods measured in units of final goods, and so Q^i_t is inversely related to the relative price of capital good i. One simple way to spell out this relationship and to outline the sectoral interpretation of the model is the following: capital goods are produced by firms, using materials M^i_t as the only input in the production process, charging a price P^i_t for their output in a perfectly competitive market. Such a firm maximises profits $P^i_t\left(Q^i_t M^i_t\right) - M^i_t$ where $\left(Q^i_t M^i_t\right)$ is the firm's output and the price of materials, in the form of final goods, is normalised at one. The first-order condition for this problem, where the firm determines its output levels taking prices and technology as given, obviously implies that $P^i_t = 1/Q^i_t$. We use this relationship in the calibration exercise, where the growth rate of Q^i_t is calibrated using series on relative prices of capital goods. As emphasised in Section 1.1, technological progress that is "embodied" in capital can be interpreted as "disembodied" technological progress in the capital-producing sector. In describing the model in the following, we follow a convention whereby capital letters denote trended variables and lower case letters indicate stationary variables. All quantity variables are measured in per capita terms.

2.1 The agents

The economy is inhabited by an infinitely-lived, representative agent who has time-separable preferences U defined over consumption C_t of final goods and leisure L_t. The agent chooses C_t, L_t and investment X_t to maximise the expected present value of contemporaneous utility, using a discount factor β, subject to the budget constraint:

$$C_t + X_t = (1-\tau_K)(r^d_t K^d_t + r^e_t K^e_t) + (1-\tau_l)W_t h_t + T_t. \tag{5}$$

Here, consumption and investment cannot exceed the sum of labour and capital rental income net of taxes and lump sum transfer, T_t; wages and hours worked are W_t and h_t respectively, and τ_l is the tax rate on labour income. Rental income has two components: there is rental income from capital of

sector-specific technological progress in the non-ICT sector too. So we implicitly assume that there is some form of quality adjustment in the non-ICT data even if that adjustment is not hedonic. This characterisation of sector-specific technological progress in the United Kingdom is consistent with Greenwood et al's analysis for the United States insofar as non-ICT investment contains non-ICT elements of equipment that Greenwood et al (1997) assume is subject to sector-specific technological progress. Gort et al (1999) use a panel data set on rental values to estimate sector-specific technological progress in US structures investment too.

[10] Fraumeni (1997) reports that geometric depreciation is in general a good approximation to the decline of asset prices with age.

type *d* at rate r_t^d and type *e* at rate r_t^e, with quantities at K_t^d and K_t^e respectively. The tax rate on rental income is τ_κ.

Agents' capital holdings of type $i = d$, e evolve according to (4), reported below as (6) for convenience:

$$K_{t+1}^i = (1-\delta_i)K_t^i + Q_t^i X_t^i, \tag{6}$$

where δ_i is the depreciation rate for capital of type *i*.

The agents maximise their expected lifetime utility subject to the budget constraint (5) and the accumulation equations (6) by choosing C_t, L_t and X_t^i. The first-order conditions for this problem are:

$$U_l(C_t, 1-h_t) = U_c(C_t, 1-h_t)(1-\tau_l)W_t$$
$$\lambda_t^e = \lambda_t^d = U_c(C_t, 1-h_t)$$
$$\lambda_t^i / Q_t^i = \beta E_t \lambda_{t+1}^i \left((1-\tau_\kappa) r_{t+1}^i + \beta(1-\delta_i)/Q_{t+1}^i\right), i = d, e \tag{7}$$

The first condition equates the marginal disutility from an additional hour of work with the marginal return to working, adjusted for taxes and measured in utility terms. The second condition describes the marginal utility of an additional unit of capital of type *i*: as there are no additional resource costs associated with changing capital from one type to the other, the marginal utilities of an additional unit of the capital goods are equal. And as capital goods can be transformed into consumption goods at no cost, the marginal utility of an additional unit of capital equals the marginal utility of consumption. The third condition is the standard Euler equation, equating the marginal cost of acquiring an additional unit of capital today in utility terms with the discounted expected return to this investment, consisting of expected after-tax rental income and the value of having this unit next period, adjusted for depreciation and possible capital losses.

2.2 Firms

In the baseline model, Q_t^i is assumed to capture all differences between production of final and investment goods: apart from technological progress, the production process is identical across goods. So a characterisation of firms producing final goods is sufficient. The firms in this economy have access to a production technology for final goods that uses capital of both types and labour:

$$Y_t = F(K_t^e, K_t^d, Z_t h_t), \tag{8}$$

where Y_t is output and Z_t is labour augmenting technological progress that applies to production of all goods. *F* is assumed to be continuous and concave in each of the inputs, and homogenous of order one. Goods and factor markets are assumed to be perfectly competitive, so that firms in their production decisions take output and factor prices as given. Firms rent capital and labour on a period by period basis - the workers hold the capital stock - so the firms' dynamic optimisation problem is identical to a sequence of the following static optimisation problems:

$$\max \Pi_t = F(K_t^e, K_t^d, Z_t h_t) - r_t^e K_t^e - r_t^d K_t^d - W_t h_t. \tag{9}$$

The first-order conditions for this problem are:

$$F_{K^i}(K_t^e, K_t^d, Z_t h_t) = r_t^i;\ i = d, e \tag{10}$$

$$F_h(K_t^e, K_t^d, Z_t h_t) = W_t. \tag{11}$$

There are no dynamic aspects to the firms' decisions, so the conditions describing factor demand simply state that marginal cost, given by real rental rates and real wages, equals marginal factor products, given by the marginal products of capital and labour.

2.3 Government

We incorporate a tax-levying government in the model because of the potentially important effects that distortionary taxes have on capital accumulation, and hence on the decomposition exercise. We are not analysing the use of taxation in demand management in this paper, and simply assume that the government balances its budget period by period by returning revenues from distortionary taxes to the agents via lump sum transfer. The government's budget constraint is then:

$$T_t = \tau_k (r_t^e K_t^e + r_t^s K_t^s) + \tau_l W_t h_t. \tag{12}$$

This completes the description of the baseline model. In the following, we characterise equilibrium and the balanced growth path.

2.4 Equilibrium and balanced growth

To facilitate our exposition of the steady state, we make assumptions about particular functional forms here. We assume a Cobb-Douglas production function[11] and a logarithmic specification for the instantaneous utility function:

$$Y_t = Z_t (K_t^e)^{\alpha_e} (K_t^d)^{\alpha_d} (h_t)^{1-\alpha_e-\alpha_d} \tag{13}$$

$$U(C_t, L_t) = \theta \ln(C_t) + (1-\theta)\ln(1-h_t). \tag{14}$$

Prior to characterising the balanced growth path, we describe the equilibrium of this economy. Equilibrium is characterised by a set of time-invariant decision rules for C_t, X_t^i and h_t, pricing functions for W_t, r_t^i, a balanced budget rule, and laws of motion for the aggregate capital stock that solve the agents' and firms' optimisation problem and satisfy the economy's resource constraint. These conditions are summarised by the following set of equations:

$$\frac{h_t}{(1-h_t)} = \frac{\theta}{1-\theta}(1-\tau_l)(1-\alpha_e-\alpha_d)\frac{Y_t}{C_t} \tag{15}$$

$$\lambda_t^i / Q_t^i = \beta E_t \lambda_{t+1}^i \left((1-\tau_\kappa)\alpha_i \frac{Y_{t+1}}{K_{t+1}^i} + (1-\delta_i)/Q_{t+1}^i \right), i = d,e \tag{16}$$

$$\lambda_t^e = \lambda_t^d = \frac{\theta}{C_t} \tag{17}$$

$$\gamma_{t+1}^L K_{t+1}^i / Q_t^i = (1-\delta_i) K_t^i / Q_t^i + X_t^i, i = d,e, \tag{18}$$

$$C_t + X_t^e + X_t^d = Z_t (K_t^e)^{\alpha_e} (K_t^d)^{\alpha_d} (h_t)^{1-\alpha_e-\alpha_d}. \tag{19}$$

The first three conditions, (15)-(17), come straightforwardly from combining the first-order conditions characterising the agent's problem with those characterising the firms' and hence need no further comment. (18) characterises the economy's accumulation of capital of type *i*, where the term γ_{t+1}^L is the gross growth rate of population. The resource constraint, (19), is obtained from combining the budget constraint of the worker with the government budget constraint, using the homogeneity properties of the production function.

We can now characterise the non-stochastic, steady state balanced growth path of this model as an equilibrium satisfying conditions (15)-(19) where all variables grow at a constant rate. Denote the *gross growth rate* of output per capita, Y_t, along the balanced growth path with g and of capital per capita, K_t^i, with g_i.[12]

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[11] Notice that we have detached the technology variable Z_t from labour inputs here, so we have not written Z_t as labour augmenting. This is purely for convenience and ease of comparison with Greenwood et al (1997): with a Cobb-Douglas production, labour augmenting and factor neutral technological progress are identical up to a constant.

[12] So, for example, a growth rate of 2% is a gross growth rate of 1.02.

A balanced growth path obviously requires that hours per worker do not grow (otherwise they will hit their upper or lower bound). Combined with the fact that this is a full employment economy, this implies that total hours grow at the rate of population: the only contribution from hours worked to output growth comes from growth in labour force, and ultimately, as participation rates along a balanced growth path are constant, from population growth. In the model, we assume no population growth along the balanced growth path, to ease the description and facilitate comparison with Greenwood et al (1997), that is assuming that $\gamma_{t+1}^{L}=1$. This has no implications for the growth accounting exercise as we are accounting for labour productivity growth, which by nature is independent of the size of the population, but would obviously affect an estimate of the growth rate of aggregate output along a balanced growth path.

From (19), balanced growth requires that the demand components of the model, that is C_t, X_t^d and X_t^e, grow at the same gross rate as output Y_t, g. Furthermore, let γ_e, γ_d and γ_z describe the steady state gross growth rates of Q_t^e, Q_t^d and Z_t. Using the production function, this implies that:

$$g=\gamma_z g_e^{\alpha_e} g_d^{\alpha_d}. \tag{20}$$

From (20), in the long run, increases in output can be accounted for by neutral technological progress or, equivalently because the production function is Cobb-Douglas, by labour augmenting technological progress, γ_z, and by increases in the capital stock per capita, equivalent to capital deepening, $g_d^{\alpha_d} g_e^{\alpha_e}$. But growth in the capital stock depends on technological progress in production of capital goods, *in addition to* neutral technological progress. The dependence stands out from the capital accumulation equations, where by (18), $g_i = g\gamma_i$. Combining this with (20), the growth rates can be expressed as functions of the exogenous growth rates of the production technologies:

$$\begin{aligned}
g &= \gamma_z^{1/(1-\alpha_e-\alpha_d)} \gamma_e^{\alpha_e/(1-\alpha_e-\alpha_d)} \gamma_d^{\alpha_d/(1-\alpha_e-\alpha_d)}, \\
g_d &= \gamma_z^{1/(1-\alpha_e-\alpha_d)} \gamma_e^{\alpha_e/(1-\alpha_e-\alpha_d)} \gamma_d^{(1-\alpha_e)/(1-\alpha_e-\alpha_d)}, \\
g_e &= \gamma_z^{1/(1-\alpha_e-\alpha_d)} \gamma_e^{(1-\alpha_d)/(1-\alpha_e-\alpha_d)} \gamma_d^{\alpha_d/(1-\alpha_e-\alpha_d)}.
\end{aligned} \tag{21}$$

