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ON THE (IR)RELEVANCE OF DIRECT SUPPLY-SIDE EFFECTS OF MONETARY POLICY

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Abstract

The relevance of direct supply-side effects of monetary policy in a New Keynesian DSGE model is studied. We extend a model with several nominal and real frictions by introducing a cost channel of monetary transmission and allowing for non-separability of money and consumption in the utility of the representative household. These features have important theoretical consequences for the output-inflation trade-off and indeterminacy of interest rate rules. The empirical evidence for these effects are then examined using a Bayesian maximum likelihood framework complemented with GMM single-equation estimation. Both estimation strategies point to weak evidence for the cost channel and non-separable utility.

JEL Classification: E42, E52, C11.

Keywords: New Keynesian model, Bayesian maximum likelihood estimation, GMM, non-separable utility, cost channel.

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1 Introduction

What are the consequences of direct supply-side effects of monetary policy? Are they empirically significant? Do these outweigh the usual demand-side effects? This paper addresses these questions in two ways. First, we develop a model, in the now standard New Keynesian tradition, by incorporating a cost channel of monetary transmission and allowing for non-separability of money and consumption in the utility of the representative household. We derive two important results. If non-separability holds (more precisely, if consumption and money are complements), the cost channel effects are significantly amplified, resulting in a transmission mechanism that generates a considerable negative inflation-output trade-off. Furthermore, when these two features are present, interest rate rules may become unstable and indeterminate, with supply-side effects counteracting the stabilization effects of the demand channel. Second, we assess the empirical relevance of these supply-side effects. Using US data, we consider evidence from both GMM single-equation estimation and Bayesian system estimation of fully-fledged New Keynesian dynamic stochastic general equilibrium (NK-DSGE) models, featuring a variety of nominal and real frictions. Both estimation methods point to weak evidence for the cost channel and non-separable utility.

The issues addressed in this paper are of substantial importance for policy purposes. While a new breed of NK-DSGE models has enjoyed considerable success in explaining and forecasting the observed properties of macroeconomic time series, recent contributions emphasize the importance of supply-side channels for the transmission of monetary policy. One strand has paid attention to the so-called 'cost channel', in which nominal interest rate fluctuations affect the cost of financing working capital, impacting on firms' marginal cost and pricing decisions. This can cause inflation and nominal interest rates to move in the same direction after a monetary policy shock, giving rise to a "price puzzle". Barth and Ramey (2001), using industry-level US data, find support for such a channel, while Christiano, Eichenbaum and Evans (2005, CEE henceforth) find that the presence of full cost channel is crucial to their empirical results, obtained by VAR-based minimum distance methods: indeed, CEE find that the absence of such an assumption generates price duration estimates which are not empirically plausible. In addition, Ravenna and Walsh (2006) and Chowdhury, Hoffmann, and Schabert (2006) obtain significant results via GMM estimation of New Keynesian Phillips curves augmented with a cost channel parameter. They estimate an interest rate elasticity larger than one, although their results depend on the set of instruments and on the normalization of the moment conditions. By contrast, Rabanal (2007), estimating using Bayesian methods a smaller-scale model than ours, finds the cost channel effect to be quantitatively very small.

A different effect arises if money is assumed to yield utility, for example, through reducing transaction costs. This opens up further channels through which money can affect the output and inflation dynamics. Nelson (2002), for example, explores ways in which base money is a significant determinant of aggregate demand. Ireland (2004) and Andrés and Vallés (2006), on the other hand, specify small-scale DSGE models for the US and the Euro area, respectively, in which real balances are allowed to affect the IS curve, unlike traditional models: however, maximum likelihood estimates suggest that money has a limited role in explaining business cycle fluctuations.

Our study introduces important novelties and contributes to the literature in several distinct ways. First, by bringing together non-separable utility and cost channel effects into a unified model, we are able to uncover non-negligible joint mechanisms through which monetary policy is transmitted. Second, we help to clarify contradictory results that have emerged in the literature concerning the empirical importance of these supply-side effects. Significantly, our two-pronged empirical strategy shows that findings from different estimation methods are broadly consistent with each other. In particular, once we adopt a more appropriate GMM estimator, the contradiction in the results reported in the literature concerning the importance of the cost channel virtually disappears. Third, our setup offers an alternative way of analysing and testing for the role of money in business cycle dynamics. Interestingly, our framework bypasses the need to observe and measure real money balances (always a controversial task), as its effects can be derived from the non-separable utility specification. This contrasts with the previous work of Ireland (2004) and Andrés and Vallés (2006). Fourth, unlike previous papers[1], prior information concerning the model parameters is introduced by employing Bayesian maximum likelihood estimation. This is computationally advantageous since parameter space is restricted to economically meaningful regions. Also, the Bayesian methods employed here utilize of all the cross-equation restrictions implied by the general equilibrium set-up, which makes estimation more efficient when compared to the partial equilibrium approaches of Ravenna and Walsh (2006) and Chowdhury, Hoffmann, and Schabert (2006). Even when single-equation estimation is employed, we make use of a preferable GMM estimator that depends neither on the normalization of the moment conditions, nor on the choice of the lags of the optimal weighting matrix. Finally, by estimating a reference NK-DSGE model based on CEE and Smets and Wouters (2003 and 2007, SW hereafter), which includes capital and makes use of seven observables and structural shocks, our analysis offers a more complete

[1] Rabanal (2007) also uses Bayesian methods, but he confines his analysis to the cost channel in smaller-scale, more incomplete model than ours. This paper came to our attention after our main results were obtained. The 2003 working paper version did not, for example, include capital.

description of the economy than most of the papers cited above. We then compare the baseline NK-DSGE model (Model 1) to a second model with a non-separable utility specification (Model 2), a model with an added cost channel (Model 3) and, finally, a more comprehensive model which incorporates both effects (Model 4).

The paper proceeds as follows. Section 2 presents a basic theoretical model which sets out the behavioural equations for households and firms with the corresponding model steady state model solutions. As mentioned, two innovations we introduce are the inclusion of a cost channel à la Ravenna and Walsh (2006) and non-separable utility in consumption and money as in Felices and Tuesta (2006). The theoretical implications of these effects are analysed in section 3. We then turn to parameter estimation, first by GMM (section 4), and then Bayesian estimation (section 5), where a linearized benchmark NK-DSGE model is extended by incorporating a cost channel and non-separable utility. Section 6 provides a final discussion.

2 The Basic Model

This section presents a New Keynesian model describing output and inflation dynamics, and incorporates a variety of nominal and real frictions. We study potential direct supply-side effects by allowing for non-separable utility in consumption decisions and by introducing a "cost channel" through which nominal interest rate fluctuations affect pricing decisions.

2.1 Households

The consumer i maximizes the following non-separable utility in consumption $C_t(i)$ and real money balances $\frac{M_t(i)}{P_t}$ and labour supply $L_t(i)$,

$$E_0\left[\sum_{t=0}^{\infty}\beta^t U_{C,t}\left[\frac{(\Phi_t(i))^{1-\sigma}}{1-\sigma}-\frac{\kappa}{1+\phi}(L_t(i))^{1+\phi}\right]\right], \tag{1}$$

where $U_{C,t}$ is a preference shock common to all households,

$$(\Phi_t(i))^{\frac{\theta-1}{\theta}} = b(C_t(i)-hC_{t-1})^{\frac{\theta-1}{\theta}} + (1-b)\left(\frac{M_t(i)}{P_t}\right)^{\frac{\theta-1}{\theta}} \tag{2}$$

and hC_{t-1} represents external habit in consumption, subject to the usual budget constraint and a demand for labour given by

$$L_t(i) = \left(\frac{W_t(i)}{W_t}\right)^{-\eta} L_t, \tag{3}$$

where $W_t(i)$ is the labour type i and $W_t = \int_0^1 W_t(i)^{1-\eta} di$ is a Dixit-Stiglitz aggregate wage index. This leads to standard first-order conditions:

$$\begin{aligned} MU_t^M(i) &= MU_t^C(i)\frac{R_t}{1+R_t} \qquad (4)\\ \frac{W_t(i)}{P_t} &= -\frac{1}{(1-\frac{1}{\eta})}\frac{MU_t)^L(i)}{MU_t^C(i)^C} \qquad (5)\\ 1 &= \beta(1+R_t)E_t\left[\left(\frac{MU_{t+1}^C(i)}{MU_t^C(i)}\frac{P_t}{P_{t+1}}\right)\right] \qquad (6) \end{aligned}$$

where r_t is the nominal interest rate and the marginal utilities of consumption, real money balances and labour supply are given respectively by

$$\begin{aligned} MU_t^C(i) &= bU_{C,t}(\Phi_t(i))^{\frac{1}{\theta}-\sigma}(C_t(i)-hC_{t-1})^{-\frac{1}{\theta}}\\ MU_t^M(i) &= (1-b)(\Phi_t(i))^{\frac{1}{\theta}-\sigma}\left(\frac{M_t(i)}{P_t}\right)^{-\frac{1}{\theta}}\\ MU_t^L(i) &= -\kappa(L_t(i))^{\phi} \end{aligned}$$

The first-order condition (4) now becomes

$$\left(\frac{M_t(i)}{P_t}\right)^{-\frac{1}{\theta}} = \frac{b}{1-b}U_{C,t}\left(C_t(i)-hC_{t-1}\right)^{-\frac{1}{\theta}}\frac{R_t}{1+R_t}.$$

Assuming complete markets, individual and aggregate consumption can be equated to give

$$
\begin{aligned}
\Phi_t &= (C_t - hC_{t-1})B_t \\
B_t^{\frac{\theta-1}{\theta}} &= b + (1-b)^{\theta} b^{1-\theta} \left(\frac{R_t}{1+R_t} \right)^{1-\theta} \\
MU_t^C &= b(C_t - hC_{t-1})^{-\sigma} B_t^{\frac{1}{\theta}-\sigma} \\
MU_t^M &= (1-b)\Phi_t^{\frac{1}{\theta}-\sigma} \left(\frac{M_t}{P_t} \right)^{-\frac{1}{\theta}} \\
\left(\frac{M_t}{P_t} \right)^{-\frac{1}{\theta}} &= \frac{b}{1-b} U_{C,t} \left(C_t - hC_{t-1} \right)^{-\frac{1}{\theta}} \frac{R_t}{1+R_t}.
\end{aligned}
$$

To assess the empirical relevance of this effect, we can use estimates of σ and θ to draw conclusions on the substitutability or complementarity of money balances and consumption. The elasticity of the marginal utility of consumption with respect to real money balances can be shown to have the same sign as $1 - \sigma\theta$. Therefore consumption and real balances are complements (as we expect) iff $\sigma\theta < 1$.

2.2 Firms

Aggregate output in the competitive final goods sector which use a continuum of intermediate goods with Dixit-Stiglitz technology is given by

$$
Y_t = \left(\int_0^1 Y_t(j)^{(\varsigma-1)/\varsigma} dj \right)^{\varsigma/(\varsigma-1)},
$$

where $Y_t(j)$ is the output of intermediate firm j producing variety j and ζ is the elasticity of substitution. Let $P_t(j)$ be the price of input f. Minimizing the cost $\int_0^1 P_t(j)Y_t(j)dj$ gives us the following demand for each intermediate good j,

$$
Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\zeta} Y_t, \tag{7}
$$

where $P_t = \left[\int_0^1 P_t(j)^{1-\zeta} dj \right]^{\frac{1}{1-\zeta}}$ is a Dixit-Stiglitz aggregate price index. Since the final good firms are competitive and the only inputs are intermediate goods, it is also the domestic price level.

