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Labour Markets and Firm-Specific Capital in New Keynesian General Equilibrium Models[*]

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ABSTRACT

This paper examines the consequences of introducing firm-specific capital into a selection of commonly used sticky price business cycle models. We find that modelling firm-specific capital markets greatly reduces the response of inflation to changes in average real marginal cost. Calibrated to US data, we find that models with firm-specific capital generate a less volatile, as well as more persistent series for inflation than those which assume an economy wide market for capital. Overall, it is not clear if assuming firm-specific capital helps our models match the US business cycle data

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1 Introduction

In this paper we enquire how introducing firm-specific capital into general equilibrium models with price and wage rigidities affects the behaviour of such models, and how far it helps such frameworks match the business cycle stylized facts. The open economy dimension complicates issues along several dimensions and so the business cycle facts we track are those of the US, which is more like a closed economy than, say, the UK. This study is motivated by the work of Woodford (2003, 2004) who argues that the common assumption of economy-wide factor markets is unappealing. Amongst other things, he argues that it may understate the degree of strategic complementarity across goods, making inflation appear more volatile and less persistent than it otherwise would be.

This is potentially an important point. The findings of Chari, Kehoe and McGrattan (2000) have been influential and contributed to a widespread view that New Keynesian models–based solely on realistic levels of nominal stickiness–have difficulty explaining inflation and output persistence, following monetary shocks. Related to this, the assumption of economy-wide factor markets may make monetary shocks appear to be less important than they really are, particularly with respect to their impact on aggregate output, as Sveen and Weinke (2004, 2005) argue. Finally, recent evidence from Bils and Klenow (2004) suggests that the degree of price rigidity (in the US) may be less than researchers have hitherto assumed. In the absence of some mechanism slowing the adjustment of the economy, standard New Keynesian models may be apt to imply that prices are more volatile, and output less volatile, than we see in the data; firm-specific capital may provide just such a mechanism.

We analyse the effects of introducing firm-specific capital in the context of two sticky price general equilibrium models. As a baseline model, we consider a canonical set-up in which labour markets are competitive and the goods markets are monopolistically competitive. Prices are sticky due to nominal rigidities. Next, we consider a model in which both goods and labour markets are imperfectly competitive and where both prices and wages are sticky.

We proceed to analyse the second moments generated by these two models under the assumption that the models are perturbed by estimated total factor productivity and interest rate shocks. We incorporate into our models an estimated interest rate feedback rule. The conclusions we draw from our assessment of the role firm-specific capital in helping our sticky price general equilibrium models match the data are mixed. In particular, even when the rate of price adjustment is higher than many economists have hitherto thought realistic, when there is more than one source of nominal rigidity in the model, we find that incorporating completely firm-specific capital may not be a decisive addition.

The remainder of this paper is structured as follows. Section 2 sets out the behavioural relations of our baseline model with economy-wide factor markets. Section 3 describes some of the variations in our baseline model. Specifically, we introduce firm-specific capital and sticky wages. Section 4 sets out the calibration of our driving processes and of the structural parameters of the model. Section 5 compares impulse response functions generated by the economy-wide capital market and firm-specific capital specifications of our models, and Section 6 compares a selection of second moments generated by our models to the unconditional second moments from the data. Before reaching some tentative conclusions from our work in Section 8, we offer some sensitivity analysis in Section 7.

2   The Baseline New Keynesian Model

We set out here, in the main body of the text, the core behavioural relations of our models, and then we develop the key extensions that we incorporate vis-à-vis the labour and capital markets. In an appendix we set out the log-linarised equations of our baseline model, and discuss in somewhat more detail the construction of our alternative models.

2.1   Representative agent: demand and supply decisions

There are a large number of agents in the economy who evaluate their utility in accordance with the following utility function:

$$E_t \left\{ \sum_{t=0}^{\infty} \beta^t U \left(C_t, M_t/P_t, N_t \right) \right\}. \tag{1}$$

E_t denotes the expectations operator at time t, β is the discount factor, C is consumption, M is the nominal money stock, P is the price-level and N is labour supply. For the moment we think of $U(\cdot)$ simply as being concave in its arguments and at least twice differentiable. We describe below the particular functional form that we adopt for our simulations.

Consumption is defined over a basket of goods and indexed by i in the manner of Spence-Dixit-Stiglitz

$$C_t \equiv \left[\int_0^1 c_t(i)^{\frac{\theta-1}{\theta}} di \right]^{\frac{\theta}{\theta-1}}, \tag{2}$$

where the price level is

$$P_t = \left[\int_0^1 p_t(i)^{1-\theta} di \right]^{\frac{1}{1-\theta}}. \tag{3}$$

The demand for each good is given by

$$c_t^d(i) = \left(\frac{p_t(i)}{P_t} \right)^{-\theta} Y_t^d, \tag{4}$$

where Y_t^d denotes aggregate demand. Agents face a time constraint each period (normalised to unity) such that leisure, L_t, is given by

$$L_t = 1 - N_t. \tag{5}$$

They also face a flow constraint of the following sort

$$\int_0^1 p_t(i)c_t(i)di + E_t \left\{ Q_{t,t+1} D_{t+1} \right\} + M_t = D_t + M_{t-1} + W_t N_t + \Pi_t. \tag{6}$$

Here D_{t+1} denotes the nominal pay-off at date $t+1$ of the asset portfolio held at the end of period t. We assume, as is typical, that financial markets are complete. We define $Q_{t,T}$ as the stochastic discount factor between period t and T, and

$$\frac{1}{1+i_t} = E_t \left\{ Q_{t,t+1} \right\}$$

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denotes the nominal interest rate on a riskless one-period bond. W_t denotes the nominal wage in period t, and Π_t is income from the corporate sector remitted to the individual (e.g., think of rental income from the capital stock along with a proportionate share in any final profits). We set out the consumer's maximisation problem (in Lagrangian form) as follows:

$$J = E_0 \sum_{t=0}^{\infty} \beta^t \left\{ U\left(C_t, M_t/P_t, N_t\right) + \mu_t \left[D_t + M_{t-1} + W_t N_t + \Pi_t - \int_0^1 p_t(i)c_t(i)di - E_t\left\{Q_{t,t+1}D_{t+1}\right\} \right] \right\},$$

where μ_t is the multiplier. In addition to the standard boundary conditions, the necessary conditions for an optimum include:

$$U'_C(C_t, M_t/P_t, N_t) = \mu_t P_t; \tag{7}$$

$$\frac{U'_M(C_t, M_t/P_t, N_t)}{U'_c(C_t, M_t/P_t, N_t)} = \frac{i_t}{1+i_t}; \tag{8}$$

$$\frac{U'_N(C_t, M_t/P_t, N_t)}{U'_C(C_t, M_t/P_t, N_t)} = w_t \equiv \frac{W_t}{P_t}; \tag{9}$$

$$E_t\left\{ \frac{\beta U'_C(C_{t+1}, M_{t+1}/P_{t+1}, N_{t+1})}{U'_C(C_t, M_t/P_t, N_t)} \frac{P_t}{P_{t+1}} \right\} = \frac{1}{1+i_t}. \tag{10}$$

Equation (7) denotes the real marginal utility of income. As we explain below, the nominal interest rate will be determined by the evolution of the output gap and inflation. Thus, equations (8) through (10) describe respectively optimal money holdings, given the interest rate; optimal labour supply given the real wage (and the marginal utility of consumption which will equalise across agents in our set-up); and the optimal growth of consumption between this period and next, given expected future marginal utility.

Finally, there is an economy-wide resource constraint such that total output is equal to the sum of consumption and investment.

$$Y_t = C_t + I_t. \tag{11}$$

An implicit assumption of this constraint is that the elasticity of substitution between individual consumption goods, θ, is the same as the elasticity of substitution between individual investment goods.

2.2 The firm: factor demands

We first consider the case of economy-wide factor markets. Firms are monopolistic competitors who produce their distinctive goods according to the following constant returns technology:

$$Y_t(i) = F(A_t, \{\bar{K}_t u_t\}, N_t(i)) \equiv A_t \left[\bar{K}_t u_t\right]^{s_K} N_t(i)^{1-s_K}. \tag{12}$$

$\bar{K}_t$ is the capital stock in period t, u_t is the rate at which capital is utilised, and $s_K < 1$. Firms contract labour and capital in economy-wide competitive markets. Capital accumulation is described by

$$\bar{K}_{t+1} = (1-\delta)\bar{K}_t + \phi\left(\frac{I_t}{\bar{K}_t}\right)\bar{K}_t. \tag{13}$$

Importantly, $\bar{K}_{-1}$ is given and assumed equal across all firms. When we come to consider the model with firm-specific capital this condition will not be met in the sense that different firms, with specific capital requirements, will be neither ex ante nor ex post identical. $\phi(\cdot)$ is strictly concave.[1] An alternative formulation, sometimes employed, is $I_t = I(\bar{K}_{t+1}/\bar{K}_t; \delta)\bar{K}_t$. These formulations are equivalent since $I(\cdot) \equiv \phi^{-1}(\cdot)$, and hence is strictly convex. The firm's optimisation problem over the capital stock, investment and capacity utilisation can be described as follows:

$$H = E_0 \sum_{t=0}^{\infty} \left(\mu_t \beta^t\right) \left[\rho_t \bar{K}_t u_t - I_t - a(u_t)\bar{K}_t\right] + E_0 \sum_{t=0}^{\infty} \left(\lambda_t \beta^t\right) \left[(1-\delta)\bar{K}_t + \phi\left(\frac{I_t}{\bar{K}_t}\right)\bar{K}_t - \bar{K}_{t+1}\right].$$

Here λ_t denotes the unknown multiplier of this Lagrangian function. $\rho_t \bar{K}_t u_t$ is the firm's earnings from supplying capital services. The function $a(u_t)\bar{K}_t$ denotes a cost, in terms of investment goods, of setting the utilisation rate to u_t. Following Altig *et al* (2004), we assume $a(u_t)$ is increasing and convex, capturing the idea that increased capital utilisation increases the maintenance cost of capital in terms of investment goods. In the steady state, we assume that $u = 1$ and $a(1) = 0$. To solve the model, we need only specify a value for the curvature of a in the steady state: $\sigma_a = \frac{a''(1)}{a'(1)} \geq 0$.