The equilibrium conditions (15)-(19) can now be transformed by expressing them in terms of the following variables, where lower case indicates stationary variables:

$$\begin{aligned}
&y_t = Y_t/g^t; c_t = C_t/g^t; x_t^e = X_t^e/g^t; x_t^d = X_t^d/g^t; k_t^d = K_t^d/g_d^t; k_t^e = K_t^e/g_e^t; \\
&q_t^e = Q_t^e/\gamma_e^t; q_t^d = Q_t^d/\gamma_d^t; z_t = Z_t/\gamma_z^t; \tilde{\lambda}_t^e = \lambda_t^e g^t; \tilde{\lambda}_t^d = \lambda_t^d g^t.
\end{aligned} \tag{22}$$

These variables are stationary, so a balanced growth path with constant growth in the non-normalised variables can be characterised as a stationary state with no growth in these transformed variables. Let no time subscript indicate stationary state values. Then the balanced growth path is characterised by the following set of equations:

$$\frac{1-\alpha_d-\alpha_e}{(1-\tau_l)}\frac{1-\theta}{\theta}\frac{y}{c}=\frac{1-h}{h} \tag{23}$$

$$\frac{\beta}{g\gamma_i}\left(\left(1-\tau_k\right)\alpha_i\frac{y}{k^i}+\left(1-\delta_i\right)\right)=1,\ i=d,e \tag{24}$$

$$\frac{k^i}{y}(g\gamma_i-(1-\delta_i))=\frac{x^i}{y},\ i=d,e \tag{25}$$

$$\tilde{\lambda}^e=\tilde{\lambda}^d=\frac{\theta}{c} \tag{26}$$

$$\frac{c}{y}+\frac{x^e}{y}+\frac{x^d}{y}=1 \tag{27}$$

Before moving on to assessing the importance of investment-specific technological progress in accounting for long-run growth, it is worth characterising the steady state growth path in words. Along the steady state path, productivity in the production of capital goods is increasing faster than productivity in production of consumption goods, so the relative price of capital goods is falling at a constant rate. Along this path, capital-labour ratios are increasing faster than labour productivity, so capital deepening is faster than output growth. Investment in capital increases in line with the capital stock and hence faster than output but, due to falling prices, investment expenditure grows in line with output, so the investment expenditure share of GDP stays constant.

3. Characterising the balanced growth path

To assess the contribution of investment-specific technological progress to long-term growth, the parameters of the model must be assigned values. We follow the calibration approach advocated by Kydland and Prescott (1982). According to this approach, parameter values are set either according to related empirical evidence or, in the absence of such evidence, to ensure that the model's balanced growth path is consistent with averages observed in UK aggregate data over the sample period. Consistency with the balanced growth path is an important feature of this approach - the parameter values must be set consistently such that for the chosen set of parameters, the equations characterising the balanced growth path, (23)-(27), are satisfied. In this sense, the model guides our interpretation of the data.

3.1 Calibration

The parameters of the model are

$\{\theta, \beta, \alpha_e, \alpha_d, \delta_d, \delta_e, \gamma_d, \gamma_e, \gamma_z, \tau_l, \tau_k\}$.

The growth rates γ_d and γ_e are calibrated directly using deflators for non-ICT and ICT investment goods.[13]

Reliable hedonic deflators for ICT goods that attempt to control for quality improvements are not available in the United Kingdom. In the absence of such data, we follow Broadbent and Walton (2000), Kneller and Young (2000) and Oulton (2000a) in employing a law of one price-type argument and use deflators from the United States, converted to GBP using the USD/GBP exchange rate.[14,15] In particular, we use estimates of nominal investment expenditure on computers, software and telecommunications in the United Kingdom derived from input-output tables (see Oulton (2000a)[16]), to weight together computer, software and telecommunications deflators from the US NIPA.[17] We treat the resulting chain-weighted Fisher price indices as our ICT investment deflator series.

According to Moulton et al (1999) and Parker and Grimm (2000), only prices for prepackaged software in the US NIPA are calculated from constant-quality price deflators based on hedonic methods. Prices for firms' own-account software in the NIPA are based on input cost indices that implicitly assume no increase in the productivity of programmers. Custom software prices are assumed to be a weighted average of prepackaged software prices and own-account software (with an arbitrary weight of 75% on own-account software). But it is implausible to assume that the productivity of programmers has not improved over time. This might lead to a significant understatement in the decline in the relative price of software and hence in our ICT deflator. To investigate the implications of this possible

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13 K_d, while representing "dull" capital, is productive capital, so excludes housing capital. This is appropriate because our measure of output, Y_t, excludes housing services.

14 Gust and Marquez (2000) discuss how Australia, Denmark and Sweden all officially use US hedonic computer deflators, exchange rate-adjusted, to proxy quality-adjusted computer prices in their respective countries.

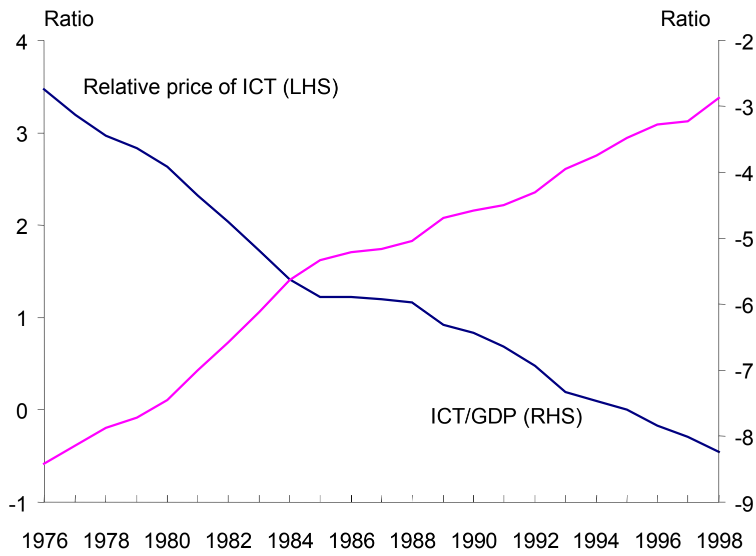
15 Because ICT products are traded on a global market, it seems likely that the rate at which quality-adjusted prices are falling over time should be the same in the United Kingdom and the United States. The *level* of prices may differ, say because of market discrimination by suppliers who possess monopoly power. But even changes in the degree of monopoly power are likely to be swamped by the huge falls in US prices related to investment-specific technological progress.

16 Oulton (2000a) notes that while the growth rates of software investment in nominal terms have been similar in the United States and the United Kingdom in the official data, the level of UK software relative to computer investment is much smaller in the United Kingdom. Oulton suggests that an upward adjustment be made to the UK data to control for this.

17 There are currently no official data available in the United Kingdom for our definition of ICT investment.

mismeasurement for assessing the importance of ICT investment-specific technological progress, we also present balanced growth accounting estimates calculated on the assumption that prepackaged software prices capture price trends for all types of software (we refer to this variant as the "high software" case as distinct from the "low software" case consistent with NIPA data).[18] The "high software" relative price and quantity-output ratio are reported in Figure 2 while the "low software" is the data underlying Figure 1.

Figure 2
Relative price of ICT goods and the ICT-output ratio.
High software.



Note: (1) All series are in logs; (2) ICT is measured in real quantities.

Of course, ICT goods are not the only types of investment good that have been subject to quality improvement (see Gordon (1990)). Hedonic price measurement by the Bureau of Economic Analysis in the United States is restricted to ICT goods. We assume for illustrative purposes that their adjustment for quality improvement for non-ICT (excluding housing) goods using methods other than hedonic regressions is again a good proxy for the quality-adjusted price of non-ICT goods in the United Kingdom. Again relying on a weak law of one price-type argument, we construct a chain-weighted Fisher price series for non-ICT goods (excluding housing) using deflators from the US NIPA. This time, as the nominal investment shares corresponding to the NIPA breakdown for non-ICT goods are not readily available for the United Kingdom, we have used US expenditure data to construct the weights. This is an assumption we will revisit in future drafts of this paper, once we have derived non-ICT investment and the corresponding deflators for the United Kingdom. Given, however, the particularly severe data constraints we face in deriving a plausible quality-adjusted non-ICT deflator for the United Kingdom, we also present balanced growth decompositions for the case where we assume that there is investment-specific technological progress for ICT investment goods only.

The growth rate g is calibrated by estimating average labour productivity growth over the sample. The within-sample properties of hours per capita and labour force participation differ from those of a balanced growth path: it is well known that since 1976, average hours per worker have declined and participation rates in the United Kingdom have increased. The correct way to estimate output/productivity growth along a balanced growth path where such changes are not possible is to

[18] Jorgenson and Stiroh (2000) go further still and report traditional growth accounting estimates under the assumption that software prices fall at the even more rapid rate reported by Brynjolfsson and Kemerer (1996) for microcomputer spreadsheets in 1987-92.

control for these factors within sample: we hence measure output growth per hour, and infer the long-run output growth by combining this measure with the balanced growth requirement that hours per worker and participation rates are constant.

The depreciation parameters δ_d and δ_e are key parameters in the construction of the ICT and non-ICT capital stocks using (6). For δ_e, we use the time series for constant price capital stock of computers, software and telecommunications in Oulton (2000a)[19] to weight together the depreciation rates for computers, software and telecommunications in Jorgenson and Stiroh (2000).[20] The sample average (1976-98) of the resulting weighted average depreciation rate series is 0.22 assuming software low and 0.20 assuming software high. The depreciation rate for non-ICT capital, δ^d, is derived using the depreciation rate for ICT capital together with a series for the implied aggregate depreciation rate. For the aggregate rate, δ_t, we use estimates of the constant price capital stock for buildings (excluding dwellings), vehicles, plant, intangible fixed assets and costs of ownership transfer from Oulton (2000b) to weight together depreciation rates taken from Fraumeni (1997). The formula we use for the implied depreciation rate is:

$$\delta_t = \frac{X_t - \Delta K_{t+1}}{K_t} \tag{28}$$

where no superscript indicates aggregate values and the capital stock is measured at the beginning of period t. From this, we derive a series for δ_t^d as a weighted average of the depreciation rate of each type of asset, where the weights are each asset's share of the aggregate capital stock. From this economy-wide depreciation rate (excluding housing) we subtract the share of ICT capital in the total non-dwelling capital stock multiplied by our estimate of the ICT depreciation rate, δ_e. The sample average of the resulting series is 0.059 (to three decimal points on both low software and high software assumptions).[21]

With these parameters determined, the balanced growth path investment-capital ratios can be determined from the capital accumulation equations (25). We then measure the ratios x^j/y using the data from Oulton (2000a,b). Given that we use the same deflator for both investment and output, these can be measured in nominal or real terms. From these we can infer the consumption-output ratio $c/y = 1 - \Sigma x^j/y$.[22]

From the income side of National Accounts, a steady state labour share of 70% is estimated. A marginal tax rate on labour income of 42.7% is used, τ_l, based on the work by Millard et al (1999). This

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19 These capital stock series are constructed by applying the perpetual inventory method to UK nominal investment data deflated by US deflators. In principle, we could have used these series for our measure of the ICT capital stock. We construct our own estimates using the perpetual inventory method in equation (6) because we wish to identify *q* separately.

