9 May, 2003

Preliminary and incomplete

SHOCKS AND FRICTIONS IN US BUSINESS CYCLES: A BAYESIAN DSGE APPROACH

Frank Smets and Raf Wouters[*]

Abstract

We estimate a dynamic stochastic general equilibrium (DSGE) model for the US economy. The model incorporates many types of real and nominal frictions: sticky nominal price and wage setting, habit formation in consumption, investment adjustment costs, variable capital utilisation and fixed costs in production. It also contains many types of shocks including productivity, labour supply, investment, preference, cost-push and monetary policy shocks. Using Bayesian estimation techniques, the relative importance of the various frictions and shocks in explaining the US business cycle are empirically investigated. We also show that this model is able to outperform standard VAR and BVAR models in out-of-sample prediction.

Key words: DSGE models; monetary policy

JEL-classification: E4-E5

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[*] Frank Smets – European Central Bank – e-mail: frank.smets@ecb.int ; Raf Wouters – National Bank of Belgium – e-mail: rafael.wouters@nbb.be . The views expressed are solely our own and do not necessarily reflect those of the European Central Bank or the National Bank of Belgium.

1. Introduction

A new generation of small-scale monetary business cycle models with sticky prices and wages (the New Keynesian or New Neoclassical Synthesis (NNS) models) has become popular in monetary policy analysis[1]. Following Smets and Wouters (2003a), this paper estimates an extended version of these models, largely based on Christiano, Eichenbaum and Evans (CEE, 2001), on US data covering the period 1957:2-2002:1 and using a Bayesian estimation methodology. The estimated model contains many shocks and frictions. It features sticky nominal price and wage setting that allow for backward indexation, habit formation in consumption and investment adjustment costs that create hump-shaped responses of aggregate demand, and variable capital utilisation and fixed costs in production. The stochastic dynamics is driven by ten orthogonal structural shocks. In addition to productivity, labour supply and investment-specific technology shocks, the model includes preference, government spending, cost-push and monetary policy shocks.

The objectives of the paper are threefold. First, as the NNS models have become the standard workhorse for monetary policy analysis, it is important to verify whether they can explain the main features of the US macro data: real GDP, hours worked, consumption, investment, real wages, prices and the short-term nominal interest rate. CEE (2001) show that a version of the model estimated in this paper can replicate the impulse responses following a monetary policy shock identified in an unrestricted VAR. As in Smets and Wouters (2003a), the introduction of a larger number of shocks allows us to estimate the full model using the seven data series mentioned above. The marginal likelihood criterion, which captures the out-of sample prediction performance, is used to test the NNS model against standard VAR and BVAR models. We find that the NNS model fits the data better than standard VAR and BVAR models. These results are confirmed by simple out-of-sample forecasting exercises. The restrictions implied by the micro-founded model lead to an improvement of the forecasting performance, in particular, at medium-term horizons.

Second, the introduction of a large number of shocks and frictions raises the question whether each of those frictions and shocks are really necessary to describe the seven data series. For example, CEE (2001) show that once one allows for nominal wage rigidity, there is no need for additional price rigidity in order to capture the impulse responses following a monetary policy shock. Using the marginal likelihood, we investigate the relative empirical importance of the different types of frictions and shocks. In contrast to CEE (2001), price stickiness is estimated to be high and empirically important. Indexation, on the other hand, is relatively unimportant especially for wage setting and only very marginally for price setting, confirming the single-equation results of Gali and Gertler (2001). While all the real frictions help in reducing the prediction errors of the NNS model, empirically the most important are the investment adjustment costs. Regarding the shocks, we find that the marginal likelihood can be improved if we leave out the equity premium shocks. However, this may partly be due to the fact that we did not use an equity price index in the estimation. Both the price and wage mark-up shocks are, however, empirically very important to capture wage and price dynamics. This points to a shortcoming of the model: It does not

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[1] See Goodfriend and King (1997), Rotemberg and Woodford (1997), Clarida, Gali and Gertler (1999) and Woodfrod (2003).

include a flexible price sector, which could explain the higher frequency volatility in aggregate prices. This volatility is picked up by the price mark-up shocks.

Finally, we analyse the relative importance of the various identified structural shocks in explaining US business cycle fluctuations using impulse response analysis, forecast error variance decompositions and historical decompositions. Broadly speaking we confirm the analysis of Shapiro and Watson (1989), who use a structural VAR methodology to examine the sources of business cycle fluctuations. While "demand" shocks explain a significant fraction of the short-run forecast variance in output, both labour supply and productivity shocks explain most of its variation in the medium to long run. In contrast to Christiano et al (2002), but in line with Gali (1999) and Francis and Ramey (2002), productivity shocks have a short-run negative impact on hours worked. This is the case even in the flexible price economy because of the slow adjustment of the two demand components following a positive productivity shock. One important issue for monetary policy is the importance of mark-up shocks in the determination of nominal wages and prices, as these shocks generate a trade-off problem if the monetary authorities aim at stabilising both inflation and the output-gap. The price mark-up shocks explain a dominant part of the forecast variance of inflation at the short to medium-term horizon.

In the next section, we derive the theoretical model and in section three we present the linearised model that is estimated. In section four, the prior and posterior parameters are discussed and the robustness of the estimation results is illustrated. The model statistics and forecast performance are compared to those of unconstrained VAR (and BVAR) models, in section five. In section six, the empirical importance of the different frictions and shock is discussed by calculating the contribution of the individual assumptions to the marginal likelihood of the model. In section seven, a list of alternative validation methods are presented: the impulse responses, the variance and historical decomposition. We also present a model-based estimate of the US output gap.

2. The micro-foundations of the linearised DSGE model

The DSGE model contains many frictions that affect both nominal and real decisions. The model is based on the work of CEE (2001) and Smets and Wouters (2003a). As in Smets and Wouters (2003b), we extend the model so that it is consistent with a steady state growth path. Households maximise a non-separable utility function with two arguments (goods and labour effort) over an infinite life horizon. Consumption appears in the utility function relative to a time-varying external habit variable. Labour is differentiated over households, so that there is some monopoly power over wages which results in an explicit wage equation and allows for the introduction of sticky nominal wages à la Calvo. Households rent capital services to firms and decide how much capital to accumulate given certain capital adjustment costs. As the rental price of capital goes up, the capital stock can be used more intensively according to some cost schedule. Firms produce differentiated goods, decide on labour and capital inputs, and set prices, again according to the Calvo model. The Calvo model in both wage and price setting is augmented by the assumption that prices that are not re-optimised, are partially indexed to past inflation rates. Prices are therefore set in function of current and expected marginal costs, but are also determined by the past inflation rate. The marginal costs depend on wages and the rental rate of capital. In the same way, wages will depend on past and expected future wages and inflation. In this Section we sketch out the main building blocks.

2.1 The household sector

The instantaneous utility function is non-separable in consumption and labour. King, Plosser and Rebelo (1988) have investigated the restrictions on preferences that are necessary for making optimising models compatible with steady-state long-run growth. The observed relative stability of labour supply over the past decennia implies that income and substitution effects of trending productivity growth must not alter labour supply. Separable utility functions fulfil this condition only in the case of a unit intertemporal substitution elasticity. Most empirical studies however find typically a lower interest rate elasticity for consumption. A non-separable utility function à la King, Rebelo and Plosser (1988) allows for an unrestricted intertemporal substitution elasticity while at the same time it is fully compatible with a steady-state growth path and stationary labour supply. Moreover, Basu and Kimball (2000) have shown that such non-separable utility functions are able to solve the empirically observed excess sensitivity of consumption with respect to current income fluctuations. Under non-separability, the first order condition for consumption growth is augmented with an additional term in labour supply reflecting the dependence of marginal utility of consumption on the employment situation. These utility functions assume complementary between consumption and labour, so that employment growth will enter the first order condition for consumption with a positive sign. Both micro-economic studies on consumption behaviour and traditional macro-consumption equations offer wide support for this kind of consumption functions. Furthermore, Basu and Kimball (2000) show that labour growth enters the consumption first-order condition in a very specific way, because the impact is restricted by the long run equality between the marginal utility of consumption and labour supply.

There is a continuum of households indicated by index τ. The instantaneous utility function of each household depends on consumption (C_t^τ) minus the external habit (H_t) and labour time (l_t):[2]

$$(1) \qquad U_t^\tau = \left(\frac{1}{1-\sigma_c} \left(C_t^\tau - H_t \right)^{1-\sigma_c} + \varepsilon_t^L \right) * \exp\left(\frac{\sigma_c - 1}{1+\sigma_l} \left(\ell_t^\tau \right)^{1+\sigma_l} \right)$$

σ_c is the coefficient of relative risk aversion of households or the inverse of the intertemporal elasticity of substitution; σ_l represents the inverse of the elasticity of work effort with respect to the real wage.

Equation (1) above also contains a preference shocks (ε_t^L) which represents a shock to the labour supply. This shock is assumed to follow a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^L = \rho_L \varepsilon_{t-1}^L + \eta_t^L$.

Each household is assumed to supply a complete set of differentiated labour types, so that household's consumption and labour income are not sensitive to the firm-specific labour and wage conditions. Labour supply (l_t^τ) that enters the household utility function is therefore an index over differentiated labour

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[2] As is done in much of the recent literature, we consider a cashless limit economy.

types.[3] Each household has a monopoly power over the supply of its labour and will set the optimal wage accordingly.

The external habit stock is assumed to be proportional to aggregate past consumption:

(2) $$H_t = hC_{t-1}$$

Each household τ maximises an intertemporal utility function given by:

(3) $$E_0 \sum_{t=0}^{\infty} \beta^t * \varepsilon_t^b * U_t^\tau$$

where β is the discount factor. ε_t^B represents a second preference shock affecting the discount rate that determines the intertemporal substitution decisions of households. This shock is also assumed to follow a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^b = \rho_b \varepsilon_{t-1}^b + \eta_t^b$.

Households maximise their objective function subject to an intertemporal budget constraint which is given by:

(4) $$b_t \frac{B_t^\tau}{P_t} = \frac{B_{t-1}^\tau}{P_t} + Y_t^\tau - C_t^\tau - I_t^\tau$$

Households hold their financial wealth in the form of bonds B_t. Bonds are one-period securities with price b_t. Current income and financial wealth can be used for consumption and investment in physical capital.

Household's total income is given by:

(5) $$Y_t^\tau = w_t^\tau l_t^\tau + (r_t^k z_t^\tau K_{t-1}^\tau - \Psi(z_t^\tau) K_{t-1}^\tau) + Div_t^\tau$$

Total income consists of three components: labour income; the return on the real capital stock minus the cost associated with variations in the degree of capital utilisation $(r_t^k z_t^\tau K_{t-1}^\tau - \Psi(z_t^\tau) K_{t-1}^\tau)$ and the dividends derived from the imperfect competitive intermediate firms (Div_t^τ).

Because of the assumption that each household supplies all types of labour, the first component in the household's income will equal aggregate labour income and the marginal utility of wealth will be identical across different households. The income from renting out capital services depends not only on the level of capital that was installed last period, but also on its utilisation rate (z_t). As in CEE (2001), it is assumed that the cost of capital utilisation is zero when capital utilisation is one ($\psi(1) = 0$). Next we discuss each of the household decisions in turn.

2.1.1. Consumption and savings behaviour

The maximisation of the objective function (1) subject to the budget constraint (4) with respect to consumption and holdings of bonds, yields the following first-order conditions for consumption:

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[3] Households are assumed to consist of many members each supplying a specific labour-type. Each member sets its optimal wage given the demand for its labour and the household consumption level. By using this setup, marginal utility will be the same for each household and independent of the supply of a specific labour-type.

$$(6)\qquad E_t\left[\beta\frac{\lambda_{t+1}}{\lambda_t}\frac{R_tP_t}{P_{t+1}}\right]=1$$

where R_t is the gross nominal rate of return on bonds ($R_t = 1+i_t = 1/b_t$) and λ_t is the marginal utility of consumption, which is given by:[4]

$$(7)\qquad \lambda_t = \varepsilon_t^b\left(C_t - H_t\right)^{-\sigma_c}\exp\left(\frac{\sigma_c-1}{1+\sigma_l}\left(\ell_t^\tau\right)^{1+\sigma_l}\right)$$

Equations (6) and (7) extend the usual first-order condition for consumption growth by taking into account the existence of external habit formation and the complementarity between labour and consumption in preferences.

2.1.2. Labour supply decisions and the wage setting equation

Households act as price-setters in the labour market. We assume that wages can only be optimally adjusted after some random “wage-change signal” is received. The probability that a particular household can change its nominal wage in period t is constant and equal to $1-\xi_w$. A household τ which receives such a signal in period t, will thus set a new nominal wage, $\tilde{w}_t^\tau$, taking into account the probability that it will not be re-optimized in the near future. In addition, we allow for an indexation of the wages that can not be adjusted to past inflation. More formally, the wages of households that can not re-optimise adjust according to:

$$(8)\qquad W_t^\tau = \left(\frac{P_{t-1}}{P_{t-2}}\right)^{\gamma_w}\left(\bar{\pi}_t\right)^{1-\gamma_w}W_{t-1}^\tau$$

where γ_w is the degree of wage indexation to past inflation. When $\gamma_w = 1$, there is complete indexation to inflation in the previous period. When $\gamma_w = 0$, wages that can not be re-optimised are indexed to the inflation objective of the central bank. This specification implies that the Calvo model is consistent with a vertical long run Phillips curve.

Households set their nominal wages for each type of labour they supply in order to maximise their intertemporal objective function subject to the intertemporal budget constraint and the demand for labour which is determined by:

$$(9)\qquad l_t^\tau = \left(\frac{W_t^\tau}{W_t}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}}L_t$$

where aggregate labour demand, L_t, and the aggregate nominal wage, W_t, are given by the following Dixit-Stiglitz type aggregator functions:

$$(10)\qquad L_t = \left[\int_0^1\left(l_t^\tau\right)^{\frac{1}{1+\lambda_{w,t}}}d\tau\right]^{1+\lambda_{w,t}},$$

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[4] Here we have already used the fact that the marginal utility of consumption is identical across households.

(11) $$W_t = \left[\int_0^1 \left(W_t^\tau \right)^{-1/\lambda_{w,t}} d\tau \right]^{-\lambda_{w,t}} .$$

This maximisation problem results in the following mark-up equation for the re-optimised wage:

(12) $$\frac{\tilde{w}_t}{P_t} E_t \sum_{i=0}^{\infty} \beta^i \xi_w^i \left(\frac{P_t}{P_{t+i}} \right) \left(\frac{P_{t+i-1}}{P_{t-1}} \right)^{\gamma_w} \left(\bar{\pi}_t \right)^{1-\gamma_w} \frac{l_{t+i}^\tau U_{t+i}^C}{1+\lambda_{w,t+i}} = E_t \sum_{i=0}^{\infty} \beta^i \xi_w^i l_{t+i}^\tau U_{t+i}^\ell$$

where U_{t+i}^l is the marginal disutility of labour and U_{t+i}^C is the marginal utility of consumption. Equation (12) shows that the nominal wage at time t of a household τ that is allowed to change its wage is set so that the present value of the marginal return to working is a mark-up over the present value of marginal cost (the subjective cost of working).[5] When wages are perfectly flexible ($\xi_w = 0$), the real wage will be a mark-up (equal to $1+\lambda_{w,t}$) over the current ratio of the marginal disutility of labour and the marginal utility of an additional unit of consumption. We assume that shocks to the wage mark-up, $\lambda_{w,t} = \lambda_w + \eta_t^w$, are IID-Normal around a constant.

Given equation (11), the law of motion of the aggregate wage index is given by:

(13) $$\left(W_t \right)^{-1/\lambda_{w,t}} = \xi \left(W_{t-1} \left(\frac{P_{t-1}}{P_{t-2}} \right)^{\gamma_w} \left(\bar{\pi}_t \right)^{1-\gamma_w} \right)^{-1/\lambda_{w,t}} + (1-\xi)\left(\tilde{w}_t \right)^{-1/\lambda_{w,t}}$$

2.1.3. Investment and capital accumulation

Finally, households own the capital stock, a homogenous factor of production, which they rent out to the firm-producers of intermediate goods at a given rental rate of r_t^k. They can increase the supply of rental services from capital either by investing in additional capital (I_t), which takes one period to be installed or by changing the utilisation rate of already installed capital (z_t). Both actions are costly in terms of foregone consumption (see the intertemporal budget constraint (4) and (5)).[6]

Households choose the capital stock, investment and the utilisation rate in order to maximise their intertemporal objective function subject to the intertemporal budget constraint and the capital accumulation equation which is given by:

(14) $$K_{t+1} = K_t \left[1-\tau \right] + \left[1 + \varepsilon_t^I - S\left(I_t / I_{t-1} \right) \right] I_t ,$$

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[5] Standard RBC models typically assume an infinite supply elasticity of labour in order to obtain realistic business cycleproperties for the behaviour of real wages and employment. An infinite supply elasticity limits the increase in marginal costs and prices following an expansion of output in a model with sticky prices, which helps to generate real persistence of monetary shocks. The introduction of nominal-wage rigidity in this model makes the simulation outcomes less dependent on this assumption, as wages and the marginal cost become less sensitive to output shocks, at least over the short term.