In the intermediate goods sector, each good j is produced by a single firm with inputs consisting only of differentiated labour, using a technology

$$
Y_t(j) = A_t L_t(j) = \left(\int_0^1 L_t(i,j)^{(\eta-1)/\eta} di \right)^{\eta/(\eta-1)}
$$

where $L_t(j)$ is an aggregate Dixit-Stiglitz index of differentiated labour types used by the firm and $L_t(i,j)$ is the labour input of type i by firm j. The term A_t is total factor productivity that is common to all firms. The firm minimizes the wage costs $\int_0^1 W_t(i)L_t(i,j)di$ of producing output $Y_t(j)$ with respect to $L_t(i,j)$ leading to the demand for labour in (3). In an equilibrium of identical households and firms, all wages adjust to the same level and it follows that $Y_t = A_t L_t$. Each firm's minimum real marginal cost is given by

$$MC_t = \frac{(1+R_t)W_t}{A_t P_t}$$

where we assume that firms must borrow to pay wages at the beginning of the period (the 'cost channel').

Turning to price-setting, firms reset prices in any given period with probability $1-\xi$. Thus the optimal price P_t^0 for any firm that sets its price at t must take into account the downward-sloping demand curve, (7). The first-order condition for profit-maximization for the jth firm over the duration of the optimal price not being reset is then given by

$$P_t^0 E_t\left[\sum_{k=0}^{\infty}\xi^k D_{t,t+k}Y_{t+k}(j)\right] = \frac{\kappa}{(1-1/\zeta)}E_t\left[\sum_{k=0}^{\infty}\xi^k D_{t,t+k}P_{t+k}MC_{t+k}Y_{t+k}(j)\right] \tag{8}$$

where the stochastic discount factor $D_{t,t+k}$ is given by

$$D_{t,t+k} = \beta^k\left(\frac{MU_{t+1}^C}{MU_t^C}\right)\frac{P_t}{P_{t+k}}$$

The first-order condition (8) is cumbersome to manipulate. However, it is possible to express this price-setting rule in terms of *difference equations* that are far easier to manipulate. To do this first note that

$$Y_{t+k}(j) = \left(\frac{P_t^0}{P_{t+k}}\right)^{-\zeta}Y_{t+k}$$

and multiplying both sides of (8) by $(\frac{P_t^0}{P_t})^{\zeta}MU_t^C$ and in addition noting that $P_{t+k}/P_t = \Pi_{t+k}...\Pi_{t+1}$, the firms' staggered price setting can be succinctly described by

$$Q_t = \Lambda_t/H_t$$

where we have defined variables Π_t, Q_t, H_t and Λ_t by

$$\begin{aligned}
\Pi_t &\equiv \frac{P_t}{P_{t-1}} \\
Q_t &\equiv \frac{P_t^0}{P_t} \\
H_t - \xi\beta E_t[\Pi_{t+1}^{\zeta-1}H_{t+1}] &= Y_t\, MU_t^C \\
\Lambda_t - \xi\beta E_t[\Pi_{t+1}^{\zeta}\Lambda_{t+1}] &= \frac{Y_t\, MC_t}{(1-1/\zeta)} = \frac{Y_t\frac{W_t(1+R_t)}{A_t P_t}}{(1-1/\zeta)}
\end{aligned}$$

including the cost channel in the cost of labour.

Assuming that the number of firms is large, we can use the law of large numbers to obtain the aggregate price level as

$$P_t^{1-\zeta} = \xi P_{t-1}^{1-\zeta} + (1-\xi)Q_t^{1-\zeta}$$

and hence aggregate inflation is given by

$$1 = \xi\Pi_t^{\zeta-1} + (1-\xi)Q_t^{1-\zeta} \tag{9}$$

It is easy to show that if there is planned *indexation* to the overall price index as well, i.e. the future price at time $t+k$ is given by $P_t^0(P_{t+k-1}/P_t)^\gamma$, then all the results presented here are the same when Π_t is replaced by Π_t/Π_{t-1}^γ.

2.3 Price Dispersion

The impact of price dispersion arises from labour input being the same for each individual, but dependent on demand for each good:

$$L_t = \int_0^1 L_t(j)dj = \frac{Y_t}{A_t}\int_0^1 \frac{Y_t(j)}{Y_t}dj = \frac{Y_t}{A_t}\int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\zeta} dj$$

Now define price dispersion $\Delta_t = \int_0^1 (\frac{P_t(j)}{P_t})^{-\zeta}dj \geq 1$. Equality is reached only when prices are flexible and therefore the same, as all firms are identical except in their timing of price changes. Now we can write down aggregate output as

$$Y_t = \frac{A_t N_t}{\Delta_t} \leq A_t N_t$$

which clearly highlights the output distortion caused by price dispersion $\Delta_t \geq 1$.

Price dispersion is linked to inflation as follows. Assuming, as before, that the number of firms is large, we obtain the following dynamic relationship:

$$\Delta_t = \xi \Pi_t^{\zeta} \Delta_{t-1} + (1-\xi) Q_t^{-\zeta}$$

Using (9) we then obtain the dynamic equation

$$\Delta_t = \xi \Pi_t^{\zeta} \Delta_{t-1} + (1-\xi) \left(\frac{1-\xi \Pi_t^{\zeta-1}}{1-\xi} \right)^{\frac{\zeta}{\zeta-1}} .$$

2.4 Equilibrium

In equilibrium, goods and the bond markets all clear. Equating supply with demand of consumer goods, we obtain

$$Y_t = \frac{A_t L_t}{\Delta_t} = C_t + G_t$$

where G_t is government spending on goods and services that are part of aggregate output. The model is Ricardian: G_t is financed out of lump-sum taxation, so the evolution of government debt is irrelevant. By Walras' law, the bond market equilibrium conditions can be dispensed with. This completes the model given the interest rate which takes the form of interest rate commitment rules discussed later.

3 Implications of Direct Interest Rate Effects

The existence of a cost channel and non-separability of utility has important consequences for the output-inflation trade-off which in turn impacts on the optimal inflation path for the Ramsey planner. There are also implications for the determinacy of interest rate rules. This section examines these issues. In this analysis, we confine ourselves to a simpler model with no habit in consumption ($h = 0$).

3.1 The Long-Term Output-Inflation Trade-Off and Ramsey Inflation Rate

Given the gross inflation rate Π, from the steady state of the model set out in Appendix A, we can solve for output Y, and price dispersion Δ in terms of Π to obtain:

$$\left(1-\frac{G}{Y}\right)^{\sigma} Y^{\sigma+\phi} = \frac{(1-\xi\beta\Pi^{\zeta})(1-\xi\beta\Pi^{\zeta-1})^{\frac{\zeta}{1-\zeta}} A^{1+\phi}\Delta^{\phi}(1-\frac{1}{\zeta})(1-\frac{1}{\eta})bB^{\frac{1}{\theta}-\sigma}}{\kappa\Pi} \tag{10}$$

$$B^{\frac{1-\theta}{\theta}} = b+(1-b)^{\theta}\left(\frac{b(\Pi-\beta)}{\Pi}\right)^{1-\theta} \tag{11}$$

$$\Delta = \frac{(1-\xi)^{\frac{1}{1-\zeta}}}{(1-\xi\Pi^{\zeta-1})^{\frac{\zeta}{1-\zeta}}(1-\xi\Pi^{\zeta})} \tag{12}$$

Equations (10) to (12) describe the output-inflation steady-state relationship. We are now in a position to ask a pertinent question: is there a long-run positive or negative inflation-output trade-off and how is it affected by the cost-channel and non-separable utility effects?

Taking logarithms and differentiating with respect to Π we find that the sign of $\frac{dY}{d\Pi}$ is the same as

$$\underbrace{(1-\Pi)\left(\frac{\xi\beta\zeta\Pi^{\zeta-2}}{(1-\xi\beta\Pi^{\zeta})(1-\xi\beta\Pi^{\zeta-1})}+\frac{\xi\phi\zeta\Pi^{\zeta-2}}{(1-\xi\Pi^{\zeta})(1-\xi\Pi^{\zeta-1})}\right)+\frac{(1-\beta)\xi\Pi^{\zeta-2}}{(1-\xi\beta\Pi^{\zeta-1})(1-\xi\Pi^{\zeta-1})}}_{\text{Sticky Price Effect}}$$
$$\underbrace{(\sigma\theta-1)B^{\frac{1}{\theta}-1}(1-b)^{\theta}b^{1-\theta}\frac{\beta}{\Pi^2}\left(\frac{\Pi-\beta}{\Pi}\right)^{-\theta}}_{\text{Non-Separable Utility Effect}} \quad \underbrace{-\frac{1}{\Pi}}_{\text{Cost Channel Effect}} \tag{13}$$

We refer to the first term in (13) as a 'sticky price effect' because it disappears as prices become flexible and $\xi \to 0$. For $\Pi \gg 1$ the term in $(1-\Pi)$ is negative, but for low inflation, where Π is close to unity, it approaches zero. This leaves a slightly positive output-inflation trade-off, since β is slightly less than unity. *Thus, for the standard problem with separable utility and no cost channel, there is only a small steady state inflation-output trade-off near zero inflation, but a negative trade-off for high values of inflation. This results in the standard result that under optimal commitment (i.e., the Ramsey problem) the steady state inflation rate is zero.*

Now consider the case of non-separable utility. If, as is usually assumed, money holdings and consumption are complements, then $\sigma\theta < 1$ and the second term in (13) shows that the non-separable utility effect adds to the negative output-inflation trade-off. The intuition here is quite simple: an increase in inflation increases the nominal interest rate and holdings of money fall. Since consumption and money balances are complements, consumption falls with a shift into leisure. Thus, work effort falls and with it output. This larger negative output-inflation trade-off leads to another standard result (see, for example, Woodford (2003), chapter 4): *the steady state Ramsey net inflation rate is negative if $\sigma\theta < 1$ (the case where money balances and consumption are complements) and lies in the interval $[\beta - 1, 0]$ where the lower bound corresponds to $R = 0$ (Friedman rule).*

Finally, the last term in (13) shows that adding the cost channel results in high inflation reducing the natural rate of output still further, because it increases marginal costs. This then pushes the steady state Ramsey net inflation rate close to the Friedman rule of $\beta - 1$.

3.2 Implications for the Stability and Determinacy of Interest Rate Rules

With $h = 0$ and suppressing shocks to government spending, the stability and determinacy of the linearized model depends on the following Euler equation and Phillips Curve

$$E_t mu_{t+1}^C = mu_t^C - (r_t - E_t\pi_{t+1}) \tag{14}$$

$$\beta E_t\pi_{t+1} = \pi_t + \gamma mu_t^C - \kappa r_t \tag{15}$$

where

$$\gamma = \lambda\left(1 + \frac{\phi}{\sigma}\right) \quad ; \qquad \kappa = \frac{\lambda\phi(\beta\alpha_c - \delta_n)}{\sigma}$$

and $\alpha_c \in [0, 1]$ is the degree of forward financing of the wage bill. The crucial parameter δ_n is defined by

$$\delta_n = \beta(1-\beta)^{-1}(\sigma\theta - 1)(1 - b_1) \tag{16}$$

where

$$b_1 = \frac{b}{\left(b + (1-b)\alpha_1^{\frac{\theta-1}{\theta}}\right)} \tag{17}$$

$$\alpha_1 = \left(\frac{(1-b)}{b(1-\beta)}\right)^{\theta} \tag{18}$$

With money balances and consumption assumed to be complements, $\sigma\theta < 1$, $\delta_n < 0$ and the cost channel and non-separable utility effects of an interest rate rise work together to increase marginal costs.

We examine a pure current inflation targeting interest-rate rule of the form

$$r_t = \rho r_{t-1} + \theta_\pi \pi_t \,; \quad \rho \in [0,1]; \; \theta_\pi > 0 \tag{19}$$

Equations (14), (15) and (19) describes the dynamics of our model economy. By an appropriate redefinition of the parameters γ and κ it also describes a model of a small open partially dollarized economy studied in Batini, Levine, and Pearlman (2008). Then using the root-locus techniques set out in Batini, Justiniano, Levine, and Pearlman (2006), the former of these papers proves the following result:

Proposition
In the system (14), (15) and (19):
(a) If $(1-\rho)\kappa > \gamma$ there is either indeterminacy or instability.
(b) If $2\kappa > \gamma > (1-\rho)\kappa$, then the system is stable and determinate for some range $1 < \theta_\pi < \bar{\theta}_\pi$.
(c) If $\gamma > 2\kappa$, then any feedback $\theta_\pi > 1$ from current inflation leads to stability and determinacy.