The optimal demand for utilised capital and labour are implied by (14) and (15) respectively

$$\rho_t = mc_t \partial F_t(i)/\partial \bar{K}_t; \tag{14}$$

$$w_t = mc_t \partial F_t(i)/\partial N_t(i). \tag{15}$$

Here ρ_t denotes the rental rate for utilised capital and mc_t denotes real marginal cost. Equation (16) provides an equation for marginal cost that will prove useful in what follows:

$$mc_t = w_t f\left[\{\bar{K}_t u_t\}, N_t(i); A_t, s_K\right] = \frac{w_t}{(1-s_K)(\bar{K}_t u_t/N_t(i))^{s_K} A_t}. \tag{16}$$

The optimality condition with respect to the rate of capital utilisation:

$$\rho_t = a'(u_t) \tag{17}$$

links capital utilisation to the demand for utilised capital. Optimal capital accumulation is described by (18) and (19),

$$\mu_t = \lambda_t \phi'\left(\frac{I_t}{\bar{K}_t}\right); \tag{18}$$

$$\lambda_t = \beta E_t \mu_{t+1}\left[\rho_{t+1} u_{t+1} - a(u_{t+1})\right] + \beta E_t \lambda_{t+1}\left[(1-\delta) - \phi'\left(\frac{I_{t+1}}{\bar{K}_{t+1}}\right)\frac{I_{t+1}}{\bar{K}_{t+1}} + \phi\left(\frac{I_{t+1}}{\bar{K}_{t+1}}\right)\right]. \tag{19}$$

Equation (18) recognises the utility foregone from investment at date t, taking into account the adjustment costs noted above. (19) captures the dynamic properties of this trade-off; a higher capital stock next period, *ceteris paribus*, enables higher consumption next period, taking into account depreciation between this period and next, and the discounted impact of next period adjustment costs.

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[1] Specifically, we assume that, evaluated at the steady state, the capital adjustment cost function has the following properties $\phi(\cdot) = \delta$, $\phi'(\cdot) = 1$ and $\phi''(\cdot) = \varepsilon$. The parameter ε_ψ that appears in linearised equations T6 and T7 of our model is the transformation $\varepsilon_\psi = \frac{\phi''(\cdot)\delta}{\phi'(\cdot)}$.

2.3 Price setting

In all the variants of the New Keynesian models that we analyse, prices are sticky in a time dependent manner. The firm will reprice in accordance with the framework suggested by Calvo (1983). That is, if the firm reprices in period t it faces the probability α^k of having to charge the same price in period $t+k$. The criterion facing a firm presented with the opportunity to reprice is given by

$$\max \sum_{k=0}^{\infty} (\alpha\beta)^k E_t \left\{ \frac{\mu_{t+k}}{\mu_t} \left[\frac{p_t(i)}{P_{t+k}} \left(\frac{p_t(i)}{P_{t+k}} \right)^{-\theta} Y_{t+k}^d - mc_{t+k} \left(\frac{p_t(i)}{P_{t+k}} \right)^{-\theta} Y_{t+k}^d \right] \right\}, \tag{20}$$

where the terms in marginal utility ensure that the price set is what would have been chosen by any individual in the economy had they been in charge of price-setting. In fact, we employed the same device above in describing the investment decision of firms. The optimal price is given by

$$p_t'(i) = \frac{\theta \sum_{k=0}^{\infty} (\alpha\beta)^k E_t \left\{ \mu_{t+k} mc_{t+k} P_{t+k}^\theta Y_{t+k}^d \right\}}{(\theta-1) \sum_{k=0}^{\infty} (\alpha\beta)^k E_t \left\{ \mu_{t+k} P_{t+k}^{\theta-1} Y_{t+k}^d \right\}}. \tag{21}$$

In the presence of economy-wide factor markets any producer given the chance to reprice will choose this value. As a result the price-level evolves in the following way:

$$P_t = \left[(1-\alpha)p_t'^{1-\theta} + \alpha P_{t-1}^{1-\theta} \right]^{\frac{1}{1-\theta}}. \tag{22}$$

3 Variations on the New Keynesian Baseline Model

3.1 The model with firm-specific factor demands

A key difference here is that the shadow value of capital is no longer determined in an economy-wide market–it is the value to the firm, at an instant of time, of possessing another unit of capital, and the consequent savings in terms of labour. This is described in detail in Woodford (2003, Chapter 5). That is, the shadow-value of capital is:

$$\rho_t(i) = w_t(i) \left[\frac{\partial Y_t(i)/\partial \bar{K}_t(i)}{\partial Y_t(i)/\partial N_t(i)} \right]. \tag{23}$$

Regardless of whether or not labour is firm-specific, and therefore whether $w_t(i)$ is firm-specifc, the price $\rho_t(i)$ is firm-specific because the capital stock and the utilisation rate now vary across firms. That means that marginal cost is firm-specific and that the optimal price is firm-specific. There are three key changes to our baseline model:

$$mc_t(i) = w_t(i)f \left[\{\bar{K}_t(i)u_t(i)\}, N_t(i); A_t, s_K \right]; \tag{16'}$$

$$\rho_t(i) = a'(u_t(i)); \tag{17'}$$

$$p_t'(i) = \frac{\theta \sum_{k=0}^{\infty} (\alpha\beta)^k E_t^i \left\{ \mu_{t+k} mc_{t+k}(i) P_{t+k}^\theta Y_{t+k}^d \right\}}{\theta-1 \sum_{k=0}^{\infty} (\alpha\beta)^k E_t^i \left\{ \mu_{t+k} P_{t+k}^{\theta-1} Y_{t+k}^d \right\}}. \tag{21'}$$

Here E_t^i indicates that expectations are conditioned on the fact that prices, with decreasing probability as $t \to \infty$, are not expected to change. These equations complicate somewhat our ability to characterise the aggregate dynamics of our model economies. However, recent work by Christiano (2004) and Woodford (2004), as a result of the insights of Sveen and Weinke (2004, 2005), has made progress on this. We leave to an appendix a description of some of the key issues in deriving the aggregate dynamic relations.

3.2   The impact of firm-specific capital

The basic impact of firm-specific capital is to slow down the adjustment of the economy following shocks. Consider first the case of economy-wide factor markets. In such an economy all firms, whether they experience high or low demand for their differentiated goods, nevertheless face the same marginal cost (see equation (16)). One may think of firms renting capital and labour in spot markets, period by period, facing the same market prices for the factors of production, and hence the capital-labour ratio equalizing across firms. If we now think of capital being firm-specific then once firms have purchased capital it is no longer possible simply to rent it to other firms when demand falls. If they wish to run down their capital stock, in our set-up, they need to either let depreciation do the work, or undertake negative investment and incur the associated adjustment costs. Similarly, if firms face high demand they would, *ceteris paribus*, wish to increase their capital stock. However, that is no longer possible; their individual capital stocks are predetermined and they need to wait one period to activate additional capital in the production process. However, that means to meet current period demand they have to hire additional labour, driving down the capital-labour ratio and short-run marginal cost rises (and hence clearly differs across firms). And because marginal cost is increasing, firms who get the opportunity to change prices will, in general, change prices by less than in the economy-wide factor market set-up. We shall return to these issues when we analyse the impulse responses of our model economy.

3.3   A model with sticky nominal wages

Recent discussions concerning optimal monetary policy and the ability of the baseline New Keynesian model to match key business cycle facts have suggested a potentially important role for sticky nominal wages. For example, sticky nominal wages may make business cycle fluctuations somewhat more costly in terms of welfare than previously thought while, at the same time, reducing the ability of monetary policy to ameliorate these fluctuations; with two distortions to cope with (sticky prices *and* sticky wages), monetary policy has to balance considerations, and the outturn in terms of welfare may not be that good (see the discussion in Erceg, Henderson, and Levin (2000), and more recently Canzoneri *et al* (2004)). In addition, sticky nominal wages coupled with sticky nominal prices may also make real wages less flexible in a manner that more closely aligns with stylized facts from the labour market. In this section, we follow the work of Erceg, Henderson, and Levin (2000) by assuming that labour is supplied by 'household unions' acting non-competitively. Household unions combine individual households' labour supply according to:

$$N_t = \left[\int_0^1 N_t(i)^{\frac{\theta_w - 1}{\theta_w}} di \right]^{\frac{\theta_w}{\theta_w - 1}}.$$

If we denote by W the price index for labour inputs and by $W(i)$ the nominal wage of worker i, then total labour demand for household i's labour is:

$$N_t(i) = \left[\frac{W_t(i)}{W_t}\right]^{-\theta w} N_t.$$

The household union takes into account the labour demand curve when setting wages. Given the monopolistically competitive structure of the labour market, if household unions have the chance to set wages every period, they will set it as a mark-up over the marginal rate of substitution of leisure for consumption. In addition to this monopolistic distortion, we also allow for the partial adjustment of wages using the same Calvo-type contract model as for price setters. This yields the following maximisation problem:

$$\max \sum_{k=0}^{\infty} (\alpha^w \beta)^k E_t \left\{ \frac{\mu_{t+k}}{\mu_t} \left[\frac{W_t(i)}{P_{t+k}} \left[\frac{W_t(i)}{W_{t+k}} \right]^{-\theta w} N_{t+k} - mrs_{t+k} \left[\frac{W_t(i)}{W_{t+k}} \right]^{-\theta w} N_{t+k} \right] \right\} \qquad (24)$$

where mrs is the marginal rate of substitution of leisure for consumption and α^w is probability that the household union does not change nominal wages in a given period. [2]

4   Calibration

There are essentially two different approaches one can follow to assess whether the introduction of firm-specific capital helps a given model explain the business cycle facts. The first, taken by Eichenbaum and Fisher (2004) and Altig *et al* (2004), estimates the reduced form of the model. Since the economy-wide capital market and firm-specific capital specifications are observationally equivalent in the reduced form sense, the role of firm-specific capital lies primarily in the interpretation of the slope coefficient of the Phillips curve. Sveen and Weinke (2005) find that for a given estimated slope coefficient of the Philips curve, assuming firm-specific capital allows one to back-out a lower and, in the face of Bils and Klenow's (2004) evidence, more realistic Calvo parameter, α. In this sense firm-specific capital allows one to reconcile microeconomic evidence on the frequency of price adjustment by firms and the macroeconomic evidence on the response of inflation to average marginal costs.

Our approach is different. We do not back out α, but rely on mircoeconomic evidence on the frequency of price adjustment by firms. We take a range of estimates of α, including the the value suggested by Bils and Klenow (2004), as well as estimates of the other determinants of the slope coefficient of the Phillips curve, and compare our two models with economy-wide capital markets and firm-specific capital. This approach is quite common in the literature, see Canzoneri, *et al* (2004), Danthine and Kurmann (2004) and Kollmann (2005) for recent examples. The rationale for this approach is twofold. First, we believe that parameters such as the Calvo coefficient have a clear economic interpretation and a micro-founded model should be based upon microeconomic evidence whenever possible. Second, we agree with Woodford (2003) who states that 'the assumption of a single economy-wide rental market for capital is plainly unrealistic, and its consequences are far from trivial...'. Hence we think that researchers will in the future increasingly make use of the

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[2] See the appendix for the resulting linearised wage inflation equation.

assumption of firm-specific capital and so this paper is a first-pass at assessing its usefulness in a range of modelling environments in improving the models' ability to match the business cycle data. Having said that, as we discuss at the end of this paper, we conclude that completely firm-specific capital is probably too extreme an assumption, in the same way that economy-wide factor markets is too extreme; inevitably the truth lies somewhere in between.