[6] This specification of the costs is preferable above a specification with costs in terms of a higher depreciation rate (see King and Rebelo, 2000; or Greenwood, Hercowitz, and Huffman, 1988; Dejong, Ingram and Whiteman, 2000) because the costs are expressed in terms of consumption goods and not in terms of capital goods. This formulation limits further the increase in marginal cost of an output expansion (See CEE, 2001).

where I_t is gross investment, τ is the depreciation rate and the adjustment cost function $S(.)$ is a positive function of changes in investment.[7] $S(.)$ equals zero in steady state with a constant investment level. In addition, we assume that the first derivative also equals zero around equilibrium, so that the adjustment costs will only depend on the second-order derivative as in CEE (2001). We also introduce a shock to the relative efficiency of investment goods. Given that our investment data are deflated by the overall price index of GDP, this shock is equivalent to a shock in the relative price of investment versus consumption goods and takes up the investment specific technological shocks. The shock is assumed to follow a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^I = \rho_I \varepsilon_{t-1}^I + \eta_t^I$.[8]

The first-order conditions result in the following equations for the real value of capital, investment and the rate of capital utilisation:

$$Q_t = E_t\left[\beta \frac{\lambda_{t+1}}{\lambda_t}\left(Q_{t+1}(1-\tau) + z_{t+1}r_{t+1}^k - \Psi(z_{t+1})\right)\right], \tag{15}$$

$$Q_t S'(\frac{I_t}{I_{t-1}})\frac{I_t}{I_{t-1}} - \beta E_t Q_{t+1}\frac{\lambda_{t+1}}{\lambda_t} S'(\frac{I_{t+1}}{I_t})(\frac{I_{t+1}}{I_t})\frac{I_{t+1}}{I_t} + 1 = Q_t(1+\varepsilon_t^I), \tag{16}$$

$$r_t^k = \Psi'\left(z_t\right) \tag{17}$$

Equation (15) states that the value of installed capital depends on the expected future value taking into account the depreciation rate and the expected future return as captured by the rental rate times the expected rate of capital utilisation. Equation (16) determines the optimal dynamics of the investment expenditures.

The first order condition for the utilisation rate (17) equates the cost of higher capital utilisation with the rental price of capital services. As the rental rate increases it becomes more profitable to use the capital stock more intensively up to the point were the extra gains match the extra output costs. One implication of variable capital utilisation is that it reduces the impact of changes in output on the rental rate of capital and therefore smoothes the response of marginal cost to fluctuations in output.[9]

2.2. Technologies and firms

The country produces a single final good and a continuum of intermediate goods indexed by *j* where *j* is distributed over the unit interval ($j \in [0,1]$). The final-good sector is perfectly competitive. The final

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[7] See CEE (2001).

[8] See Greenwood, Hercowitz and Krusell (1998) and ACEL (2002) for a similar treatment of the investment productivity shock. We tested also for a separate deterministic trend process in this shock. Although the trend was positive and around 1% on annual basis, it could not be estimated significantly and it did not influence the overall estimation outcomes. Therefore we dropped this deterministic trend for investment specific technological progress in the final model specification.

[9] Another assumption which has the same effect is that capital is perfectly mobile between firms. This is a strong hypothesis. Recently, Woodford (2000) has illustrated how this assumption can be relaxed in a model with sticky prices and adjustment costs in investment. The hypothesis has important consequences for the estimation of the degree of price stickiness. With capital specific to the firm, firms will be more reluctant to change the price of their good as the resulting demand response will have a much stronger impact on the marginal cost of production. The assumption of capital mobility across firms therefore biases the estimated degree of price stickiness upwards.

good is used for consumption and investment by the households. There is monopolistic competition in the markets for intermediate goods: each intermediate good is produced by a single firm.

2.2.1. Final-good sector

The final good is produced using the intermediate goods in the following technology:

$$Y_t = \left[\int_0^1 \left(y_t^j \right)^{1/(1+\lambda_{p,t})} dj \right]^{1+\lambda_{p,t}} \tag{18}$$

where y_t^j denotes the quantity of domestic intermediate good of type j that is used in final goods production, at date t. $\lambda_{p,t}$ is a stochastic parameter which determines the time-varying mark-up in the goods market. Shocks to this parameter will be interpreted as a “cost-push” shock to the inflation equation. We assume that $\lambda_{p,t} = \lambda_p + \eta_t^p$, where η_t^p is a IID-Normal.

The cost minimisation conditions in the final goods sector can be written as:

$$y_t^j = \left(\frac{p_t^j}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t \tag{19}$$

and where p_t^j is the price of the intermediate good j and P_t is the price of the final good. Perfect competition in the final goods market implies that the latter can be written as:

$$P_t = \left[\int_0^1 \left(p_t^j \right)^{-1/\lambda_{p,t}} dj \right]^{-\lambda_{p,t}} \tag{20}$$

2.2.2. Intermediate goods producers

Each intermediate good j is produced by a firm j using the following technology[10]:

$$y_t^j = \varepsilon_t^a (\tilde{K}_{j,t})^{\alpha} (L_{j,t} e^{\gamma * t})^{1-\alpha} - \Phi * e^{\gamma * t}, \tag{21}$$

where ε_t^a is the productivity shock (assumed to follow a first-order autoregressive process: $\varepsilon_t^a = \rho_a \varepsilon_{t-1}^a + \eta_t^a$), $\tilde{K}_{j,t}$ is the effective utilisation of the capital stock given by $\tilde{K}_{j,t} = z_t K_{j,t-1}$, $L_{j,t}$ is an index of different types of labour used by the firm given by (10), Φ is a fixed cost and γ is the constant rate of technological progress.

Cost minimisation implies:

$$\frac{W_t L_{j,t}}{r_t^k \tilde{K}_{j,t}} = \frac{1-\alpha}{\alpha} \tag{22}$$

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[10] See Kim (2001) and Rotemberg and Woodford (1995) for a very similar specification of the production function. See also King and Watson (199?) for a discussion of fixed costs in the production function. Kim (2001) also considers an additive productivity shock affecting the fixed costs in the production function.

Equation (22) implies that the capital-labour ratio will be identical across intermediate goods producers and equal to the aggregate capital-labour ratio. The firms' marginal costs are given by:

$$(23) \qquad MC_t = \frac{W_t^{1-\alpha} r_t^{k\alpha} \left(\alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}\right)}{\varepsilon_t^a * e^{\gamma * t *(1-\alpha)}}$$

This implies that the marginal cost, too, is independent of the intermediate good produced.

Nominal profits of firm j are then given by:

$$(24) \qquad \pi_t^j = (p_t^j - MC_t)\left(\frac{p_t^j}{P_t}\right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} (Y_t) - MC_t \Phi$$

Each firm j has market power in the market for its own good and maximises expected profits using a discount rate $(\beta\rho_t)$ which is consistent with the pricing kernel for nominal returns used by the shareholders-households: $\rho_{t+k} = \frac{\lambda_{t+k}}{\lambda_t}\frac{1}{P_{t+k}}$.

As in Calvo (1983), firms are not allowed to change their prices unless they receive a random "price-change signal". The probability that a given price can be re-optimised in any particular period is constant and equal to $1-\xi_p$. Following CEE (2001), prices of firms that do not receive a price signal are indexed to the weighted sum of last period's inflation rate and the inflation objective of monetary policy.[11] Profit optimisation by producers that are "allowed" to re-optimise their prices at time t results in the following first-order condition:

$$(25) \qquad E_t \sum_{i=0}^{\infty} \beta^i {\xi_p}^i \lambda_{t+i} y_{t+i}^j \left(\frac{\tilde{p}_t^j}{P_t} \left(\frac{P_t}{P_{t+i}}\right) \left(\frac{P_{t-1+i}}{P_{t-1}}\right)^{\gamma_p} (\bar{\pi}_t)^{1-\gamma_p} - (1+\lambda_{p,t+i}) mc_{t+i} \right) = 0$$

Equation (25) shows that the price set by firm j, at time t, is a function of expected future marginal costs. The price will be a mark-up over these weighted marginal costs. If prices are perfectly flexible ($\xi_p = 0$), the mark-up in period *t* is equal to $1+\lambda_{p,t}$. With sticky prices the mark-up becomes variable over time when the economy is hit by exogenous shocks. A positive demand shock lowers the mark-up and stimulates employment, investment and real output.

The definition of the price index in equation (20) implies that its law of motion is given by:

$$(26) \qquad (P_t)^{-1/\lambda_{p,t}} = \xi_p \left(P_{t-1} \left(\frac{P_{t-1}}{P_{t-2}}\right)^{\gamma_p} (\bar{\pi}_t)^{1-\gamma_p} \right)^{-1/\lambda_{p,t}} + (1-\xi_p)\left(\tilde{p}_t^j\right)^{-1/\lambda_{p,t}} .$$

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[11] Erceg, Henderson and Levin (2000) use indexation to the average steady state inflation rate. Allowing for indexation of the non-optimised prices on lagged inflation, results in a linearised equation for inflation that is an average of expected future inflation and lagged inflation. This result differs from the standard Calvo model that results in a pure forward looking inflation process. The more general inflation process derived here results, however, from optimising behaviour and this makes the model more robust for policy and welfare analysis. Another consequence of this indexation is that the price dispersion between individual prices of the monopolistic competitors will be much smaller compared to a constant price setting behaviour. This will also have important consequences for the welfare evaluation of inflation costs.

2.3. Market equilibrium

The final goods market is in equilibrium if production equals demand by households for consumption and investment and the government:

$$Y_t = C_t + G_t + I_t + \psi(z_t)K_{t-1} \tag{27}$$

The capital rental market is in equilibrium when the demand for capital by the intermediate goods producers equals the supply by the households. The labour market is in equilibrium if firms' demand for labour equals labour supply at the wage level set by households.

The interest rate is determined by a reaction function that describes monetary policy decisions (See the main text). In the capital market, equilibrium means that the government debt is held by domestic investors at the market interest rate, R_t.

3. The linearised DSGE model

In this Section, we describe the log-linearised DSGE model that we subsequently estimate using US data.

The dynamics of aggregate *consumption* is given by:

$$\begin{aligned}\hat{C}_t &= \frac{h}{1+h}\hat{C}_{t-1} + \frac{1}{1+h}E_t\hat{C}_{t+1} + \frac{(\sigma_c - 1)}{\sigma_c(1+\lambda_w)(1+h)}(\hat{l}_t - \hat{l}_{t+1}) \\ &\quad - \frac{1-h}{(1+h)\sigma_c}(\hat{R}_t - E_t\hat{\pi}_{t+1}) + \frac{1-h}{(1+h)\sigma_c}(\hat{\varepsilon}_t^b - E_t\hat{\varepsilon}_{t+1}^b)\end{aligned} \tag{28}$$

Consumption depends on the ex-ante real interest rate and, with external habit formation, on a weighted average of past and expected future consumption. When $h = 0$, only the traditional forward-looking term is maintained. In addition, due to the non-separability of the utility function (see the Appendix), consumption will also depend positively on expected employment growth when $\sigma_c > 1$, indicating a complementarity between consumption and labour supply. During the estimation procedure, the expression containing the effect of the preference shock is simplified to reduce the non-linearity so that the error term is rescaled with $\frac{(1-h)(1-\rho_b)}{(1+h)\sigma_c}$.

The *investment equation* is given by:

$$\hat{I}_t = \frac{1}{1+\beta}\hat{I}_{t-1} + \frac{\beta}{1+\beta}E_t\hat{I}_{t+1} + \frac{1/\varphi}{1+\beta}(\hat{Q}_t + \hat{\varepsilon}_t^I) \tag{29}$$

where $\varphi = \overline{S}''$. As discussed in CEE (2001), modelling the capital adjustment costs as a function of the change in investment rather than its level introduces additional dynamics in the investment equation, which is useful in capturing the hump-shaped response of investment to various shocks including monetary policy shocks. A positive shock to the investment-specific technology, $\hat{\varepsilon}_t^I$, increases investment in the same way as an increase in the value of the existing capital stock $\hat{Q}_t$.

The corresponding *Q equation* is given by:

$$(30) \qquad \hat{Q}_t = -(\hat{R}_t - \hat{\pi}_{t+1}) + \frac{1-\tau}{1-\tau+\bar{r}^k} E_t\, \hat{Q}_{t+1} + \frac{\bar{r}^k}{1-\tau+\bar{r}^k} E_t\, \hat{r}^k_{t+1} + \eta^Q_t$$

where $\beta = 1/(1-\tau+\bar{r}_k)$. The current value of the capital stock depends negatively on the ex-ante real interest rate, and positively on its expected future value and the expected rental rate. The introduction of a shock to the required rate of return on equity investment, η_t^Q, is meant as a shortcut to capture changes in the cost of capital that may be due to stochastic variations in the external finance premium.[12] We assume that this equity premium shock follows an IID-Normal process. In a fully-fledged model, the production of capital goods and the associated investment process could be modelled in a separate sector. In such a case, imperfect information between the capital producing borrowers and the financial intermediaries could give rise to a stochastic external finance premium. For example, in Bernanke, Gertler and Gilchrist (1998), the deviation from the perfect capital market assumptions generates deviations between the return on financial assets and equity that are related to the net worth position of the firms in their model. Here, we implicitly assume that the deviation between the two returns can be captured by a stochastic shock, whereas the steady-state distortion due to such informational frictions is zero.[13] During the estimation, both η_t^I and η_t^Q are scaled with $\frac{1/\varphi}{1+\beta}$.

The *capital accumulation equation* becomes a function not only of the flow of investment but also of the relative efficiency of these investment expenditures as captured by the investment-specific technology shock:

$$(31) \qquad \hat{K}_t = (1-\tau)\hat{K}_{t-1} + \tau\hat{I}_{t-1} + \tau\,\varepsilon^I_{t-1}$$

With partial indexation to lagged inflation, the *inflation equation* becomes a more general specification of the standard new-Keynesian Phillips curve:

$$(32) \qquad \begin{aligned} \hat{\pi}_t - \bar{\pi}_t = {} & \frac{\beta}{1+\beta\gamma_p}(E_t\hat{\pi}_{t+1} - \bar{\pi}_t) + \frac{\gamma_p}{1+\beta\gamma_p}(\hat{\pi}_{t-1} - \bar{\pi}_t) + \\ & \frac{1}{1+\beta\gamma_p}\frac{(1-\beta\xi_p)(1-\xi_p)}{\xi_p}\left[\alpha\hat{r}^k_t + (1-\alpha)\hat{w}_t - \hat{\varepsilon}^a_t - (1-\alpha)\gamma t\right] + \eta^p_t \end{aligned}$$

The deviation of inflation from the target inflation rate depends on past and expected future inflation deviations and on the current marginal cost, which itself is a function of the rental rate on capital, the real wage and the productivity parameter and on the price mark-up shock. When $\gamma_p = 0$, this equation reverts to the standard purely forward-looking Phillips curve. By assuming that all prices are still indexed to the inflation objective in that case, the Phillips curve will be vertical. Announcements of changes in the inflation objective will be completely neutral even in the short run. This is based on the strong assumption that prices will immediately adjust to the new inflation objective. With $\gamma_p > 0$, the degree of indexation to lagged inflation determines how backward looking the inflation process is or, in other words, how

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[12] This is the only shock that is not directly related to the structure of the economy.

[13] For alternative interpretations of this equity premium shock and an analysis of optimal monetary policy in the presence of such shocks, see Dupor (2001).

much exogenous persistence there is in the inflation process. The elasticity of inflation with respect to changes in the marginal cost depends mainly on the degree of price stickiness. When all prices are flexible ($\xi_p = 0$) and the price-mark-up shock is zero, this equation reduces to the normal condition that in a flexible price economy the real marginal cost should equal one.

Similarly, the indexation of nominal wages results in the following real wage equation:

$$
\begin{aligned}
\hat{w}_t = {} & \frac{\beta}{1+\beta} E_t \hat{w}_{t+1} + \frac{1}{1+\beta} \hat{w}_{t-1} + \frac{\beta}{1+\beta} (E_t \hat{\pi}_{t+1} - \overline{\pi}_t) - \frac{1+\beta\gamma_w}{1+\beta} (\hat{\pi}_t - \overline{\pi}_t) + \frac{\gamma_w}{1+\beta} (\hat{\pi}_{t-1} - \overline{\pi}_t) \\
& - \frac{1}{1+\beta} \frac{(1-\beta\xi_w)(1-\xi_w)}{(1+\frac{(1+\lambda_w)\sigma_L}{\lambda_w})\xi_w} \left[\hat{w}_t - \sigma_L \hat{L}_t - \frac{\sigma_c}{1-h} (\hat{C}_t - h\hat{C}_{t-1}) + \hat{\varepsilon}_t^L \right] + \eta_t^w
\end{aligned}
\tag{33}
$$

The real wage is a function of expected and past real wages and the expected, current and past inflation rate where the relative weight depends on the degree of indexation to lagged inflation of the non-optimised wages. When $\gamma_w = 0$, real wages do not depend on the lagged inflation rate. There is a negative effect of the deviation of the actual real wage from the wage that would prevail in a flexible labour market. The size of this effect will be greater, the smaller the degree of wage rigidity, the lower the demand elasticity for labour and the lower the inverse elasticity of labour supply (the flatter the labour supply curve).