Thus, *the combined presence of a full cost channel effect* $\alpha_c = 1$ *and the complementarity of money and consumption (*$\delta_n < 0$*) can lead to instability or indeterminacy.* The intuition behind this result is that with $\kappa > 0$, which holds if money and consumption are complements, supply and demand effects of nominal interest rate changes operate in opposite directions, with the former undermining the stabilization effects of the latter. However, in the absence of both a cost channel and non-separable utility effect, case (c) holds and any current interest rate rule results in stability and determinacy. Also, interest rate smoothing (a high ρ) helps to induce determinacy, a result obtained in Batini, Justiniano, Levine, and Pearlman (2006) for both current and forward-looking inflation targeting rules.

4 GMM Estimation

As an empirical counterpoint to our subsequent system Bayesian estimations, we obtain estimates of sections of the above model, which have previously been discussed in a single-equation setting. The main focus is the estimation of a NKPC with cost channel. We then briefly look at GMM estimation of the consumption Euler equation.

4.1 Estimation of the NKPC

Regarding the NKPC with an added cost channel, we reassess the empirical evidence produced by Ravenna and Walsh (2006) and Chowdhury, Hoffmann, and Schabert (2006). Using standard GMM procedures, these authors found some evidence of a direct effect of fluctuations in the nominal interest rate on the dynamics of inflation. However, there are reasons to question the validity of these findings. First, it is well known that the usual two-step GMM estimator has poor finite sample properties.[2] On the other hand, the estimators used in the above mentioned papers are not invariant to transformations of the moment conditions, which means that the results depend on the normalization adopted for the estimation.

We address these issues by resorting to the continuous-updating (CU) GMM procedure of Hansen, Heaton, and Yaron (1996). This estimator is, in principle, preferable, given its higher order efficiency and superior small sample properties when compared to a standard, often biased, GMM estimator (see Newey and Smith (2004) and Anatolyev (2005)). Also, it does not depend on the normalization adopted for the moment conditions. This will allow us to focus on the economic specifications, rather than on their econometric implementation. Moreover, since there is no *a priori* reason to choose a particular bandwidth for the GMM optimal weighting matrix, we compute this matrix using the data-dependent method proposed by Andrews (1991).

Ravenna and Walsh (2006) estimate a forward-looking NKPC with real marginal cost as the driving variable for inflation dynamics[3], as suggested by Galí and Gertler (1999) and Sbordone (2002). In the basic model without capital, real marginal cost is given by $MC_t = W_t L_t / P_t Y_t$. If we add a cost channel effect, the real marginal cost (proportional deviations from the steady state in lower case letters) is $mc_t = \alpha_c r_t + s_t$, where s_t is the share of labour.

From (B.15), we can then write the forward-looking NKPC, in log-linear form about the steady state, in terms of realized variables as

$$\pi_t = \frac{\beta}{1+\beta\gamma}\pi_{t+1} + \frac{\gamma}{1+\beta\gamma}\pi_{t-1} + \lambda(\alpha_c r_t + s_t) + \varsigma_t \tag{20}$$

where

$$\lambda \equiv \frac{(1-\beta\xi)(1-\xi)}{(1+\beta\gamma)\xi} \tag{21}$$

which requires augmenting the model with a disturbance term ς_t (capturing expectational

[2] See Newey and Smith (2004), Anatolyev (2005) and the special issue of the Journal of Business Economics and Statistics (1996, vol. 14).

[3] Chowdhury, Hoffmann, and Schabert (2006) extend the specification to the hybrid version of the NKPC, incorporating a lagged inflation term.

or measurement errors, for example), which should be orthogonal to the agents' information set Ω_t. This then leads to orthogonality conditions of the type

$$E\{[\pi_t - \frac{\beta}{1+\beta\gamma}\pi_{t+1} - \frac{\gamma}{1+\beta\gamma}\pi_{t-1} - \lambda(\alpha_c r_t + s_t)]\}\mathbf{z}_t = 0, \tag{22}$$

where $\mathbf{z}_t$ is a vector of variables orthogonal to ς_t, which will typically contain past observations of the variables in (20), but may also include other variables which are judged to contain information orthogonal to ς_t. We can then estimate (20) by GMM using data for π_t, s_t and r_t, as well as instruments in z_t. The inflation rate is measured as GDP deflator inflation, marginal cost is proxied by non-farm business sector real unit labour costs and interest is the 3-month T-bill rate. Instruments include four lags of: π_t, s_t, r_t, the CRB commodity price index inflation, wage inflation, the term spread and HP-filtered output gap, as in Ravenna and Walsh (2006).

Table 1 presents results for the estimation of (20), using quarterly data for the period 1960:1-2004:4. We estimate the NKPC with and without indexation. Moreover, we also present estimates assuming $\beta = 0.99$, a value commonly used and close to the implicit β in our sample. The CU-GMM is computed using a weighting matrix with the sample moments in mean deviation form and an automated lag-length selection procedure as in Andrews (1991), employing the Bartlett kernel. This avoids an arbitrary choice for the truncation lag.

Unlike Ravenna and Walsh (2006) and Chowdhury, Hoffmann, and Schabert (2006), we found no substantial evidence of a cost channel effect, as the estimates of α_c are always insignificant. While it is true that t-tests or Wald tests of the hypothesis that $\alpha_c = 1$ are not rejected, this is due to the large standard error associated with the estimates of α_c. In addition, our estimates of α_c are substantially lower than those presented in Ravenna and Walsh (2006) and, therefore, distant from the benchmark value of $\alpha_c = 1$. The other parameters are estimated much more precisely and their values are consistent with results reported elsewhere: estimates of β range[4] between 0.96 and 1.01, while the coefficient for Calvo prices ξ_P lies in the interval $(0.82, 0.92)$. These values appear to be more sensible that those reported in Ravenna and Walsh (2006). If one allows for indexation, estimates of the backward-looking component γ range between 0.39 and 0.47.

The reported differences cannot be attributed to the use of a different sample period. When we restrict the sample size to be the same as in Ravenna and Walsh (2006) (1960 to 2001), results[5] are not qualitatively different from those in Table 1. We also estimated

[4] The parameter space was not constrained in the estimation. Tests for the hypothesis that $\beta < 1$ are never rejected.

[5] Even when using the same dataset of Ravenna and Walsh (2006), it was not possible to reproduce

the NKPC with the sample starting in 1980, as in Chowdhury, Hoffmann, and Schabert (2006) and thus excluding the two oil shocks, but no significant differences emerge.[6]

In order to avoid potential weak identification problems, Ravenna and Walsh (2006) suggest using a smaller set of instruments (instrument set B), which considers the first two lags of the variables in the instrument set A, with the exception of the inflation rate and the interest rate, with four lags. The bottom half of Table 1 presents estimates using the smaller set and we can observe that the 'B' estimates are very similar to those obtained employing the larger instrument set.

We further account for the possibility of weak identification by computing the identification-robust statistics of Kleibergen (2005), who proposed a set of inference procedures that are valid regardless of whether the parameters are strongly or weakly identified. One can obtain a confidence set for values θ_0 of a generic set of parameters θ for which the null hypothesis $H_0 : \theta = \theta_0$ is not rejected using Kleibergen's K statistic. This statistic is based on a quadratic form in the first-order conditions of the CUE, and has a $\chi^2(p)$ limiting distribution that depends only on the number of parameters p.

The K statistic may be appropriately transformed if one wishes to test a sub-vector of θ, for instance if one or more parameters are deemed to be strongly identified. Focusing on the forward-looking specification, and from the results discussed above, it is relatively safe to assume that the parameters β and ξ_P are well identified. Thus, we can concentrate our attention on the main parameter of interest and conduct tests for $H_0 : \alpha_c = \alpha_c^0$, using subset tests. Specifically, we perform a grid search over the parameter space of α[7], we test $H_0 : \alpha_c = \alpha_c^0$ and collect the values α_c^0 for which the p-value exceeds a joint 5% significance level.[8] To save space, we report results[9] when $\{\beta, \xi_P\}$ is fixed at $\{0.99, 0.85\}$.

Figure 1 plots the sequence of the Kleibergen K^* statistic for the grid of values α_c^0. We can observe that the region for which the null $H_0 : \alpha_c = \alpha_c^0$ is not rejected is formed by, approximately, the interval $(-0.15, 0.9)$. Two important points should hence be noted. First, while the interval contains economically relevant values for α_c, it also includes the case of no cost channel. Second, it unambiguously excludes both the baseline case of $\alpha_c = 1$ and the estimated values reported by Ravenna and Walsh (2006) and Chowdhury,

their findings.

[6]Results not reported are available upon request.

[7]We choose the interval $(-0.5, 2)$, with increments of 0.01, thus including values close to 0 (no cost channel) and values larger than 1, consistent with estimates presented in Ravenna and Walsh (2006) and Chowdhury, Hoffmann, and Schabert (2006).

[8]We follow the suggestion of Kleibergen (2005) by combining his K statistic with the asymptotically independent $J(\theta)$ statistic for overidentifying restrictions. For the combined J-K test, denoted K^*, we use a significance level of 1% for the J-test and 4% for the K-test, therefore emphasizing simple parameter hypothesis testing, see paper for details.

[9]Results do not change qualitatively if we choose other economically relevant values for β and ξ_P, or when CU-GMM estimates are used instead.

Hoffmann, and Schabert (2006) of around 1.2-1.3.

Thus by using an estimation procedure that is not sensitive to the specification of the orthogonality conditions and is, in theory, more efficient that those used in Ravenna and Walsh (2006), we conclude that there is no substantial evidence of a cost channel. Furthermore, even when we allow for weak identification, our evidence is not consistent with the results of Ravenna and Walsh (2006) and Chowdhury, Hoffmann, and Schabert (2006) and therefore one cannot safely reject that there is no direct interest rate effect on inflation.

4.2 Estimation of the Euler Equation

The same approach can be used estimate the separable utility parameter δ_n by single-equation estimation of the linearized Euler equation.[10] From (B.14) and (B.13), a little algebra gives

$$\begin{aligned} c_t &= \frac{h}{1+h}c_{t-1} + \frac{1}{1+h}E_t c_{t+1} \\ &- \frac{(1-h)}{(1+h)\sigma}((1-\delta_n)r_t - E_t\pi_{t+1} + E_t u_{C,t+1} - u_{C,t}) \end{aligned} \tag{23}$$

Since we do not observe preference shocks in the GMM estimation, we must leave these out in (23).

As in the previous section, we can re-write (23) in terms of orthogonality conditions. For instruments we use four lags of the observables in (23), in addition to four lags of output growth and the interest rate spread. Preliminary joint estimation of the parameters h, σ and δ_n was disappointing, in that convergence proved hard to achieve and numerical estimates lacked economic meaning. This may be due to identification problems or the existence of several local minima.

We chose to calibrate the utility parameter and then obtain estimates of h and δ_n. Table 2 shows results for this estimation strategy, for $\sigma = \{1, 1.5, 2, 2.5\}$. We observe that δ_n is never statistically significant, thus implying that the marginal utility of consumption is found to be unaffected by changes in real money balances changes. On the other hand, estimates of the habit parameter estimates are broadly in line with values found previously in the literature, though perhaps exhibit a little too much persistent (namely for $\sigma = 2.5$).

[10] An alternative strategy would be the direct estimation of the non-linear Euler equation (6), plus (7) and (7), obtaining estimates for h, b, σ and θ. We could also estimate (7), which in linearized form becomes $m_t - p_t = \frac{1}{1-h}c_t - \frac{h}{1-h}c_{t-1} - \frac{\beta^2\theta}{1-\beta}i_t$, in a two-equation estimation with (23).