4.1 Driving processes

There are two types of shocks hitting our model economies; there are shocks to total factor productivity and there are 'monetary policy shocks'. We wanted to focus on the post-Volcker period as we think linearized models stand the best chance of matching the data in this relatively stable economic period. However, related studies such as Canzoneri *et al* (2004) and others, suggest that measured TFP over such a relatively short sample may be subject unduly to cyclical factors, and we found this also. Hence, we opted to estimate TFP over a longer sample period, whilst estimating our monetary policy rule (and shocks) over the post-Volcker period. Since a large part of our interest is in clarifying whether firm-specific capital yields bigger effects of monetary shocks, as some have argued, this seemed preferable to trying to estimate a monetary rule for the longer sample period. That strategy would have compounded our difficulties as we would have run up against issues such as nominal regime shifts, as documented by Gavin and Kydland (1999).

We measure total factor productivity by the Solow residual. We estimate the Solow residual using quarterly US data from 1960 $q1$ through 2003 $q4$. We estimate the following relationship:

$$\ln A_t = \rho \ln A_{t-1} + \varepsilon_{A,t},$$

where $\ln A$ donotes the log of the linearly detrended Solow residual.[3] The estimated coefficient ρ and the standard error of the regression are shown in Table 1 (t-statistics are in parentheses).

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Table 1: Estimated Solow residual

ρ	$\sigma_{\varepsilon A}$
0.946287	7.524×10^{-3}
(40.01)	

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To estimate a monetary policy feedback rule, we choose a shorter sample period from 1984 $q1$ to 2003 $q4$. We estimate the following Taylor rule using ordinary least squares:

$$i_t = c + \phi_i i_{t-1} + (1 - \phi_i)\phi_\pi \pi_t + (1 - \phi_i)\phi_{\bar{y}}(y_t - \bar{y}_t) + \varepsilon_{i,t}.$$

In our theoretical model, we define the output gap $(y_t - \bar{y}_t)$ as the difference between actual output and 'natural' output, where we calculate natural output under the assumption that prices are flexible, are expected to remain flexible and have been flexible in the past. This measure of the output gap does not have a direct empirical counter part. Instead, we use the Congressional Budget Office measure of potential output, which no doubt involves considerable measurment error, but is in line with the literature, e.g. Canzoneri et al (2004).

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[3]In the appendix we provide details of how we constructed our Solow Residual.

Table 2: Estimated Taylor rule coefficients

c	ϕ_i	$(1-\phi_i)\phi_\pi$	$(1-\phi_i)\phi_{\bar{y}}$	$\sigma_{\varepsilon i}$
0.000	0.937	1.506	0.4997	1.225×10^{-3}
(0.14)	(35.24)	(2.72)	(3.17)	

(t-statistics are in parentheses)

The statistical properties of our shocks appear familiar from the literature and are summarised as follows:

Table 3: Table Caption

Shock	Persistence	Standard deviation (in %)
Productivity	0.946	0.752
Monetary policy	0	0.122

These constitute the driving processes used in simulations of our linearised models. The appendix contains a list of data sources and definitions.

4.2 Structural parameters

Our calibration is basically standard and is described as follows. We assume a discount factor of 0.988, which yields an annualised steady-state rate of interest of 5%. We assume that utility is logarithmic in both consumption and labour supply, such that $\sigma = \phi = 1$. We assume an elasticity of substitution between individual varieties, $\theta = 7.67$, which yields a steady state mark-up over unit costs of 15%, a value commonly used in the literature (e.g., Rotemburg and Woodford, 1997). We follow Erceg, Henderson and Levin (2000) in setting the elasticity of substitution between varieties of labour to 4.03, which yields a mark-up over the marginal rate of substitution between consumption and leisure of some 33%. Following Canzoneri *et al* (2004), we choose the probability that a firm can not change prices in a given period to be 0.67, which implies that firms receive a signal to adjust prices on average every 3 quarters. This corresponds to evidence put forward by Nakamura and Steinsson (2007) who find that the median implied duration of finished goods producer prices is 8.7 months. We also examine what happens if firms change their prices more frequently–on average every 2 and every 1.4333 quarters as suggested by Kackmeister (2002) and Bils and Klenow (2004), respectively. We assume that unions re-optimise wages on average once every 4 quarters. On the production side of the model, we assume an annualised depreciation rate of the capital stock of 10% and a share of capital in production of 25%, as in Canzoneri *et al.* (2004). The adjustment cost parameter, ε_ψ, is chosen so as to match to the data the relative volatility of investment to GDP generated by the calibrated models. For the curvature of the capacity utilisation function, we choose Altig et al's (2004) baseline value, $\sigma_a = 2.02$.

We summarise our chosen parameter values in Table 4

Table 4: Parameters of the models

Parameter	Estimate	Parameter	Estimate
β	0.988	θ_w	4.03
r	0.0125	δ	0.025
$\bar{N}$	0.8	ε_ψ	varies
$\bar{L}$	0.2	s_K	0.25
σ	1	α	[0.67, 0.5, 0.3023]
ϕ	1	α_w	0.75
θ	7.67	σ_a	2.03

5 Impulse response analysis

In this section we analyse impulse response functions for the model with economy wide capital markets (the solid lines) and with firm specific capital (dashed lines). We analyse two types of shocks, a 1% increase in total factor productivity, and a negative interest rate shock of 100 basis points (at an annualised rate) lasting for one quarter.

Before discussing the variants of our models, we briefly describe how our New Keynesian models respond, in general, to our two canonical shocks. First, consider our long-lasting productivity shocks. In a New Keynesian framework one recognises that output is demand determined and that firms have price-setting power. Hence, as factors become more productive, marginal cost falls and so do newly posted prices and inflation. Demand and output rise while consumption also rises, but by less than output. Initially, employment may actually fall–this is especially pronounced when nominal wages are also sticky. This reflects the fact that as prices are sticky agents initially benefit from an income effect; note the increase in real wages. To sustain the rise in output, however, increased factor inputs are required and real wages and the shadow price of capital (not shown) are persistently above steady state. Monetary policy responds by lowering the nominal interest rate in an attempt to stabilise prices. In our set-up the decrease in the interest rate looks modest and appears to breach the Taylor principle (i.e., it looks like real rates may 'go the wrong way'). However, recall that in our estimated monetary policy rule the interest rate is very persistent and it turns out that the present value change in the interest rate is indeed stabilising. Future changes in the interest rate are relevant 'today' in our model because the pricing decisions of firms, and hence the economy-wide Phillips curve, is forward looking.

A surprise temporary cut in interest rates plays out broadly as follows: It tends to boost private demand by reducing the real interest rate (bringing forward consumption), and increasing expected future profits (increasing investment). At the economy-wide level, output rises increasing employment and real wages. This leads to a rise in marginal cost, and hence an increase in inflation as producers increase their prices.

Figures 1 and 2 show the impulse response functions for the baseline model following an expansionary productivity and interest rate shock, respectively. The charts in the top rows of figures 1 and 2 show the responses of GDP and its components. In both cases output, consumption and investment increase in response to the shock. For productivity shocks, output, consumption and investment increase by slightly less in the firm-specific model than in the specification that assumes

economy-wide capital markets. For interest rate shocks, we observe the opposite. The model generates more volatile and more persistent series for output and its components under firms-specific capital. This finding is in line with our prior that an increase in nominal rigidities amplifies the response of real variables to nominal shocks. Faced with an increase in aggregate demand, firms with specific factors face a rising short-run marginal cost curve; they are less likely to change prices as a result.

The second rows of figures 1 and 2 shows impulse responses for inflation, marginal costs and the policy rate. For both types of shocks, inflation is significantly less volatile in the firm-specific case than in the case with economy-wide capital markets. Introducing firm specific capital lowers the coefficient on average marginal costs in the price setting equation for the reasons outlined above. For our calibration, this coefficient in the firm-specific model, κ_{FS}, is around 0.4 of the corresponding coefficient in the economy wide capital markets model, κ_{EW}. Our impulse responses however suggest that inflation is not 2.5 times as volatile in the economy wide capital markets model than in the firm specific model. This suggests that marginal costs must be more volatile with firm-specific capital than with economy-wide capital markets. Figures 1 and 2 indicate this. Why should marginal cost be more volatile? Consider a positive shock to productivity. In our model this impacts on all firms. However, some firms may change prices and some may not. Hence, some firms face low demand and some face high demand. Under economy-wide markets, although the total capital stock is fixed, capital may flow between firms to its most productive use. When capital is firm-specific this is not possible, and marginal cost in such an economy, must be at least as high, and almost always will be strictly higher, than with economy-wide factor markets.

For the response of the policy rate, we have to take into account the response of the output gap, not reported. Since allowing for firm-specific capital leads to greater price inertia, the response of the output gap following a productivity shock is greater under firm-specific capital than under economy-wide capital markets. The response of the policy rate depends on the weights attached by the policy maker to the output gap and inflation. For our estimated Taylor rule, the policy rate becomes less volatile in the firm-specific case under productivity shocks. This may help to explain why real variables react less to productivity shocks under firm-specific capital than under economy-wide capital markets. For a given productivity shock, the economy experiences less of a monetary expansion in the firm-specific case. Following an interest rate shock, the policy rate is more volatile in the firm-specific case than in the economy-wide case. Figures 1 and 2 also show that the response of hours worked, the real wage and capacity utilisation are smaller in the case of firm-specific capital under productivity shocks, than for economy-wide capital markets, and larger under interest rate shocks.

Figures 3 and 4 repeat the analysis for our model with both sticky prices and wages. As in the baseline model, output, investment and consumption are less volatile under firm-specific capital than under economy-wide capital markets following a productivity shock, but very slightly more volatile following an interest rate shock. In terms of the dynamics of inflation, marginal costs and the policy rate, introducing firm-specific capital has the same effect in this model as in the baseline model: Inflation is less volatile, but average marginal costs are slightly more volatile. The policy rate responds by less following a productivity shock, but by more (only slightly) following a monetary shock. Under both firm-specific and economy-wide capital markets, hours worked initially decline following a productivity shock. This is more pronounced than in the sticky-price baseline model. This is because nominal wages *and* prices are sticky, and hence so too are real wages. As

a result, following a rise in total factor productivity, marginal costs fall substantially (compared with the sticky-price only model) and so too do prices (and hence inflation). As a result, there is a relatively large income effect and agents substitute into leisure.

Following an expansionary interest rate shock, hours worked rise, by about the same amount in both capital market specifications. Following a positive productivity shock, the real wage increases by more in the economy-wide capital market case than in the firm-specific case. Following an unexpected cut in the policy rate, we find that the real wage rises marginally in the both capital market specifications.