The equalisation of marginal cost implies that, for a given installed capital stock, *labour demand* depends negatively on the real wage (with a unit elasticity) and positively on the rental rate of capital:

$$
\hat{L}_t = -\hat{w}_t + (1+\psi)\hat{r}_t^k + \hat{K}_{t-1}
\tag{34}
$$

where $\psi = \frac{\psi'(1)}{\psi''(1)}$ is the inverse of the elasticity of the capital utilisation cost function.

The *goods market equilibrium condition* can be written as:

$$
\begin{aligned}
\hat{Y}_t &= (1 - \tau k_y - g_y)\hat{C}_t + \tau k_y \hat{I}_t + g_y \gamma t + \varepsilon_t^G \\
&= \phi \hat{\varepsilon}_t^a + \phi\alpha \hat{K}_{t-1} + \phi\alpha\psi\hat{r}_t^k + \phi(1-\alpha)(\hat{L}_t + \gamma t) - (\phi - 1)\gamma t
\end{aligned}
\tag{35}
$$

where k_y is the steady state capital-output ratio, g_y the steady-state government spending-output ratio and ϕ is one plus the share of the fixed cost in production. We assume that the government spending shock follows a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^G = \rho_G \varepsilon_{t-1}^G + \eta_t^G$. Empirically, this shock will not only capture changes in government spending, but also net trade and inventories.

Finally, the model is closed by adding the following empirical monetary policy reaction function:

$$
\begin{aligned}
\hat{R}_t = {} & \overline{\pi}_{t-1} + \rho(\hat{R}_{t-1} - \overline{\pi}_{t-1}) + (1-\rho)\{r_\pi (\hat{\pi}_{t-1} - \overline{\pi}_{t-1}) + r_Y (\hat{Y}_{t-1} - \hat{Y}_{t-1}^p)\} + \\
& r_{\Delta\pi} \left[(\hat{\pi}_t - \overline{\pi}_t) - (\hat{\pi}_{t-1} - \overline{\pi}_{t-1}) \right] + r_{\Delta y} \left[(\hat{Y}_t - \hat{Y}_t^p) - (\hat{Y}_{t-1} - \hat{Y}_{t-1}^p) \right] + \eta_t^R
\end{aligned}
\tag{36}
$$

The monetary authorities follow a generalised Taylor rule by gradually responding to deviations of lagged inflation from an inflation objective and the lagged output gap defined as the difference between actual and potential output (Taylor, 1993). Consistently with the NNS model, potential output is defined as the level of output that would prevail under flexible price and wages in the absence of the three "cost-push" shocks.[14] The parameter ρ captures the degree of interest rate smoothing. In addition, there is also a short-run feedback from the current changes in inflation and the output gap. Finally, we assume that there are two monetary policy shocks: one is a temporary IID-Normal interest rate shock (η_t^R) also denoted a monetary policy shock; the other is a permanent shock to the inflation objective ($\bar{\pi}_t$) which is assumed to follow a random walk process ($\bar{\pi}_t = \bar{\pi}_{t-1} + \eta_t^{\pi}$). In the empirical exercise, we assume that this policy rule together with the process for the stochastic shocks is able to describe the behaviour of monetary authorities over the sample period. While the hypothesis of a stable monetary policy rule over the full sample period is frequently rejected in the literature (e.g. Clarida, Gali and Gertler, 1999), allowing for shifts in the monetary policy objective should alleviate the potential problem of instability. Changes in the inflation objective may also take up the impact of persistent mis-measurement of the output gap. Indeed, using real time data, Orphanides (200?) shows that the reaction function of the Fed over the sample period was relatively stable and close to a Taylor rule. Following Sims (1999), in Section 4.3, we investigate the sensitivity of the estimation results to a shift in the variance of the interest rate shocks in the early Volcker period.

Equations (28) to (36) together with their flexible price counterparts determine the nine endogenous sticky-price variables: $\hat{\pi}_t$, $\hat{w}_t$, $\hat{K}_{t-1}$, $\hat{Q}_t$, $\hat{I}_t$, $\hat{C}_t$, $\hat{R}_t$, $\hat{r}_t^k$, $\hat{L}_t$ and their flexible-price counterparts. The stochastic behaviour of the system of linear rational expectations equations is driven by ten exogenous shock variables: five shocks arising from technology and preferences ($\varepsilon_t^a, \varepsilon_t^I, \varepsilon_t^b, \varepsilon_t^L, \varepsilon_t^G$) which are assumed to follow an AR(1) process, three "cost-push" shocks (η_t^w, η_t^p and η_t^Q) which are assumed to follow a white-noise process and two monetary policy shocks ($\bar{\pi}_t$ and η_t^R).

4. Parameter estimates

In this Section we present the results of estimating the model presented in the previous section with Bayesian estimation techniques using seven key macro-economic time series (real GDP, consumption, investment, hours worked, real wages, prices and a short-term interest rate) as observable variables. First, we estimate the mode of the posterior distribution by maximising the log posterior function, which combines the prior information on the parameters with the likelihood of the data. In a second step, the

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[14] In practical terms, we expand the model consisting of equations (2) to (9) with a flexible-price-and-wage version in order to calculate the model-consistent output gap.

Metropolis-Hastings algorithm is used to get a complete picture of the posterior distribution and to evaluate the marginal likelihood of the model[15].

4.1 Prior distribution of the parameters

The priors on the stochastic processes are harmonised as much as possible. The standard errors of the innovations are assumed to follow an inverse-gamma distribution with a mean of 0.25 (0.05 for the permanent inflation objective shock) and two degrees of freedom, which corresponds with a rather loose prior. The persistence of the AR(1) processes is beta distributed with mean 0.85 and standard deviation 0.1. The three mark-up shocks to prices, wages and equity prices are assumed to be IID white noise processes. The deterministic growth rate in technology is assumed to be Normal distributed with mean 0.4 (quarterly growth rate) and standard deviation 0.1.

Five parameters are restricted before the estimation procedure. The discount rate is set at 0.99; the depreciation rate is set at 0.025 (both on a quarterly basis), the share of consumption and investment are set at 0.65 and 0.17 respectively and the capital income share in the Cobb Douglas production function is set at 0.24. These parameters are difficult to estimate unless the absolute values of the time series are taken into account in the estimation process through the definition of the steady state.

The parameters describing the monetary policy rule are based on a standard Taylor rule: the long run reaction on inflation and the output gap are described by a Normal distribution with mean 1.5 and 0.125 (0.5 divided by 4) and standard errors 0.1 and 0.05 respectively. The persistence of the policy rule is determined by the coefficient on the lagged rate which is Normal around 0.75 with a standard error of 0.1. The prior on the short run reaction coefficients to inflation and output-gap changes reflect the assumptions of a gradual adjustment towards the long run.

The parameters of the utility function are assumed to be distributed as follows. The intertemporal elasticity of substitution is set at 1 with a standard error of 0.375; the habit parameter is assumed to fluctuate around 0.7 with a standard error of 0.1 and the elasticity of labour supply is assumed to be around 2 with a standard error of 0.75. The prior on the adjustment cost parameter for investment is set around 4 with a standard error of 2 (based on CEE, 2001) and the capacity utilisation elasticity is set at 0.2 with a standard error of 0.1, which includes the 0.1 of King and Rebelo (2000). The share of fixed costs in the production function is assumed to be distributed around 0.25. Finally there are the parameters

---

[15] See Smets and Wouters (2003a) for a more elaborate description of the methodology. A sample of 250.000 draws was created (neglecting the first 10.000 draws). The Hessian resulting from the optimisation procedure was used for defining the transition probability function that generates the new proposed draw. A step size of 0.3 resulted in a rejection rate of 0.65. The resulting sample properties are not sensitive to the step size. Two methods were used to test the stability of the sample. The difference between the means of the two sub-samples (100.000 first and 100.000 last drawings) should be distributed Normally with a standard error proportional to the square of the summed sub-sample variances divided by the sample size, if the draws are i.i.d. distributed. However the drawings of the MH algorithm are highly correlated. By selecting only each n drawing from the overall sample, the i.i.d. distribution is approximated. For bigger step sizes, the hypothesis of equality in mean of the two sub-samples can no longer be rejected for most of the parameters. The second method to evaluate the stability is a graphical test based on the cumulative mean minus the overall mean (see Bauwens et al). Starting from a minimal cumulative mean of 25.000 drawings, this ratio remains within a 10% band for all the parameters. In sum, an exact statistical test for the stability of the sample is complicated by the highly autocorrelated nature of the MH-sampler. However from an economic point of view the differences between subsamples and independent samples of size 100.000 or more is negligible.

describing the price and wage setting. The Calvo probabilities are assumed to be around 0.75 for both prices and wages, suggesting an average length of price and wage contracts of one year. The degree of indexation to past inflation is set at 0.5

In Section 4.3. we analyse the sensitivity of the estimation results to the prior assumptions by increasing the standard errors of the prior distributions of the behavioural parameters.

4.2 Posterior estimates of the parameters

Table 1 gives the parameters estimated by maximising the posterior distribution (the mode of the posterior) and five percentiles of the posterior distribution obtained by the Metropolis-Hastings algorithm. A direct comparison of the full posterior and prior distributions of the parameters and their estimated mode can be found in Graphs 1 to 3.

A number of observations are worth making regarding the estimated processes for the exogenous shock variables (Graph 1). Shocks to the non-stationary inflation objective have a relatively high standard error of 0.075%. This corresponds to a change in the inflation objective of 0.3% on a yearly basis. Graph 4 shows that the estimated inflation objective increases from relatively low levels in the early 1960s to reach its maximum at the beginning the 1980s, after which it falls back to its long-run average.

The productivity, the labour supply and the government spending processes are estimated to be very persistent. The persistence of each of those shocks converges towards the upper limit of 1 implied by the beta distribution (0.99). The standard error of the shock to the productivity process is 0.48. The trend growth rate is estimated to be around 0.32. This is considerably smaller than the average growth rate of output per capita, which is around 1.6% on a yearly basis. As can be seen in Graph 4, the remaining part of the growth process is captured by a positive trend in the stochastic productivity process in the first half of the sample. The high persistence of the productivity and labour supply shocks implies that at long horizons most of the forecast error variance of the real variables will be explained by those two supply shocks. The shocks to the three 'demand' processes all have a relatively high standard error, but the consumption preference and the investment shock have a relatively low persistence.

Also the standard error of the interest rate shock is relatively high. However, as is clear from Graph 4 this estimate is strongly influenced by the high variability at the beginning of the 1980s. This instability in the standard error of the interest rate shocks is also identified by Sims (1999) as the main reason for instability in small US-models.

Graph 2 presents the posterior distributions for the main behavioural parameters. Overal, the posterior distributions are relatively close to the prior assumptions, with the notable exception of the Calvo parameter for price setting, which implies a very high stickiness in price adjustment. These estimates confirm the single-equation estimates by Gali and Gertler (1999). The degree of indexation is relatively low, in particular, for wages. The posterior estimates of the fixed cost parameter is very high (1.5).

Finally, Graph 3 presents the posterior distributions of the reaction function parameters. The mode of the long-run reaction coefficient on inflation is relatively high (1.48), while the short-run response is relatively small. There is a considerable degree of interest rate smoothing as the mode of the coefficient on the lagged interest rate is estimated to be 0.87. Policy does not appear to react very strongly to the output gap level, but does respond strongly to changes in the output-gap. Overall, these results are close to those obtained by Orphanides and Wieland (1998) over a shorter sample (1980-1996).

4.3 Alternative model and data hypothesis

To test the sensitivity of the parameter estimates to the specific prior assumptions and a few other modelling assumptions, some alternative estimates are summarised in Table 2.

First, the model was re-estimated using a less informative prior for the behavioural parameters of the model. More precisely, the standard errors of the prior distributions were increased by 50% (a larger standard error provides problems for the implied shape of the beta distributions). Overall, the second column of Table 2 shows that the estimated parameters are very similar. There are, however, a number of changes, which may indicate that in some cases the assumptions on the prior distribution may be binding. For instance, the elasticity of substitution increases further away from one, reducing the interest rate sensitivity of consumption. As a result, the standard error of the consumption preference shocks increases, while its persistence falls. Similarly, the fixed cost parameter increases to 1.7 which seems implausibly high. Finally, the estimated degree of price stickiness also increases. These results point out the usefulness of the prior restriction on the parameter outcomes. The marginal likelihood of the model will indicate whether these restrictions are indeed acceptable for the overall performance of the model.

The second alternative model estimate is based on the same data set that is detrended using a quadratic time trend for each series individually preliminary to the model estimation. Preliminary detrending of the data reduces the estimated persistence of the driving processes. However, the outcomes for the behavioural parameters remain very robust. It is worth noting that although the estimated price stickiness turns out to be somewhat lower, it remains relatively high. Nevertheless, the restriction on the joint long run movements in the data by estimating one common deterministic growth rate imposes clearly some restrictions on the marginal cost variable and its relation to the inflation process.

Finally, the last two columns of Table 2 present two alternative specifications that are related to the transmission of monetary shocks. First, we apply a different timing assumption on the effectiveness of monetary policy shocks. As in Rotemberg and Woodford (1997) and CEE 2001, we assume that interest rates are set at the end of the period so that monetary policy shocks only affect next period decisions of private agents. This timing assumption on monetary shocks improves slightly the overall performance of the model. The impact on some of the behavioural parameters is as expected: the interest rate sensitivity of investment and consumption increases (lower capital adjustment cost and lower habit) and the nominal decisions (at least for wages) are slightly less backward looking. The last column in Table 2 allows for a temporal regime shift in the variance of the interest rate shocks during the first years of Volcker's chairmanship (1979:3 -1984:4). Not suprisingly, the standard error of the interest rate shocks is estimated to be much lower after correcting for this regime shift (see Sims (1999) and Sims and Zha (2001)). This specification also very much improves the marginal likelihood of the model. The other parameters of the monetary policy reaction function remain, however, very stable.

Overall these exercises illustrate that the estimated parameters are relatively robust to minor re-specifications of the model or prior assumptions. In section 6, we will discuss more in detail the sensitivity of the outcomes to alternative assumptions regarding the shocks and frictions in the model.

5. Model statistics: comparison with VAR models

The marginal likelihood of the estimated NNS model, which can be interpreted as a summary statistic for its out-of-sample prediction performance, forms a natural benchmark for comparing it with alternative specifications and other statistical models. The marginal likelihood can also be translated in posterior odds for the alternative models. As discussed in Geweke (1997), the Metropolis-Hastings-based sample of the posterior distribution can be used to evaluate the marginal likelihood of the model. Following Geweke (1997), we calculate the modified harmonic mean to evaluate the integral over the posterior sample. An alternative approximation is the Laplace approximation around the posterior mode, which is based on a normal distribution. As shown in Table 4, the results of both approximations are very close in the case of our estimated DSGE model. This is not too surprising given the close correspondence between the histograms of the posterior sample and the normal distribution around the estimated mode for the individual parameters shown in Graphs 1 to 3. Given the large advantage of the Laplace approximation in terms of computational costs, we will use this approximation for comparing alternative model specifications in the next section.

Following Schorfheide (2002) and Rabanal and Rubio-Ramirez (2001), we compare the marginal likelihood of our model with that of unconstrained VAR and BVAR models. Starting with standard VAR models, it is clear from Table 4 that a VAR model of order two has the highest marginal likelihood and is thus preferred over both a VAR model of order one or three. However, it is also clear that its marginal likelihood remains far below the one of the estimated DSGE model. The efficiency gains from reducing the number of parameters to 32 (including the description of the covariance structure) are overwhelming.

The weak prediction performance of unconstrained VAR models is well know since the introduction of BVAR models in Doan, Litterman and Sims (1984). A comparison of the marginal likelihood of the DSGE model with that of BVAR models is therefore more informative. For that we use two types of BVAR models. The first one is based on the traditional Minnesota prior (as, for example, also applied in Chang, Gomes and Schorfheide, 2002). Table 4 shows that the BVAR with a Minnesota prior of order 3 performs best in terms of the marginal likelihood (higher orders were not considered due to the computational cost of the Gibbs sampler and the quadratic increasing tightness in lag structure). We also estimated a BVAR using the VAR coefficients estimated on simulated data from our estimated DSGE model as priors (Del negro and Schorfheide, 2002). This more complicated prior on the VAR coefficients further reduces slightly the marginal likelihood. However, in all cases the DSGE model clearly remains the dominant model with a posterior odds ratio equal to one.[16]

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[16] Of course, we could further improve the marginal likelihood of the BVAR models by, for example, optimising in terms of tightness of the variance structure

The superior prediction performance of the DSGE model compared to the VAR and BVAR models is further illustrated by the results of a traditional out-of-sample exercise. Each of the three models were estimated over the sample period from 1957:2 to 1989:4. The estimated models were then used to predict the seven data series from 1990:1 to 2002:2, whereby the VAR and BVAR models were re-estimated every quarter, whereas the DSGE model was re-estimated every year. Table 5 presents the logarithm of the determinant of the covariance matrix as a summary statistic of the prediction performance. In Table 6 the prediction performance with respect to each of the individual variables is given. It is clear from Table 5 that the DSGE model dominates the VAR and BVAR models at all forecasting horizons. However, the most striking gains are obtained at longer horizons.[17]

Table 6 shows that the relative gain in forecast precision is obtained mainly for output, even at the one-period horizon, and for interest rates, wages and hours for the longer horizons. The DSGE model does not perform very well in forecasting consumption, possibly pointing to some specification problems in the consumption process.