5 Bayesian Estimation

We now turn to the estimation of the whole system using Bayesian methods, and compare variants of the model with and without a cost channel and non-separable utility effect. In short, Bayesian maximum likelihood estimation enables us to estimate the same parameters as GMM, but in a system framework. We extend the basic model discussed in section 2, and linearized in Appendix B, by introducing further rigidities and frictions, following the influential papers of CEE and Smets and Wouters (2003). In particular, we add wage stickiness, adjustment costs in capital accumulation, variable capital utilization, and close the model with an 'empirical' Taylor-type rule (C.49). The model is then estimated using seven macroeconomic series as observable variables, augmented with seven orthogonal structural shocks capturing changes in technology and preferences, cost-push factors, and policy shocks. With these additions, our benchmark model - without a cost channel and with separable utility - is similar to the SW model (Smets and Wouters (2003)), thus allowing us to conduct relevant empirical comparisons. The model in log-linear form about the deterministic zero-inflation steady state is given in Appendix C.

5.1 Bayesian Methods and Priors

Bayesian estimation entails obtaining the posterior distribution of the model's parameters θ, conditional on the data. From Bayes' theorem, the posterior distribution is obtained as:

$$p(\theta/Y^T) = \frac{L(\theta/Y^T)p(\theta)}{\int L(\theta/Y^T)p(\theta)} \tag{24}$$

where $p(\theta)$ denotes the prior density of the parameter vector θ, $L(\theta/Y^T)$ is the likelihood of the sample Y^T with T observations (evaluated with the Kalman filter) and $\int L(\theta/Y^T)p(\theta)$ corresponds to the marginal likelihood. Since there is no closed form analytical expression for the posterior, this must be simulated[11]. One of the main advantages of adopting a Bayesian approach is that it facilitates a formal comparison of different models through their posterior marginal likelihoods, computed using the Geweke (1999) modified harmonic-mean estimator. If the prior probability of each competing model is assigned equal weight, then the posterior odds ratio (or Bayes Factor, see Kass and Raftery

[11] 200,000 random draws (though the first 30% "burn-in" observations are discarded) from the posterior density were obtained via the MCMC-Metropolis Hastings algorithm (MH), with the variance-covariance matrix of the perturbation term in the algorithm being adjusted in order to obtain reasonable acceptance rates (between 20%-40%), see Schorfheide (2000) for more details.

(1995)) is simply the ratio of marginal likelihoods

$$B = \frac{P(M_j/D)}{P(M_i/D)} \propto \frac{P(D/M_j)}{P(D/M_i)} = \frac{\exp^{LL_j}}{\exp^{LL_i}} \qquad (25)$$

where $P(M/D)$ represents the posterior model probabilities given data, while $P(D/M)$ is the marginal data density. The specification which attains the highest odds outperforms its rivals and is therefore favoured.

In order to implement Bayesian estimation, it is first necessary to define prior distributions for the parameters. We keep seven of the structural parameters are fixed in the estimation procedure. As suggested by Adolfson (2007), these parameters can often be related to the steady state values of the observed variables in the model and are, therefore, calibrated so as to match their sample mean. Thus, the discount factor β is set to 0.99, which implies an annual steady state nominal interest rate of 4 percent. The depreciation rate δ is set to 0.025, which implies an annual depreciation rate of 10% on capital. According to previous studies for the US economy, we assume the following implied steady state relationships: the consumption-output ratio c_y is 0.56, the government spending-output ratio g_y is 0.20 and the investment-output ratio i_y is 0.24. The labour share in production α is fixed to 0.36, which is a conventional value for the US and finally the wage markup parameter λ_w is set to 0.20 in all models, as this parameter[12] is not identified. For the remainder of parameters inverse gamma distributions are used as priors when non-negativity constraints are necessary, and beta distributions for fractions or probabilities. Normal distributions are used when more informative priors seem to be necessary.

The prior means and distributions of these parameters can be found in Table 4 and all priors are assumed to be the same across specifications. A common theme in papers estimating DSGE models is the difficulty in pinning down the parameter of labour supply elasticity ϕ, as inference on the inverse Frisch elasticity of labour supply has been found susceptible to model specifications, exhibiting wide posterior probability intervals (see Batini, Justiniano, Levine, and Pearlman (2006)). As a result, based on the values assumed in the real business cycle literature, we assume a normal distribution with mean 1.2 and standard deviation of 0.5 for the parameter ϕ. Following previous studies conducted for both closed and open economies, notably Smets and Wouters (2005), Smets and Wouters (2007) and Levin, Onatski, Williams, and Williams (2005), we use a beta distribution for the habit, price indexation and wage indexation parameters and set the means to 0.5 and standard deviations to 0.15 for the indexation parameters and 0.2 for habit. Similarly, the risk aversion parameter σ is assumed normally distributed and centered at 2.0 with

[12] λ_w enters into the wage setting equation, where $\eta = \frac{1+\lambda_w}{\lambda_w}$.

a standard deviation of 0.5. The Calvo coefficients ξ_W and ξ_P are assumed to be beta distributed with prior means of 0.5 and prior standard deviations of 0.2, implying that prices and wages are sticky for two quarters, given that the quarterly discount factor is calibrated to 0.99. For the degree of cost channel α_C we use an intermediate value 0.5 as the mean and a beta distribution with standard deviation equal to 0.2. Finally, the prior means for the other parameters, including the coefficients of the interest rate rule, the AR(1) shocks and their standard deviations are chosen in line with those in Smets and Wouters (2005) and Levin, Onatski, Williams, and Williams (2005). Next, a more detailed discussion is provided concerning the choice of prior for the non-separable utility parameter.

5.2 Choice of Prior for δ_n

According to our model, this parameter is obtained from (16) - (18), and implies we cannot identify both b and θ as yet. However, we now show how observed data for real money balances as a proportion of consumption and estimates of the elasticity of the marginal utility of consumption with respect to total money balances (Ψ, say) can be used to calibrate the preference parameters b and θ in (16)-(18). Consider the utility of the representative agent in the steady state:

$$U = \left[b[(1-h)C]^{\frac{\theta-1}{\theta}} + (1-b)M_r^{\frac{\theta-1}{\theta}} \right]^{\frac{(1-\sigma)\theta}{(\theta-1)}} \text{ plus a term in labour supply} \tag{26}$$

where $M_r \equiv \frac{M}{P}$ are real money balances. From the definition of Φ, (2), we have that

$$\frac{\Phi}{C\Phi_C} = \frac{(1-b)cz^{\frac{1-\theta}{\theta}} + b}{b} \tag{27}$$

Now let $cz \equiv \frac{C(1-h)}{M_r}$ be the 'effective-consumption'–real money balance ratio (allowing for external habit). Then differentiating (26), the elasticity the marginal utility of consumption with respect to total money balances, Ψ, is given by

$$\Psi \equiv \frac{ZU_{CZ}}{U_C} = \frac{1-\sigma\theta}{\theta} \frac{(1-b)}{(bcz^{\frac{\theta-1}{\theta}} + 1 - b)} \tag{28}$$

where we define range of plausible values of [13] $\Psi \in [0, 0.02]$. Since $\Psi > 0$ we impose on our calibration the property that money and consumption are *complements*.

From the first-order conditions of the household in the zero-inflation steady state we

[13] See Woodford (2003), chapter 2 for a discussion of this parameter.

have that

$$
\begin{aligned}
U_{M_r} &= U_C \frac{R}{1+R} && (29)\\
1 &= \beta(1+R) && (30)
\end{aligned}
$$

Differentiating (26) and using (27) and (29) obtains

$$\frac{b(1-h)}{1-b} cz^{-\frac{1}{\theta}} = (1-\beta) \tag{31}$$

Thus, given σ, β, h, cz and Ψ, equations (27)–(31) can be solved for b and θ. Figure 2 shows calculations for these parameters for values: $\sigma = 2, 3$, $\beta = 0.99$, $h = 0.5$, and $\frac{C}{M_r} = \frac{c_y}{m_y} = \frac{0.7}{0.25}$ where m_y are money balances as a proportion of quarterly GDP. For $\Phi \in [0.0.02]$ we find a range $-\delta_n \in [0, 0.5]$. Our prior, $\delta_n = -0.25$ lies at the mid-point of this range.

5.3 Posterior Estimates and Model Comparison

To estimate the system we use seven macro-economic observables at quarterly frequency: real GDP, real consumption, real investment, the GDP deflator, real wages, employment and the nominal interest rate. Since the variables in the model are measured as deviations from a constant steady state, the time series are simply detrended against a linear trend. The estimation results are based on a sample from 1970:1 to 2004:4 and 39 observations are used to initialize the Kalman recursion. The following four model variants were estimated:

1. benchmark (SW) model: $(\delta_n = \alpha_c = 0)$
2. $\delta_n < 0$, $\alpha_c = 0$.
3. $\alpha_c \in (0, 1]$, $\delta_n = 0$.
4. $\alpha_c \in (0, 1]$, $\delta_n < 0$.

Table 5 reports the parameter estimates using the Bayesian methods described above. It summarizes posterior means of the studied parameters and 90% confidence intervals for the four specifications, as well as the posterior model odds. Overall, parameter estimates are plausible and reasonably robust across specifications. The results are generally similar to those of Levin, Onatski, Williams, and Williams (2005) for the US.

The estimation results of Model 3 and Model 4 show that the degree of cost channel, α_c, is somewhat higher when the model also assumes that money and consumption in the household's utility is non-separable. However, we also note that the 90% confidence intervals do not include the baseline case of $\alpha_c = 1$ and are much smaller than the estimates of α_c reported in Ravenna and Walsh (2006) and Chowdhury, Hoffmann, and Schabert (2006). Also, note that unlike CEE, whether or not α_c is included in the model has no effect on the magnitude of wage and price stickiness parameters (and therefore contract and price durations): recall that CEE justified the inclusion of a cost channel on the grounds that without it, estimated durations were implausibly long.

The last row of Table 5 reports the posterior model odds, revealing that Model 3 (with only the cost channel effect) slightly outperforms its three rivals with a posterior probability of 35%. This suggests that incorporating a cost channel seems to offer some improvements in terms of the model fitness to the data in the US economy. On the other hand, Model 2 (with only the non-separable utility effect) finds little support. However, the differences in log marginal likelihoods or the posterior odds ratio are not substantive. For example, the log marginal likelihood difference between Model 3 and Model 2 is 0.68. As suggested by Kass and Raftery (1995), in order to choose Model 3 over Model 2, we need a prior probability over Model 3 $1.97(= e^{0.68})$ times larger than our prior probability over Model 2. This factor is believed to be small and therefore we are unable to conclude that Model 3 outperforms Model 2. Equivalently, in a Bayesian model comparison expressed in (25), a posterior Bayes factor B needs to be at least 3 for there to be a positive evidence favouring Model M_j. As a result, we cannot find substantial evidence that the addition of a cost channel improves the ability of the benchmark model to explain US data.

Figure 3 plots the prior and posterior distributions for the 'best' model (Model 3). The location and the shape of the posterior distributions are largely independent of the priors we have selected since priors are broadly less informative. Most of the posterior distributions seem to be roughly symmetric implying that the mean and median coincide. According to Figure 3, there is little information in the data for some parameters where prior and posterior overlap. Notably, this is true for parameters $sd(\varepsilon_{\pi_t})$ and α_c. This is in accordance with the results in section 4.1, for GMM estimation of the cost channel.

For completeness we also present the posteriors and priors for Model 4 (Figure 4). We note that in all instances, posteriors bear considerable similarities to those in Model 3. This is not surprising given the reported results in Table 5. We also find it useful to compare the degree of cost channel in both models (Figure 5). While posteriors suggest that there is *some* information in the data to inform our estimates of α_c (i.e., curves do not overlap each other), profiles do remain close to the priors. Indeed, the posteriors for both models are almost identical.