20 Specifically, we assume depreciation rates of 31.5% per year for computers and software and 11% per year for telecommunications.

21 This method of calculating ICT and non-ICT capital stocks produces estimates of the real wealth stock at replacement value. The economic depreciation rates, δ_t^j, denote the decline in the replacement value of a unit of capital (relative to the price of new capital) that occurs as the unit ages. But it is the real productive capital stock that enters into the production function in (13). So the appropriate depreciation rate is actually a physical decay rate: the rate at which a unit of capital of a given vintage becomes less capable of producing output as it ages. In a simple model of vintage capital with investment-specific technological progress, Whelan (2000) shows that the real wealth stock backed out using quality-adjusted real investment and geometric, quality-adjusted economic depreciation rates is identical to the productive capital stock. This reflects the fact that the quality-adjusted economic depreciation rate in the simple model equals the rate of physical decay. But Whelan (2000) notes that the simple model does not allow for the technological obsolescence we observe in the real world: firms sometimes retire productive capital when the marginal product falls below some fixed "IT support cost". (Whelan quotes research in the United States by the Gartner Group (1999) that for every \$1 spent on computers in 1998, there was another \$2.4 spent on wages of IT workers and consultants.) Whelan shows that allowing for such technological obsolescence in the vintage capital model leads to a breakdown of the equivalence between real wealth measures of the capital stock and the productive capital stock. In particular, the economic depreciation rate now exceeds the physical decay rate that should be used in derivation of the productive capital stock. The depreciation rates we use in our study are economic depreciation rates based on studies underlying the US NIPA measures of the real wealth stock. So on Whelan's arguments they may be too high for growth accounting purposes.

22 Note that ICT and non-ICT investment includes government investment in these assets respectively. And our measure of the consumption-output ratio includes government consumption.

is the average value of the marginal tax rate faced by a worker on average earnings over the period 1976-98. Specifically, it is the basic rate of income tax plus the marginal national insurance contribution faced by such a worker, divided by one plus the marginal national insurance contribution faced by their employer. With Cobb-Douglas and perfect competition, the labour share is equal to 1 – α_d – α_e. We also determine h, the proportion of hours available used for work, as 0.26. This is the average portion of non-sleeping time spent in work reported in two "use of time" studies in the United Kingdom discussed by Jenkins and O'Leary (1997). This is very similar to the 0.24 used by Greenwood et al (1997) for the United States. With these estimates at hand, the first-order condition for labour characterising the balanced growth path determines the utility parameter θ, (23).

Finally, to determine the remaining parameters, β, α_d, α_e and τ_κ, we estimate the average after-tax real rate of return on capital. We assume that this equals 5.3% as in Bakhshi et al (1999). This is computed using estimates of the "effective" marginal tax rate on savings in the United Kingdom (which is based on estimates for the average marginal income tax rate on capital income following King and Fullerton (1984) and estimates of the effective tax rate on capital gains). This ties down the ratio β/g. This obviously ties down β for a given estimate of g, but also the three remaining parameters as the solution to the two steady state Euler equations, (24), and the restriction that (1 – α_d – α_e) is equal to labour share of income. The resulting values are α_d = 0.2616 and α_e = 0.0305 for the "low software" case, and α_d = 0:2618 and α_e = 0:0303 in the "high software" case.

Table 1 summarises the baseline calibration.

Table 1

Calibration of baseline model

	Low	**High**		**Low**	**High**		**Low**	**High**		
γ_d	1.02	1.02	δ_d	0.059	0.059	α_d	0.262	0.262	τ_t	0.427
γ_e	1.15	1.19	δ_e	0.190	0.212	α_e	0.031	0.030	h	0.26
γ_z	1.01	1.01	δ	0.065	0.065	τ_κ	0.320	0.280	β	0.972
									x^d/y	0.137
									x^e/y	0.019

Note: "Low"/"high" refers to the case where productivity growth in software production is assumed to be low/high.

3.2 Accounting for growth

We use our 1976-98 sample period, for which we have a complete data set, to estimate γ_d and γ_e. Given our estimates of α_d and α_e, we use the production function in (13) to back out a series for Z_t. The annual percentage change in Z_t gives us our estimate of γ_z. With our estimates of γ_z, γ_d, γ_e, α_d and α_e we can use equation (20) to decompose long-run growth into contributions from investment-specific technological progress for ICT and non-ICT separately and for neutral technological progress. The derived series for Z_t is illustrated in Figure 3. Two points can be noted. First, Z_t fell at the beginning of the 1990s, having peaked in 1988, and only recovered to this level in 1997. Second, this period of weak sector neutral technological progress coincides with the period where investment-specific technological progress for ICT takes off. So when changes in investment-specific technological progress are allowed for, the weakness of TFP in the early 1990s becomes even more pronounced. Of course, movements in Z and Q^e will reflect cyclical as well as trend movements in technological progress.

Table 2 summarises the results for both the low software and high software cases. This shows that ICT investment-specific technological progress contributes between 0.66 and 0.78 percentage points to labour productivity growth along the balanced growth path; non-ICT investment-specific technological progress contributes 0.85 percentage points and the remaining 1.57-1.59 percentage points is explained by TFP.

Figure 3

ICT investment-specific and neutral technological progress

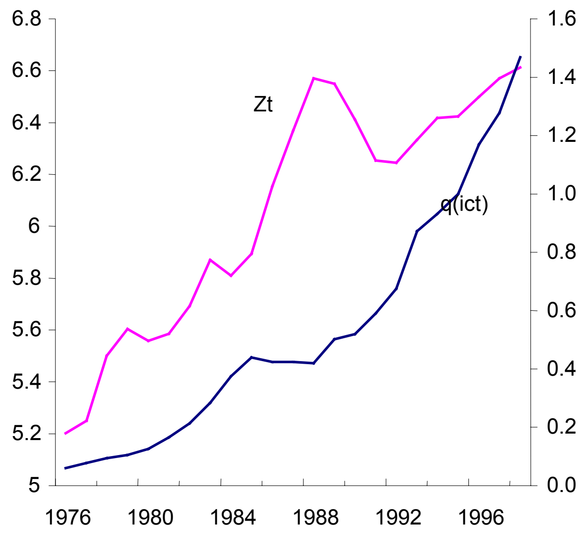


Table 2

Decomposing labour productivity growth

	TFP	ICT-specific	Non-ICT specific	Implied total
"Low software"	1.59%	0.66%	0.85%	3.12%
"High software"	1.57%	0.78%	0.85%	3.23%

Note: The implied total does not equal actual average labour productivity growth over the 1976-98 sample period. The error reflects differences between the sample average and the balanced growth path.

The particularly severe data constraints we face for quality-adjusted non-ICT prices for the United Kingdom were discussed in Section 3.1. Due to these constraints, we compute a balanced growth decomposition on the assumption that investment-specific technological progress occurs for ICT only (ie γ_d = 1 at all times). Table 3 summarises the results from this exercise. In this case, ICT investment-specific technological progress of course still contributes 0.66-0.78 percentage points to labour productivity growth along the balanced growth path, while TFP contributes the remaining 1.50-1.52 percentage points.

Table 3

Decomposing labour productivity growth

	TFP	ICT-specific	Implied total
"Low software"	1.52%	0.66%	2.18%
"High software"	1.50%	0.78%	2.29%

Note: The implied total does not equal actual average labour productivity growth over the 1976-98 sample period. The error reflects differences between the sample average and the balanced growth path.

These contributions from ICT-specific technological progress appear very large (around 20-30% of total labour productivity growth). They reflect the dual assumptions of very sharply falling relative prices of ICT investment goods and the fact that the ICT capital stock as a percentage of GDP in the United Kingdom appears to have been at near-US levels over our sample period. To the extent that the significant contribution of ICT to long-run growth is predicated on sustained falls in the relative price of ICT goods, this echoes the conclusions of Jorgenson and Stiroh (2000), Oliner and Sichel (2000), Gordon (2000), Bosworth and Triplett (2000) and others. They have argued that sustained high productivity growth rates in the United States will in part depend on continued sharp falls in the relative price of computers. This is an important lesson to come out from our balanced growth accounting exercise too.

4. Dynamic aspects of the baseline model

In the previous section, we characterised the balanced growth path of the model. In the following, we will analyse fluctuations around this steady state path, caused by temporary but persistent shocks to technology. This analysis is based on a log-linearised approximation to the economy characterised by (15)-(19), solved using the techniques described in King et al (1988). Using this approximation, we can describe the dynamics of the variables of interest as percentage deviations from the steady state path described above. Notice that, as before, we assume a constant population so variations in labour inputs are caused by variations in hours. In an economy with deterministic population growth, these variables should be interpreted in per capita terms. The details of these derivations are omitted here, but a technical appendix setting out the details is available on request.

To analyse the effects of shocks to technological progress, a stochastic process for the exogenous shocks must be specified. For that purpose we write:

$$Q_t^i = X_t^i q_t^i,$$

$$Z_t = X_t^z z_t$$

where capital letters indicate the trend component and lower case letters denote the cyclical component. The baseline case that we have used in the growth accounting exercise assumes a deterministic trend so that:

$$\ln\left(X_t^i\right) = \gamma_0^i + t\ln\left(\gamma^i\right). \tag{29}$$

To characterise business cycle fluctuations around this trend, we specify that:

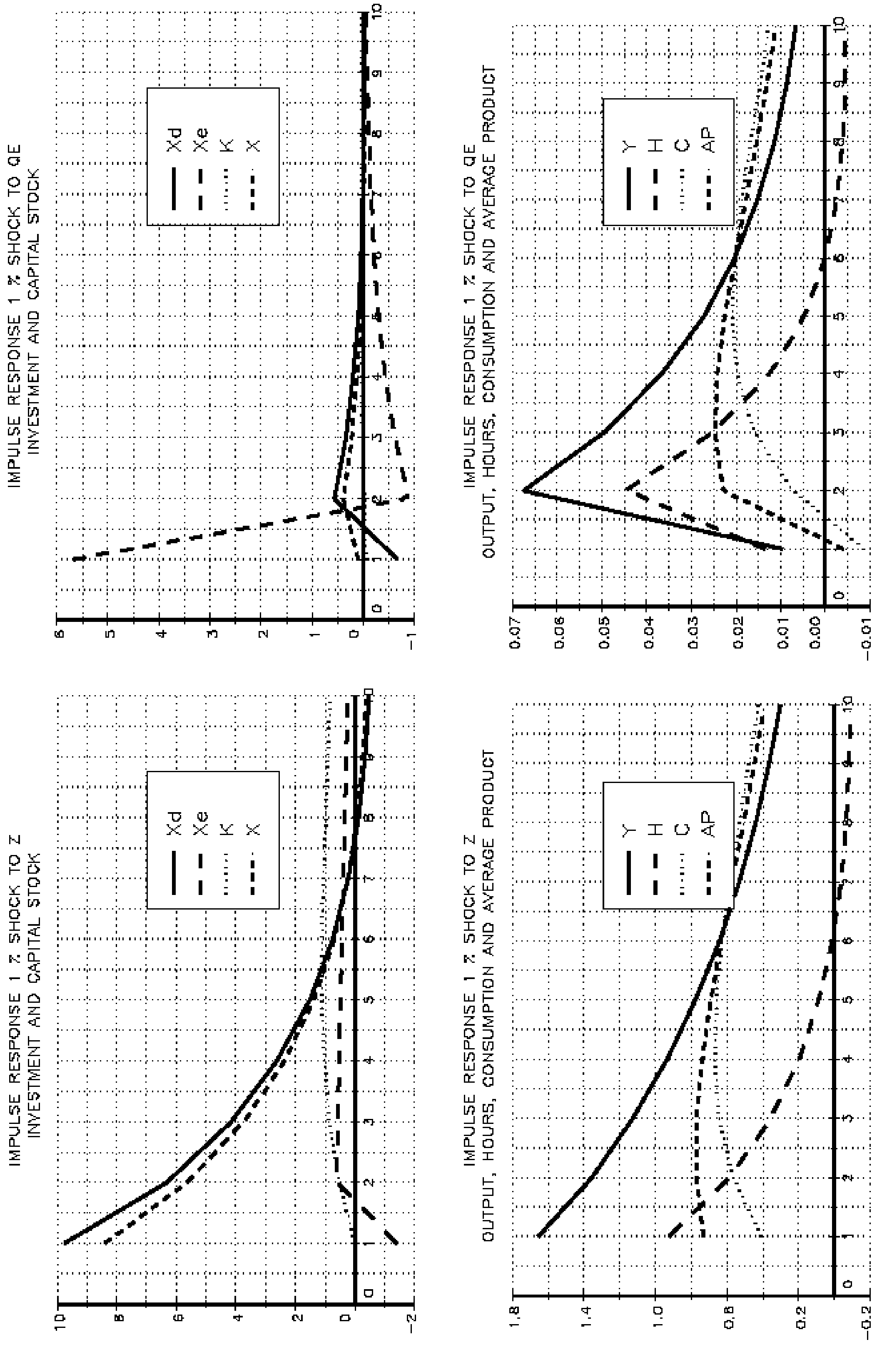
$$q_t^i = \exp\left(a_t^i\right);\, a_t^i = \rho_i a_{t-1}^i + \varepsilon_t^i,\ i = d,e$$