6. Model sensitivity: testing the contribution of frictions and shocks

The introduction of a large number of shocks and frictions raises the question which of those are really necessary to capture the dynamics of the data. In this Section we examine the contribution of each of the shocks and frictions to the marginal likelihood of the DSGE model.

6.1 Empirical importance of the various frictions

Table 6 presents the estimates of the mode of the parameters and the marginal likelihood when each of frictions (price and wage stickiness, price and wage indexation, investment adjustment costs and habit formation, capital utilisation and fixed costs in production) are drastically reduced one at a time. This table also gives an idea of the robustness of the parameters and the model performance with respect to the various frictions included in the model. For comparison, the first column reproduces the baseline estimates (mode of the posterior) and the marginal likelihood based on the Laplace approximation..

The second column of Table 7 gives the parameter estimates and marginal likelihood for the model with a fixed value of the degree of calvo price stickiness of 0.42. This value corresponds with the benchmark estimate in Altig, Christiano, Eichenbaum and Linde (ACEL, 2002). A Calvo parameter of 0.42 implies that the average length of contracts is only 2 to 3 quarters. As a result of this restriction, the estimated parameter for price indexation (driving the degree of inflation persistence) increases strongly. At the same time, the estimated standard error of the price mark-up shock is multiplied by almost ten. It is clear from the dramatic fall in marginal likelihood that the data do not like this specification with more flexible prices very much (see last rows of Table 7). In fact, comparing across columns it turns out that, from an empirical viewpoint, the sticky price friction is the most important friction included in the model.

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[17] The superior performance of New-Keynesian DSGE models for longer horizon forecasts is also found in Lubik and Schorfheide (2003).

The cost of reducing the degree of wage stickiness to 0.42 is much less (see the third column of Table 7). The main impact of this restriction on the other parameters concerns the elasticity of wages with respect labour effort: the marginal disutility of working becomes much smaller. In terms of short run dynamics, these changes more or less cancel out, leaving the impact of labour effort on wage dynamics unaffected.

While both Calvo frictions are empirically quite important, neither price nor wage indexation do play a very important role in the model dynamics. Restricting those indexation parameters to a low value of 0.1 does not have any noticeable impact on the other parameters. Moreover, reducing wage indexation increases the marginal likelihood of the model suggesting that empirically it would be better to leave this friction out.

Turning to the real frictions, the most important in terms of the marginal likelihood are the investment adjustment costs. Also reducing habit formation in consumption is quite costly. The reduced hump-shaped endogenous dynamics of the model due to these restrictions is compensated mainly by higher and more persistent exogenous shocks to investment and consumption decisions, but the overall performance of the model deteriorates.

Somewhat surprisingly, increasing the cost of variable capital utilisation has a relatively small impact on the overall marginal likelihood. It does influence the estimated shock parameters somewhat and also further increases the size of the fixed costs in production. Contrary to the discussion in King and Rebelo, the absence of variable capital utilisation does not increase the standard error of the productivity shock in our model. In contrast, reducing the fixed costs in production does mechanically increase the size of the productivity shock, also the estimated constant trend growth in productivity is higher in that case.

Overall, the results from this sensitivity exercise illustrate that the estimated parameters appear relatively robust to changes in the frictions one by one. Price and wage indexation and variable capital utilisation are of relatively minor importance in terms of the overall empirical performance of the model. In contrast to the findings of CEE (2001) and ACEL (2002), price stickiness is of crucial importance. The other frictions also make an important contribution to the overall dynamic correlations.

6.2 Empirical importance of the various shocks

A similar exercise can also be performed with respect to the various shocks in the model. Table 8 summarises the estimation results when one of the shocks is left out.

As far as the three (i.i.d.) cost-push shocks are concerned, it is clear from columns 2, 3 and 4 of Table 8 that both price and wage mark-up shocks are empirically quite important. The equity-premium shock, on the other hand, is of minor importance and could easily be deleted. The latter result is partly due to the fact that we have not included an equity price index in the estimation of the model. As a result the role of the equity-premium shock can easily be taken up by a higher variance and lower persistence of the investment specific technology shocks.

As expected, not allowing for a time-varying inflation objective (column 5 of Table 8), substantially increases the estimated persistence in the Phillips curve as captured by the price indexation parameter. The cost of this restriction in terms of the model’s marginal likelihood is, however, relatively modest.

In contrast, dropping the persistent shocks to the discount factor, investment specific technology and labour supply all do have an important cost in terms of marginal likelihood. Moreover, dropping each of these shocks has an impact on the related structural parameters. For instance, not allowing for a preference shock increases the intertemporal substitution parameter, the degree of habit formation and the degree of nominal wage stickiness. Dropping the labour supply shock increases the degree of nominal wage stickiness, but also affects the persistence of the preference shock. Finally, dropping the investment specific techology shock, not surprisingly, leads to a strong increase in the variance of the equity premium shock. The impact on the other parameters is, however, relatively limited.[18]

7. Alternative model validation methods

The marginal likelihood of a model offers a simple way to evaluate and compare models. However, economic models can also be evaluated on alternative statistical and economic criteria. In this section, we first compare the dynamic cross-covariances between the main macro-economic variables implied by the model with those implied by the data. Then, we will evaluate the model from an economic point of view by looking at the impulse-responses of the different shocks, the variance decomposition, and the implied historical decomposition of the time series.

7.1 Model-based versus data-based cross-covariances

Graph 5 plots the implied cross-covariances of the estimated model plus the 5% and 95% bounds and the same statistics in the data. The cross-covariances are calculated based on an estimated VAR(3) model. The model-based cross-covariances are calculated from a VAR estimated on simulated data from a sample of parameter values from the model's posterior distribution. For each draw from the parameter distribution, 200 data sets are simulated of equal length as the historically observed data series (the VAR is estimated over the period 1957:2-2002:2). The possible non-stationary trend in the data is removed by using the filter proposed by Rotemberg (2002).[19]

Graph 5 shows that most of the historical cross-covariances are within the bounds generated from the model's posterior distribution. Note, however, that the bounds generated for the interest rate and inflation are extremely large possibly because of the non-stationary specification of the monetary policy objective. This may suggest that the random walk hypothesis for the inflation objective is not a very realistic specification.

The model is estimated under the assumption that the ten identified structural shocks are independently distributed. In many structural models this assumption is responsable for important failures in the cross-correlation structure of the variables. Although this assumption is certainly a strong hypothesis, in our setup with an large number of shocks, it does not seem to create significant problems for the estimated model.

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[18] We could not drop the public spending shock because it creates a singularity problem. In addition, no meaningful results were obtained after dropping the productivity shock.

[19] In a few cases the resulting VAR remained non-stationary. Those outcomes were disregarded in the calculation of the cross-covariances

7.2 Estimated impulse responses of the structural shocks

In order to check whether the estimated effects of the various identified structural shocks are economically “reasonable” compared with alternative estimates that can be found in the literature, Graphs 6 to 13 present the estimated impulse responses of the ten structural shocks on the main endogenous variables of our DSGE model. Each graph depicts the 5 and 95 percent confidence bounds. For the five 'fundamental' supply and demand shocks that are assumed to affect the central bank’s target level of output or potential output, both the sticky (upper panel) and the flexible (lower panel) price and wage outcomes are presented. The difference between the sticky and flexible price response of output can thus be interpreted as the response of the output gap that enters the Fed’s reaction function.

Recently the effects of productivity shocks have been hotly debated. Graph 6 presents the estimated effects of such a shock in our model. As expected, a positive productivity shock leads to an expansion of aggregate demand, output and real wages. However, due to habit persistence and investment adjustment costs aggregate demand increases only gradually with the increased productivity level. Moreover, nominal wage stickiness precludes wages from immediately adjusting to the higher labour productivity level as is clear from a comparison with the flexible price-wage outcome (lower panel of Graph 6). As a result, there is an important drop in the real marginal production cost and downward pressure on inflation. Monetary policy responds by reducing nominal and real interest rates, also because output remains clearly below the 'natural output' level as defined by the corresponding flexible price outcome. The resulting drop in real interest rates is, however, much less than the corresponding drop of the equilibrium real interest rate in the flexible price economy.

One of the most striking responses following the productivity shock is, however, the important and very significant drop in hours worked. This finding is in line with the results presented by Gali (1999) and Francis and Ramey (2002) which use various identified VAR models to estimate the impulse responses of a productivity shock in the US economy. ACEL (2002) have questioned these empirical results both from a theoretical and empirical point of view. Empirically, the impact of a productivity shock in the VAR models, identified as the only shock that affects the long run productivity shock, appears to depend on the setup of the VAR: a VAR with the hours variable in levels is more likely to produce a positive impact of a productivity shock on hours worked than the VARs with hours worked in first differences as in Gali (1999) and Francis and Ramey (2002). Theoretically, ACEL (2002) show how the impact of a productivity shock on hours worked depends on the degree of price stickiness, the sluggishness in the demand response and the degree of central bank accommodation. Our estimation results, show that it is mainly the estimated degree of habit persistence and the importance of capital adjustment costs that explain the negative impact of productivity on hours worked. This is clearly illustrated in the lower panel of Graph 6, which depicts the flexible price outcome. Our results therefore seem to confirm the analysis of Francis and Ramey (2002). Given these estimates, it is unlikely that a more accommodative monetary policy would lead to positive employment effects. As discussed by Gali (1999), given the high unconditional correlation between output and employment, this finding has implications for whether productivity shocks can explain most of the business cycle variations in output.

Two other remarks are important to understand possible discrepancies between some of the VAR based evidence on productivity shocks and our results in the framework of an estimated DSGE model. First, in the context of DSGE models it is standard to specify the productivity shock as an AR(1) process. This implies however an ad hoc and rather unrealistic restriction on the dynamics of the productivity shock process[20]. ACEL (2002) specify a higher order AR process in order to reproduce the short run dynamics of the VAR impulse response of the productivity shock. Second, the productivity shock identified in VAR models based on long run labour productivity restrictions combines the impact of traditional 'total factor productivity' shocks with 'investment specific' technology shocks. We specify and estimate these two types of shocks as separate processes in our DSGE model. Graph 10 indicates that an investment-specific technology shock has very different implications for the way labour input responds. Such a shock causes investment, output and labour effort to increase simultaneously. Also the implications for the inflation response and the monetary policy reaction are different, as a positive investment-specific technology shock leads to a positive output gap. From this point of view, the investment-specific shock is much closer to a positive demand shock, that generates a positive output-gap and inflation, than to a supply shock. The impulse-response of an investment specific technology shock are similar to the results presented by Fischer (2002), in spite of the use of a different identification strategy[21]. Output, hours and the real rate increase while consumption remains more or less constant.

Graph 9 presents the impulse response of the third supply shock in our model, a labour supply shock. This shock increases output, the two demand components and hours worked simultaneously. In contrast to the productivity shock, the labour supply shock leads to downward pressure on real wages. As inflation falls and a negative output gap emerges, monetary policy eases, thereby accommodating the output expansion.

The two demand shocks, the intertemporal preference shock (Graph 7) and the public spending shock (Graph 8) have very similar qualitative effects on the US economy. The rise in output and hours worked leads to an increase in real wages and the rental rate on capital. Higher marginal costs feed into higher inflation and together with the positive output-gap this causes higher real interest rates. As a result, there is a relatively strong crowding out effect on the interest-sensitive expenditures, in particular investment.

The impulse responses following a temporary monetary policy shock (Graph 11) are qualitatively in line with the VAR evidence as, for example, presented in the CEE (1998-2001) and Leeper and Zha (2002). The relative response of consumption and investment is also in line with this evidence. The major difference with the VAR evidence is the speed with which demand and particularly prices react to the interest rate tightening. Inflation responds instantaneously and peaks after four quarters. In the typical VAR results, the response of inflation is much slower. As discussed in Section 4, we have estimated an alternative set-up in which following CEE (2001) and Rotemberg and Woodford (1997) current private sector decisions are predetermined with respect to the current interest rate shock. The results indeed illustrate that a time lag slightly improves the marginal likelihood of the model, although it does not

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[20] See for instance Rotemberg (2002) for arguments favoring a slow appearance of major productivity advances in output growth.

[21] Fischer identifies the investment specific technology shock in a VAR as the only shock that drives the long run relative price of investment goods.

significantly change the other parameter estimates. The inclusion of such an information lag does lead a reduced importance of the backward looking terms in price and expenditures decisions.

Compared to temporary monetary policy shocks, permanent changes in the inflation objective of the central bank (lower panel of Table 11) have a much lower sacrifice ratio and do not create a negative liquidity effects on the interest rate. As the model is characterised by a vertical long run Phillips curve, permanent changes in the inflation rates have only temporary real effects.

Finally, Graphs 12 and 13 present the effects of the three mark-up shocks. As discussed before these shocks are assumed not to affect the output level that is targeted by monetary policy. A negative equity premium shock leads to a short run expansion of investment and output. The inflationary consequences of these effect are, however, minimised by a relatively strong interest rate reaction. Positive price mark-up shocks cause a decline in demand and output levels, although sticky nominal wages also imply a decline in real wages. A wage mark-up shock has similar but more persistent effects than a price mark-up shock.

7.3 What drives US business cycles?

In order to investigate the sources of business cycle fluctuations in the US economy, Table 3 presents the forecast error variance decomposition of the seven observable variables at various horizons, while Graph 14 summarises the historical contributions of the various shocks to output and inflation developments.

Regarding the sources of output fluctuations, the first column of Table 3 shows that in the short run (within a year) movements in real GDP are primarily driven by the various demand shocks, in particular the government spending, consumption preference and investment shocks. Not surprisingly, consumption preference shocks explain a big part of the short-run variations in consumption, while the investment shock explains the largest part of investment. However, in line with the results of Shapiro and Watson (1989), it is mostly the two supply shocks, the productivity and labour supply shock, that account for most of the output variations in the medium to long run. Indeed, even at the two year horizon, the productivity and labour supply shocks account each for more than 25% of the variations in output. Those shocks also become dominant forces in the long-run developments of consumption and to a lesser extent investment. Not surprisingly, labour supply shocks are also the dominant factor behind long-run movements in hours worked. From the four temporary shocks in our model, only the monetary policy shocks seem to explain a significant part of output variations. Their contribution does, however, on average not exceed much more than 10 percent. Interestingly, the contribution of the price and wage mark-up shocks to output variations is very low at all horizons. These findings are confirmed by the historical contribution depicted in the lower panel of Graph 14. Quite striking is the significant negative contribution to output developments of the disinflation policy in the early 1980s.

This overall picture is quite different when focusing on the sources of inflation developments (second column of Table 3). In the short run, inflation and wages are mostly driven by mark-up shocks. However, even at the medium to long-run horizons, the “fundamental” supply and demand shocks only explain a very minor fraction of the total variation in inflation. While the contribution of the mark-up shocks falls as the horizon lengthens, it is mostly the monetary policy shocks that explain the remainder. Indeed, the inflation objective shock explains more than 50 percent of the long-run variations in inflation. This is also clear from the upper panel of Graph 14, which depicts the historical contribution of the monetary policy shocks to inflation over the sample period. The dominant role of shifts in the inflation objective in explaining the rise and fall of inflation in the 1970s and 1980s is very clear. In contrast, the short-run volatility in inflation is mainly picked up by the mark-up shocks.

There are at least two reasons why the various demand and supply shocks have only limited effects on inflation. First, the estimated degree of price stickiness is very high, so that only large and persistent changes in the marginal cost will have an impact on inflation. Second, and more importantly, under the estimated monetary policy reaction function the Fed responds quite aggressively to emerging output gaps and their impact on inflation. This is reflected in the fact that at the short and medium-term horizon more than 60 percent of variations in the nominal interest rate are due to the various demand and supply shocks, in particular the consumption preference shock. Only in the long run, does the inflation objective shock become a dominant source of movements in nominal interest rates.

7.4 A model based estimate of the US output gap

As discussed in Section 4, one of the by-products of the estimation of the DSGE model is that it delivers an estimate of the US output gap, defined as the difference between actual output and the output level that would prevail under flexible prices and wages in the absence of price and wage mark-up shocks. Graph 15 presents the estimate of the output gap with a 5-95% confidence interval. This estimate suggests that the output gap was mostly positive during the 1960s and 1970s and became negative following the disinflation policies of the early 1980s. According to those estimates, the boom of the second half of the 1990s served to close a record negative output gap of about 6% in the early 1990s.

8. Concluding remarks

In this paper, we have shown that modern micro-founded New Neoclassical Synthesis models are able to fit the main US macro data very well, if one allows for a sufficiently rich stochastic structure and set of frictions. Our results support the earlier approaches by Rotemberg and Woodford (1997) and Christiano, Eichenbaum and Evans (2001). Although the estimated structural model is highly restricted, it clearly outperforms standard VAR and BVAR models in out-of-sample forecasting, indicating that the theory embedded in the structural model is helpful in improving the forecasts of the main US macro variables, in particular at business cycle frequencies. Moreover, the estimated impulse responses to the various structural shocks and the forecast error variance decompositions compare well with those obtained from unrestricted identified VARs.

Of course, the estimated model remains very stylised and should be further developed. In particular, a deeper understanding of the various nominal and real frictions that have been introduced would increase the confidence in using this type of models for welfare analysis. Our analysis also raises questions about the deeper determinants of the various “structural” shocks such as productivity, labour supply and mark-up shocks that are identified as being important driving factors of output and inflation developments? However, we hope to have shown that the Bayesian approach followed in this paper offers an effective tool for comparing and selecting between such alternative micro-founded model specifications.