5.4 Robustness checks

In order to verify the robustness of the results discussed above, we conduct a series of experiments on some variants of our model. Initially, we carry out an informal check on the inherent identifiability of Model 4's structure by running a series of Monte Carlo simulations. We generate 1000 artificial datasets for all the observable variables, each sample being initialised with different sample values from the variables. We simulate the data by imposing the prior means to the parameters for all the iterations. We then re-estimate Model 4 using the artificial datasets with $T = 200$ and check whether the means and standard deviations of the ML estimates recover the DSGE model's priors[14]. The simulation and estimation results are then compared with the prior distributions and reported in Table 4. The results show that a number of deep parameters seem to have difficulties to get back to the parameter prior values. The problematic parameters that exhibit relatively larger biases compared to the other structural parameters (percentage deviations $\geqq$ 10%) are highlighted in Table 4. Significantly, α_c is among this group, suggesting that there is some difficulty in recovering this parameter using our fully-fledged DSGE model.

Additionally, we experimented with different priors for the cost channel and separable utility parameters, and variants of the models were re-estimated. Our complete findings are reported in Gabriel, Levine, Spencer, and Yang (2008), and the remainder of this section restricts itself to key results. Model 3 was re-estimated we using a 'diffuse' prior for α_c based on a uniform $(0, 1)$ distribution, similar to Rabanal (2007). We find that the posteriors are sensitive to this change, as the new estimate of α_c becomes 0 and the log marginal likelihood deteriorates significantly (-556.38). When imposing $\alpha_c = 1$ in Model 3 as in CEE, we find indeterminacy, as predicted in section 3 and hence we were unable to obtain any parameter estimates for this case. Imposing $\alpha_c = 0.8$ eventually yields determinacy of the equilibrium of the modified Model 3, but the model's marginal likelihood of -476.83 suggests that it fails to compete with all previous models. It appears that calibrating the model with higher degrees of cost channel leads to indeterminacy for all parameter values in our system or worsens the fit of the model. Further, a comparison of the estimated posterior impulse response functions of Model 3 (cost channel) and Model 1 (benchmark SW) reveals that adding a cost channel leads to very little differences between Model 3 and model 1: here, we restrict our attention to the case of an interest rate shock as shown in Figure 6.[15] The IRFs generated from such a shock strengthens the

[14] We also tried an alternative experiment where parameter values from their prior distributions are randomly drawn, as well as a sample of $T = 1000$, but results are similar (the full set of results is available in the working paper version of this article).

[15] Again, see Gabriel, Levine, Spencer, and Yang (2008) for fuller details of the (very similar) impulse

argument of there being insufficient information in the data to support the presence of a cost channel. We also note that our impulse responses are consistent with with those of Rabanal (2007), who finds a zero posterior probability of observing an inflation increase following a monetary policy shock.

Model 2 was then tested by using a 'diffuse' prior for δ_n, based on the uniform $(-0.5, 0.5)$ distribution, reflecting our uncertainty about the value of this parameter. We find that the posteriors are relatively insensitive to the change. Notably, the posterior mean of δ_n changes from -0.37 to -0.41 even if we relax the restriction that $-\delta_n$ is positive. Moreover, this model performs as well as Model 2 with the original prior, yielding a log marginal likelihood of -458.56.

Alternatively, we also estimated the parameter b directly in order to derive an estimate of δ_n. Notice that δ_n is defined by (16). We set θ to be 0.3, while β is 0.99. b is either assumed beta distributed with prior mean of 0.5 and prior standard deviation of 0.2 or imposed to be 1 so that the effect of δ_n in the models is minimum. The resulting estimate of b is 0.55 and 0.56 for models 2 ($LL = -457.92$) and 4 ($LL = -459.62$), thus implying values of -0.72 and -0.70 for δ_n, respectively. Overall, the results are consistent with our previous findings.

6 Conclusion

Are direct supply-side effects of monetary policy relevant? Potentially, they are: the theoretical implications derived in the model identify possible non-negligible cost channel effects. Empirically, however, our findings suggest this may not be the case. To recap, we opened this paper by deriving the theoretical implications of assuming a cost channel and non-separable utility, first for the output-inflation trade-off, and second, for the optimal inflation path of the Ramsey planner. The determinacy of interest rate rules were also addressed as part of this second avenue of investigation. It was within this theoretical framework that potential non-negligible cost channel effects were obtained. We then tackled these issues empirically, using a two-pronged strategy of single-equation GMM procedures and system-estimation Bayesian techniques. The results arising from both strategies provided weak support for the presence of a cost channel for monetary policy. While Bayesian estimation favours a model with the cost channel, the improvements in model fit are not sufficiently compelling. Further, evidence for the non-separability of money and consumption in the utility of the representative household is feeble. In the Bayesian estimation, there appears to be very little information in the data about α_c and

responses generated from the other shocks listed in Table 4

δ_n. We therefore suggest the two-pronged empirical strategy adopted here demonstrates that once appropriate methods are put to use, previous contradictions in the literature seem to vanish.

Note, however, that we do not claim these supply side effects are inexistent: rather, what we show is that for the period considered, they appear small. One possible explanation for our findings is that any such effects are dominated by traditional demand-side factors. It may be the case that supply-side effects become more acute depending on the phase on the business cycle, but are then averaged out when longer periods are considered. It is also conceivable that these channels become more relevant in developing economies, with a less stable history of inflation and less efficient financial markets. This, in turn, has implications for optimal policy and for the gains from international policy coordination, see for example Coto-Martinez (2007). Thus, further investigation of these issues represents a worthwhile endeavor.

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A The Steady State

Given an *arbitrary* steady state gross inflation rate Π, the steady state of the model with $h = 0$ takes the form[16]

$$MU^M = MU^C \frac{R}{1+R} \tag{A.1}$$

$$\frac{W}{P} = -\frac{1}{\left(1-\frac{1}{\eta}\right)} \frac{MU^L}{MU^C} \tag{A.2}$$

$$MU^L = -\kappa L^{\phi} \tag{A.3}$$

$$MU^C = bC^{-\sigma} B^{\frac{1}{\theta}-\sigma} \tag{A.4}$$

$$B^{\frac{\theta-1}{\theta}} = b + (1-b)^{\theta} \left(\frac{bR}{1+R}\right)^{1-\theta} \tag{A.5}$$

$$1 = \frac{\beta(1+R)}{\Pi} \tag{A.6}$$

$$Y = AL = C + G \tag{A.7}$$

$$Q \equiv \frac{P^0}{P} = \frac{\Lambda}{H} \tag{A.8}$$

$$H(1 - \xi\beta\Pi^{\zeta-1}) = YMU^C \tag{A.9}$$

$$\Lambda(1 - \xi\beta\Pi^{\zeta}) = \frac{Y\frac{W(1+R)}{AP}MU^C}{(1-1/\zeta)} \tag{A.10}$$

$$1 = \xi\Pi^{\zeta-1} + (1-\xi)Q^{1-\zeta} \tag{A.11}$$

$$\Delta = \frac{(1-\xi)Q^{-\zeta}}{1-\xi\Pi^{\zeta}} \tag{A.12}$$

giving in effect 13 equations in 13 endogenous variables MU^M, MU^C, R, $\frac{W}{P}$, MU^N, L, C, B, Y, Q, Λ, H and Δ, given Π.

B Linearization of the Basic Model

We linearize around a zero inflation steady state (though, as we have seen, with non-separable utility and cost channel the Ramsey optimum is $\beta - 1 < 0 = -0.01$ in our calibration). All variables are expressed in deviation form[17] about the steady state. The

[16] The steady state of variable X_t is denoted by X.

[17] That is, for a typical variable X_t, $x_t = \frac{X_t - X}{X} \simeq \log\left(\frac{X_t}{X}\right)$ where X is the baseline steady state. For variables expressing a rate of change over time, π_t and r_t, $x_t = X_t - X$. Since steady-state inflation is zero π_t is the actual inflation rate, but $r_t = I_t - I$.

Euler equation and NKPC are respectively:

$$
\begin{aligned}
E_t mu_{t+1}^C &= mu_t^C - (r_t - E_t \pi_{t+1}) && \text{(B.13)}\\
mu_t^C &= -\frac{\sigma}{1-h}(c_t - hc_{t-1}) + \delta_n r_t + u_{C,t} && \text{(B.14)}\\
\pi_t &= \frac{\beta}{1+\beta\gamma} E_t \pi_{t+1} + \frac{\gamma}{1+\beta\gamma}\pi_{t-1} + \frac{(1-\beta\xi)(1-\xi)}{(1+\beta\gamma)\xi} mc_t && \text{(B.15)}\\
mc_t &= \beta r_t + w_t - p_t - a_t && \text{(B.16)}\\
w_t - p_t &= mu_t^L - mu_t^C && \text{(B.17)}\\
mu_t^L &= \phi l_t = \phi(y_t - a_t) && \text{(B.18)}
\end{aligned}
$$

The first term in (B.16) represents the cost channel. From (B.13) and (B.16)–(B.18) we subsequently obtain

$$
mc_t = \frac{\sigma}{(1-h)}(c_t - hc_{t-1}) + \phi l_t - a_t - \delta_n r_t - u_{C,t}
$$

without the cost channel and

$$
mc_t = \frac{\sigma}{(1-h)}(c_t - hc_{t-1}) + \phi l_t - a_t + (\beta - \delta_n) r_t - u_{C,t}
$$

with the cost channel. The parameter δ_n is defined by (16).

Given the interest rate, the linearized model is completed with

$$
\begin{aligned}
l_t &= y_t - a_t && \text{(B.19)}\\
y_t &= c_y c_t + (1 - c_y) g_t \text{ where } c_y = \frac{C}{Y} && \text{(B.20)}\\
g_{t+1} &= \rho_g g_t + \epsilon_{g,t+1} && \text{(B.21)}\\
a_{t+1} &= \rho_a a_t + \epsilon_{a,t+1} && \text{(B.22)}\\
u_{C,t+1} &= \rho_C u_{C,t} + \epsilon_{C,t} && \text{(B.23)}
\end{aligned}
$$

The flexi-price output, $\hat{y}$, consistent with zero inflation is then found by putting $mc_t = \pi_t = 0$ and is then given by the system

$$
\begin{aligned}
E_t \widehat{mu}_{t+1}^C &= \widehat{mu}_t^C - \hat{i}_t && \text{(B.24)}\\
\widehat{mu}_t^C &= -\sigma(\hat{c}_t - h\hat{c}_{t-1}) + \delta_n \hat{i}_t + u_t && \text{(B.25)}\\
\frac{\sigma}{(1-h)}(\hat{c}_t - h\hat{c}_{t-1}) &= -\phi \hat{l}_t + a_t - (\beta - \delta_n)\hat{i}_t && \text{(B.26)}
\end{aligned}
$$

$$\hat{l} = \hat{y} - a_t \tag{B.27}$$

$$\hat{y}_t = c_y \hat{c}_t + (1 - c_y) g_t \tag{B.28}$$

which defines $[\hat{i},\ \hat{mu}_t^C,\ \hat{c}_t,\ \hat{l}_t,\ \hat{y}_t]$, given exogenous processes $[a_t,\ g_t,\ u_t]$.

In terms of the 'output gap', $x_t = y_t - \hat{y}_t$, the NKPC becomes

$$\begin{aligned} \pi_t &= \frac{\beta}{1+\beta\gamma} E_t \pi_{t+1} + \frac{\gamma}{1+\beta\gamma}\pi_{t-1} \\ &+ \frac{(1-\beta\xi)(1-\xi)}{(1+\beta\gamma)\xi}\left(\frac{(\sigma + \phi(1-h)c_y)}{(1-h)c_y} x_t - \frac{\sigma h}{(1-h)c_y} x_{t-1} + (\beta - \delta_n)(r_t - \hat{i}_t)\right) \end{aligned} \tag{B.29}$$

It is noted that the interest rate effects of the cost channel and the non-separable utility enter the NKPC with the same signs - since $\delta_n < 0$ - if money and consumption are complements, which we assume. Additionally, with $h = \gamma = 0$ (no habit nor indexation) and $c_y = 1$ (no government spending), (B.29) now corresponds to equation (4.8), page 421, of Woodford (2003).