$$z_t = \exp\left(a_{zt}\right);\, a_{zt} = \rho_z a_{t-1}^z + \varepsilon_t^z \tag{30}$$

We focus solely on impulse response functions, so the only parameters of interest are the persistence parameters ρ_i, $i = d, e, z$. We estimate ρ_i by fitting an AR(1) with a constant and a linear trend to the series for (the natural logs of) Q_t^d, Q_t^e and Z_t derived previously. Depending on the exact measures (low or high software), this exercise suggests that $\rho_d = \rho_e = 0.7$ and $\rho_z = 0.8$ are reasonable values.

Here, we compare the dynamic response to shocks to z_t and to q_t^e. Given the specification chosen, the shocks we are considering are temporary increases beyond the deterministic trend in productivity: these shocks are persistent, but in both cases the productivity variable returns to trend. We will later discuss the implication of non-stationary shocks, that is, one-off shocks that permanently raise the level of productivity of the economy (though not the growth rate). There are crucial differences in the dynamic responses to these different shocks, but the economic mechanisms are essentially the same.

Figure 4
Impulse responses - baseline model



The impulse responses of the baseline model are illustrated in Figure 4. The *x*-axis of these charts is time, where each period is one year. Shocks occur in period 1. The *y*-axis is the percentage deviation from the trend path: in the baseline specification, the variables are trend stationary. Both shocks increase investment in capital of type *e* by increasing the expected marginal product of this type of capital - but while a shock to z_t increases the marginal product of capital on both types of capital, a shock to q_t^e only raises the marginal product of type *e*. This difference in productivity of capital leads to an immediate reallocation of capital from production of *d* to production of *e* capital: a shock to q_t^e initially causes substitution from investment in *d* to investment in type *e*. But the subsequently high *e* capital stock raises the marginal product of capital on *d*-type capital, leading to a subsequent counterflow in investment of type *d*: so the initial substitution effect of a shift in relative prices from investment of type *d* to *e* is offset in the following periods by a "complementarity effect" that shifts resources back towards *d* capital.

To study the response of the aggregate capital stock, the aggregate capital stock is defined as the weighted sum of the two types of capital, where the weights are the relative prices of capital goods to output:

$$K_t = P_t^d K_t^d + P_t^e K_t^e = K_t^d \big/ Q_t^d + K_t^e \big/ Q_t^e,$$

$$k_t = k_t^d \big/ q_t^d + k_t^e \big/ q_t^e. \tag{31}$$

The aggregate capital stock is hence measured in units of final output - within this one-sector model, this is equivalent to the Office for National Statistics' measure of the capital stock at replacement value, cf the discussion of this issue above. So the capital stock K_t grows at the same rate as output, and the output-capital ratio, Y_t/K_t, is stationary. Importantly, K_t is not a state variable: a positive shock to q_t^e lowers the relative price of a component of the capital stock, and hence the replacement value of the entire stock. A shock to z_t, on the other hand, has no such direct effect on the capital stock.

In addition to these differences in the investment response, shocks to q_t^e and to z_t differ in terms of their output implications. A shock to z_t raises output on impact, as more output is produced for given factor inputs. Hours worked also increase as the return to working increases, raising output further; but due to the direct effect of z_t on output, average labour productivity increases on impact. A shock to q_t^e, on the other hand, has no immediate direct effect on output - the effect comes from an increased return to investment, and hence an increase in the capital stock. Output is increased on impact through an increase in hours worked, but this implies a negative rather than a positive effect on average labour productivity. Note how long it takes for labour productivity to settle back to its balanced growth path in both cases. Also, unlike the shock to z_t, the initial effect of a shock to q_t^e on consumption is negative, as resources for extra investment are brought about by a decrease not only in consumption of leisure but also in consumption of goods.

The quantitative effects of the two shocks obviously differ: a shock to q_t^e affects only a small proportion of production and a shock to z_t is obviously more "powerful" in the sense that it applies to all production. Yet it is noteworthy that a shock to q_t^e has a stronger effect on output than its share of production would suggest: the peak effect of a 1% shock to ICT-specific technological progress is 0.07%. This suggests that if fluctuations in q_t^e are relatively large, ICT-specific technological progress may account for a large proportion of business cycle fluctuations, despite a relatively small output share. This is in line with Greenwood et al (2000), who make a similar inference based on technological progress specific to investment in equipment.

5. Extending the baseline model

Above, we provided a brief characterisation of the baseline model. In this section, we highlight shortcomings of the baseline model as a tool for business cycle analysis. To address these, we modify the model and add features to bring the model more into line with well known empirical regularities. These do tend to obscure the basic mechanisms discussed in the section above, but the gain is a richer dynamic structure. The features we build in are drawn largely from the existing literature: the main purpose of the exercise is not to provide new theoretical insights, but to analyse the issue at hand, sector-specific technological progress, in a model with these features.

One striking feature of the baseline model is that a sector-specific shock causes negative co-movements between sectoral inputs and outputs: a shock to q_t^e leads to an increase in investment of type *e* but a fall in inputs into production of consumption and *d*-type investment goods. Similarly, a shock to z_t shifts resources, in the form of hours worked, away from production of consumption goods into production of investment goods (though the net effect on consumption is positive, unlike a shock to investment-specific technological progress). The DGE literature on multisector models, reviewed by Greenwood et al (2000), addresses this issue by including materials (Hornstein and Praschnik (1997)) or intrasectoral adjustment costs (Huffman and Wynne (1999)). The home production model by Benhabib et al (1991) provides a different mechanism to address this issue that is easily implementable in the model considered here: by introducing a home sector to which workers can allocate hours, labour supply to market activities becomes more responsive. In this model, a positive shock to "market activities", whether investment neutral or sector neutral technological progress, implies that workers shift hours from the home sector in addition to lowering leisure. This issue is analysed in detail in Greenwood et al (1995).

One aspect of the baseline model that might appear implausible is the rapid reallocation of resources from investment in one type of capital to another or, equivalently, the speed with which the capital stock adjusts in response to shocks. The obvious solution in this context is to implement costs to adjusting the capital stock - this, in addition to slowing down the response of the capital stock, affects the response of the price of capital stock by effectively inserting a wedge between Q_t^i and P_t^i. This is explored in detail in Christiano and Fisher (1995) (who also include habits in consumption). In addition, inclusion of adjustment costs tends to strengthen the propagation mechanism, thus addressing a fundamental weakness of the standard real business cycle model.

The final aspect we look at is variable utilisation rates of capital. Effective capital input then consists of the stock of capital, utilised at a variable rate, with utilisation being costly in the form of increased depreciation. This is important for at least two reasons. First, variable utilisation rates imply that effective capital inputs into production can be increased immediately in response to shocks, making output more responsive to shocks and strengthening the propagation mechanism. The implications of this are explored in the literature associated with, amongst others, Burnside and Eichenbaum (1996). Second, a shock to Q_t^i that tends to lower the price of capital of type *i* implies a loss in value for existing capital holders. And a lower price of the capital stock implies a lower cost, measured in consumption units, of depreciation. This price effect makes it less costly to increase utilisation rates in response to sector-specific shock. This will tend to amplify the output response of a sector-specific shock relative to a neutral shock.

In the following, we provide the details of these extensions to the model. The extensions are implemented in such a way that the steady state growth path is identical to that of the baseline model. A general property of these extensions is that Q_t^i no longer corresponds directly to the inverse of the deflators. As with the baseline model, we characterise the model by looking at impulse response functions.

5.1 Home production

We introduce home production in the simplest possible way by assuming a home production technology without capital that is linear in hours worked:

$$Y_t^H = Z_t^H h_t^H, \tag{32}$$

where Y_t^H is production of home-produced goods, h_t^H is labour input into home production and Z_t^H is labour productivity in the home sector. Home-produced goods are distinct from market goods in that home-produced goods cannot be saved, so consumption of home-produced goods necessarily equals production, that is $C_t^H = Y_t^H$. The agent's time constraint is modified to include hours worked at home such that:

$$h_t + h_t^H + l_t = 1. \tag{33}$$

As mentioned in the previous section, the model extensions are formulated in such a way that the extended model nests the baseline model. To do so here, we assume the existence of a consumption aggregate $\zeta_t = \zeta\left(C_t, C_t^H\right)$, where ζ is a convex and homogenous aggregator, and write the utility function as $U\,(\zeta_t, L_t)$: the baseline specification then simply requires that $\zeta_t = C_t$.

This modification alters the agent's dynamic maximisation problem, adding a first-order condition for hours worked in production at home, and modifying the first-order condition for hours worked in market activities:

$$h_t^H : Z_t^H U_\zeta(\zeta_t, l_t)\zeta_{C^H}(C_t, C_t^H) = U_l(\zeta_t, l_t)\,, \tag{34}$$

$$h_t : U_l(\zeta_t, l_t) = U_\zeta(\zeta_t, l_t)\zeta_C(C_t, C_t^H)W_t(1-\tau_l)\,. \tag{35}$$

The first condition balances the marginal disutility of an extra hour worked with the return to working an additional hour at home, Z_t^H, measured in utility terms, while the second relates the marginal disutility of an extra hour worked with the returns to market activities. These conditions describe how home production alters labour supply: an increase in the real wage now affects labour supply through two channels: it represents a decrease not only in the relative price of market consumption goods relative to leisure but also in that of market consumption goods relative to the price of home-produced goods. So in this sense, introduction of home production strengthens the substitution effect of an increase in real wages.