Appendix on data used for the US

Equations (28) to (36) are estimated using seven key macro-economic time series: output, consumption, investment, hours worked, real wages, prices and a short-term interest rate. The Bayesian estimation methodology is extensively discussed in Smets and Wouters (2003a).

GDP, consumption and investment are taken from the US Department of Commerce - Bureau of Economic Analysis databank. Real Gross Domestic Product is expressed in Billions of Chained 1996 Dollars. Nominal Personal Consumption Expenditures and Fixed Private Domestic Investment is deflated with the GDP-deflator.[22] Inflation is the first difference of the log of the Implicit Price Deflator of GDP.

Hours and wages come from the BLS (hours and hourly compensation for the NFB sector for all persons). Hourly compensation is divided by the GDP price deflator in order to get the real wage variable. Hours are adjusted to take into account the limited coverage of the NFB sector compared to GDP (the index of average hours for the NFB sector is multiplied with the Civilian Employment (16 years and over)[23]. The aggregate real variables are expressed per capita by dividing with the population over 16. All series are seasonally adjusted. The interest rate is the Federal Funds Rate.

Consumption, investment, GDP, wages and hours/employment are expressed in 100xlog. The interest rate and inflation rate are expressed on a quarterly basis corresponding with their appearance in the model (in the graphs the series are translated on an annual basis).

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[22] We follow Altig, Christiano, Eichenbaum and Linde (2002) here. This approach avoids the positive trend in the investment share of output that results from the decline in the relative investment expenditures deflator. A fully specified model would start from a two-sector model allowing for a separate trend in technological progress in the investment good sector. In such a two sector model, the relative price of investment and consumption goods can be used to identify the investment specific technological progress. In our one sector model, it was difficult to identify a separate deterministic trend in investment specific technology. However, there are significant short run shocks around this trend that influence investment in the short and medium run.

[23] This correction is also used in Chang, Gomes and Schrofheide (2002) ?

Tables and Graphs Appendix

Table 1: Parameter estimates

	Prior distribution			Estimated posterior mode		Posterior sample based				
	type	mean	st. error	mode	st.error (Hessian)	0.05%	0.10%	50%	90%	95%
σ productivity shock	inv gamma	0.250	2.000	0.480	0.027	0.439	0.447	0.479	0.515	0.527
σ inflation obj. shock	inv gamma	0.050	2.000	0.075	0.017	0.059	0.063	0.084	0.108	0.115
σ cons.pref. shock	inv gamma	0.250	2.000	1.271	0.428	0.758	0.869	1.396	2.090	2.286
σ gov.spending shock	inv gamma	0.250	2.000	0.602	0.032	0.556	0.566	0.605	0.647	0.661
σ labour supply shock	inv gamma	0.250	2.000	2.111	0.495	1.489	1.626	2.197	2.911	3.140
σ investment shock	inv gamma	0.250	2.000	0.357	0.105	0.246	0.274	0.401	0.547	0.583
σ interest rate shock	inv gamma	0.250	2.000	0.210	0.016	0.189	0.195	0.215	0.237	0.244
σ equity premium shock	inv gamma	0.250	2.000	0.615	0.166	0.205	0.259	0.539	0.749	0.798
σ price mark-up shock	inv gamma	0.250	2.000	0.186	0.012	0.169	0.173	0.188	0.205	0.211
σ wage mark-up shock	inv gamma	0.250	2.000	0.259	0.016	0.236	0.242	0.261	0.282	0.288
ρ productivity shock	beta	0.850	0.100	0.998	0.001	0.992	0.994	0.997	0.998	0.999
ρ cons.pref. shock	beta	0.850	0.100	0.580	0.109	0.391	0.424	0.558	0.690	0.722
ρ gov. spending shock	beta	0.850	0.100	0.996	0.004	0.979	0.983	0.993	0.997	0.998
ρ labour supply shock	beta	0.850	0.100	0.993	0.003	0.984	0.986	0.992	0.996	0.997
ρ investment shock	beta	0.850	0.100	0.717	0.078	0.571	0.596	0.687	0.779	0.804
investment adj cost	Normal	4.000	1.500	6.014	1.006	4.719	5.049	6.404	7.924	8.365
σ consumption utility	Normal	1.000	0.375	1.815	0.279	1.179	1.291	1.692	2.082	2.198
h consumption habit	beta	0.700	0.100	0.636	0.060	0.555	0.579	0.662	0.737	0.757
σ labour utility	Normal	2.000	0.750	1.942	0.597	1.213	1.386	2.087	2.896	3.150
fixed cost	Normal	1.250	0.125	1.584	0.066	1.493	1.516	1.600	1.688	1.711
capital util. adj.cost	Normal	0.200	0.075	0.270	0.064	0.194	0.214	0.289	0.367	0.390
calvo wages	beta	0.750	0.050	0.809	0.032	0.757	0.769	0.812	0.851	0.862
calvo prices	beta	0.750	0.050	0.902	0.014	0.883	0.887	0.905	0.923	0.927
indexation wages	beta	0.500	0.150	0.324	0.111	0.175	0.208	0.333	0.475	0.518
indexation prices	beta	0.500	0.150	0.470	0.107	0.283	0.317	0.443	0.568	0.603
r inflation	Normal	1.500	0.100	1.488	0.106	1.333	1.368	1.497	1.622	1.661
r d(inflation)	Normal	0.300	0.100	0.182	0.051	0.104	0.123	0.186	0.253	0.271
r lagged interest rate	beta	0.750	0.100	0.876	0.024	0.836	0.846	0.878	0.906	0.913
r output	Normal	0.125	0.050	0.059	0.030	0.032	0.038	0.069	0.116	0.132
r d(output)	Normal	0.063	0.050	0.235	0.030	0.191	0.200	0.239	0.281	0.296
trend	Normal	0.400	0.100	0.322	0.022	0.292	0.300	0.326	0.357	0.368

* For the Inverted Gamma function the degrees of freedom are indicated.

Table 2 : Alternative model specification and data definitions

	Baseline model	Prior sensitivity St. Error Prior		Data detrendend Lin-Quadratic trend	Timing assumption interest rate shock	Policy regime shift St. Error interest shock
σ productivity shock	0.480	x 1.0	0.465	0.479	0.482	0.476
σ inflation obj. shock	0.075	x 1.0	0.076	0.067	0.086	0.078
σ cons.pref. shock	1.271	x 1.0	2.737	1.619	0.256	2.019
σ gov.spending shock	0.602	x 1.0	0.603	0.591	0.602	0.601
σ labour supply shock	2.111	x 1.0	2.278	1.873	3.504	2.272
σ investment shock	0.357	x 1.0	0.560	0.455	0.467	0.518
σ interest rate shock	0.210	x 1.0	0.215	0.206	0.203	0.138 / 0.472
σ equity premium shock	0.615	x 1.0	0.205	0.443	0.247	0.250
σ price mark-up shock	0.186	x 1.0	0.182	0.186	0.188	0.185
σ wage mark-up shock	0.259	x 1.0	0.252	0.266	0.257	0.258
ρ productivity shock	0.998	x 1.0	0.997	0.989	0.994	0.998
ρ cons.pref. shock	0.580	x 1.0	0.303	0.441	0.873	0.435
ρ gov. spending shock	0.996	x 1.0	0.991	0.945	0.996	0.993
ρ labour supply shock	0.993	x 1.0	0.995	0.974	0.991	0.997
ρ investment shock	0.717	x 1.0	0.590	0.640	0.660	0.627
investment adj cost	6.014	x 1.5	6.804	5.600	5.256	6.374
σ consumption utility	1.815	x 1.5	2.358	1.645	2.070	1.829
h consumption habit	0.636	x 1.5	0.683	0.658	0.495	0.703
σ labour utility	1.942	x 1.5	2.167	1.994	2.693	2.102
fixed cost	1.584	x 1.5	1.723	1.527	1.551	1.624
capital util. adj.cost	0.270	x 1.5	0.342	0.260	0.307	0.252
calvo wages	0.809	x 1.5	0.846	0.805	0.819	0.842
calvo prices	0.902	x 1.5	0.926	0.881	0.901	0.908
indexation wages	0.324	x 1.5	0.216	0.338	0.320	0.303
indexation prices	0.470	x 1.5	0.491	0.551	0.407	0.477
r inflation	1.488	x 1.5	1.479	1.528	1.470	1.455
r d(inflation)	0.182	x 1.5	0.172	0.220	0.147	0.185
r lagged interest rate	0.876	x 1.5	0.887	0.836	0.861	0.884
r output	0.059	x 1.5	0.041	0.062	0.038	0.049
r d(output)	0.235	x 1.5	0.218	0.235	0.161	0.205
trend	0.322	x 1.5	0.352	-	0.316	0.322

Table 3: Variance decomposition: 5%-95% bounds

	y	pinf	r	h	w	cons	inve
t = 0							
productivity shock	0.03 - 0.10	0.01 - 0.03	0.03 - 0.10	0.31 - 0.43	0.01 - 0.02	0.05 - 0.18	0.00 - 0.02
inflation objective shock	0.01 - 0.02	0.02 - 0.12	0.00 - 0.01	0.00 - 0.01	0.00 - 0.01	0.01 - 0.02	0.00 - 0.02
preference shock	0.17 - 0.27	0.00 - 0.01	0.16 - 0.38	0.10 - 0.17	0.00 - 0.02	0.52 - 0.78	0.00 - 0.02
gov. spending shock	0.37 - 0.50	0.00 - 0.00	0.00 - 0.03	0.25 - 0.33	0.00 - 0.00	0.00 - 0.03	0.00 - 0.01
labour supply shock	0.03 - 0.11	0.00 - 0.00	0.03 - 0.13	0.02 - 0.09	0.00 - 0.01	0.05 - 0.21	0.01 - 0.03
investment shock	0.04 - 0.17	0.00 - 0.01	0.00 - 0.02	0.03 - 0.11	0.00 - 0.01	0.00 - 0.01	0.41 - 0.89
interest rate shock	0.04 - 0.10	0.00 - 0.02	0.40 - 0.68	0.02 - 0.06	0.00 - 0.02	0.05 - 0.12	0.02 - 0.07
equity premium shock	0.01 - 0.08	0.00 - 0.00	0.00 - 0.06	0.00 - 0.05	0.00 - 0.00	0.00 - 0.00	0.03 - 0.49
price mark-up shock	0.00 - 0.01	0.83 - 0.95	0.00 - 0.07	0.00 - 0.00	0.17 - 0.26	0.00 - 0.00	0.00 - 0.01
wage mark-up shock	0.00 - 0.00	0.00 - 0.02	0.00 - 0.00	0.02 - 0.03	0.68 - 0.80	0.00 - 0.00	0.00 - 0.00
t = 1							
productivity shock	0.06 - 0.15	0.02 - 0.06	0.04 - 0.11	0.23 - 0.35	0.02 - 0.05	0.08 - 0.22	0.01 - 0.02
inflation objective shock	0.01 - 0.03	0.05 - 0.24	0.01 - 0.04	0.00 - 0.02	0.00 - 0.02	0.01 - 0.03	0.00 - 0.02
preference shock	0.16 - 0.26	0.00 - 0.01	0.20 - 0.47	0.12 - 0.20	0.00 - 0.03	0.43 - 0.69	0.00 - 0.02
gov. spending shock	0.24 - 0.38	0.00 - 0.01	0.01 - 0.04	0.20 - 0.29	0.00 - 0.00	0.00 - 0.04	0.00 - 0.01
labour supply shock	0.05 - 0.18	0.00 - 0.01	0.03 - 0.16	0.04 - 0.16	0.00 - 0.02	0.08 - 0.26	0.01 - 0.04
investment shock	0.07 - 0.21	0.00 - 0.01	0.00 - 0.04	0.05 - 0.15	0.00 - 0.01	0.00 - 0.01	0.53 - 0.89
interest rate shock	0.06 - 0.13	0.00 - 0.05	0.28 - 0.55	0.04 - 0.10	0.00 - 0.03	0.05 - 0.13	0.03 - 0.09
equity premium shock	0.00 - 0.06	0.00 - 0.00	0.00 - 0.05	0.00 - 0.05	0.00 - 0.00	0.00 - 0.00	0.02 - 0.30
price mark-up shock	0.00 - 0.01	0.66 - 0.89	0.01 - 0.06	0.00 - 0.00	0.17 - 0.30	0.00 - 0.01	0.00 - 0.02
wage mark-up shock	0.00 - 0.00	0.01 - 0.03	0.00 - 0.00	0.01 - 0.03	0.58 - 0.78	0.00 - 0.00	0.00 - 0.00
t = 4							
productivity shock	0.12 - 0.24	0.03 - 0.10	0.05 - 0.13	0.11 - 0.22	0.08 - 0.21	0.15 - 0.34	0.02 - 0.05
inflation objective shock	0.01 - 0.04	0.15 - 0.48	0.04 - 0.14	0.01 - 0.04	0.00 - 0.03	0.01 - 0.04	0.01 - 0.03
preference shock	0.08 - 0.19	0.00 - 0.03	0.19 - 0.49	0.08 - 0.19	0.00 - 0.05	0.23 - 0.48	0.00 - 0.02
gov. spending shock	0.12 - 0.21	0.00 - 0.01	0.01 - 0.05	0.14 - 0.22	0.00 - 0.00	0.01 - 0.06	0.00 - 0.02
labour supply shock	0.10 - 0.29	0.00 - 0.02	0.03 - 0.18	0.11 - 0.33	0.00 - 0.03	0.14 - 0.39	0.01 - 0.07
investment shock	0.11 - 0.23	0.00 - 0.03	0.03 - 0.13	0.10 - 0.21	0.01 - 0.05	0.00 - 0.01	0.62 - 0.85
interest rate shock	0.06 - 0.18	0.01 - 0.12	0.16 - 0.38	0.06 - 0.16	0.01 - 0.09	0.05 - 0.15	0.04 - 0.13
equity premium shock	0.00 - 0.03	0.00 - 0.00	0.00 - 0.04	0.00 - 0.03	0.00 - 0.00	0.00 - 0.00	0.01 - 0.13
price mark-up shock	0.00 - 0.02	0.38 - 0.66	0.01 - 0.05	0.00 - 0.01	0.14 - 0.35	0.00 - 0.01	0.00 - 0.03
wage mark-up shock	0.00 - 0.00	0.01 - 0.04	0.00 - 0.00	0.01 - 0.02	0.36 - 0.67	0.00 - 0.00	0.00 - 0.00
t = 10							
productivity shock	0.19 - 0.36	0.03 - 0.09	0.04 - 0.12	0.06 - 0.13	0.24 - 0.52	0.23 - 0.45	0.04 - 0.12
inflation objective shock	0.01 - 0.05	0.27 - 0.66	0.13 - 0.36	0.01 - 0.05	0.00 - 0.04	0.01 - 0.03	0.01 - 0.04
preference shock	0.04 - 0.09	0.00 - 0.03	0.13 - 0.37	0.04 - 0.12	0.00 - 0.05	0.10 - 0.25	0.00 - 0.02
gov. spending shock	0.07 - 0.13	0.00 - 0.02	0.01 - 0.05	0.10 - 0.18	0.00 - 0.01	0.01 - 0.08	0.00 - 0.05
labour supply shock	0.14 - 0.39	0.00 - 0.03	0.03 - 0.16	0.23 - 0.52	0.00 - 0.04	0.19 - 0.50	0.03 - 0.14
investment shock	0.09 - 0.20	0.00 - 0.04	0.06 - 0.21	0.09 - 0.20	0.01 - 0.08	0.00 - 0.02	0.53 - 0.76
interest rate shock	0.05 - 0.18	0.02 - 0.16	0.11 - 0.27	0.06 - 0.19	0.02 - 0.13	0.03 - 0.13	0.04 - 0.17
equity premium shock	0.00 - 0.02	0.00 - 0.00	0.00 - 0.04	0.00 - 0.02	0.00 - 0.00	0.00 - 0.00	0.01 - 0.07
price mark-up shock	0.00 - 0.03	0.22 - 0.47	0.01 - 0.03	0.00 - 0.01	0.09 - 0.26	0.00 - 0.01	0.01 - 0.04
wage mark-up shock	0.00 - 0.01	0.01 - 0.04	0.00 - 0.01	0.01 - 0.02	0.16 - 0.40	0.00 - 0.01	0.00 - 0.00
t = 30							
productivity shock	0.28 - 0.52	0.01 - 0.06	0.02 - 0.09	0.03 - 0.09	0.63 - 0.84	0.28 - 0.55	0.13 - 0.31
inflation objective shock	0.00 - 0.03	0.46 - 0.82	0.32 - 0.67	0.00 - 0.03	0.00 - 0.03	0.00 - 0.02	0.01 - 0.04
preference shock	0.01 - 0.04	0.00 - 0.02	0.07 - 0.24	0.02 - 0.06	0.00 - 0.02	0.03 - 0.09	0.00 - 0.01
gov. spending shock	0.04 - 0.09	0.00 - 0.02	0.01 - 0.05	0.07 - 0.17	0.00 - 0.00	0.01 - 0.11	0.00 - 0.11
labour supply shock	0.22 - 0.51	0.00 - 0.03	0.02 - 0.12	0.44 - 0.74	0.00 - 0.02	0.25 - 0.58	0.08 - 0.31
investment shock	0.04 - 0.11	0.00 - 0.03	0.04 - 0.16	0.04 - 0.12	0.01 - 0.06	0.00 - 0.02	0.29 - 0.54
interest rate shock	0.02 - 0.10	0.01 - 0.13	0.07 - 0.17	0.03 - 0.13	0.01 - 0.10	0.01 - 0.07	0.03 - 0.16
equity premium shock	0.00 - 0.01	0.00 - 0.00	0.00 - 0.02	0.00 - 0.01	0.00 - 0.00	0.00 - 0.00	0.00 - 0.04
price mark-up shock	0.00 - 0.01	0.11 - 0.31	0.00 - 0.02	0.00 - 0.01	0.03 - 0.09	0.00 - 0.01	0.00 - 0.03
wage mark-up shock	0.00 - 0.01	0.00 - 0.02	0.00 - 0.00	0.00 - 0.02	0.05 - 0.12	0.00 - 0.00	0.00 - 0.01