The rate of capacity utilisation also increases for both shocks and models. In the case of a productivity shock, the rate increases by somewhat more in the economy-wide capital market case than in the firm-specific capital model. The response of the utilisation rate is virtually identical across capital market specifications following an interest rate shock.[4]

For a given probability of not changing prices in a particular period, the firm-specific model yields a lower response of inflation to changes in marginal costs. Given this increase in nominal inertia, we expect a greater response of output and its components to interest rate shocks. This intuition is borne out by our impulse responses. What is, perhaps, surprising is the small size of the difference, particularly in the model with nominal rigidities in the labour market. When our models are hit by supply shocks, the real variables display less volatility under firm-specific capital than under economy-wide capital markets. For all our models we find that inflation is less volatile under the firm-specific capital specification. As a result the policy rate, which is pro-cyclical under supply shocks, responds by less in this specification leading to a smaller response of real variables.

6   Comparing second moments

Having analysed the impulse response functions for productivity and money shocks, in this section we compare a selection of second moments generated by our models with the unconditional second moments of the data. In both cases the data, covering the period from 1960 to 2003, as well as the models' output is of quarterly frequency and is logged and then Hoderick-Prescott filtered. The appendix describes our data sources. In particular, we examine if the model with firm-specific capital comes closer to the data than the model which assumes an economy-wide rental market for capital. In tables 5, as well as in tables 6 and 7, we choose the capital adjustment cost parameter, ϵ_ψ, to match the standard deviation of investment relative to the standard deviation of GDP for the economy-wide capital market specification, and then impose that value of ϵ_ψ on the specification with firm-specific capital. Table 6.1 reports the second moments of our artificial model economies when firm change prices on average every 3 quarters, $\alpha = 0.67$.

Baseline model. Compared to the data, our baseline model with economy-wide capital markets performs reasonably well. The model comes close to matching the absolute volatility of GDP,

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[4]In an earlier working paper version of this paper, we reported results for a model with sticky prices and real labour market rigidities, in the spirit of Danthine and Kurmann (2004). The effects of allowing for firm-specific capital in this model are basically the same as in the previous two models. In the real rigidities model, hours worked increase following a productivity shock as well as an interest rate shock. A particular feature of this model is the 'hump' shaped response of the real wage to both productivity and interest rate shocks. In response to a shock, firms adjust the quantity of employment, and to a much lesser extent the wage. This is because of the effects of changes in the real wage on the effort of all workers.

1.45% compared to 1.57% in the data. The model also generates series for consumption, hours, inflation, and the policy rate that are less volatile than GDP, just as in the data. There are however differences in the magnitudes, particularly for the policy rate. In the baseline model real wages are more volatile than GDP, whereas in the data, they are only half as volatile. Cross-correlation coefficients of our variables of interest with GDP are correctly signed, except for the policy rate. The data shows that the Federal Funds rate is moderately pro-cyclical (0.36), whereas our model generates strongly counter-cyclical policy rates. We find this for all models and specifications. This reflects a missing source of shocks such as demand shocks that moves output and inflation and therefore the policy rate in the same direction. This is a shortcoming in the current vintage of all New Keynesian models. We experimented with government purchase shocks and found this did little to improve our models' fit with the data. As a result, we decided to stick with our two 'conventional' driving processes, about which there is more of a consensus in the literature. In terms of persistence, measured by the autocorrelation coefficient of a given variable, our model generates series for GDP, consumption, investment and inflation that are less persistent than the data suggests.

Introducing firm-specific capital changes the model's moments along the following dimensions: The standard deviation of GDP has increased slightly, from 1.45% to 1.49%, which moves the model somewhat closer to the data. The relative volatility of consumption is marginally reduced by the introduction of firm-specific capital. The model moves closer to the data in terms of the relative volatilities of hours worked and the policy rate (only marginally so for the latter variable). In terms of cyclicality, introducing firm-specific capital only yields a slight improvement for hours worked. The degree of persistence of inflation is also increased by introducing firm-specific capital, which rises from 0.30 for the economy-wide model to 0.41 for the firm-specific, relative to 0.30 in the data.

As we gleaned from our analysis of impulse response functions, introducing firm-specific capital makes inflation both more persistent, and less volatile. However, when the Calvo parameter is set to $\alpha = 0.67$, our baseline model already matches reasonably closely the relative volatility of inflation. Introducing firm-specific capital lowers the volatility of inflation, thus moving the model further away from the data. The other key second moment where allowing for firm-specific capital moves the model away from the data is the relative volatility of real wages. Here the firm specific capital model generates a series for real wages that is 1.13 times as volatile as GDP (relative to 1.09 generated by the economy-wide model, compared to a figure of 0.48 in the data). Firm specific capital raises the volatility of investment, both in absolute terms as well as relative to that of GDP.

Sticky price and sticky wage model. Columns 5 and 6 of table 5 show our selection of second moments for the model with both sticky prices and sticky wages. Overall, this specification performs quite well and we view it as an improvement on the baseline model with sticky prices and flexible wages. The models with economy-wide capital markets comes close to matching the actual data for the volatility of GDP, and the magnitude of the relative volatility of investment (by construction), hours worked and the real wage. Price inflation, wage inflation and the policy rate are less volatile than GDP, as the data suggest, but the magnitude is some way off, particularly for price and wage inflation. The correlation between price inflation and GDP has the wrong sign. Again, this reflects a source of missing demand shocks about which relatively little is currently known. The sticky price and wage model, suggests counter-cyclical inflation rates. The correlation between wage inflation and GDP has the correct sign but the wrong magnitude. The model suggests a stronger degree of

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pro-cyclicality than the data. As in the baseline model the sticky price and wage model generates a counter-cyclical policy rate.

Introducing firm-specific capital into the sticky wage and price model does not significantly alter the moments of the model or move it much closer to the data. As in the baseline model, firm-specific capital reduces the volatility and increases the persistence of inflation. Compared to the economy-wide capital case, this moves the model away from the data along both dimensions.

7   Sensitivity analysis

Our basic conclusion so far is that introducing firm-specific capital does not significantly improve our models' ability to match the data. In this section we examine how sensitive that conclusion is to varying the frequency with which firms are assumed to change prices. Table 6 repeats the analysis of table 5 for $\alpha = 0.5$, implying the firms receive a signal to change prices about every 2 quarters. For the baseline model, most of the relative characteristics are carried over, except that the firm-specific capital model is now better able to match the relative volatility and the persistence of inflation. For this parameter setting, introducing firm-specific capital moves the model closer to the data. For the sticky wage and price model, introducing firm-specific capital does not improve the model along the same dimension. Indeed, in both cases, the second moments of inflation in the economy-wide capital market version are closer to the data than those generated by the model with firm-specific capital.

Table 7 considers the second moments of the models when $\alpha = 0.3023$, i.e. when firms change prices on average every 4.3 months, a figure suggested by Bils and Klenow (2004). As in table 6, introducing firm-specific capital improves the baseline model's ability to match the relative volatility and persistence of inflation. For the sticky wage model, firm-specific capital brings the model closer to the data in terms of the persistence of inflation.

Next, we examine how sensitive the difference is in the slope of the Phillips curves (i.e., differences in κ) between our two specifications to the introduction of variable capacity utilisation. The dynamics of our model in general and the slope of the Phillips curve in the firm-specific capital model in particular depend on the curvature of our cost of capital utilisation function, σ_a. Indeed, the potential parameter space for σ_a spans two special cases highlighted in figures 5 and 6. In the case where $\sigma_a = 0$, such that the rate of capacity utilisation can be costlessly varied, the slope coefficients of the firm-specific model coincides with that of the economy-wide capital market model. Essentially if the rate of utilisation can be freely varied, individual firms can instantly adjust their desired holding of 'utilised' capital, just as in the economy-wide capital market case. In this case, the two capital market specifications are identical, and there are no macroeconomic implications of assuming that capital is firm specific. For very high values of σ_a, as shown in figure 6, changing the utilisation rate becomes very costly and under firm-specific capital the slope of the Phillips curve approaches the one that would pertain under constant capacity utilisation. Overall, we find that introducing variable capital utilisation reduces the difference between the firm-specific and economy-wide capital market models. For further sensitivity analysis on the parameter κ in firm-specific capital model, we refer the reader to work of Sveen and Weinke (2004).

8   Conclusions

In this paper we ask the question: Does the assumption of firm-specific capital help the sticky price business cycle model explain the data? To answer this question, we consider two familiar sticky-price business cycle models and compare their economy-wide capital market specification to their firm-specific capital specification. We find that introducing firm-specific capital is most useful in the baseline model, where only prices are sticky as well as for low values of the Calvo parameter. The benefits are less clear in the case where there is more than one source of nominal rigidity. The overall assessment of the data-congruency of New Keynesian models in general, and of firm-specific capital models in particular, awaits the incorporation of important demand shocks. Uncovering just what these shocks might be remains an open question and an important issue for future research.

Finally, an important issue for future work will be developing models which incorporate varying degrees of factor specificity. We compared two extreme cases, that of economy-wide and completely firm specific factors. As we have seen, allowing for variable capacity utilisation to some extent offsets our extreme assumption of firm-specific capital. Nevertheless, it will be important to see if intermediate versions of such models can capture the data in the face of multiple sources of nominal and perhaps real rigidities.

Table 5: Data and model economies: 1960:1 - 2003:4

$\alpha = 0.67$	Data	Baseline EW	Baseline FS	Sticky wage EW	Sticky wage FS
Slope of the Philips curve κ		0.166	0.0663	0.166	0.0663
Capital adjustment costs ϵ_ψ		-8.5	-8.5	-8.76	-8.76
Standard deviation of GDP	1.57	1.45	1.49	1.62	1.56
Standard deviations relative to GDP					
Consumption	0.79	0.58	0.57	0.58	0.58
Investment	3.18	3.18	3.22	3.18	3.17
Hours	0.92	0.65	0.69	0.76	0.80
Real wage	0.48	1.09	1.13	0.42	0.36
Inflation	0.31	0.27	0.14	0.15	0.10
Wage inflation	0.33			0.06	0.06
Interest rate	0.25	0.04	0.05	0.07	0.07
Cross-correlation with GDP					
Consumption	0.86	0.99	0.98	0.99	0.99
Investment	0.89	0.99	0.99	0.99	0.99
Hours	0.88	0.70	0.72	0.79	0.77
Real wage	0.26	0.94	0.94	0.72	0.68
Inflation	0.37	0.47	0.50	-0.24	-0.29
Wage inflation	0.18			0.77	0.83
Policy rate	0.36	-0.86	-0.82	-0.90	-0.90
Autocorrelations					
GDP	0.85	0.61	0.62	0.73	0.72
Consumption	0.87	0.66	0.67	0.75	0.74
Investment	0.90	0.55	0.57	0.71	0.70
Inflation	0.30	0.30	0.41	0.46	0.55