To parameterise this extension, only a consumption aggregator is needed. We specify ζ as a CES aggregator:

$$\zeta_t = \{(1-\theta^H)(C_t)^e + \theta^H (C_t^H)^e\}^{\frac{1}{e}} \tag{36}$$

which implies that home and market goods are imperfect substitutes with an elasticity of 1/(1 – e), with θ^H measuring the "bias" towards home-produced goods. Existence of a steady state growth path requires that productivity in the home sector Z_t^H grows at the same rate as market output, ie g: this assumption also ensures that the extended model has the same steady state path as the baseline model. To calibrate the remaining parameters, observe that the first-order condition for allocation of labour implies the following steady relationship:

$$\left(\frac{c}{c^H}\right)^{-e} \frac{c}{y}\frac{h}{h^H} = (1-\alpha_d-\alpha_e)(1-\tau_l)\frac{(1-\theta^H)}{\theta^H} \tag{37}$$

We follow Greenwood et al (1995) and set $h^H = 0.25$ and $e = 0$, implying a unit elasticity of substitution between home-produced and market goods. The baseline model's calibration of the remaining parameters and steady state ratios then implies a value for θ^H.

5.2 Capital

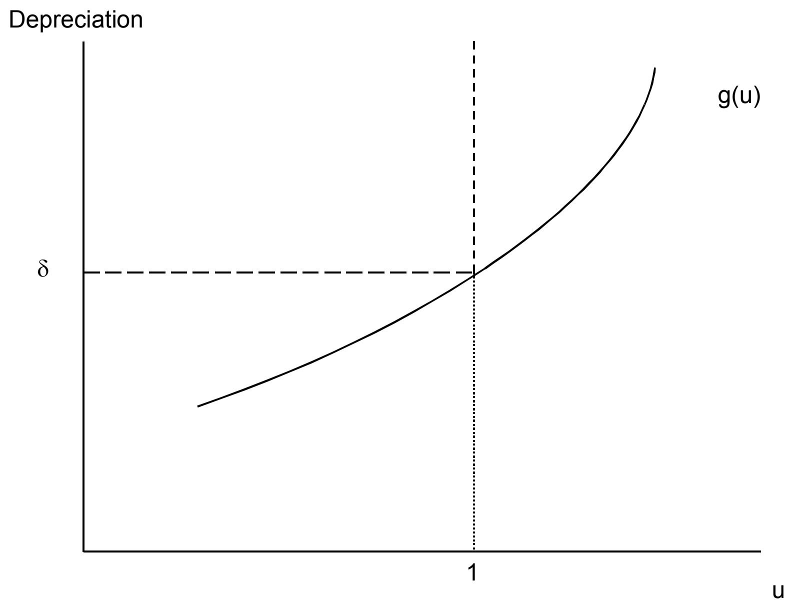
As in the baseline model, we assume that the agents own the capital stock and rent it to firms on a period by period basis. The rental contract specifies an amount of *effective capital input* $K_t^{i*} = u_t^i K_t^i$ that the agent will provide to the firm at a fixed price r_t, but the agents determine the composition of the input between utilisation u_t^i and quantities K_t^i. The agent is assumed to determine the capital stock prior to observing the shocks but utilisation after observing the shocks. Increasing utilisation is costly: if the agent decides to increase effective capital supply by increasing utilisation, this results in a higher depreciation rate. Depreciation of capital good i at t is given by:

$$\delta_{it} = g_i\left(u_t^i\right), i = d, e \tag{38}$$

where g_i is a continuous and convex function $g_i'(.) > 0$ and $g_i''(.) > 0$: increased utilisation of capital increases depreciation at an increasing rate. The properties of the depreciation function are illustrated in Figure 5. In characterising the deviations from steady state, it is the derivative and the elasticity of the derivative that are important, that is, how much increases in utilisation translate into increases in depreciation and the elasticity of this response. The baseline case emerges when the elasticity $g_i''(1)u_i / g_i'(1) \to \infty$ (illustrated with the dashed line). In that case, the returns to changing utilisation are becoming infinitely small. This will not affect steady state utilisation, as this is related to the levels of *g*, not the derivatives.

Figure 5

The depreciation function $g(u_t^i)$



In addition to variable utilisation, we introduce a cost of adjusting the capital stock. In particular, we assume the existence of a wedge between investment expenditure measured in units of capital goods, $Q_t^i X_t^i$, and the increase in the capital stock, given by:

$$\psi_i\left(\frac{Q_t^i X_t^i}{K_t^i}\right)K_t^i,\ i = d,e.$$

The adjustment costs are assumed to be convex by assuming that ψ is concave in its arguments, $\psi_j'(.) > 0$ and $\psi_j''(.) < 0$.

These extensions add an additional first-order condition to the agent's problem, characterising utilisation, and alter the equations that characterise the marginal value of an additional unit of capital and the asset Euler equation. The first-order condition for utilisation dictates that the marginal product of additional utilisation, adjusted for tax and measured in utility terms, equals the marginal cost in the form of increased depreciation:

$$\lambda_t(1-\tau_k)r_t^i K_t^i = \lambda_t^i g_i'(u_t^i)\frac{K_t^i}{Q_t^i},\ i = d,e \tag{39}$$

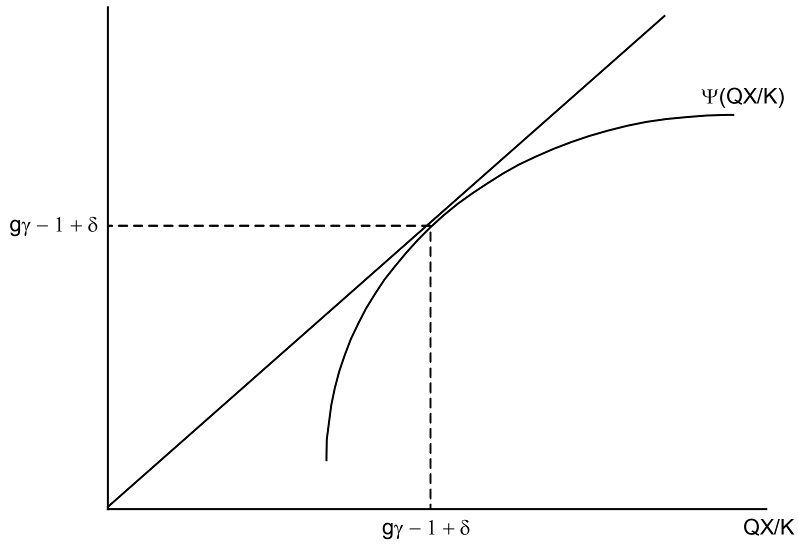
where λ_t is the marginal utility of consumption at time *t*. Here, $g_i'(u_t^i)$ is the marginal increase in the rate of depreciation of the capital stock K_t^i. The presence of adjustment costs implies that out of steady state, there is a wedge between the marginal values of capital stock and the marginal utility:

$$\lambda_t = \lambda_t^d \psi_{dt}' = \lambda_t^e \psi_{et}'. \tag{40}$$

Hence the ratio $1/\psi'_{it}$ measures the marginal value in output terms of an additional unit of capital and can thus be interpreted as a measure of Tobin's marginal q[23] (not to be confused with q_i!): if the derivative of the adjustment cost function is less than 1, this suggests firms should increase investment, see Figure 6; in the absence of adjustment costs, q is always 1. Notice that the baseline specification requires that the elasticity of ψ' in steady state is 0, while values smaller than 0 indicate more curvature.

Figure 6

Adjustment cost function



Variable utilisation and adjustment costs obviously also modify the Euler asset price equation:

$$\frac{\lambda_t^i}{Q_t^i} = \beta i_t\left(1 - g_i\left(u_t^i\right) + \psi_{it+1} - \psi'_{it+1}\frac{Q_{t+1}^i X_{t+1}^i}{K_{t+1}^i}\right)\frac{\lambda_{t+1}^i}{Q_{t+1}^i}$$

$$+ \beta i_t \lambda_{t+1}(1-\tau_k) r_{t+1}^i u_{t+1}^i. \quad (41)$$

Finally, the accumulation equation for individuals' holding of capital is altered to reflect utilisation and adjustment costs:

$$K_{t+1}^i = \left(1 - g_i\left(u_t^i\right)\right)K_t^i - \psi_i\left(\frac{Q_t^i X_t^i}{K_t^i}\right)K_t^i,\ i = d,e. \quad (42)$$

We calibrate the extended model to ensure that the steady state path is identical to that of the baseline model. To illustrate the restrictions we impose on the adjustment cost function, we return to the sectoral interpretation used previously in Section 2. A capital-producing firm makes output decisions by choosing expenditure on materials M_t, conditional on Q_t^i and K_t^i and given prices P_t^i, to maximise profits $P_t^i \psi_i (Q_t^i M_t / K_t^i) K_{it} - M_t$. The first-order condition for this problem implies that:

$$P_t^i Q_t^i \psi'_i\left(\frac{Q_t^i X_t^i}{K_t^i}\right) = 1. \quad (43)$$

[23] See Hayashi (1982).

In the baseline model, the inverse relationship between P_t^i and Q_t^i holds in all equilibria, whether these are on or off the steady state path. To establish the same relationship on the steady state path for the extended model, we specify and calibrate the functional form such that $\psi_i'(g\gamma_i - 1 + \delta_i) = 1$ - this implies a steady state value of one for Tobin's marginal *q*. Notice that in the extended model the inverse relationship between P_t^i and Q_t^i holds only in steady state.

The accumulation equation function (42) imposes an additional restriction on ψ_i: for this accumulation equation to reproduce (18) in steady state, we impose that:

$$\psi\,(g\gamma_i - 1 + \delta_i) = g\gamma_i - 1 + \delta_i, \tag{44}$$

where $g\gamma_i - 1 + \delta_i$ is the investment/capital ratio in the baseline steady state.

In the log-linearised economy, the only additional parameter in ψ_i that needs calibration is the elasticity of ψ_i' in steady state - recall that we have already tied down the level and first derivative in steady state, so we effectively only need to determine the curvature of ψ in the vicinity of steady state. There is no readily available empirical evidence on these two parameters, so we calibrate this parameter by looking at the model's adjustment path when the capital stock is away from steady state. In practice, we set the convergence rate to steady state at 25% a year, implying a half-life of capital stock deviations from steady state of approximately 2.4 years. This is roughly equivalent to the values in Basu et al (2000).

For the utilisation function, we impose the restriction that:

$$g_i\,(u^i) = \delta_i,\ i = d, e, \tag{45}$$

that is, in steady state, the depreciation rate in the extended model equals that of the baseline model. Notice also that from the first-order condition for utilisation, in steady state:

$$g_i'(u^i)u^i = (1 - \tau_k)\alpha_d \frac{y}{k^i}. \tag{46}$$

By restricting the depreciation function to be a CES function, (45) and (46) are sufficient to tie down the necessary parameters.