Table 4: Model statistics compared to VAR models

Summary of the model statistics : VAR - BVAR - SDGE

	VAR(1)	**VAR(2)**	**VAR(3)**	**SDGE-model**
RMSE in sample from T0+1:T with OLS estimates 1:T				
y	0.84	0.78	0.75	0.83
pi	0.28	0.25	0.25	0.27
r	0.23	0.21	0.19	0.23
lab	0.59	0.52	0.49	0.58
w	0.50	0.50	0.49	0.54
cons	0.62	0.59	0.58	0.72
inv	2.03	1.80	1.79	1.95

Posterior probability approximation T0+1:T

	VAR(1)	**VAR(2)**	**VAR(3)**	**SDGE-model**
Prediction error decomposition[1]	-1246.30	-1241.40	-1290.80	
Laplace approximation	-1248.67	-1242.18	-1293.53	-1086.59
Modified harmonic mean[2]	-1244.70	-1236.20	-1284.60	-1086.40
Bayes factor rel. to SDGE model	0.00	0.00	0.00	1.00
Prior probabilities	0.25	0.25	0.25	0.25
Posterior odds	0.00	0.00	0.00	1.00

Minnesota prior	**BVAR(1)**	**BVAR(2)**	**BVAR(3)**	**SDGE**
Prediction error decomposition	-1196.90	-1165.40	-1163.00	-1086.40
Bayes factor rel. to SDGE model	0.00	0.00	0.00	1.00
Prior probabilities	0.25	0.25	0.25	0.25
Posterior odds	0.00	0.00	0.00	1.00

DSGE prior	**BVAR(1)**	**BVAR(2)**	**BVAR(3)**	**SDGE**
Prediction error decomposition	-1182.90	-1158.30	-1153.60	-1086.40
Bayes factor rel. to SDGE model	0.00	0.00	0.00	1.00
Prior probabilities	0.25	0.25	0.25	0.25
Posterior odds	0.00	0.00	0.00	1.00

[1] Posterior probability computed recursively using the predictive density evaluation (treating first T0 obs given)

[2] Posterior probability approximation via sampling: MC for the VAR, Gibbs for the BVAR, MH for the SDGE model

Both the VAR and BVAR models have constant but no trend.

Table 5: Out-of-sample prediction performance

Comparing out-of-sample forecast : overall performance

Logarithm of determinant of uncentered covariance matrix of forecast errors 1990:1-2002:2

	Forecast Horizon				
	1 quarter	2 quarters	4 quarters	8 quarters	12 quarters
DSGE-model	-13.09	-7.71	-3.16	0.74	1.22
VAR(1)	-11.96	-6.31	-0.99	2.99	4.02
VAR(2)	-12.13	-6.72	-0.95	3.26	3.92
VAR(3)	-11.75	-6.46	-1.33	2.70	3.94
BVAR(1)	-12.68	-7.04	-1.97	1.95	4.71
BVAR(2)	-12.69	-7.03	-1.93	2.06	4.67
BVAR(3)	-12.71	-7.05	-1.95	2.08	4.63

VAR - BVAR models are re-estimated each quarter.
DSGE model is re-estimated each year.
BVAR model uses symmetric prior with decay=2, off-diagonal=1 and overall tightness=0.05.

Table 6: Out-of-sample prediction performance

Comparing out-of-sample forecast : performance for individual variables

RMSE-statistics - for different forecast horizons

DSGE-model	y	pinf	r	h	w	cons	inve
1	0.52	0.22	0.12	0.44	0.66	0.59	1.67
2	0.80	0.26	0.22	0.73	1.04	0.91	3.26
4	1.36	0.28	0.36	1.22	1.69	1.66	6.77
8	1.88	0.38	0.45	1.80	2.52	3.40	10.98
12	2.01	0.45	0.45	1.81	3.32	5.24	12.08

VAR(1)	y	pinf	r	h	w	cons	inve
1	0.67	0.34	0.15	0.57	0.66	0.53	1.85
2	1.12	0.47	0.29	0.96	1.04	0.89	3.16
4	1.95	0.56	0.50	1.49	1.79	1.83	5.40
8	3.37	0.47	0.61	2.07	3.03	3.53	9.49
12	4.87	0.46	0.58	2.26	4.44	4.72	13.89

VAR(2)	y	pinf	r	h	w	cons	inve
1	0.64	0.33	0.12	0.45	0.70	0.55	1.66
2	1.10	0.39	0.22	0.78	1.09	0.90	3.05
4	2.10	0.48	0.41	1.32	1.83	1.84	6.21
8	3.72	0.39	0.47	2.04	3.07	3.51	11.48
12	4.79	0.36	0.47	2.24	4.44	4.33	15.22

VAR(3)	y	pinf	r	h	w	cons	inve
1	0.63	0.33	0.14	0.44	0.71	0.56	1.63
2	1.03	0.39	0.27	0.75	1.11	0.86	2.94
4	1.93	0.45	0.48	1.22	1.82	1.68	5.85
8	3.64	0.39	0.53	1.90	3.07	3.46	10.91
12	5.04	0.33	0.51	2.30	4.44	4.54	14.68

BVAR(1)	y	pinf	r	h	w	cons	inve
1	0.62	0.24	0.14	0.55	0.66	0.57	1.91
2	1.06	0.30	0.26	0.96	1.04	0.91	3.38
4	1.86	0.39	0.47	1.60	1.78	1.67	5.89
8	2.91	0.50	0.66	2.26	3.01	3.01	9.38
12	3.95	0.59	0.71	2.37	4.47	4.19	13.18

BVAR(2)	y	pinf	r	h	w	cons	inve
1	0.61	0.24	0.13	0.53	0.66	0.57	1.88
2	1.05	0.31	0.26	0.93	1.04	0.92	3.35
4	1.86	0.40	0.47	1.54	1.78	1.71	5.89
8	3.01	0.50	0.63	2.16	3.02	3.11	9.56
12	4.13	0.58	0.68	2.27	4.47	4.32	13.44

BVAR(3)	y	pinf	r	h	w	cons	inve
1	0.61	0.24	0.13	0.53	0.66	0.57	1.86
2	1.05	0.31	0.25	0.92	1.04	0.92	3.33
4	1.88	0.39	0.46	1.52	1.78	1.71	5.89
8	3.05	0.50	0.62	2.15	3.01	3.12	9.61
12	4.18	0.57	0.66	2.26	4.47	4.32	13.51

BVAR(4)	y	pinf	r	h	w	cons	inve
1	0.56	0.23	0.12	0.51	0.67	0.55	1.89
2	0.94	0.27	0.23	0.91	1.06	0.83	3.43
4	1.61	0.26	0.44	1.59	1.82	1.43	6.33
8	2.21	0.38	0.67	2.37	3.10	2.15	10.30
12	2.64	0.56	0.83	2.61	4.54	2.68	14.10

VAR(4)	y	pinf	r	h	w	cons	inve
1	0.67	0.34	0.14	0.44	0.73	0.58	1.60
2	1.04	0.39	0.27	0.76	1.12	0.87	3.00
4	1.82	0.39	0.46	1.19	1.82	1.66	5.92
8	3.25	0.31	0.52	1.69	3.02	3.33	10.49
12	4.50	0.23	0.47	2.02	4.33	4.33	14.18

Table 7: Testing the model sensitivity to frictions

MODEL ROBUSTNESS TEST: SENSITIVITY OF PARAMETER ESTIMATES AND MODEL PERFORMANCE TO ALTERNATIVE HYPOTHESIS ON FRICTIONS

	BASELINE	CALVO P	CALVO W	INDEXATION P	INDEXATION W	INV ADJ COST	HABIT	CAP.UTIL COST	FIXED COSTS
σ productivity shock	0.480	0.521	0.472	0.482	0.479	0.504	0.487	0.459	0.604
σ inflation obj. shock	0.075	0.065	0.082	0.098	0.077	0.110	0.095	0.098	0.093
σ cons.pref. shock	1.271	1.004	0.483	1.073	1.322	1.262	0.114	0.341	0.674
σ gov.spending shock	0.602	0.600	0.602	0.602	0.602	0.602	0.601	0.601	0.603
σ labour supply shock	2.111	2.014	1.820	2.009	2.176	2.127	1.112	1.449	1.692
σ investment shock	0.357	0.313	0.235	0.373	0.368	5.000	0.421	0.404	0.323
σ interest rate shock	0.210	0.208	0.234	0.210	0.209	0.256	0.228	0.212	0.224
σ equity premium shock	0.615	0.680	0.810	0.616	0.603	0.202	0.561	0.505	0.715
σ price mark-up shock	0.186	1.146	0.185	0.214	0.189	0.198	0.183	0.189	0.192
σ wage mark-up shock	0.259	0.258	0.270	0.261	0.253	0.261	0.266	0.265	0.260
ρ productivity shock	0.998	0.999	0.997	0.997	0.998	0.998	0.984	0.993	0.995
ρ inflation obj. shock									
ρ cons.pref. shock	0.580	0.579	0.765	0.630	0.567	0.354	0.957	0.862	0.636
ρ gov. spending shock	0.996	0.995	0.998	0.995	0.995	0.996	0.992	0.995	0.993
ρ labour supply shock	0.993	0.994	0.995	0.993	0.993	0.999	0.992	0.990	0.994
ρ investment shock	0.717	0.775	0.795	0.704	0.708	0.792	0.657	0.813	0.737
investment adj cost	6.014	5.321	5.712	6.053	6.011	0.100	6.083	5.710	5.155
σ consumption utility	1.815	1.663	2.012	1.796	1.798	2.982	2.965	2.485	1.710
h consumption habit	0.636	0.598	0.486	0.610	0.643	0.428	0.100	0.394	0.484
σ labour utility	1.942	1.909	0.830	1.922	1.889	2.827	1.869	1.957	1.849
fixed cost	1.584	1.374	1.655	1.565	1.593	1.435	1.479	1.705	1.100
capital util. adj.cost	0.270	0.297	0.300	0.286	0.268	0.394	0.373	10.000	0.225
calvo wages	0.809	0.795	0.420	0.819	0.805	0.851	0.870	0.857	0.829
calvo prices	0.902	0.420	0.894	0.902	0.902	0.913	0.908	0.884	0.931
indexation wages	0.324	0.162	0.348	0.296	0.100	0.265	0.380	0.390	0.337
indexation prices	0.470	0.940	0.476	0.100	0.442	0.212	0.396	0.389	0.318
r inflation	1.488	1.474	1.536	1.481	1.484	1.513	1.501	1.572	1.493
r d(inflation)	0.182	0.158	0.185	0.176	0.180	0.131	0.188	0.189	0.163
r lagged interest rate	0.876	0.876	0.822	0.877	0.881	0.872	0.800	0.820	0.879
r output	0.059	0.077	0.075	0.073	0.059	0.149	0.059	0.089	0.047
r d(output)	0.235	0.286	0.302	0.238	0.238	0.373	0.250	0.267	0.314
trend	0.322	0.286	0.320	0.322	0.325	0.294	0.300	0.297	0.396
Posterior probability	-1086.6	-1312.5	-1112.4	-1089.8	-1084.6	-1191.7	-1114.1	-1089.1	-1124.8
Bayes factor relative to baseline		0.000	0.000	0.040	7.281	0.000	0.000	0.084	0.000

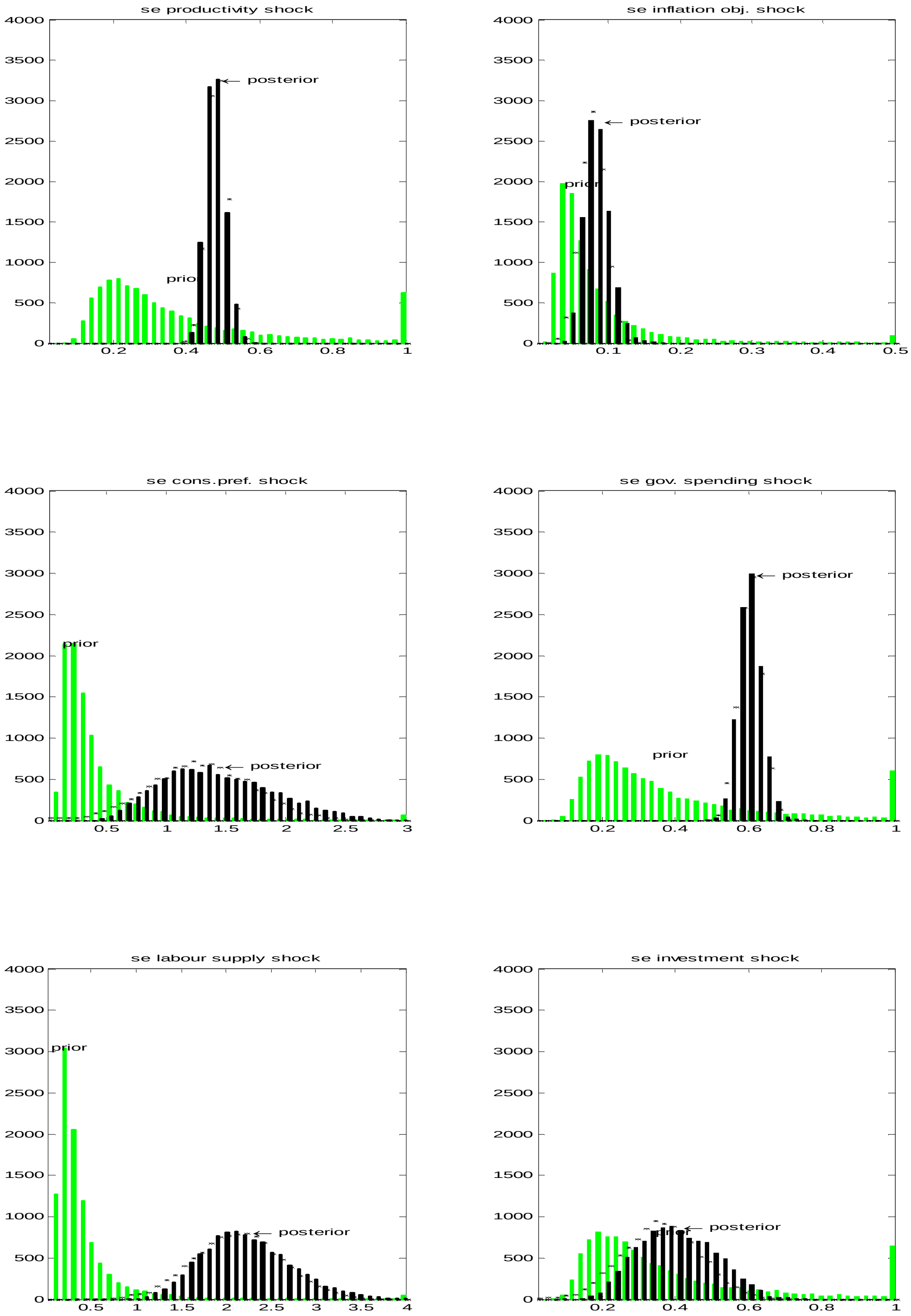
Table 8: Testing the model sensitivity to shocks