Table 6: Data and model economies: 1960:1 - 2003:4					
	Data	Baseline EW	Baseline FS	Sticky wage EW	Sticky wage FS
$\alpha = 0.5$					
Slope of the Philips curve κ		0.5062	0.200	0.5062	0.199
Capital adjustment costs ϵ_ψ		-9.55	-9.55	-8.82	-8.82
Standard deviation of GDP	1.57	1.37	1.46	1.68	1.63
Standard deviations relative to GDP					
Consumption	0.79	0.58	0.56	0.57	0.58
Investment	3.18	3.18	3.29	3.18	3.18
Hours	0.92	0.52	0.64	0.73	0.77
Real wage	0.48	0.98	1.07	0.47	0.43
Inflation	0.31	0.50	0.30	0.22	0.16
Wage inflation	0.33			0.05	0.05
Interest rate	0.25	0.03	0.04	0.07	0.07
Cross-correlation with GDP					
Consumption	0.86	0.99	0.98	0.99	0.99
Investment	0.89	0.99	0.99	0.99	0.99
Hours	0.88	0.68	0.72	0.81	0.79
Real wage	0.26	0.95	0.94	0.75	0.73
Inflation	0.37	0.36	0.47	-0.22	-0.23
Wage inflation	0.18			0.67	0.75
Policy rate	0.36	-0.91	-0.82	-0.89	-0.90
Autocorrelations					
GDP	0.85	0.63	0.60	0.73	0.73
Consumption	0.87	0.68	0.67	0.75	0.75
Investment	0.90	0.57	0.53	0.71	0.71
Inflation	0.30	0.15	0.27	0.31	0.44

Table 7: Data and model economies: 1960:1 - 2003:4

$\alpha = 0.3023$	Data	Baseline EW	Baseline FS	Sticky wage EW	Sticky wage FS
Slope of the Philips curve κ		1.6189	0.638	1.6189	0.638
Capital adjustment costs ϵ_ψ		-11.03	-11.03	-8.88	-8.88
Standard deviation of GDP	1.57	1.31	1.38	1.72	1.69
Standard deviations relative to GDP					
Consumption	0.79	0.57	0.56	0.57	0.57
Investment	3.18	3.18	3.29	3.18	3.18
Hours	0.92	0.34	0.50	0.68	0.72
Real wage	0.48	0.84	0.94	0.51	0.48
Inflation	0.31	0.75	0.54	0.29	0.24
Wage inflation	0.33			0.05	0.05
Interest rate	0.25	0.03	0.03	0.07	0.07
Cross-correlation with GDP					
Consumption	0.86	0.99	0.99	0.99	0.99
Investment	0.89	0.99	0.99	0.99	0.99
Hours	0.88	0.75	0.70	0.83	0.82
Real wage	0.26	0.98	0.95	0.77	075
Inflation	0.37	0.17	0.34	-0.26	-0.23
Wage inflation	0.18			0.59	0.65
Policy rate	0.36	-0.97	-0.92	-0.87	-0.88
Autocorrelations					
GDP	0.85	0.69	0.63	0.71	0.73
Consumption	0.87	0.72	0.69	0.72	0.74
Investment	0.90	0.66	0.57	0.70	0.71
Inflation	0.30	0.02	0.11	0.14	0.28

Table 8: Linear dynamic system for model with economy-wide factor markets

$$E_t \hat{c}_{t+1} = \hat{c}_t + \frac{1}{\sigma}\left(\hat{\imath}_t - E_t \pi_{t+1}\right) \tag{T 1}$$

$$\hat{w}_t = \sigma \hat{c}_t + \phi \hat{n}_t \tag{T 2}$$

$$\hat{m}_t = \frac{1}{\sigma}\hat{c}_t - \frac{\beta}{1-\beta}\hat{\imath}_t \tag{T 3}$$

$$\hat{\rho}_t = \widehat{mc}_t + (1-s_K)\hat{n}_t - (1-s_K)\widehat{\overline{k}}_t(1-s_K)\hat{u}_t + \hat{A}_t \tag{T 4}$$

$$\widehat{\overline{k}}_{t+1} = \delta \hat{x}_t + (1-\delta)\widehat{\overline{k}}_t \tag{T 5}$$

$$E_t \hat{\lambda}_{t+1} = \frac{1}{(1-\delta)\beta}\hat{\lambda}_t - \frac{1}{\delta(1-\delta)\varepsilon_\psi}\left(E_t \widehat{\overline{k}}_{t+1} - E_t \hat{x}_{t+1}\right) - \frac{r+\beta}{(1-\delta)}\left(E_t \hat{\rho}_{t+1} - E_t \hat{\mu}_{t+1}\right) \tag{T 6}$$

$$\hat{\mu}_t = \hat{\lambda}_t + \frac{1}{\varepsilon_\psi}\left(\hat{x}_t - \widehat{\overline{k}}_t\right) \tag{T 7}$$

$$\hat{\mu}_t = -\sigma\left[\frac{Y}{C}\hat{y}_t - (\frac{Y}{C}\frac{X}{Y})\hat{x}_t\right] \tag{T 8}$$

$$\widehat{mc}_t = \hat{w}_t + s_K \hat{n}_t - s_K \widehat{\overline{k}}_t - s_K \hat{u}_t - \hat{A}_t \tag{T 9}$$

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \kappa_p \widehat{mc}_t \tag{T 10}$$

$$\hat{\imath}_t = \phi_i \hat{\imath}_{t-1} + (1-\phi_i)\phi_\pi \hat{\pi}_t + (1-\phi_i)\phi_Y(\hat{y}_t - \bar{y}_t) \tag{T 11}$$

$$\hat{y}_t = s_K \widehat{\overline{k}}_t + s_K \hat{u}_t + (1-s_K)\hat{n}_t + \hat{A}_t \tag{T 12}$$

$$\hat{y}_t = \frac{X}{Y}\hat{x}_t + \frac{C}{Y}\hat{c}_t \tag{T 13}$$

$$\hat{n}_t = \frac{L}{N}\hat{l}_t \tag{T 14}$$

$$\hat{\rho}_t = \sigma_a \hat{u}_t \tag{T 15}$$

A   The linear dynamic system

Having described the non-linear dynamics as well as key steady state equations of the model in the text, this appendix sets out the linear dynamic system. We linearise the model around its deterministic steady state. We embed our estimated policy rule in this system of linear difference equations, and we solve the model incorporating the statistical information from Table 3.1. In table B.1 we present the set of linear difference equations for our base-line model. We describe below the key changes we need to make in order to incorporate differing assumptions concerning capital and labour markets.

Equations T1 - T3 derive from the first order conditions of bondholding, labour supply and money holdings, respectively. Equations T4 - T8 pertain to the optimal paths of investment and capital. Equations T10 describes the dynamics of price inflation as a function of deviations of marginal cost from its steady state (T 9). The nominal side of the model is closed though an interest rate feedback rule (T 11), which links deviations in the nominal interest rate from its steady state level to deviations in inflation and the output gap. The output gap is derived by solving the model under the assumption of price stability. Finally, equations T12 -T15 are the linearised production function, the economy-wide resource constraint, the time constraint, and an expression linking the marginal cost of capacity utilisation to the shadow value of capital, respectively.

A.1   Incorporating firm-specific capital

For the case of firm-specific capital it will be useful to write some of our equations in a slightly different format. We use the log-linear version of the production technology to substitute out for

$(\hat{K}_t + \hat{N}_t)$ in terms of $(\hat{Y}_t(i) - \hat{K}_t(i))$. We then calculate the economy-wide analogue for equation (2.15') and subtract it from the frim-specifc equation. We then have

$$\hat{mc}_t(i) = \hat{mc}_t + \frac{s_K \sigma_a}{(1 - s_K)\sigma_a + 1}\left[\left(\hat{Y}_t(i) - \hat{Y}_t\right) - \left(\widehat{\overline{K}}_t(i) - \widehat{\overline{K}}_t\right)\right] \tag{25}$$

an equation relating firm-specific marginal cost to the average marginal cost in the economy. Finally, using the log-linear demand function, $\hat{Y}_t(i) - \hat{Y}_t = -\theta(\hat{p}_t(i) - \hat{P}_t)$ facing the firm we may write this as

$$\hat{mc}_t(i) = \hat{mc}_t - \frac{\theta s_K}{1 - s_K}\frac{(1 - s_K)\sigma_a}{(1 - s_K)\sigma_a + 1}\left(\hat{p}_t(i) - \hat{P}_t\right) - \frac{s_K}{1 - s_K}\frac{(1 - s_K)\sigma_a}{(1 - s_K)\sigma_a + 1}\left(\widehat{\overline{K}}_t(i) - \widehat{\overline{K}}_t\right) \tag{26}$$

Following similar steps, we can write an equation for the (firm-specific) shadow-price of capital as

$$\hat{\rho}_t(i) = \hat{\rho}_t - \frac{\theta}{1 - s_K}\frac{(1 - s_K)\sigma_a}{(1 - s_K)\sigma_a + 1}\left(\hat{p}_t(i) - \hat{P}_t\right) - \frac{1}{1 - s_K}\frac{(1 - s_K)\sigma_a}{(1 - s_K)\sigma_a + 1}\left(\widehat{\overline{K}}_t(i) - \widehat{\overline{K}}_t\right) \tag{27}$$

These equations make clear the complication in characterising aggregate price and output dynamics for the economy characterised by firm-specific factor technologies. Following the recommendations in Woodford (2004) and Christiano (2004) we proceed using a method of undetermined coefficients.