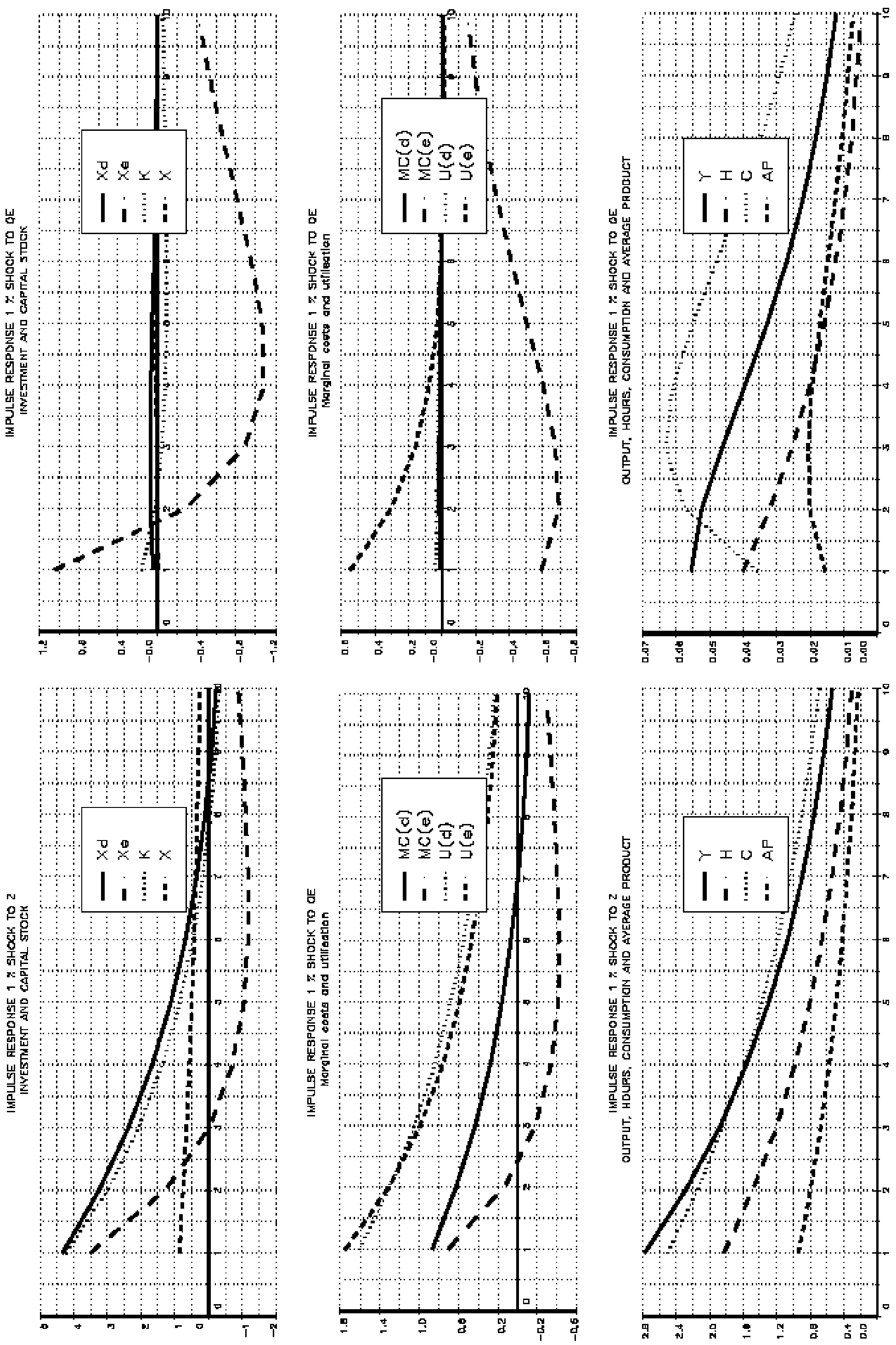
5.3 Dynamic aspects of the extended model

As already noted, the extended model is set up in such a way that the steady state growth path is exactly identical to that of the baseline model - so it only remains to characterise the differences in dynamics around this unchanged steady state path. As before, we characterise the model by looking at impulse response functions. The impulse responses are illustrated in Figure 7, where the left-hand set of charts show responses to a 1% shock to z_t, while the right-hand set show responses to a 1% shock to q_t^e.

As suggested earlier, the presence of adjustment costs implies that there is a wedge between p_t^i and $1/q_t^i$. Prices of capital goods are less responsive to sector-specific shocks because the marginal costs of producing capital goods are sluggish. To illustrate the mechanics of this, recall that marginal costs of producing capital goods are $(q_t^i\psi_t')^{-1}$ and that $\psi'' < 0$. A positive shock to q_t^i directly lowers marginal costs of producing new capital goods, but an increase in production of these goods implies a decrease in ψ_t', offsetting the direct cost effect. This tends to dampen the strong "substitution effect" seen in the baseline model that leads to a reallocation of resources from production of *d* to production of *e*. There is still a "complementarity effect": a large capital stock of type *e* raises the marginal product of capital of type *d*. With a weakened "substitution effect", this complementarity effect combined with the incentive to smooth investment provided by the adjustment costs implies that investment in capital of type *d* increases in response to a shock to q_t^e where in the baseline model the "substitution effect" dominated (though the effect is quantitatively small). The presence of a home sector reinforces this co-movement: a shock to q_t^e raises the return to market activities relative to home, and this tends to raise production of all market goods. But there are still differences compared with the response of investment in the two types to a sector neutral z_t shock: the positive co-movement between investment into the two sectors is still much stronger in that case.

Figure 7

Impulse responses - extended model



The inclusion of adjustment costs also affects the output and consumption responses, primarily by dampening the responses. Importantly, variable utilisation of capital implies that effective capital inputs can be raised immediately in response to shocks - this implies that output can be increased on impact by both increasing hours and utilisation. The return to utilisation increases in response to shocks to both z_t and q_t^e, but a shock to q_t^e has the added effect that the expected future capital loss on existing capital stock, coming from future lower prices, decreases the cost of increased depreciation measured in output terms. The outcome is that in response to a shock to q_t^e, output now increases by more than hours, increasing average labour productivity (unlike in the baseline model).

6. Scenarios for structural change

In the preceding analysis, the maintained assumption has been that a non-stochastic trend is a good description of the economy's steady state growth path. In this section, we change and relax this assumption in a number of ways. In doing this, we are essentially trying to use the model as a tool for "scenario analysis" of different contemporary examples of structural change. The exercises we consider include temporary and permanent changes to the growth rate of technological progress, as opposed to the temporary changes to the *level* studied in the previous sections. We also look at the implications of changing the technical coefficient α_e on expenditure shares and the aggregate depreciation rate.

6.1 Permanent shocks to technology

The extensions to the model discussed in Section 5 alter the dynamics around the deterministic path, but maintain the stationary trend assumption. An obvious question is what difference a change in the stochastic properties of the shock would make: Rotemberg and Woodford (1996), for instance, argue in favour of permanent rather than temporary shocks to technology. In the UK context, Ravn (1997) shows that the distinction is important when explaining UK data, but argues that assuming non-stationary shocks alone is insufficient when explaining business cycle facts. While being somewhat agnostic on this issue, we want to consider the implications of permanent shocks to technological progress in our model. Arguably, such a shock is a better characterisation of the views of proponents of the "new economy" hypothesis: they argue that the US economy may have experienced an increase in medium-term productivity growth, but that it is still too early to conclude anything about long-run growth. And on this view, a temporary shock to the growth rate of productivity might be a more pertinent simulation for policymakers in the United Kingdom who wish to embed a "new economy" shock into their macroeconomic forecasts. We do this by modifying (29) so that:

$$\ln\left(X_t^i\right) = \ln\left(\gamma^i\right) + \ln\left(X_{t-1}^i\right) + \varepsilon_t^i,\ i = d,e,z \qquad (47)$$

We set the drift parameter such that the average growth rates of the model with non-stationary shocks are identical to those of the baseline model, so that in the absence of shocks the two economies would follow the same growth path. Furthermore, we assume that there are no temporary shocks.[24] So a shock in this new economy shifts the level of productivity permanently, whereas in the baseline model, a shock only has a temporary (though persistent) effect. We analyse this issue using the baseline specification of the model.

This change in the stochastic properties of the shocks changes the normalisation of variables. We replace the terms g^t, g_d^t and g_e^t that characterise the non-stochastic steady state path with three stochastic terms:

$$N_t = Z_t^{\frac{1}{\alpha_l}}\left(Q_t^d\right)^{\frac{\alpha_d}{\alpha_l}}\left(Q_t^e\right)^{\frac{\alpha_e}{\alpha_l}};\ N_t^d = Q_t^d N_t;\ N_t^e = Q_t^e N_t, \qquad (48)$$

where $\alpha_l = 1 - \alpha_e - \alpha_d$. The variables are now normalised as follows:[25]

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[24] By assuming that there are only permanent shocks, we avoid a potential signal extraction problem: if there were both permanent and temporary shocks, then the agents would have to separately identify the shocks.

[25] Notice that the growth rates γ_t^d, γ_t^e and γ_t^z are now stochastic. Moreover, to accommodate a stochastic growth rate, we have changed the timing convention on the capital stock normalisation.

$$y_t = Y_t/N_t\,;\; c_t = C_t/N_t\,;\; x_t^e = X_t^e/N_t\,;\; x_t^d = X_t^d/N_t\,;\; k_t^d = K_t^d/N_{t-1}^d\,;\; k_t^e = K_t^e/N_{t-1}^e\,;$$

$$\gamma_t^d = Q_t^d/Q_{t-1}^d\,;\; \gamma_t^e = Q_t^e/Q_{t-1}^e\,;\; \gamma_t^z = Z_t/Z_{t-1}\,;\; \tilde{\lambda}_t^e = \lambda_t^e N_t\,;\; \tilde{\lambda}_t^d = \lambda_t^d N_t\,. \tag{49}$$

The stationary system is then characterised by the following sets of equations:

$$\frac{h_t}{1-h_t} = \frac{\theta}{1-\theta}(1-\tau_l)(1-\alpha_e-\alpha_d)\frac{y_t}{c_t}$$

$$\tilde{\lambda}_t^e = \tilde{\lambda}_t^d = \frac{\theta}{\tilde{C}_t}$$

$$c_t + x_t^e + x_t^d = \left(\frac{1}{\gamma_t^N\gamma_t^d}\right)^{\alpha_d}\left(\frac{1}{\gamma_t^N\gamma_t^e}\right)^{\alpha_e}\left(k_t^e\right)^{\alpha_e}\left(k_t^d\right)^{\alpha_d} h_t^{1-\alpha_e-\alpha_d}$$

$$\tilde{\lambda}_t^i = \beta\tilde{\lambda}_{t+1}^i\left(1-\tau_k\right)\alpha_i\frac{y_{t+1}}{k_{t+1}^i} + \beta\tilde{\lambda}_{t+1}^i\left(1-\delta_i\right)\frac{1}{\gamma_{t+1}^N\gamma_{t+1}^i}$$

$$k_{t+1}^i = \left(1-\delta_i\right)k_t^i\frac{1}{\gamma_t^N\gamma_t^i} + x_t^i,\; i = d,e \tag{50}$$

where

$$\gamma_t^N = \left(\gamma_t^z\right)^{\frac{1}{\alpha_l}}\left(\gamma_t^d\right)^{\frac{\alpha_d}{\alpha_l}}\left(\gamma_t^e\right)^{\frac{\alpha_e}{\alpha_l}}. \tag{51}$$