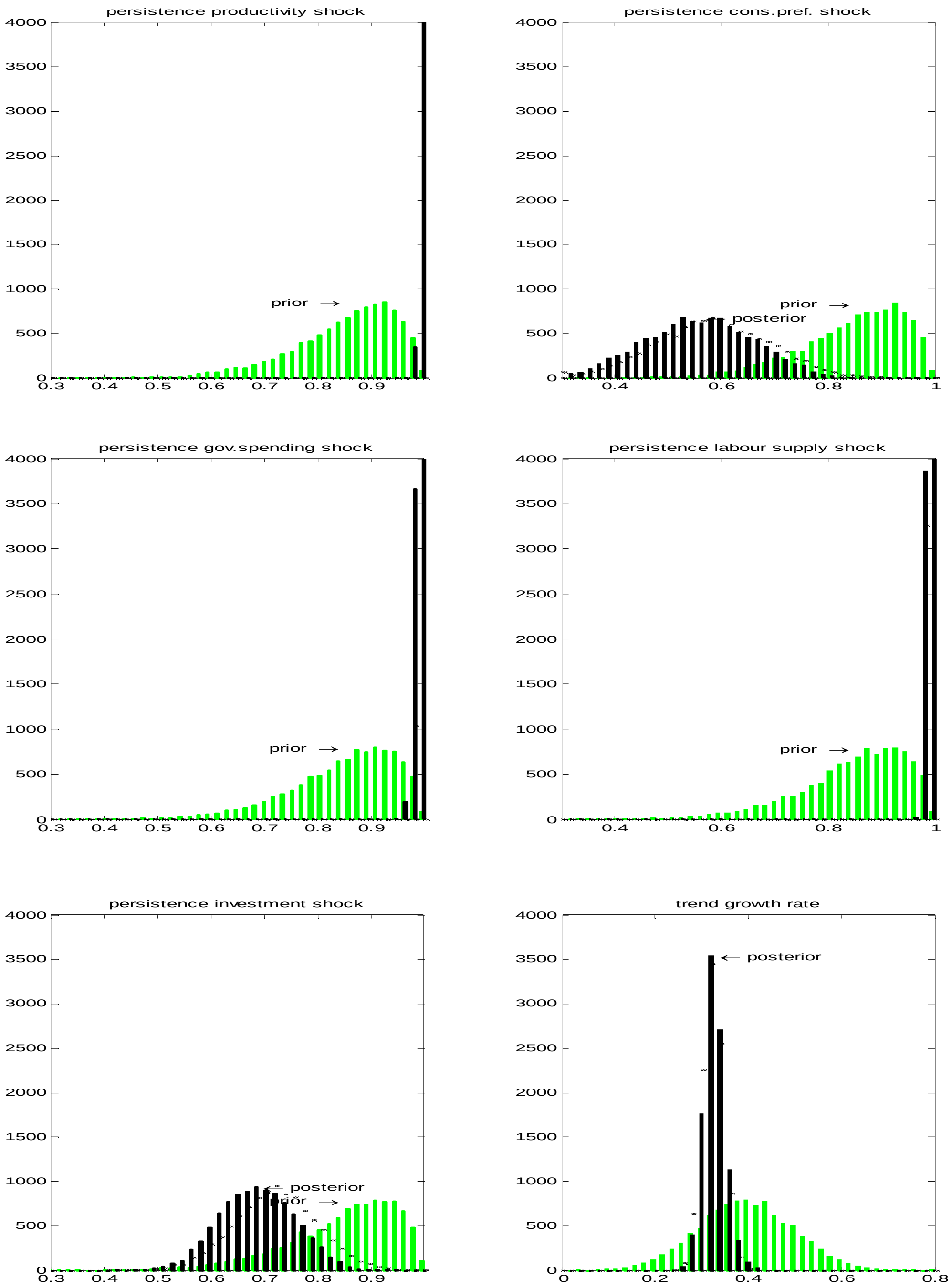
MODEL ROBUSTNESS TEST: SENSITIVITY OF PARAMETER ESTIMATES AND MODEL PERFORMANCE TO ALTERNATIVE HYPOTHESIS ON SHOCHS

	BASELINE	$\eta^Q = 0$	$\eta^P = 0$	$\eta^W = 0$	$\pi^{obj} = 0$	$\varepsilon^b = 0$	$\varepsilon^I = 0$	$\varepsilon^L = 0$
σ productivity shock	0.480	0.479	0.461	0.469	0.481	0.479	0.482	0.484
σ inflation obj. shock	0.075	0.074	0.320	0.073	$\boxed{0.000}$	0.125	0.075	0.098
σ cons.pref. shock	1.271	1.576	2.849	1.840	1.842	$\boxed{0.000}$	1.307	0.303
σ gov.spending shock	0.602	0.601	0.595	0.602	0.602	0.600	0.602	0.602
σ labour supply shock	2.111	2.142	3.213	3.577	2.651	7.059	2.030	$\boxed{0.000}$
σ investment shock	0.357	0.572	0.313	0.236	0.288	0.112	$\boxed{0.000}$	0.328
σ interest rate shock	0.210	0.214	0.220	0.249	0.210	0.273	0.213	0.229
σ equity premium shock	0.615	$\boxed{0.000}$	0.591	0.663	0.655	0.484	1.286	0.646
σ price mark-up shock	0.186	0.186	$\boxed{0.000}$	0.182	0.183	0.182	0.185	0.185
σ wage mark-up shock	0.259	0.258	0.283	$\boxed{0.000}$	0.261	0.272	0.259	0.265
ρ productivity shock	0.998	0.998	0.990	0.998	0.999	0.984	0.997	0.995
ρ inflation obj. shock								
ρ cons.pref. shock	0.580	0.515	0.493	0.456	0.473	$\boxed{0.000}$	0.565	0.892
ρ gov. spending shock	0.996	0.994	0.990	0.996	0.999	0.970	0.992	0.998
ρ labour supply shock	0.993	0.994	0.984	0.989	0.988	0.986	0.997	$\boxed{0.000}$
ρ investment shock	0.717	0.599	0.751	0.803	0.799	0.879	$\boxed{0.000}$	0.727
investment adj cost	6.014	6.017	7.852	6.675	6.017	6.261	7.283	7.036
σ consumption utility	1.815	1.867	0.987	1.686	1.944	0.587	1.671	1.862
h consumption habit	0.636	0.658	0.851	0.739	0.681	0.895	0.665	0.517
σ labour utility	1.942	2.061	2.862	0.250	2.324	2.320	1.757	2.870
fixed cost	1.584	1.596	1.590	1.677	1.597	1.544	1.578	1.538
capital util. adj.cost	0.270	0.268	0.271	0.267	0.233	0.175	0.195	0.312
calvo wages	0.809	0.810	0.833	0.620	0.797	0.858	0.799	0.913
calvo prices	0.902	0.904	0.912	0.900	0.887	0.907	0.911	0.898
indexation wages	0.324	0.317	0.557	0.295	0.372	0.380	0.317	0.244
indexation prices	0.470	0.475	0.039	0.497	0.752	0.225	0.494	0.488
r inflation	1.488	1.484	1.496	1.430	1.426	1.531	1.489	1.433
r d(inflation)	0.182	0.187	0.291	0.203	0.207	0.230	0.177	0.175
r lagged interest rate	0.876	0.875	0.842	0.830	0.862	0.866	0.887	0.831
r output	0.059	0.058	0.131	0.039	0.035	0.112	0.068	0.018
r d(output)	0.235	0.237	0.210	0.196	0.211	0.187	0.227	0.190
trend	0.322	0.326	0.319	0.348	0.311	0.316	0.333	0.292
Posterior probability	-1086.6	-1088.4	-1147.2	-1139.8	-1100.9	-1121.8	-1115.2	-1107.9
Bayes factor relative to baseline		0.174	0.000	0.000	0.000	0.000	0.000	0.000

The public spending shock and the productivity shock

Graph 1 : Prior and posterior distributions of the shock parameters

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persistence cons.pref. shock
prior
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persistence gov.spending shock
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persistence labour supply shock
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persistence investment shock
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trend growth rate
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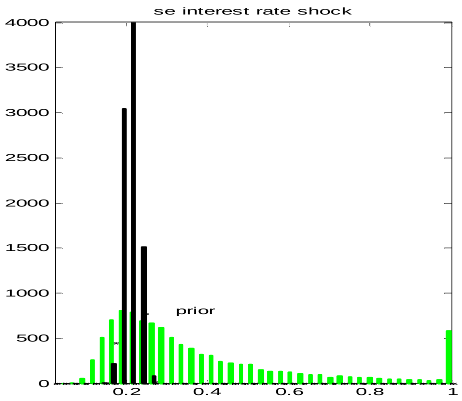
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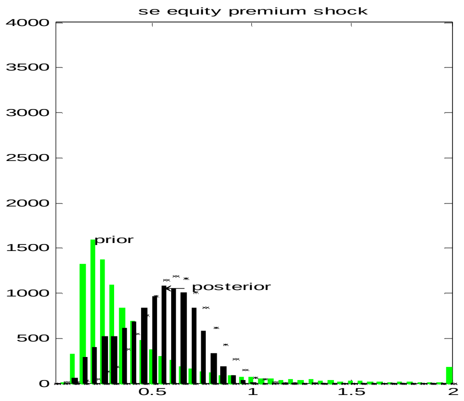
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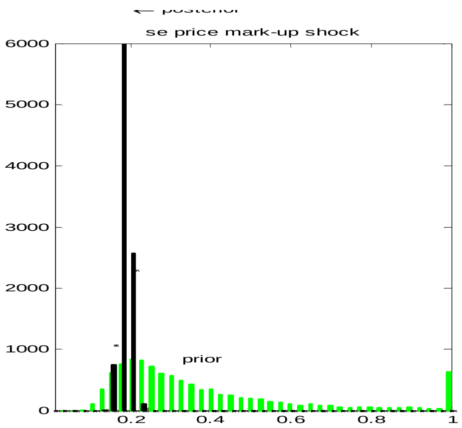
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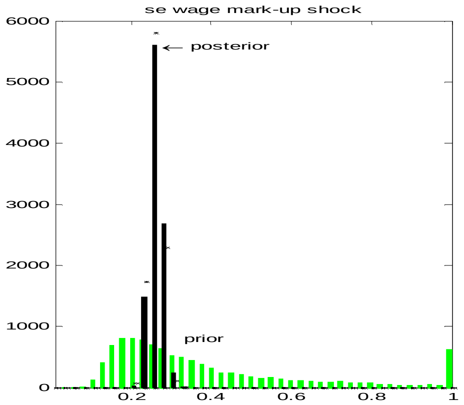
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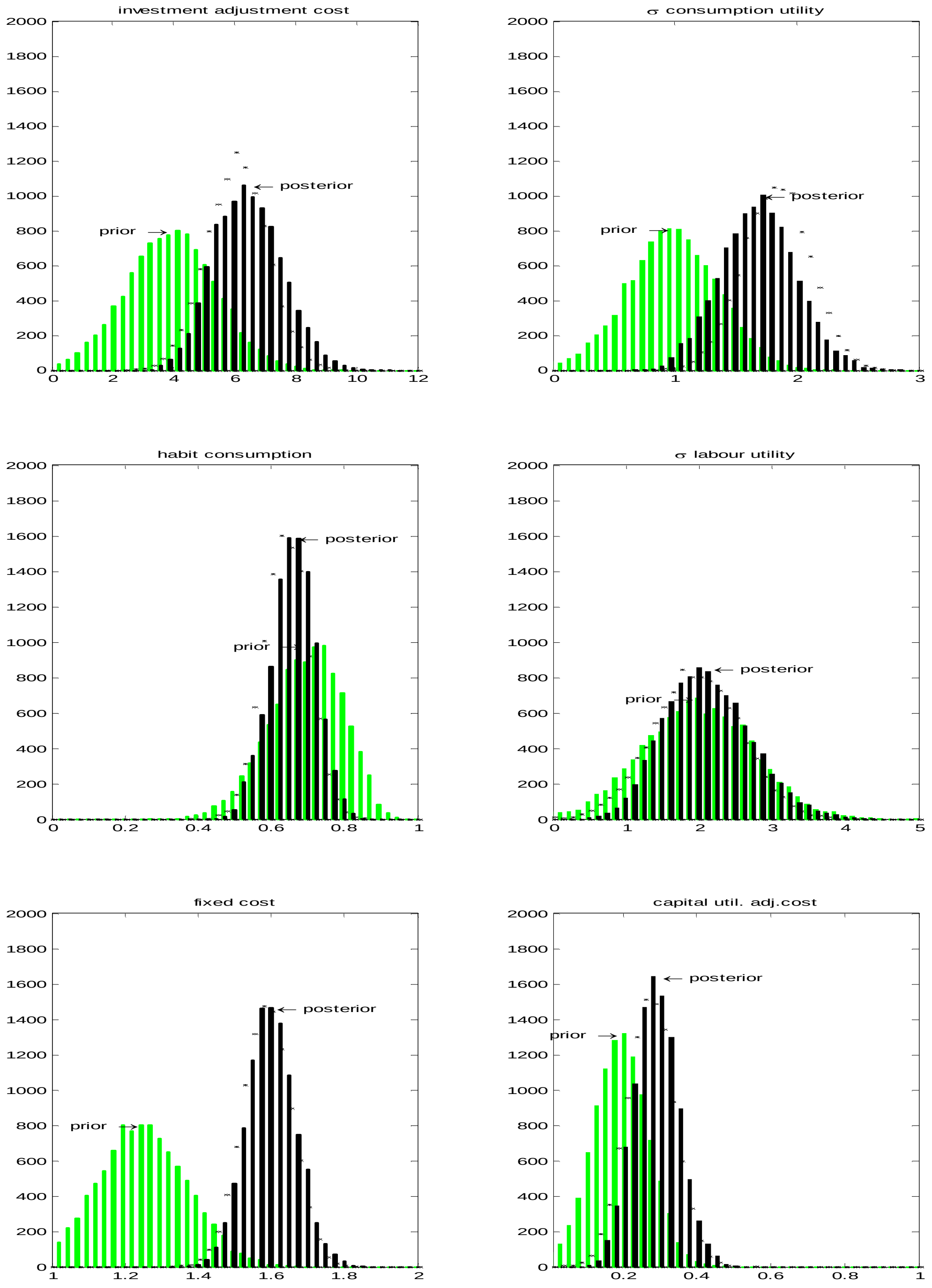
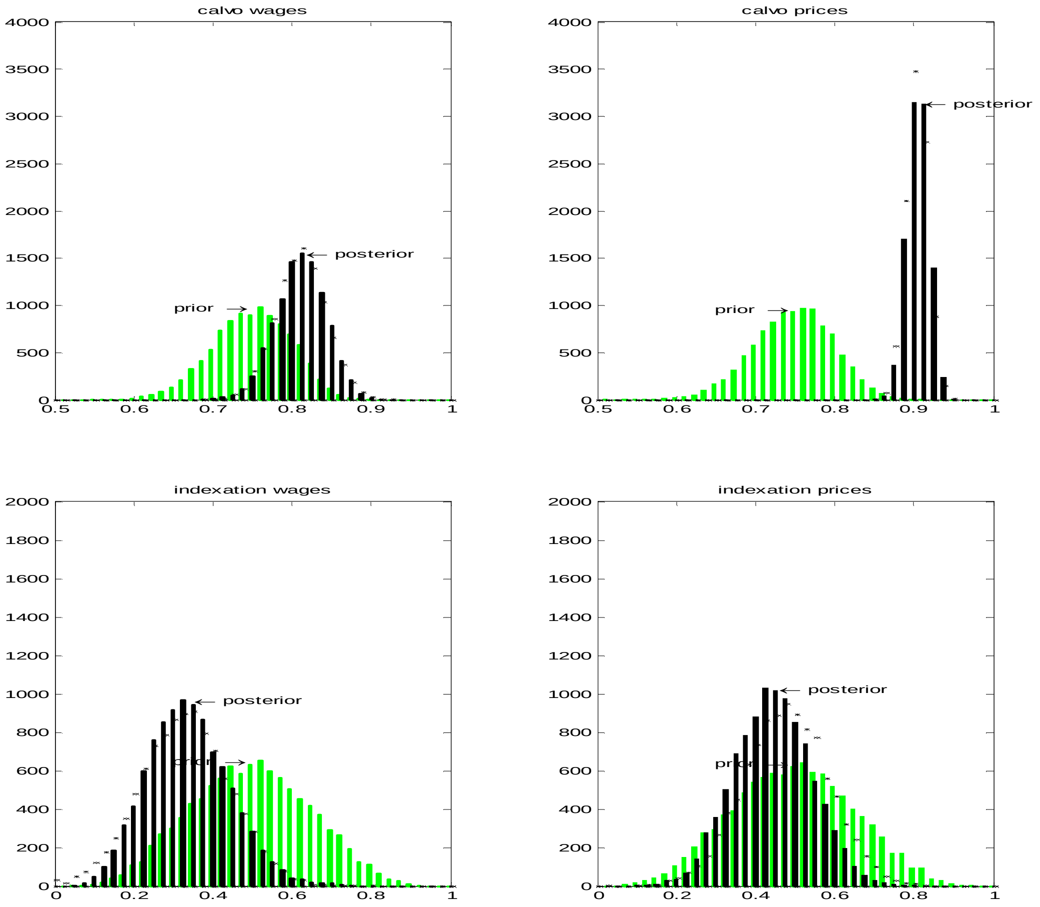
Graph 2: Prior and posterior distributions of the behavioural parameters