Our linearized investment equations are as follows:

$$\hat{\mu}_t = \hat{\lambda}_t + \epsilon_K^{-1}\left[\hat{I}(i)_t - \widehat{\overline{K}}(i)_t\right], \tag{28}$$

and

$$\hat{\lambda}_t = \frac{1 - \delta}{1 + r}E_t\left(\hat{\lambda}_{t+1} - \frac{(I/K)\epsilon_K^{-1}}{1 - \delta}\left[\hat{I}(i)_{t+1} - \widehat{\overline{K}}(i)_{t+1}\right]\right) + \frac{r + \delta}{1 + r}E_t\left(\hat{\rho}(i)_{t+1} + \hat{\mu}_{t+1}\right), \tag{29}$$

along with the linear version of (2.16). Use (B.4) in (B.5) recalling (2.13). We get that

$$\hat{\mu}_t = \frac{\epsilon_K^{-1}}{\delta}E_t\left(\widehat{\overline{K}}(i)_{t+1} - \widehat{\overline{K}}(i)_t\right) - \frac{1 - \delta}{1 + r}E_t\left(\hat{\mu}_{t+1} - \frac{\epsilon_K^{-1}}{\delta}\left[\widehat{\overline{K}}(i)_{t+2} - \widehat{\overline{K}}(i)_{t+1}\right]\right)$$

$$- \frac{(I/K)\epsilon_K^{-1}}{(1 - \delta)\delta}E_t\left[\widehat{\overline{K}}(i)_{t+2} - \widehat{\overline{K}}(i)_{t+1}\right] +$$

$$\frac{r + \delta}{1 + r}E_t\left[\frac{1}{1 - s_K}\frac{(1 - s_K)\sigma_a}{(1 - s_K)\sigma_a + 1}\left(\hat{Y}_{t+1}(i) - \widehat{\overline{K}}(i)_{t+1}\right) + \frac{(1 - s_K)\sigma_a}{(1 - s_K)\sigma_a + 1}q_{t+1}\right].$$

Here $q_{t+1} \equiv \phi\hat{N}_t - \frac{1}{1 - s_K}\hat{A}_t$. We note that a similar relation holds at the economy-wide level, and so subtracting one from the other yields, after some simplification,

$$\beta E_t\left(\widehat{\overline{K}}(i)_{t+2} - \widehat{\overline{K}}_{t+2}\right)$$

$$- \left[1 + \beta + \frac{(r + \delta)\epsilon_{\overline{K}}^{-1}}{(1 + r)}\frac{1}{(1 - s_K)}\frac{(1 - s_K)\sigma_a}{(1 - s_K)\sigma_a + 1}\right]E_t\left(\widehat{\overline{K}}(i)_{t+1} - \widehat{\overline{K}}_{t+1}\right)$$

$$+ \left(\widehat{\overline{K}}(i)_t - \hat{K}_t\right) = \frac{(r + \delta)\epsilon_{\overline{K}}^{-1}}{(1 + r)}\frac{\theta}{(1 - s_K)}\frac{(1 - s_K)\sigma_a}{(1 - s_K)\sigma_a + 1}E_t\left(\hat{p}_{t+1}(i) - \hat{P}_{t+1}\right),$$

where $\epsilon_{\bar{K}}^{-1} \equiv \epsilon_K^{-1}/\delta$. From (2.20') and (B.1) we have that

$$\hat{p}(i)_t' = \sum_{k=1}^{\infty}(\alpha\beta)^k E_t\pi_{t+k} + \frac{(1+\sigma_a(1-s_K))(1-\alpha\beta)}{1+\sigma_a(1-s_K)-\sigma_a\theta s_K}\sum_{k=0}^{\infty}(\alpha\beta)^k E_t mc_{t+k}$$
$$-\frac{\sigma_a s_K(1-\alpha\beta)}{1+\sigma_a(1-s_K)-\sigma_a\theta s_K}E_t^i\sum_{k=0}^{\infty}(\alpha\beta)^k\left(\widehat{\bar{K}}(i)_t - \widehat{\bar{K}}_t\right).$$

Following the recommendation in Woodford (2004) and Christiano (2004) we solve using a method of undetermined coefficients. We posit a relation of the following sort:

$$\hat{p}(i)_t' = \hat{p}_t' - \psi\left(\widehat{\bar{K}}(i)_t - \widehat{\bar{K}}_t\right), \tag{30}$$

where $\hat{p}(i)_t'$ is the real price of firm i upon repricing in period t and $\hat{p}_t'$ is the economy-wide average for this price, where $\pi_t = [(1-\alpha)/\alpha]\hat{p}_t'$. Similarly, we posit that

$$\left(\widehat{\bar{K}}(i)_{t+1} - \widehat{\bar{K}}_{t+1}\right) = \kappa_1\left(\widehat{\bar{K}}(i)_t - \widehat{\bar{K}}_t\right) + \kappa_2\left(\hat{p}_t(i) - \hat{P}_t\right). \tag{31}$$

Using these relations one can show that

$$E_t^i\sum_{k=0}^{\infty}(\alpha\beta)^k\left(\hat{K}(i)_t - \hat{K}_t\right) = \frac{1}{1-\kappa_1\alpha\beta}\left(\hat{K}(i)_t - \hat{K}_t\right) + \frac{\alpha\beta\kappa_2}{(1-\kappa_1\alpha\beta)(1-\alpha\beta)}\hat{p}(i)_t'$$
$$-\frac{\alpha\beta\kappa_2}{(1-\kappa_1\alpha\beta)(1-\alpha\beta)}\sum_{k=1}^{\infty}(\alpha\beta)^k E_t\pi_{t+k}.$$

If we use this in (B.6) we find

$$\hat{p}(i)_t' = \sum_{k=1}^{\infty}(\alpha\beta)^k E_t\pi_{t+k} + \frac{(1+\sigma_a(1-s_K))(1-\alpha\beta\kappa_1)(1-\alpha\beta)}{(1+\sigma_a(1-s_K)-\sigma_a\theta s_K)(1-\alpha\beta\kappa_2)+\alpha s_K\beta\kappa_2}\sum_{k=0}^{\infty}(\alpha\beta)^k E_t mc_{t+k}$$
$$-\frac{s_K(1-\alpha\beta)\sigma_a}{(1+\sigma_a(1-s_K)-\sigma_a\theta s_K)(1-\alpha\beta\kappa_2)+\alpha s_K\beta\kappa_2}E_t^i\sum_{k=0}^{\infty}(\alpha\beta)^k\left(\widehat{\bar{K}}(i)_t - \widehat{\bar{K}}_t\right).$$

Hence, $\psi = \frac{s_K(1-\alpha\beta)\sigma_a}{(1+\sigma_a(1-s_K)-\sigma_a\theta s_K)(1-\alpha\beta\kappa_2)+\alpha s_K\beta\kappa_2}$. Recall that

$$\beta E_t\left(\widehat{\bar{K}}(i)_{t+2} - \widehat{\bar{K}}_{t+2}\right)$$
$$-\left[1+\beta+\frac{(r+\delta)\epsilon_{\bar{K}}^{-1}}{(1+r)}\frac{1}{(1-s_K)}\frac{(1-s_K)\sigma_a}{(1-s_K)\sigma_a+1}\right]E_t\left(\widehat{\bar{K}}(i)_{t+1} - \widehat{\bar{K}}_{t+1}\right)$$
$$+\left(\widehat{\bar{K}}(i)_t - \hat{K}_t\right) = \frac{(r+\delta)\epsilon_{\bar{K}}^{-1}}{(1+r)}\frac{\theta}{(1-s_K)}\frac{(1-s_K)\sigma_a}{(1-s_K)\sigma_a+1}E_t\left(\hat{p}_{t+1}(i) - \hat{P}_{t+1}\right), \quad \text{(B 8)}$$

Again, we follow Christiano (2004). First, note that

$$E_t \left(\hat{p}_{t+1}(i) - \hat{P}_{t+1} \right) = \alpha \left[\left(\hat{p}_t(i) - \hat{P}_{t+1} - E_t \pi_{t+1} \right) \right] + (1-\alpha) E_t \left[\hat{p}'_{t+1} - \psi \left(\widehat{\overline{K}}(i)_{t+1} - \widehat{\overline{K}}_{t+1} \right) \right].$$

Using the definition of inflation, $\pi_t = [(1-\alpha)/\alpha] \, \hat{p}'_t$, we may write this as

$$E_t \left(\hat{p}_{t+1}(i) - \hat{P}_{t+1} \right) = \alpha \left(\hat{p}_t(i) - \hat{P}_{t+1} \right) + (1-\alpha) \, \psi \left(\widehat{\overline{K}}(i)_{t+1} - \widehat{\overline{K}}_{t+1} \right).$$

If we use this expression along with (B.7) in (B.8) and simplify, we recover a relation of the following sort:

$$\Phi \left(\kappa_1, \kappa_2, \psi; \Theta \right) \left(\widehat{\overline{K}}(i)_t - \widehat{\overline{K}}_t \right) + \Psi \left(\kappa_1, \kappa_2, \psi; \Theta \right) \left(\hat{p}_t(i) - \hat{P}_t \right) = 0. \tag{32}$$

Here Θ denotes a vector of known parameters (i.e., parameters whose values we can infer from outside the system of equations defined by (B.6), (B.7) (B.8) and $\pi_t = [(1-\alpha)/\alpha] \, \hat{p}'_t$).

Finally, recall that

$$\hat{p}(i)'_t = \sum_{k=1}^{\infty} (\alpha\beta)^k E_t \pi_{t+k} + \frac{(1+\sigma_a(1-s_K))(1-\alpha\beta\kappa_1)(1-\alpha\beta)}{(1+\sigma_a(1-s_K)-\sigma_a\theta s_K)(1-\alpha\beta\kappa_2)+\alpha s_K \beta \kappa_2} \sum_{k=0}^{\infty} (\alpha\beta)^k E_t mc_{t+k}$$

$$- \frac{s_K(1-\alpha\beta)\sigma_a}{(1+\sigma_a(1-s_K)-\sigma_a\theta s_K)(1-\alpha\beta\kappa_2)+\alpha s_K \beta \kappa_2} E_t^i \sum_{k=0}^{\infty} (\alpha\beta)^k \left(\hat{K}(i)_t - \hat{K}_t \right).$$

Since the opportunity to reprice is random we have that

$$\hat{p}(i)'_t = \sum_{k=1}^{\infty} (\alpha\beta)^k E_t \pi_{t+k} + \frac{(1+\sigma_a(1-s_K))(1-\alpha\beta\kappa_1)(1-\alpha\beta)}{(1+\sigma_a(1-s_K)-\sigma_a\theta s_K)(1-\alpha\beta\kappa_2)+\alpha s_K \beta \kappa_2} \sum_{k=0}^{\infty} (\alpha\beta)^k E_t mc_{t+k}.$$

This expression may be quasi-differenced and, using our solutions for $(\kappa_1, \kappa_2, \psi)$, we can infer the slope of the resulting New Keynesian Phillips curve,

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \gamma \widehat{mc}_t. \tag{T 10 i}$$

Here, as we have just seen, γ is a function of the structural parameters of the model, including but not only those determining κ_p.

A.2 Incorporating sticky wages

Adding sticky nominal wages alters the equations of our model in the following way: Equation (T 2) which equates the real wage to the marginal rate of substitution between consumption and labour is replaced by an expression describing the evolution of nominal wages:

$$\hat{\omega}_t = \beta E_t \hat{\omega}_{t+1} + \frac{(1-\alpha_w)(1-\alpha_w\beta)}{\alpha_w(1+\phi\theta_w)} \left[\sigma \hat{c}_t + \phi \hat{n}_t - \hat{w}_t \right], \tag{T 2 ii}$$

the derivation of which follows directly from Erceg et al. (2000). To describe the dynamics of the real wage, we need a further equation, which follows from the definition of the real wage:

$$\hat{w}_t = \hat{w}_{t-1} + \hat{\omega}_t - \hat{\pi}_t. \tag{T 15}$$

B   The data

Our data are of quarterly frequency and come from two main sources: the *US Department of Commerce: Bureau of Economic Analysis* (BEA) and *US Department of Labor: Bureau of Labor Statistics* (BLS) and span the sample period 1960:1 to 2003:4.

1. GDP refered to in tables 5, 6 and 7 is real GDP per capita from BEA's NIPA table 7.1. 'Selected Per Capita Product and Income Series in Current and Chained Dollars', seasonally adjusted. The series was logged and H-P filtered.