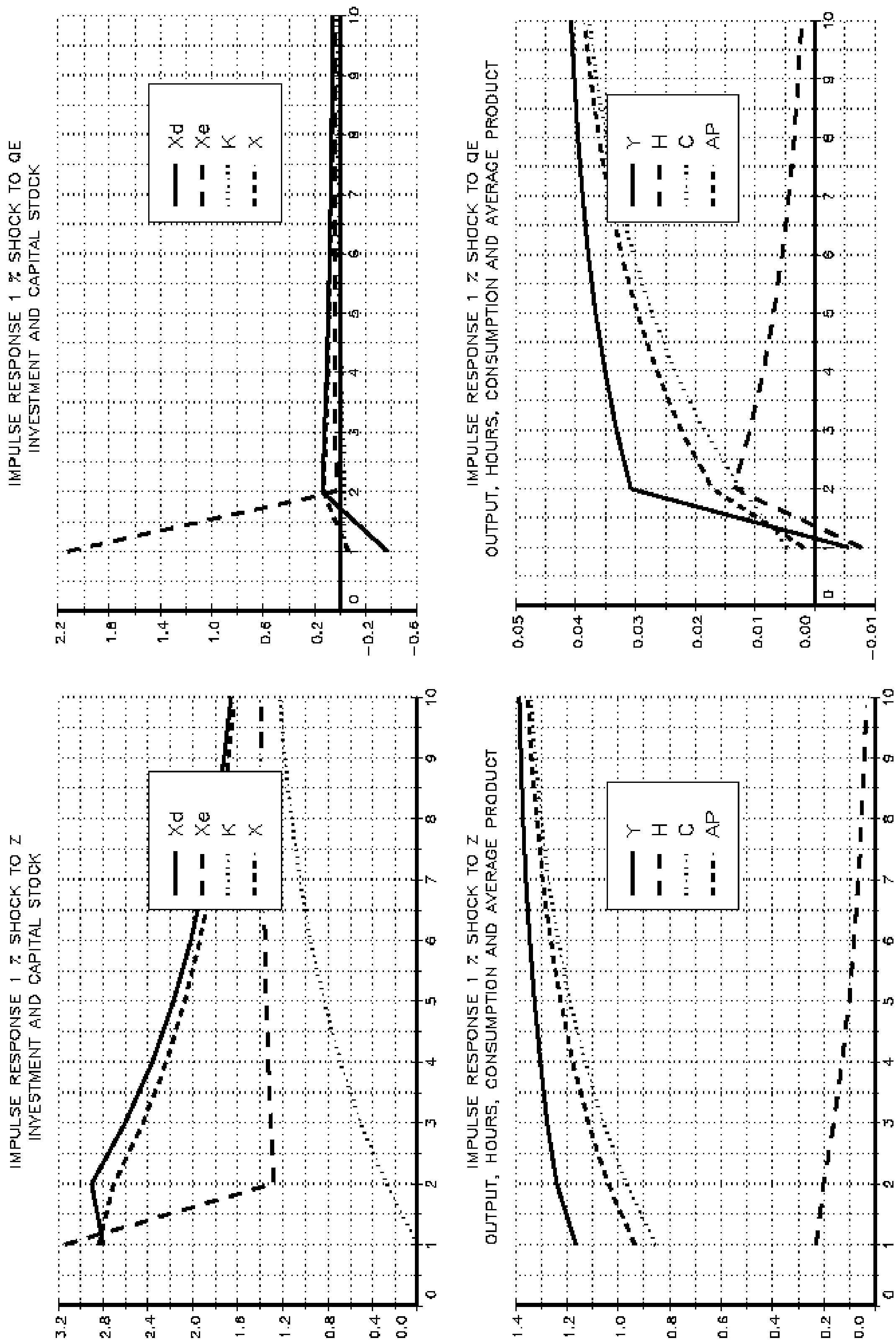
As mentioned, the shocks now permanently change the steady state level of output. From (48), a 1% permanent increase in the level of z_t permanently raises the steady state path of output by $1/\alpha_\iota$%, whereas a similar shock to Q_t^e shifts the steady state path by α_e/α_ι. The dynamics of the adjustment paths are illustrated in Figure 8 - the economic mechanisms discussed at length in Section 4 are the same, but the dynamics differ. Unlike a neutral shock, a permanent increase in Q_t^e initially decreases output as hours worked fall. We ascribe this to the income effect dominating the substitution effect: having observed a permanent shock to technology, whether sector-specific or neutral, agents will know that long-run income levels have increased. This tends to lower labour supply. In the case of a sector neutral shock, there is a strong offsetting substitution effect from an immediate increase in wages (or equivalently, an increase in the cost of leisure). With a sector-specific shock, there is no such effect in the first period because increases in Q_t^e do not affect output on impact. Productivity and hence wages only increase in subsequent periods, which then increases labour supply.

The income/substitution effects also distinguish the investment/consumption responses in the two cases. Here, the counterbalancing is between a falling price of investment goods or an increasing return to investment on the one hand (substitution effect), and a permanent increase in income which tends to increase consumption at the expense of investment on the other (income effect). With a neutral shock, the return to investment increases for both types of capital good. This dominates the income effect, so aggregate investment overshoots its long-run levels and the consumption-output ratio decreases. A shock that is specific to production of investment goods of type *e* only raises the return to investment in capital of this type: it shifts resources from production of type *d* goods, but aggregate investment undershoots its long-run level as the income effect dominates the substitution effect and the consumption-output ratio increases.

6.2 ICT investment expenditure share

Even with permanent shocks to productivity growth, the balanced growth path is characterised by constant expenditure shares: production becomes increasingly ICT-intensive but the price of this capital good is falling, leaving the investment expenditure share constant. Arguably, one feature of the recent US experience is a sharp increase in the ICT investment expenditure share-certainly, in the United Kingdom the investment expenditure share rose sharply over the period, with the ICT share increasing from 0.7% in 1976 to 3.6% in 1998.

Figure 8
Impulse responses - permanent shocks



Accounting for this phenomenon poses a challenge to the model we are using. To some extent, the model can account for this as a *temporary* phenomenon: in the baseline model, a fall in the price of ICT capital goods leads to a large temporary increase in investment that exceeds the drop in prices, so that the ICT investment expenditure share temporarily increases. But with very rapid adjustments of factor inputs, the steady state expenditure share is quickly restored. The extensions of the baseline model dampen and slow down this adjustment, implying a smaller but more persistent response of the investment expenditure share. The baseline model cannot account for this as a *permanent* phenomenon: along the steady state growth path where growth is balanced, the expenditure shares are constant. To analyse *permanent* changes to the investment expenditure share, we need to consider changes in structural parameters. In the following, we perform some comparative static exercises and characterise how changes in some structural parameters change the balanced growth path, holding all other parameters at their steady state values.

The obvious first candidate to change is the growth rate of sector-specific technological progress, that is, to consider changes to γ^e in (47), similar to the exercise in Pakko (2000). From (51), an increase in γ^e also increases the aggregate growth rate γ^N. Such a change has two offsetting effects on the investment expenditure share. To see this, consider the steady state version of the capital accumulation and the Euler equations from (50):[26]

$$(1-\tau_k)\alpha_e \frac{y}{k^e} + \frac{(1-\delta_e)}{\gamma^N \gamma^e} = \frac{1}{\beta},$$

$$1 - \frac{(1-\delta_e)}{\gamma^N \gamma^e} = \frac{x^e}{k^e} \tag{52}$$

An increase in the growth rate γ^e leads to an increase in the y/k_e ratio through a negative "capitalisation effect": the return to investing in one unit of capital is the after-tax marginal product of capital, plus the value of the capital stock next period, $(1 - \delta_e)/\gamma^N\gamma^e$. An increase in γ^e lowers the value of the capital, because the intertemporal price of capital good *e* is falling faster. For a given discount factor, this will require an increase in the return to capital, ie an increase in the y/k^e ratio to increase the marginal product of capital. On the other hand, there is an "accumulation effect": an increase in growth rate will require an increase in the investment-capital ratio, x^e/k^e, to maintain balanced growth. In combination, the ratio x^e/y is given by:

$$\frac{x^e}{y} = \frac{x^e}{k^e}\frac{k^e}{y} = \frac{\gamma^N\gamma^e - (1-\delta_e)}{\gamma^N\gamma^e - \beta(1-\delta_e)}\beta(1-\tau_k)\alpha_e. \tag{53}$$

It is straightforward to establish that, provided $\beta < 1$, x^e/y is increasing in γ^e, so in other words, the accumulation effect dominates. Figure 9 depicts this relationship: notice that even substantial changes in γ^e (the *x*-axis) lead to fairly small changes in expenditure share (the *y*-axis). Hence, an increase in γ^e to match the increased ICT investment expenditure ratios would require the growth rate γ^e to increase substantially, implying in turn a substantial increase in the steady state growth rate.[27]

Figure 9 also shows the effect on the aggregate depreciation rate of varying γ^e: an increase in the growth rate of ICT-specific technological progress would imply a decrease in the aggregate depreciation rate. So despite the fact that an increase in γ^e leads to higher growth in intensity of a capital good with a relatively higher depreciation rate, the aggregate depreciation rate falls. This, essentially, is caused by the capitalisation effect. To see this, we define the aggregate depreciation rate as

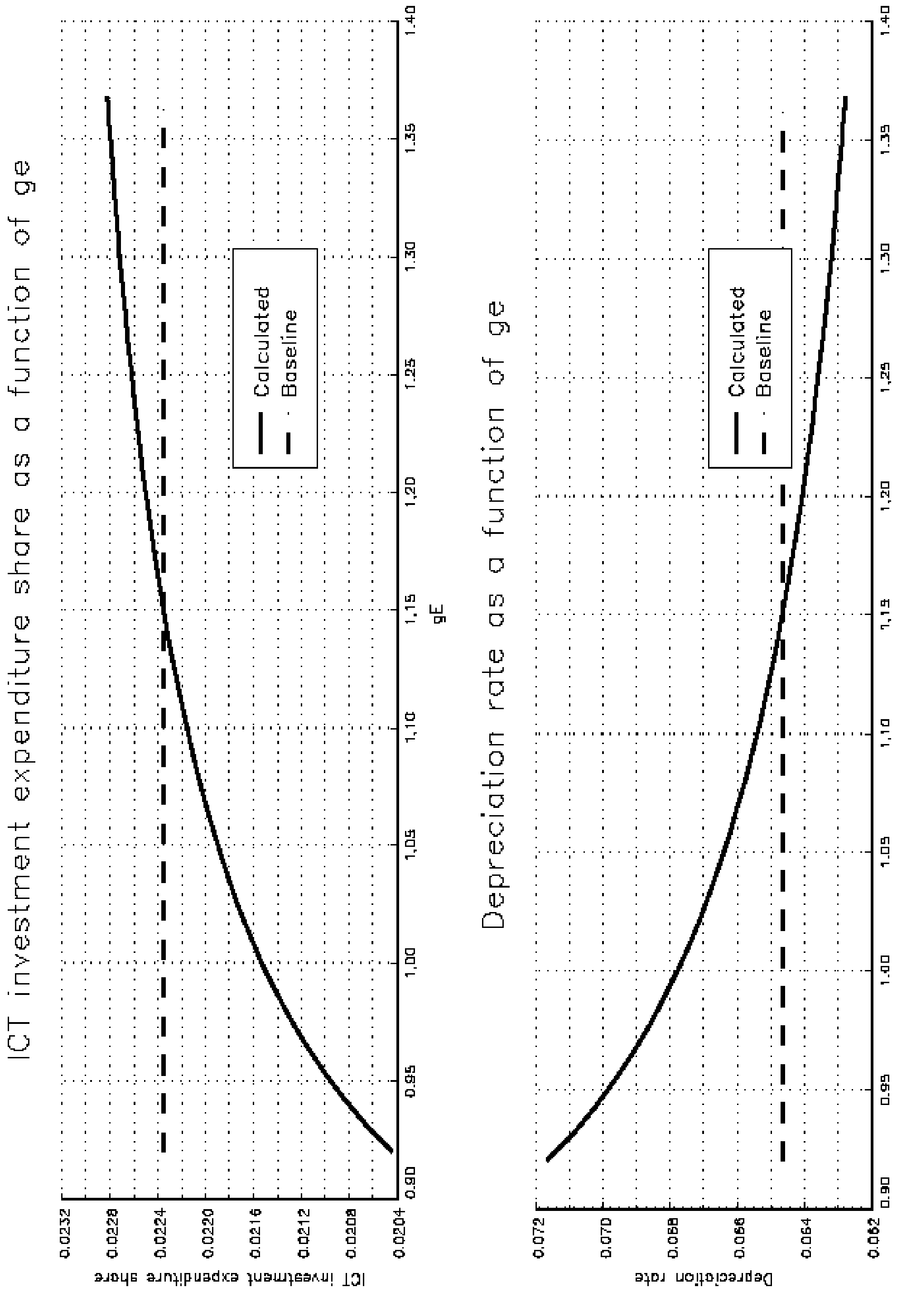
$$\delta_t = \omega_{dt}\delta_d + \omega_{et}\delta_d \tag{54}$$

[26] Recall that the capital stock of type *i* is normalised on $N_{t-1}Q^i_{t-1}$.