C Linearization of Extended Model

In addition to the Euler equation defined by (B.13) and (B.14) and the NKPC, (B.15), we have the following:

$$q_t = \beta(1-\delta)E_t q_{t+1} - (r_t - E_t\pi_{t+1}) + \beta Z E_t r_{K,t+1} + \epsilon_{Q,t} \tag{C.30}$$

$$z_t = \frac{r_{K,t}}{Z\Psi''(Z)} = \frac{\psi}{R_K} r_{K,t} \quad \text{where } \psi = \frac{\Psi'(Z)}{Z\Psi''(Z)} \tag{C.31}$$

$$i_t = \frac{1}{1+\beta} i_{t-1} + \frac{\beta}{1+\beta} E_t i_{t+1} + \frac{1}{S''(1)(1+\beta)} q_t \tag{C.32}$$

$$+ \frac{\beta E_t u_{I,t+1} - u_{I,t}}{1+\beta} \tag{C.33}$$

$$\pi_t = \frac{\beta}{1+\beta\gamma_P} E_t\pi_{t+1} + \frac{\gamma_P}{1+\beta\gamma_P}\pi_{t-1} + \frac{(1-\beta\xi_P)(1-\xi_P)}{(1+\beta\gamma_P)\xi_P} mc_t + \epsilon_{P,t} \tag{C.34}$$

$$k_t = (1-\delta)k_{t-1} + \delta i_{t-1} \tag{C.35}$$

$$mc_t = (1-\alpha)(wr_t + \beta\alpha_c r_t) + \frac{\alpha}{R_K} r_{K,t} - a_t \tag{C.36}$$

$$wr_t = \frac{\beta}{1+\beta} E_t wr_{t+1} + \frac{1}{1+\beta} wr_{t-1} + \frac{\beta}{1+\beta} E_t \pi_{t+1} - \frac{1+\beta\gamma_W}{1+\beta}\pi_t + \frac{\gamma_W}{1+\beta}\pi_{t-1} \tag{C.37}$$

$$+ \frac{(1-\beta\xi_W)(1-\xi_W)}{(1+\beta)\xi_W(1+\eta\phi)}(mrs_t - wr_t) + \epsilon_{W,t} \tag{C.38}$$

$$
\begin{aligned}
mrs_t &= mu_t^L - mu_t^C && \text{(C.39)}\\
mu_t^L &= \phi l_t + u_{L,t} + u_{C,t} && \text{(C.40)}\\
l_t &= k_{t-1} + \frac{1}{R_K}(1+\psi)r_{K,t} - wr_t && \text{(C.41)}\\
y_t &= c_y c_t + g_y g_t + i_y i_t + k_y \psi r_{K,t} && \text{(C.42)}\\
y_t &= \phi_F[a_t + \alpha(\frac{\psi}{R_K} r_{K,t} + k_{t-1}) + (1-\alpha)l_t] \text{ where } \phi_F = 1 + \frac{F}{Y} && \text{(C.43)}\\
u_{C,t+1} &= \rho_C u_{C,t} + \epsilon_{C,t+1} && \text{(C.44)}\\
u_{L,t+1} &= \rho_L u_{L,t} + \epsilon_{L,t+1} && \text{(C.45)}\\
u_{I,t+1} &= \rho_I u_{I,t} + \epsilon_{I,t+1} && \text{(C.46)}\\
g_{t+1} &= \rho_g g_t + \epsilon_{g,t+1} && \text{(C.47)}\\
a_{t+1} &= \rho_a a_t + \epsilon_{a,t+1} && \text{(C.48)}
\end{aligned}
$$

where "inefficient cost-push" shocks $\epsilon_{Q,t}$, $\epsilon_{P,t}$ and $\epsilon_{W,t}$ have been added to value of capital, the marginal cost and marginal rate of substitution equations, respectively, and $[\epsilon_{C,t}, \epsilon_{L,t}, \epsilon_{g,t}, \epsilon_{a,t}]$ are i.i.d. disturbances. Table 3 summarizes the notation.[18]

To implement the monetary rule we require the *output gap* to be the difference between output for the sticky price model obtained above and output when prices and wages are flexible, $\hat{y}_t$ say. Following SW, the inefficient shocks are also eliminated from this target level of output. The latter is obtained by setting $\xi_p = \xi_w = \epsilon_{Q,t} = \epsilon_{P,t} = \epsilon_{W,t} = 0$ in the linearized model above.

The empirical Taylor rule used in the estimation is given by

$$
\begin{aligned}
r_t &= \rho r_{t-1} + (1-\rho)[\bar{\pi}_t + \theta_\pi E_t(\pi_{t+j} - \bar{\pi}_{t+j}) + \theta_y o_t] + \theta_{\Delta\pi}(\pi_t - \pi_{t-1})\\
&+ \theta_\Delta(\pi_t - \pi_{t-1}) + \theta_{\Delta y}(o_t - o_{t-1}) && \text{(C.49)}
\end{aligned}
$$

where $o_t = y_t - \hat{y}_t$ is the output gap and $\bar{\pi}_t$ an exogenous inflation target.

[18] Letting the shares of labour and capital be respectively, $s_{L,t}$ and $s_{K,t}$ in deviation form, with Cobb-Douglas technology with a steady-state capital share α, marginal costs can be written $mc_t = \alpha_c(1-\alpha)r_t + (1-\alpha)s_{L,t} + \alpha s_{K,t} = \alpha_c(1-\alpha)r_t + \bar{mc}_t$ where $\bar{mc}_t$ is the marginal cost without the cost channel. In the GMM estimation of the previous section, the data consists of the wage share. It follows that the $\alpha_c(1-\alpha)$ in this section is comparable with our GMM estimates of α_c.

D Tables of Results

Table 1: Cost-channel Phillips curve, single-equation GMM

Instrument set A	β	ξ	α_c	γ	J-test (p-values)
No indexation					
Restricted	1.009 (0.025)	0.891 (0.184)	-	-	0.318
Unrestricted	1.004 (0.025)	0.836 (0.106)	0.326# (0.516)	-	0.361
$\beta = 0.99$	-	0.822 (0.081)	0.246# (0.294)	-	0.399
Indexation					
Restricted	0.965 (0.044)	0.876 (0.268)	-	0.397 (0.165)	0.762
Unrestricted	0.966 (0.045)	0.861 (0.235)	0.190# (0.838)	0.392 (0.157)	0.723
$\beta = 0.99$	-	0.917 (0.449)	0.876# (9.944)	0.435 (0.238)	0.752
Instrument set B					
No indexation					
Restricted	0.995 (0.026)	0.950 (0.469)	-	-	0.189
Unrestricted	0.987 (0.026)	0.846 (0.125)	0.371# (0.685)	-	0.220
$\beta = 0.99$	-	0.851 (0.112)	0.399# (0.702)	-	0.274
Indexation					
Restricted	0.957 (0.052)	0.816 (0.190)	-	0.429 (0.152)	0.627
Unrestricted	0.961 (0.052)	0.815 (0.185)	0.087# (0.379)	0.415 (0.152)	0.561
$\beta = 0.99$	-	0.851 (0.255)	0.304# (1.397)	0.465 (0.182)	0.596

Note - standard errors in brackets; #: statistically insignificant estimate

Table 2: Euler equation, GMM estimates

	h	δ_n
$\sigma = 1$	0.801	-0.612
	(0.163)	(1.002)
$\sigma = 1.5$	0.821	-1.056
	(0.231)	(2.131)
$\sigma = 2$	0.875	-2.044
	(0.298)	(6.248)
$\sigma = 2.5$	0.948	-6.175
	(0.365)	(47.242)

Table 3: Summary of Notation (Variables in Deviation Form)

π_t	producer price inflation over interval $[t-1, t]$
r_t	nominal interest rate over interval $[t, t+1]$
$wr_t = w_t - p_t$	real wage
mc_t	marginal cost
mrs	marginal rate of substitution between work and consumption
l_t	employment
z_t	capacity utilization
k_t	end-of-period t capital stock
i_t	investment
$r_{K,t}$	return on capital
q_t	Tobin's Q
c_t	consumption
y_t, $\hat{y}_t$	output with sticky prices and flexi-prices
$o_t = \hat{y}_t - y_t$	output gap
$u_{i,t+1} = \rho_a u_{i,t} + \epsilon_{i,t+1}$	AR(1) processes for utility preference shocks, $u_{i,t}$, $i = C, L, I$
$a_{t+1} = \rho_a a_t + \epsilon_{a,t+1}$	AR(1) process for factor productivity shock, a_t
$g_{t+1} = \rho_g g_t + \epsilon_{g,t+1}$	AR(1) process government spending shock, g_t
β	discount parameter
γ_p, γ_w	indexation parameters
h	habit parameter
$1 - \xi_p$, $1 - \xi_w$	probability of a price, wage re-optimization
σ	risk-aversion parameter
ϕ	disutility of labour supply parameter
φ	$\frac{1}{S''(1)}$
ϕ_F	$1 + \frac{F}{Y}$
δ	depreciation rate
α	share of capital

Table 4: Prior Distributions and ML estimation results based on Monte Carlo realizations (Model 4)

					T=200 ◇			
Parameter	notation	prior mean	density	prior sd.	mean	st. err.	bias⋆	perc. dev.✠
Investment adjustment	$S''(1)$	4.00	normal	1.50	5.05	0.99	1.07	**0.27**
Risk aversion	σ	2.00	normal	0.50	2.13	0.26	0.13	0.06
Domestic consumption habit	h_C	0.50	beta	0.20	0.47	0.20	0.03	0.06
Elasticity of disutility (labour)	ϕ	1.20	normal	0.50	1.31	0.39	0.11	0.09
Fixed cost	ϕ_F	1.45	normal	0.125	1.47	0.07	0.02	0.01
Capital utilisation	ψ	1.00	normal	0.50	1.69	0.64	0.69	**0.69**
Calvo wages	ξ_W	0.50	beta	0.20	0.57	0.19	0.07	**0.13**
Calvo prices	ξ_P	0.50	beta	0.20	0.55	0.21	0.05	**0.10**
Wage indexation	γ_W	0.50	beta	0.15	0.52	0.15	0.02	0.03
Price indexation	γ_P	0.50	beta	0.15	0.48	0.16	0.02	0.04
Separable utility effect	δ_n	-0.25	gamma	0.10	0.25	0.22	0.00	0.00
Degree of cost channel	α_c	0.50	beta	0.20	0.32	0.19	0.18	**0.35**
Int. rate rule-inflation gap (-1)	θ_π	2.00	normal	0.50	2.12	0.27	0.12	0.06
Int. rate rule-inflation growth	θ_{Δ_π}	0.20	normal	0.10	0.23	0.10	0.03	**0.16**
Int. rate rule-output gap growth	θ_{Δ_y}	0.25	gamma	0.25	0.31	0.25	0.06	**0.26**
Int. rate rule-smoothing	ρ	0.80	beta	0.10	0.80	0.10	0.00	0.00
AR(1) coef.-technology	ρ_a	0.85	beta	0.10	0.88	0.09	0.03	0.03
AR(1) coef.-inflation objective	ρ_{π_t}	0.85	beta	0.10	0.87	0.14	0.02	0.02
AR(1) coef.-preference	ρ_C	0.85	beta	0.10	0.85	0.11	0.00	0.00
AR(1) coef.-government	ρ_g	0.85	beta	0.10	0.87	0.10	0.02	0.02
AR(1) coef.-labour supply	ρ_L	0.85	beta	0.10	0.86	0.12	0.01	0.02
AR(1) coef.-investment	ρ_I	0.85	beta	0.10	0.55	0.32	0.30	**0.35**
AR(1) coef.-markup shock	ρ_P	0.50	beta	0.15	0.48	0.16	0.02	0.04
Sd.of shock	$sd(\epsilon_a)$	0.60	inv.gamma	2.00	-	-	-	-
Sd.of shock	$sd(\epsilon_{\pi_t})$	0.10	inv.gamma	10.0	-	-	-	-
Sd.of shock	$sd(\epsilon_C)$	2.00	inv.gamma	2.00	-	-	-	-
Sd.of shock	$sd(\epsilon_g)$	1.67	inv.gamma	2.00	-	-	-	-
Sd.of shock	$sd(\epsilon_L)$	3.00	inv.gamma	2.00	-	-	-	-
Sd.of shock	$sd(\epsilon_I)$	0.10	inv.gamma	2.00	-	-	-	-
Sd.of shock (interest rate)	$sd(\epsilon_r)$	0.10	inv.gamma	2.00	-	-	-	-
Sd.of shock (equity premium)	$sd(\epsilon_Q)$	5.00	inv.gamma	2.00	-	-	-	-
Sd.of shock (price markup)	$sd(\epsilon_P)$	0.20	inv.gamma	2.00	-	-	-	-
Sd.of shock (wage markup)	$sd(\epsilon_W)$	0.20	inv.gamma	2.00	-	-	-	-

◇ We generated 1000 artificial data observations of length T=200 by imposing the prior means to all of the parameters for all the iterations. The results presented here are based on maximum likelihood estimates for these T=200 observations.