2. Consumption referred to in tables 5, 6 and 7 is total consumption expenditures deflated by the relevant GDP deflator, both from BEA's NIPA tables 2.3.5 and 1.1.9.

3. Investment referred to in tables 5, 6 and 7 is real fixed investment per capita from BEA's NIPA table 5.3.3. Real Private Fixed Investment by Type. Population is from NIPA table 7.1.

4. Hours referred to in tables 5, 6 and 7 is per capita hours worked in non-farm businesses, from BLS, series code PRS85006033. Population is from NIPA table 7.1.

5. Real wage referred to in tables 5, 6 and 7 is real hourly compensation from BLS, series code PRS85006153.

6. Inflation referred to in tables 5, 6 and 7 is defined as $\pi = \log(P_t/P_{t-1})$, where P is consumer price index for all urban consumers, from BLS series CUSR0000SA0.

7. Wage inflation referred to in tables 5, 6 and 7 is constructed using nominal hourly compensation from BLS, series code PRS85006103 W_t. $\omega = \log(W_t/W_{t-1})$.

8. Interest rate referred to in tables 5, 6 and 7 is the effective US federal funds rate.

9. Potenital output used to construct the output gap measure in our estimated Taylor rule is taken from the *Congressional Budget Office* measure of potential output.

10. The Solow residual is constructed as follows:

$$A_t = ynfb_t - s_k \log(K_t) - s_k \log(u_t) - (1 - s_k) \log(N_t)$$

where $ynfb$ is the log of real GDP in the non-farm business sector, series PRS85006043 from BLS. N_t is aggregate hours worked, as above, but not deflated by the population. K is real non-residential fixed assets, constructed following Stock and Watson (1999), and u_t is the FRB capacity utilisation in manufacturing (SIC) series G17/CAPUTL/CAPUTL.B00004.S.Q.