[27] Notice that changes in x^i/y that lead to changes in c/y will affect the hours worked *h*. First, $\frac{c}{y} = 1 - \sum_i \frac{x^i}{y}$; using this, $h = \left(\frac{1-\tau_t}{\alpha_l}\frac{\theta}{1-\theta}\frac{c}{y}\right) / \left(1 + \frac{1-\tau_t}{\alpha_l}\frac{\theta}{1-\theta}\frac{c}{y}\right)$.

Figure 9

Effects of variations in γ^e



where the weights ω_{it} are shares in aggregate capital stock. This we can write as:

$$\delta_t = \frac{K_t^d / Q_t^d}{K_t}\delta_d + \frac{K_t^e / Q_t^e}{K_t}\delta_e$$

$$= \frac{k_t^d / y_t}{k_t / y_t}\frac{1}{\gamma_t^d \gamma_t^N}\delta_d + \frac{k_t^e / y_t}{k_t / y_t}\frac{1}{\gamma_t^e \gamma_t^N}\delta_e \qquad (55)$$

where the aggregate capital stock and capital-output ratios are defined as:[28]

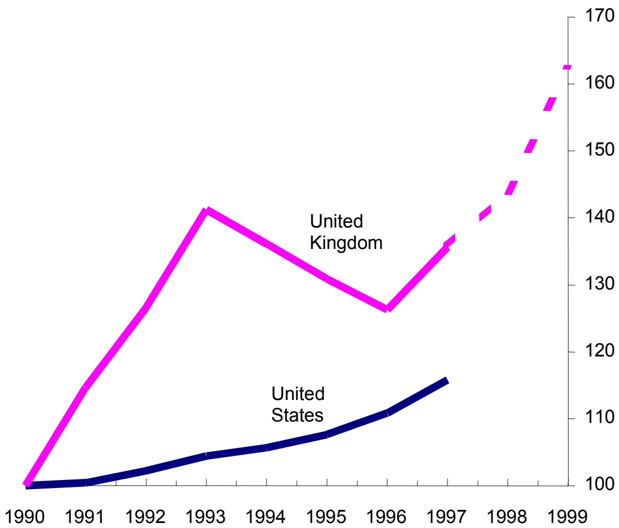
$$K_t = P_t^d K_t^d + P_t^e K_t^e,$$

$$\frac{k_t}{y_t} = \frac{k_t^d}{y_t}\frac{1}{\gamma_t^d \gamma_t^N} + \frac{k_t^e}{y_t}\frac{1}{\gamma_t^e \gamma_t^N}$$

From (55), an increase in γ^e lowers the weight on δ^e, implying a lower aggregate depreciation rate. This means that an increase of γ^e is inconsistent with the empirical evidence on depreciation rates. Official investment and capital stock data at the plant and machinery level are available for both the United Kingdom and the United States.[29] These can be used to back out implied depreciation rates as in (28). Figure 10 shows that the implied depreciation rates for both the United Kingdom and the United States have increased since 1990.

Figure 10

Implied depreciation rates for plant and machinery.
United States and United Kingdom



In summary, an increase in γ^e can increase the investment expenditure share, but accounting for the observed increase would require a substantial increase in γ^e. In addition, such an increase lowers the aggregate depreciation rate, which is at odds with the empirical evidence.

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28 Notice that while K_t^d and K_t^e are state variables, the aggregate capital stock K_t is not: the fact that K_t is measured in units of final goods means that K_t can change instantaneously in response to shocks. For this reason, K_t is normalised on N_t rather than N_{t-1}.

29 We are grateful to Stacey Tevlin for providing us with the US data. The implied rates are calculated using a fixed-weight measure of the capital stock. These data include computers and communications equipment, but exclude software.

A direct change in the technical parameter α_e also increases the investment expenditure share and, contrary to the previous experiment, the aggregate depreciation rate. In the experiment we consider here, we increase α_e but hold $\alpha_e + \alpha_d$ constant - that is, an increase in α_e is offset by a decrease in α_d. By calculating the derivative of γ^N with respect to α_e under this assumption, it is straightforward to establish that provided $\gamma^e > \gamma^d$, the steady state growth rate γ^N increases with an increase in α_e. So while there are still capitalisation and accumulation effects, stemming from increases in growth rates, the capitalisation effect is now offset by a direct increase in the return to investment. Figure 11 draws out the change in steady state investment expenditure ratios and depreciation rates, as a function of a change in α_e, holding $\alpha_d + \alpha_e$ constant. To increase the ICT investment share of output to match the last observation in our data set, α_e should be increased to 0.054, from a benchmark value of 0.031. This implies an increase in the depreciation rate from the steady state value of 6.45% to 6.9%, or an approximately 7% increase. This increases the growth rate of output to 2.6%.[30]

7. Conclusion

In this paper, we have decomposed labour productivity growth along the balanced growth path of the UK economy into investment-specific and sector neutral technological progress. Using US hedonic deflators for ICT investment goods, we find that ICT investment-specific technological progress makes a significant contribution to productivity growth along the balanced growth path, explaining as much as 20-30% of labour productivity growth. One obvious conclusion is that sustained improvements in labour productivity growth from this source will rely on continued sharp declines in the relative price of ICT goods.

We have drawn out the different implications of shocks to investment-specific technological progress on the one hand, and sector neutral technological progress on the other. Such differences are important for policymakers who wish to incorporate future "new economy" productivity shocks into their macroeconomic forecasts. In addition to this dynamic analysis, we have also performed some comparative static exercises, characterising how the balanced growth path is affected by changes in underlying parameters. We have not, in this paper, considered the exact dynamics of how the economy might move from one balanced growth path to another, although the model can obviously be used for such an exercise.

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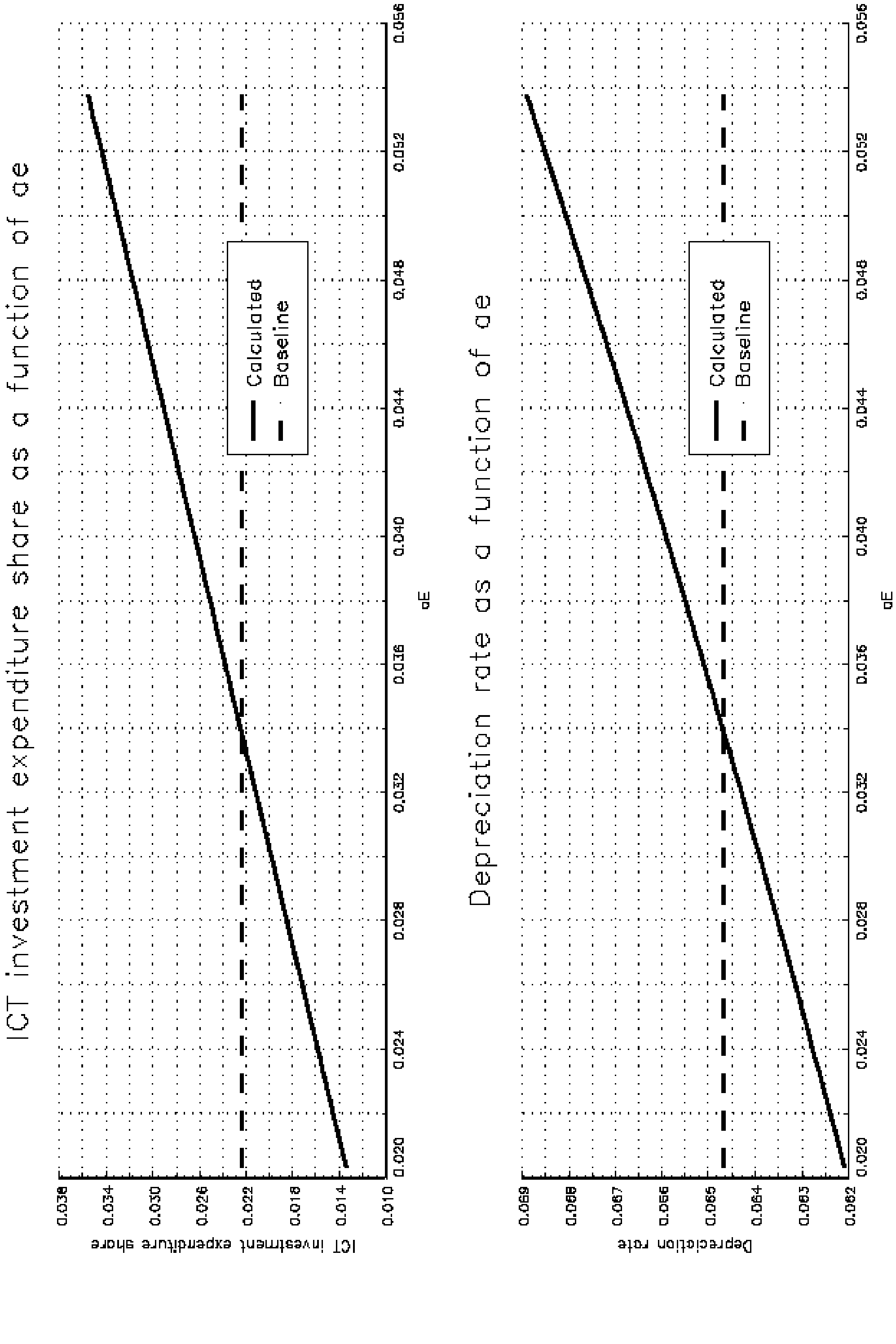
[30] One could obviously also consider changing the capital stock aggregator - a CES rather than a Cobb-Douglas aggregator could give rise to changes in the investment expenditure share without changing the parameters. An increase in the ICT share of the aggregate capital stock would then require that the elasticity of substitution between the two types of capital was *greater* than one.

Figure 11

Effects of variations in α_e



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