⋆ Note that *bias* is measured as the absolute value of the difference between the prior mean and the mean of ML estimates for each parameter.

✠ We define perc. dev. as $\frac{bias}{priormean}$. ‘Problem’ parameters (i.e., those with percentage deviations greater than or equal to 10 percent) are highlighted in bold.

Table 5: Bayesian Posterior Distributions

Parameter	Model 1	Model 2	Model 3	Model 4
$S''(1)$	3.60 [1.96:5.01]	3.50 [1.85:5.13]	3.72 [2.07:5.28]	3.66 [1.97:5.30]
σ	2.45 [1.91:2.99]	2.49 [1.90:3.10]	2.45 [1.91:2.99]	2.58 [2.06:3.12]
h_C	0.47 [0.31:0.62]	0.50 [0.17:0.83]	0.45 [0.30:0.59]	0.50 [0.17:0.83]
ϕ	1.64 [0.97:2.25]	1.62 [0.99:2.25]	1.58 [0.97:2.21]	1.57 [0.93:2.17]
ϕ_F	1.55 [1.42:1.69]	1.54 [1.41:1.67]	1.55 [1.41:1.68]	1.54 [1.41:1.67]
ψ	2.39 [1.82:2.94]	2.39 [1.83:2.97]	2.43 [1.85:2.96]	2.40 [1.85:3.01]
ξ_W	0.90 [0.86:0.94]	0.90 [0.87:0.94]	0.89 [0.85:0.94]	0.90 [0.86:0.94]
ξ_P	0.79 [0.73:0.85]	0.79 [0.73:0.85]	0.79 [0.73:0.85]	0.79 [0.73:0.85]
γ_W	0.70 [0.55:0.87]	0.69 [0.54:0.86]	0.70 [0.55:0.87]	0.68 [0.52:0.84]
γ_P	0.23 [0.08:0.36]	0.23 [0.09:0.36]	0.22 [0.09:0.36]	0.23 [0.09:0.37]
α_c	-	-	0.46 [0.20:0.73]	0.49 [0.24:0.75]
δ_n	-	-0.37 [-0.51:-0.21]	-	-0.35 [-0.48:-0.22]
θ_π	2.11 [1.65:2.55]	2.02 [1.63:2.41]	2.12 [1.62:2.63]	2.08 [1.62:2.54]
θ_{Δ_π}	0.24 [0.13:0.36]	0.23 [0.10:0.36]	0.22 [0.11:0.34]	0.21 [0.09:0.33]
θ_{Δ_y}	0.27 [0.20:0.33]	0.28 [0.21:0.35]	0.26 [0.19:0.32]	0.27 [0.20:0.34]
ρ	0.80 [0.75:0.86]	0.80 [0.75:0.85]	0.81 [0.75:0.86]	0.81 [0.76:0.86]
ρ_a	0.91 [0.87:0.95]	0.91 [0.87:0.95]	0.91 [0.86:0.94]	0.90 [0.87:0.94]
ρ_{π_t}	0.86 [0.72:0.99]	0.84 [0.69:0.99]	0.87 [0.72:0.99]	0.86 [0.72:0.99]
ρ_C	0.75 [0.58:0.92]	0.81 [0.69:0.96]	0.76 [0.61:0.93]	0.80 [0.67:0.94]
ρ_g	0.95 [0.92:0.99]	0.95 [0.92:0.99]	0.95 [0.92:0.99]	0.95 [0.92:0.99]
ρ_L	0.83 [0.65:0.99]	0.82 [0.65:0.99]	0.86 [0.70:0.99]	0.84 [0.66:0.99]
ρ_I	0.95 [0.91:0.99]	0.96 [0.91:0.99]	0.95 [0.91:0.99]	0.96 [0.93:0.99]
ρ_P	0.86 [0.78:0.94]	0.86 [0.78:0.94]	0.85 [0.77:0.94]	0.85 [0.78:0.94]
$sd(\epsilon_a)$	0.35 [0.30:0.39]	0.35 [0.30:0.39]	0.35 [0.30:0.39]	0.35 [0.30:0.39]
$sd(\epsilon_{\pi_t})$	0.07 [0.03:0.11]	0.07 [0.03:0.11]	0.07 [0.03:0.12]	0.08 [0.03:0.12]
$sd(\epsilon_C)$	2.11 [1.46:2.74]	2.02 [1.36:2.68]	1.96 [1.40:2.49]	1.85 [1.29:2.42]
$sd(\epsilon_g)$	1.49 [1.30:1.67]	1.49 [1.30:1.67]	1.47 [1.29:1.66]	1.49 [1.30:1.67]
$sd(\epsilon_L)$	1.97 [1.09:2.82]	2.05 [1.07:3.05]	1.96 [1.10:2.73]	2.02 [1.11:2.85]
$sd(\epsilon_I)$	0.46 [0.26:0.67]	0.48 [0.27:0.69]	0.41 [0.22:0.60]	0.42 [0.23:0.61]
$sd(\epsilon_r)$	0.17 [0.13:0.22]	0.16 [0.09:0.22]	0.16 [0.12:0.21]	0.15 [0.09:0.21]
$sd(\epsilon_Q)$	8.59 [4.92:12.45]	8.45 [4.64:13.40]	9.59 [5.01:13.84]	9.48 [5.22:13.76]
$sd(\epsilon_P)$	0.07 [0.05:0.09]	0.07 [0.06:0.09]	0.07 [0.05:0.09]	0.07 [0.05:0.09]
$sd(\epsilon_W)$	0.31 [0.27:0.35]	0.31 [0.27:0.35]	0.31 [0.27:0.35]	0.31 [0.27:0.35]
Price contract length$^\diamondsuit$	4.76	4.76	4.76	4.76
LL	-457.85	-458.29	-457.61	-458.15
Prob.	0.27	0.18	0.35	0.20

$^\diamondsuit$ Price contract length is defined as $\frac{1}{1-\xi_P}$.