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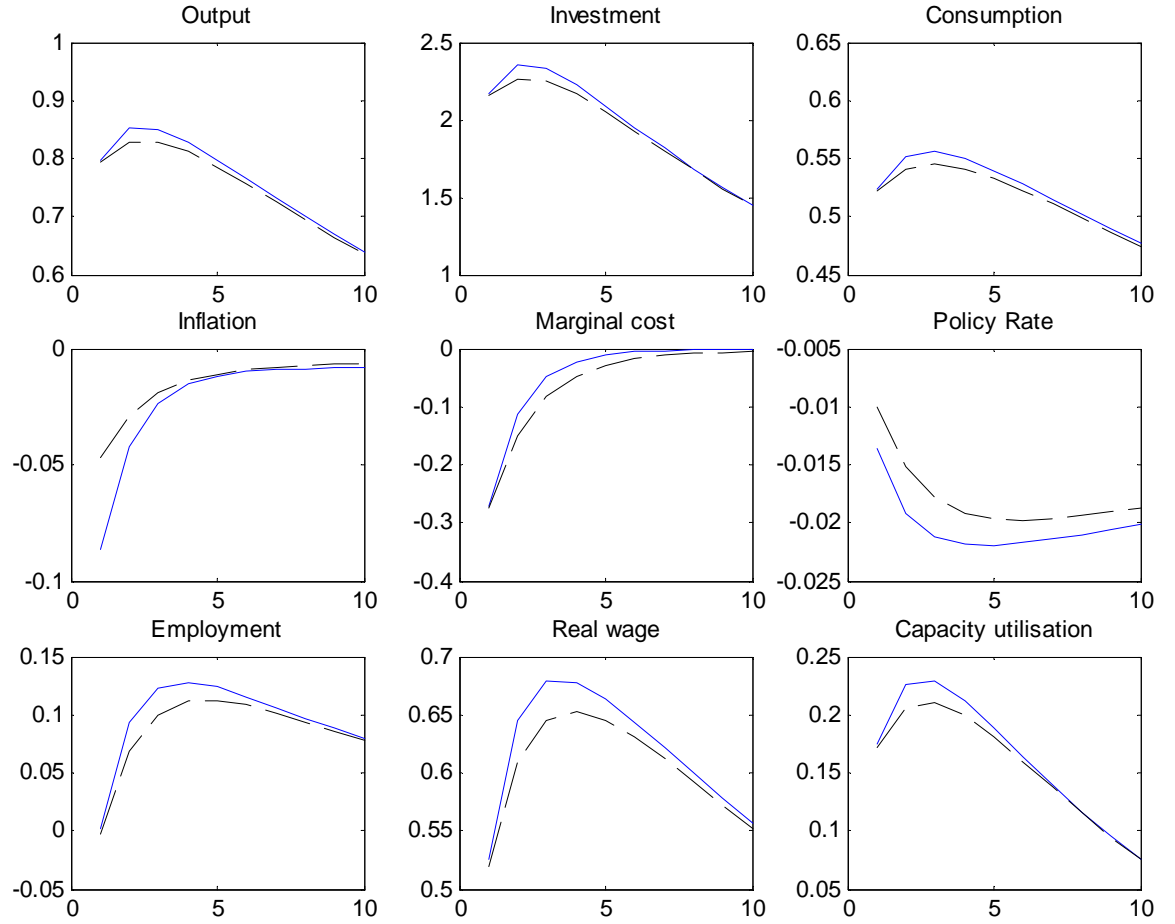
Figure 1: Impulse response functions with respect to a 1% productivity shock for the flexible wage model with economy-wide factor markets (solid) and firm-specific capital (dashed).
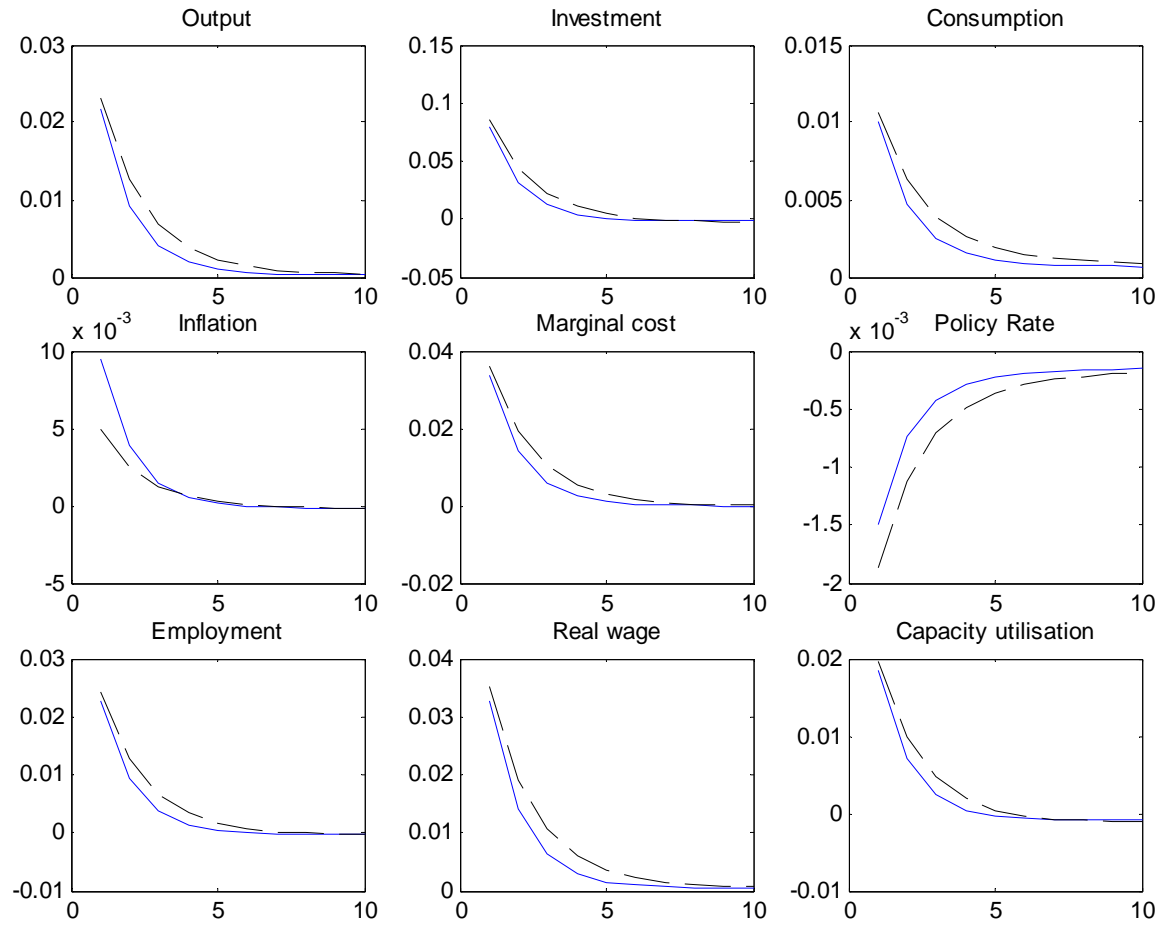
Figure 2: Impulse response functions with respect to an unanticipated 100 basis point decrease in the policy rate for the flexible wage model with economy-wide factor markets (solid) and firm-specific capital (dashed).
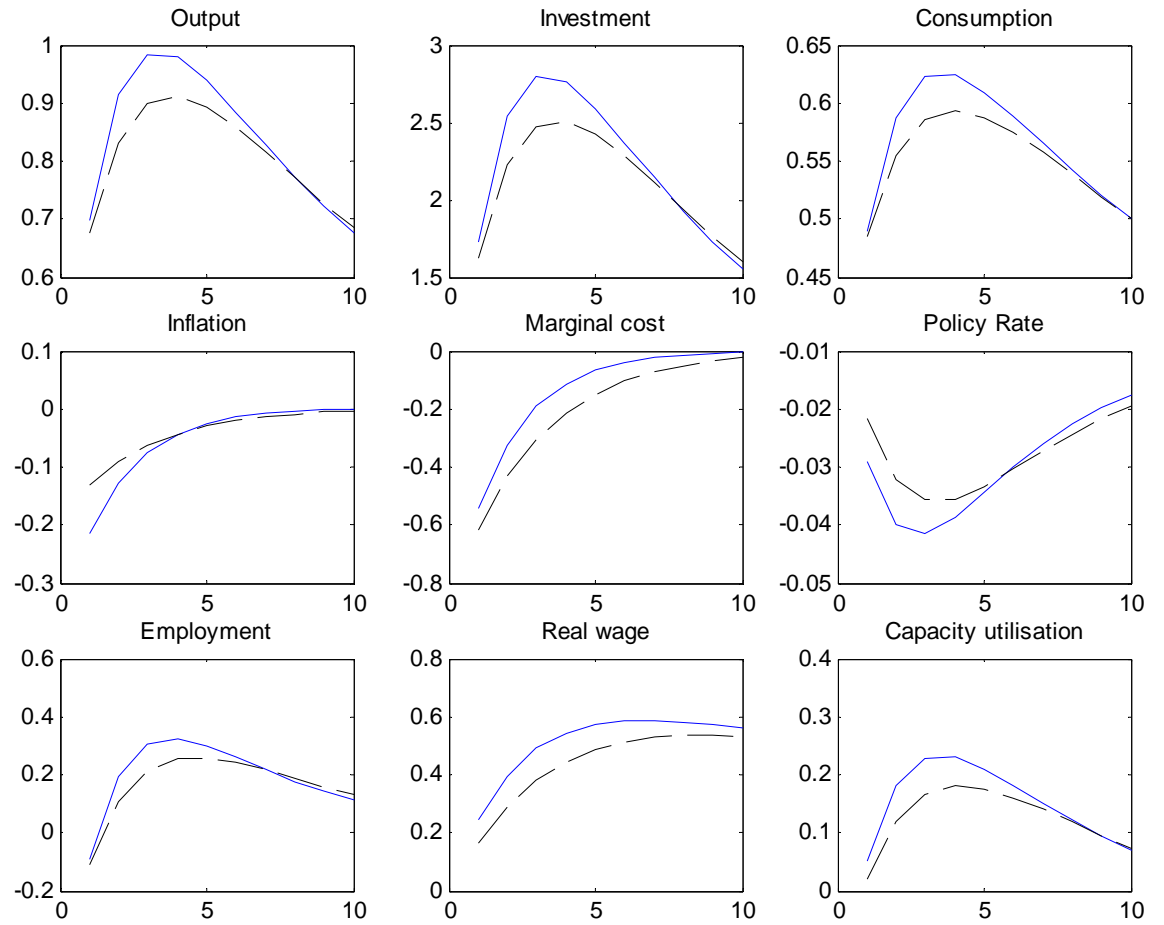
Figure 3: Impulse response functions with respect to a 1% productivity shock for the sticky wage model with economy-wide factor markets (solid) and firm-specific capital (dashed).
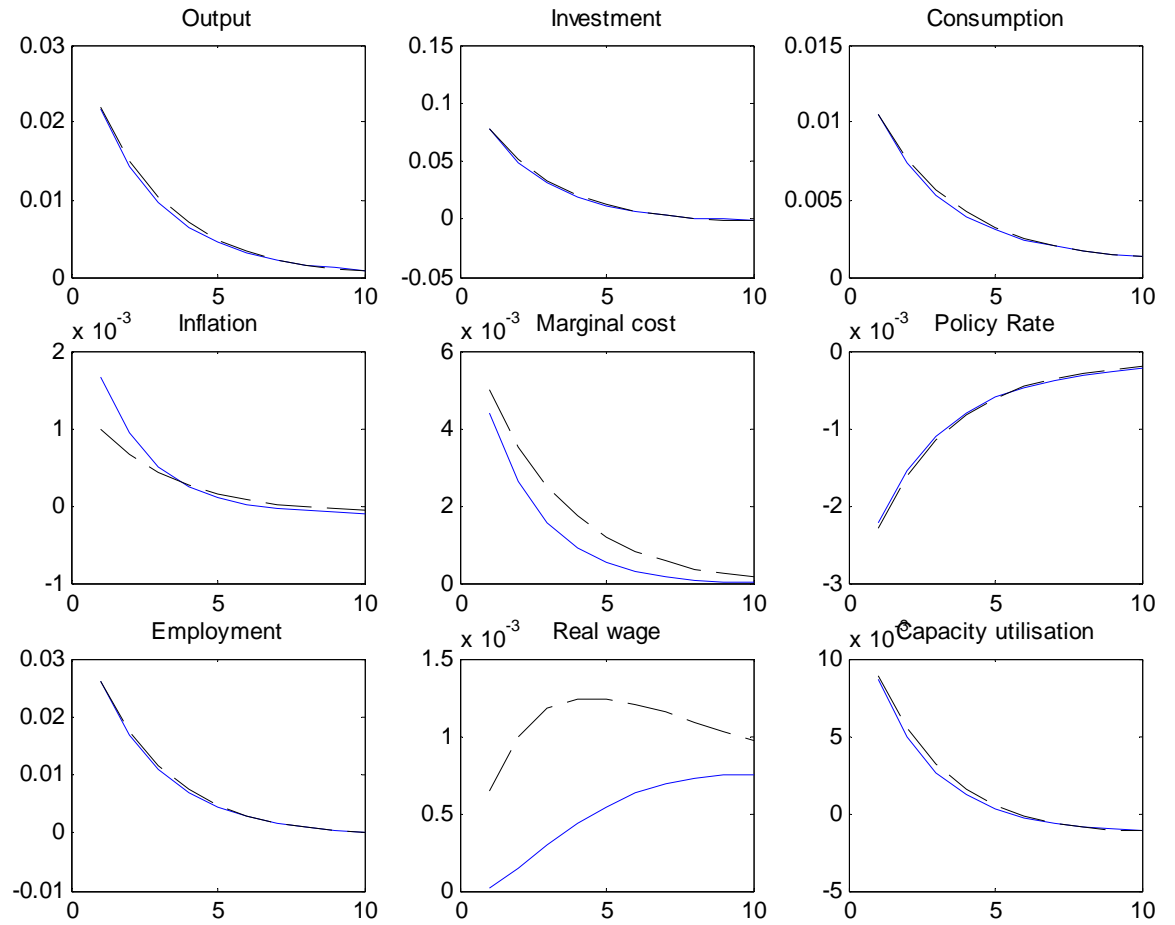
Figure 4 : Impulse response functions with respect to an unanticipated 100 basis point decrease in the policy rate for the sticky wage model with economy-wide factor markets (solid) and firm-specific capital (dashed).
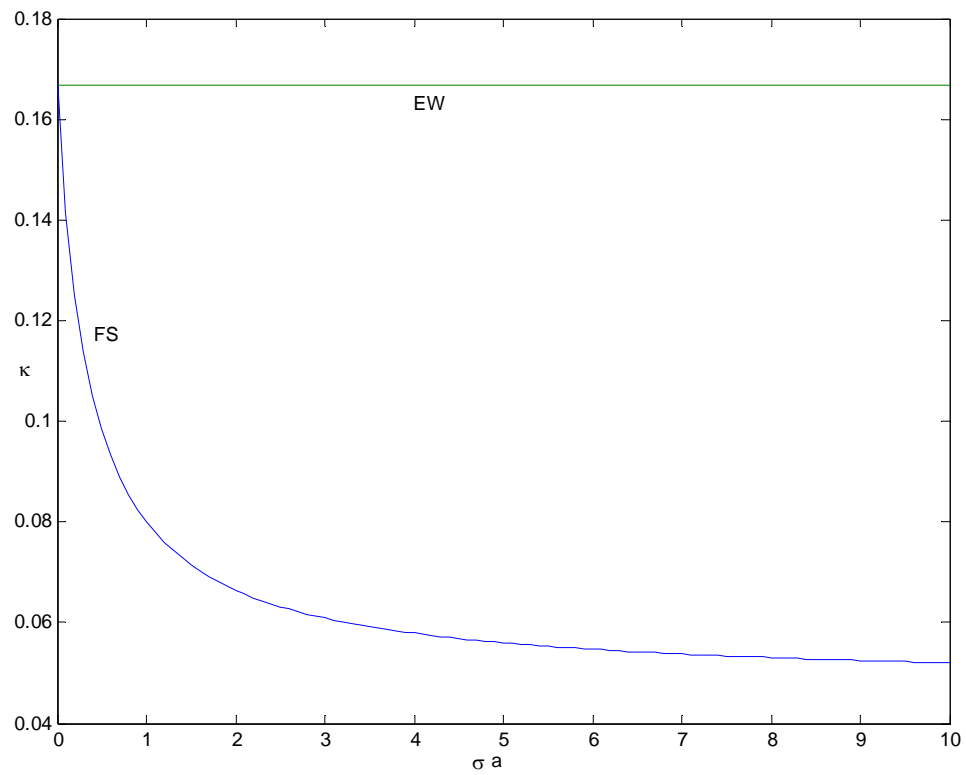
Figure 5: The coefficient on marginal cost in the new Keynesian Philips curve, κ for various values of elasticity of capacity utilization, σa. When σa=0, there is no effect of firm-specific capital on the coefficient on marginal cost.
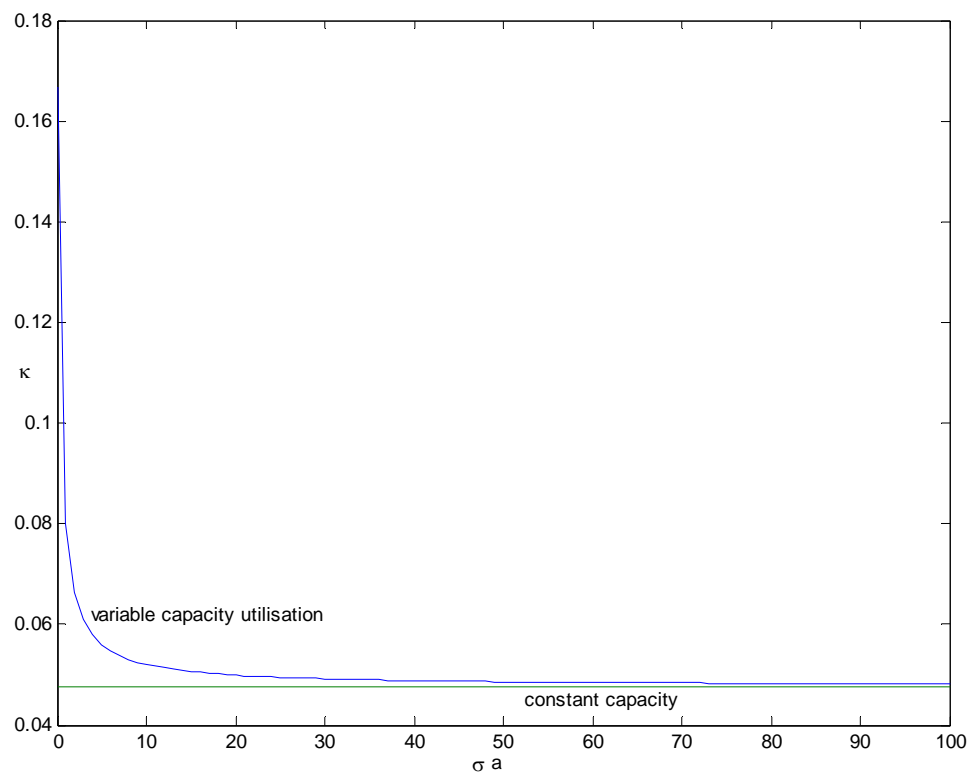
Figure 6: The coefficient on marginal cost in the new Keynesian Philips curve, κ for the model with variable and constant capacity utilization.

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