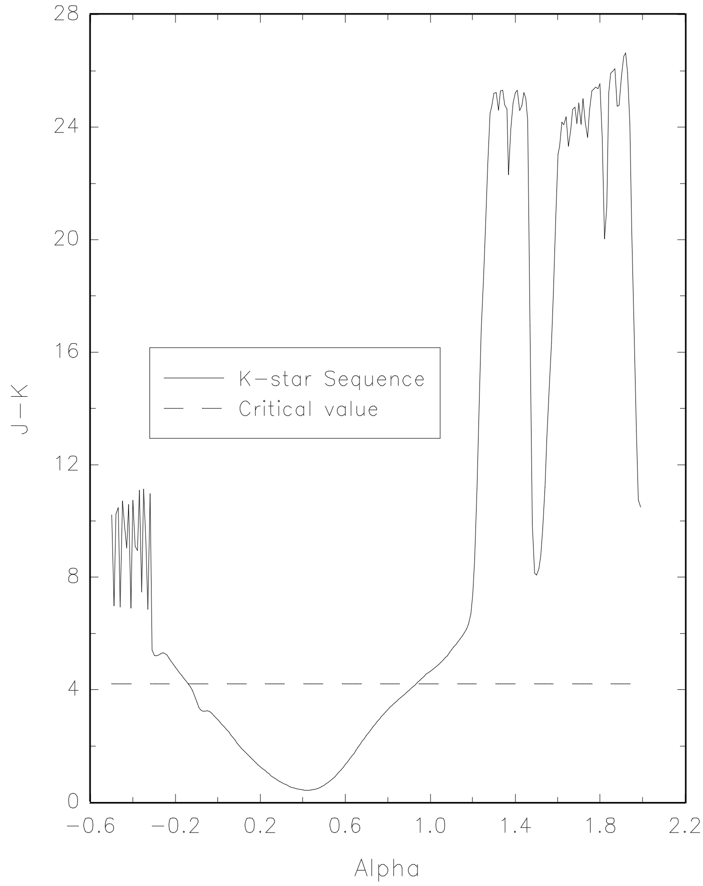


FIGURE 1: Kleinbergen statistic values for α_c

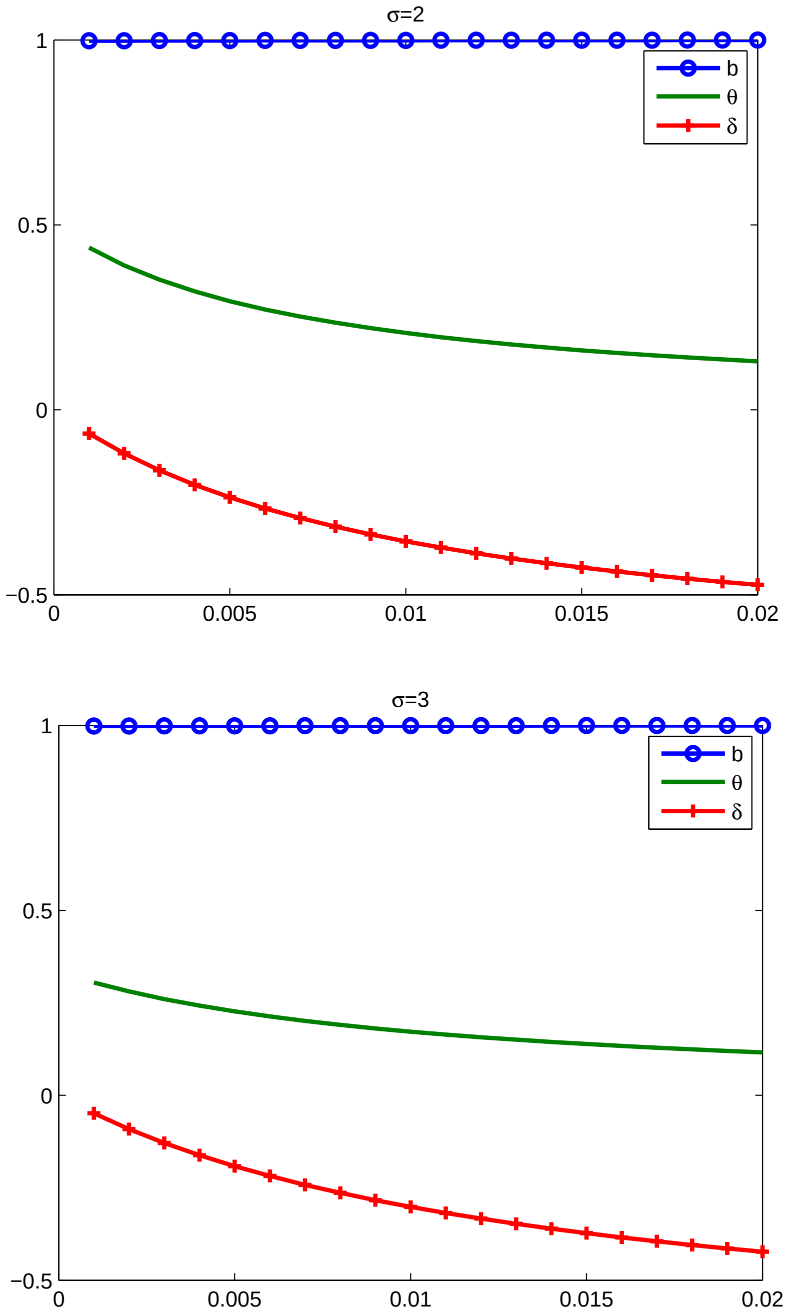


FIGURE 2: Calibration of b, θ and δ_n

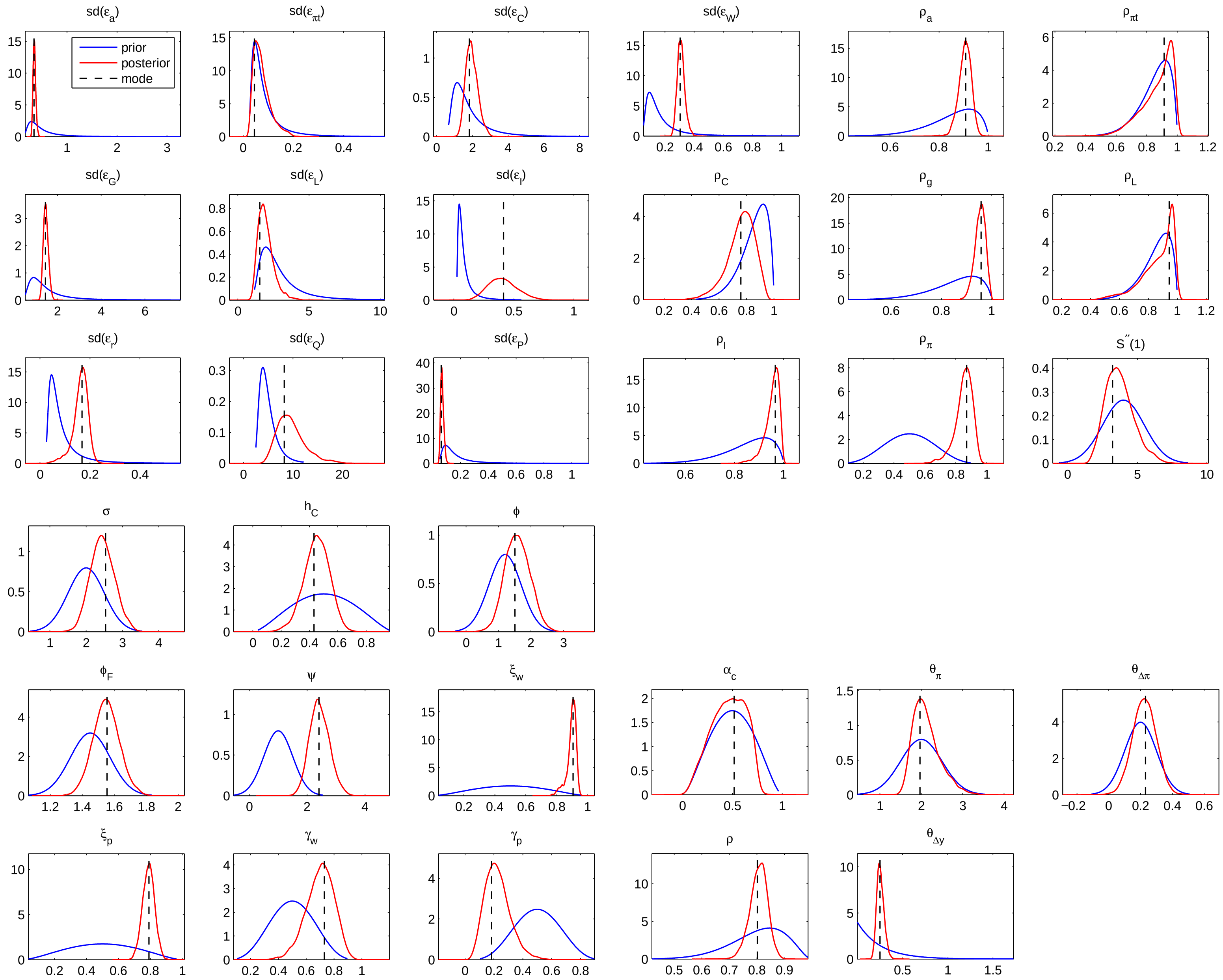


FIGURE 3: Priors and Posteriors (Model 3)

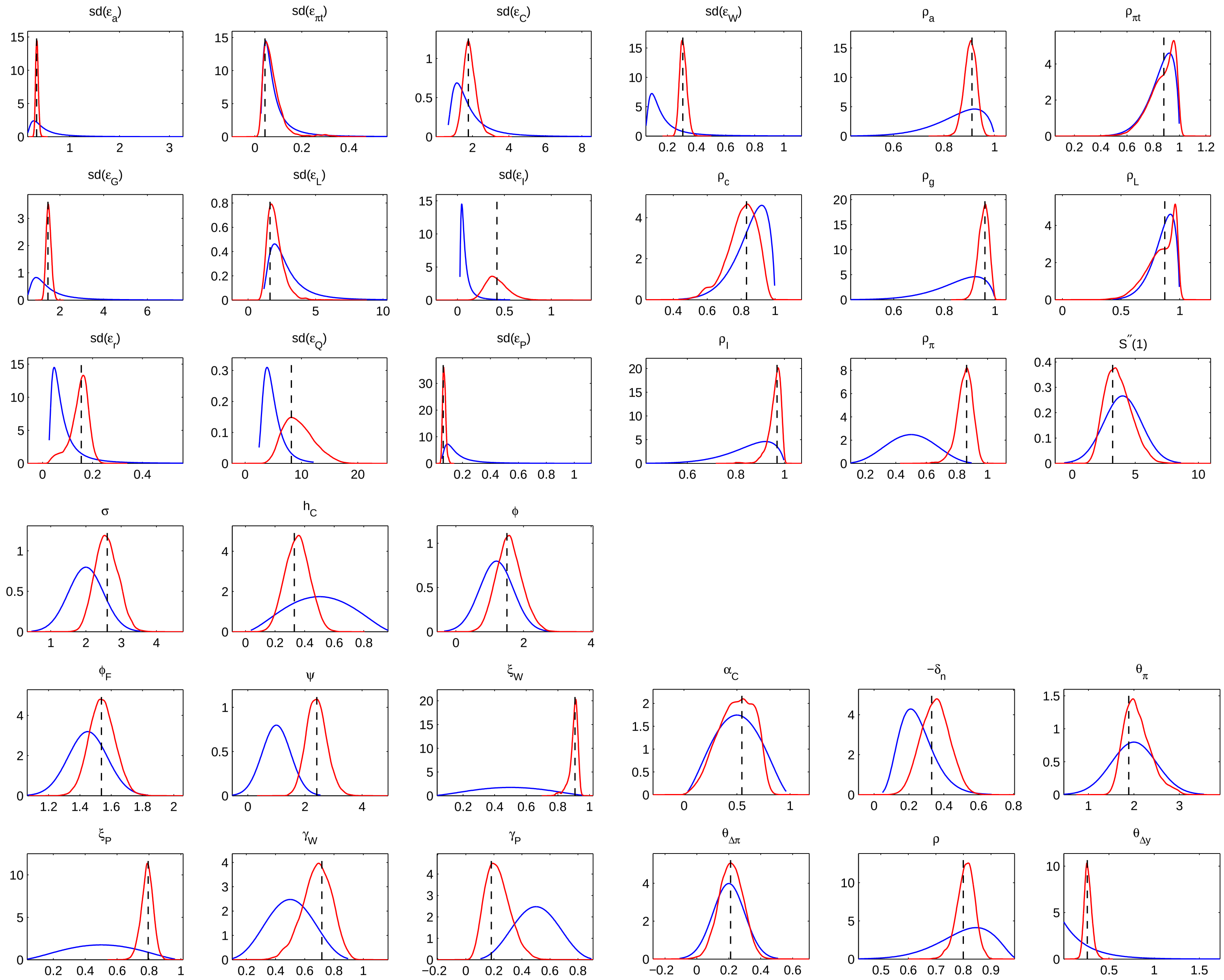


FIGURE 4: Priors and Posteriors (Model 4)

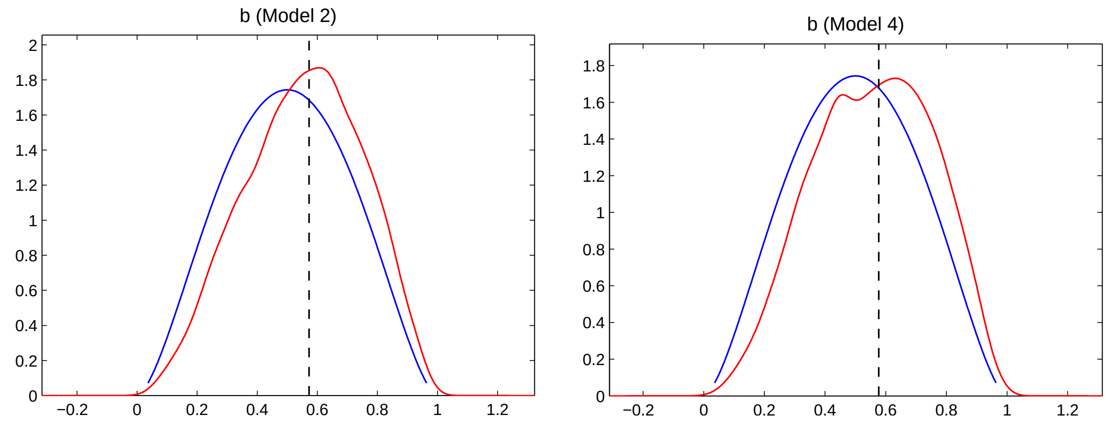
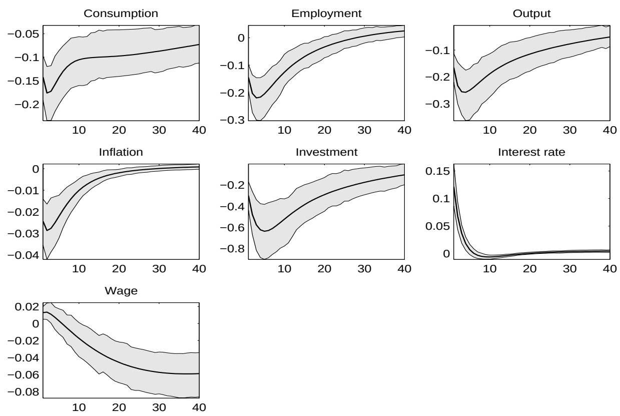
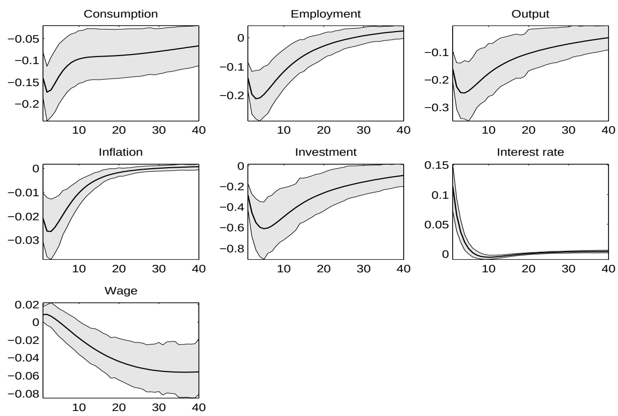


FIGURE 5: Parameter profiles for b



(a) Model 1



(b) Model 3

FIGURE 6: Estimated Posterior Impulse Responses to an Interest Rate Shock