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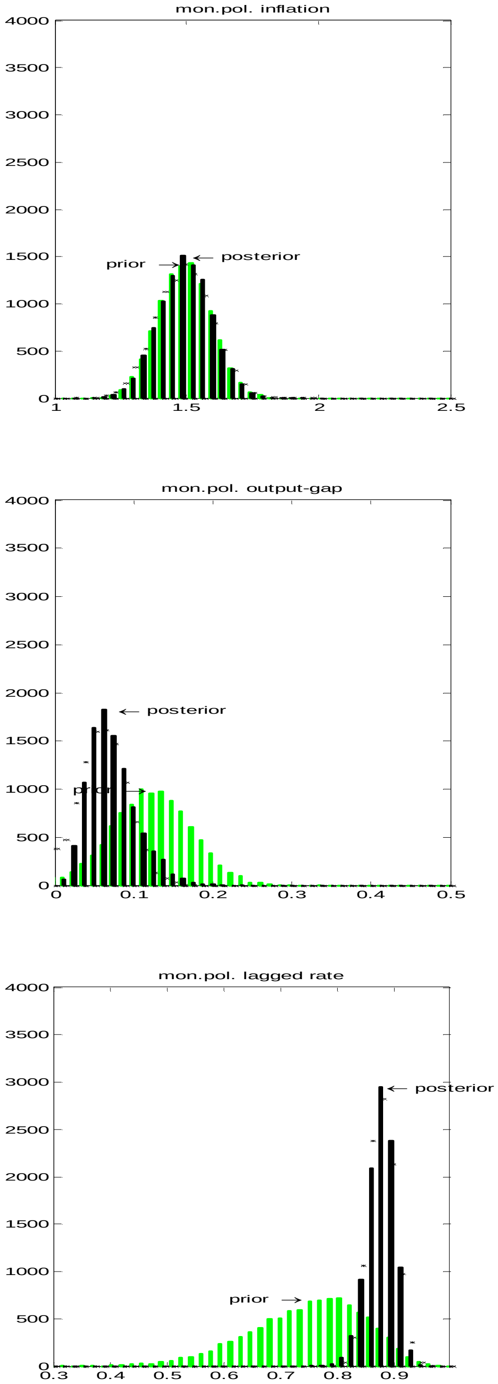
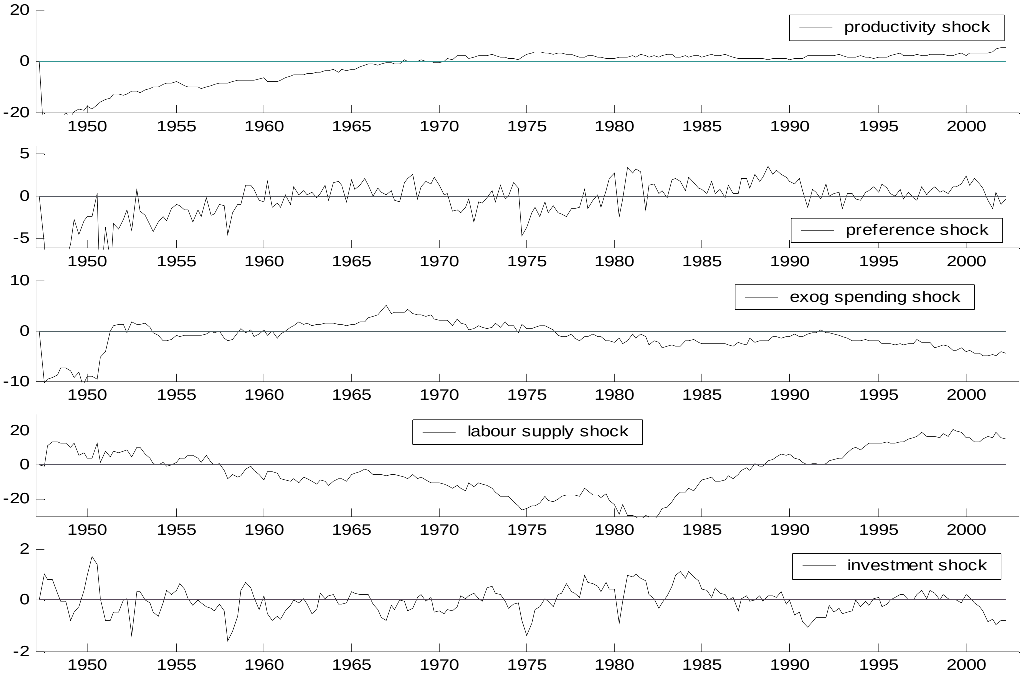
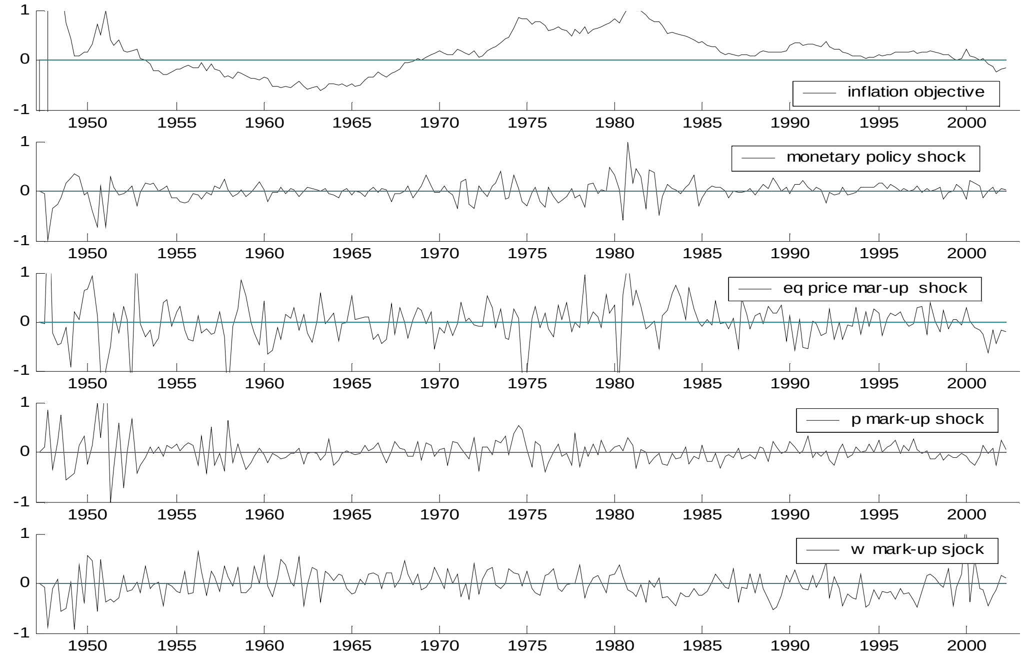
2500
3000
3500
4000
0.5
0.6
0.7
0.8
0.9
1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
0.2
0.4
0.6
0.8
1

Graph 3: Prior and posterior distributions of the reaction function parameters

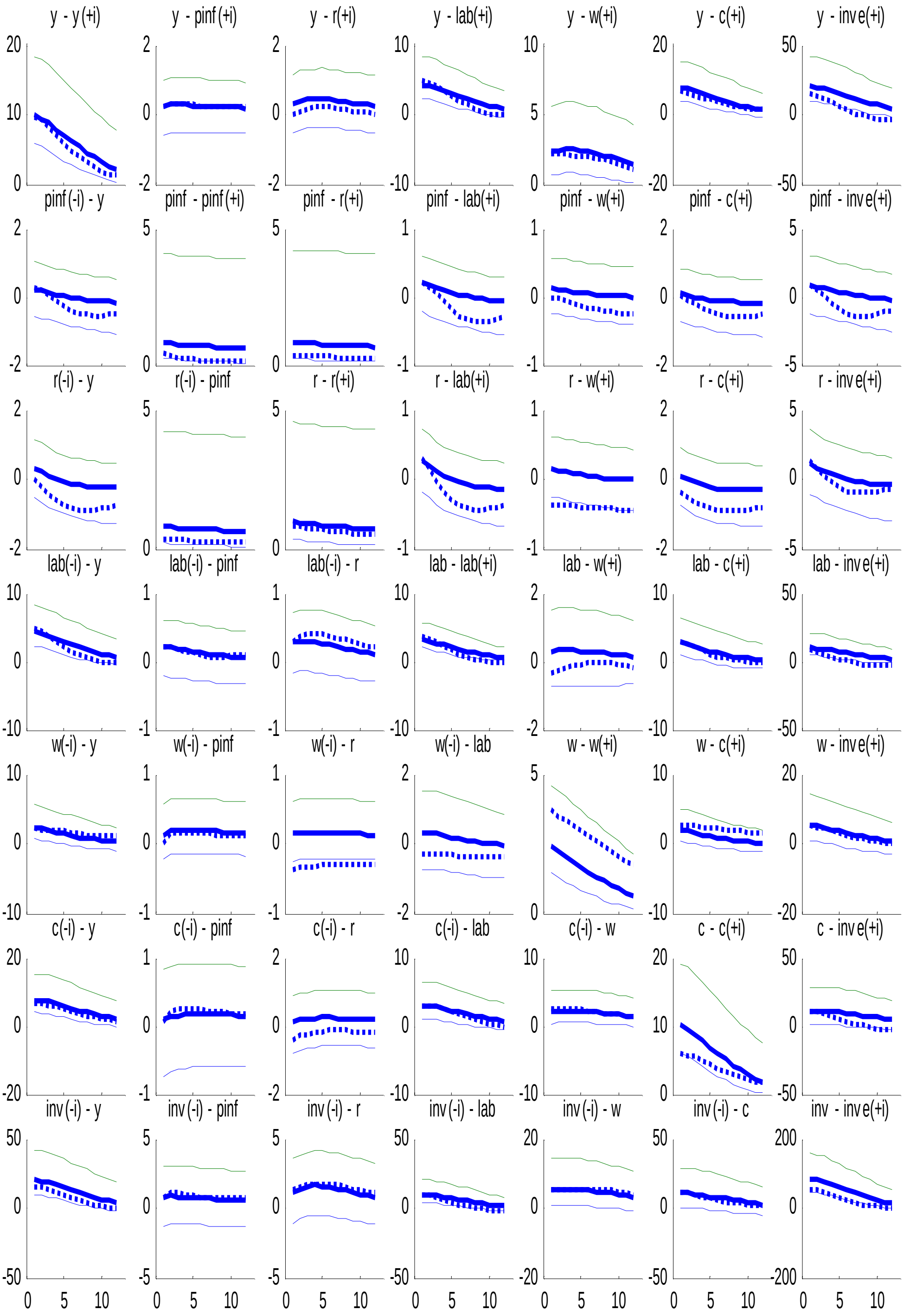


Graph 4: Estimates of the underlying driving processes

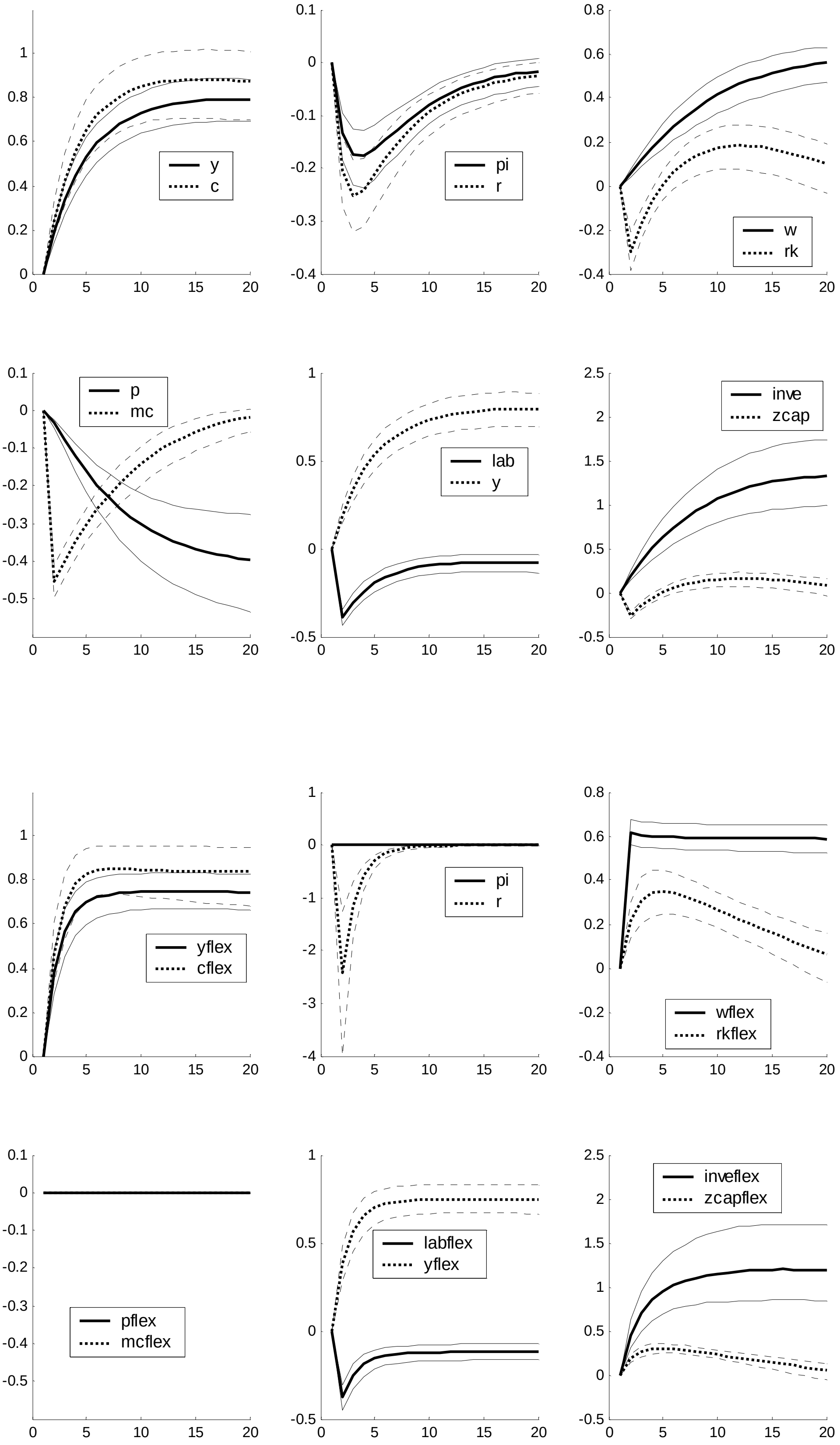




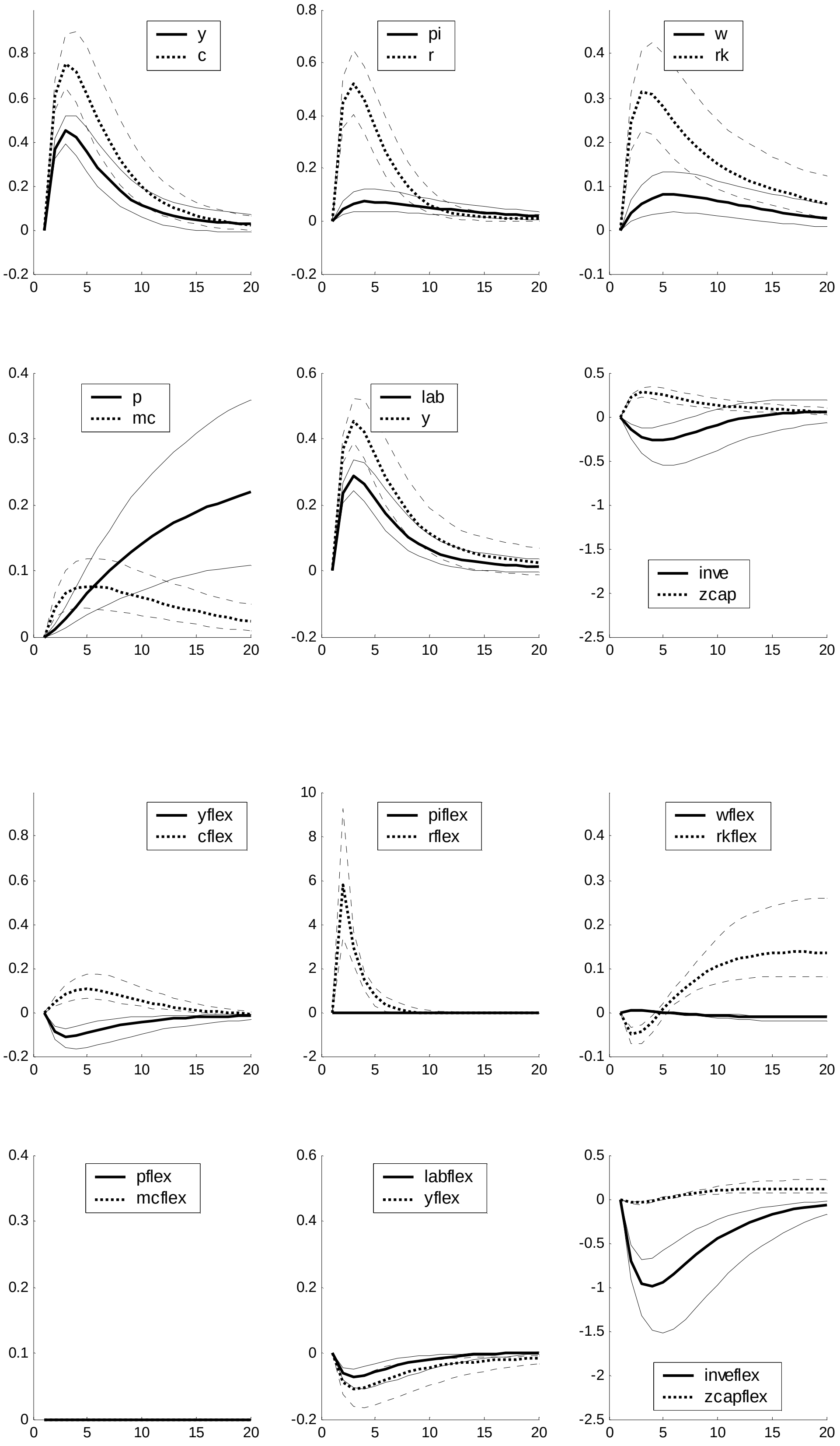
Graph 5: Comparison of the covariance based on the DSGE model and the observed data (dotted line)



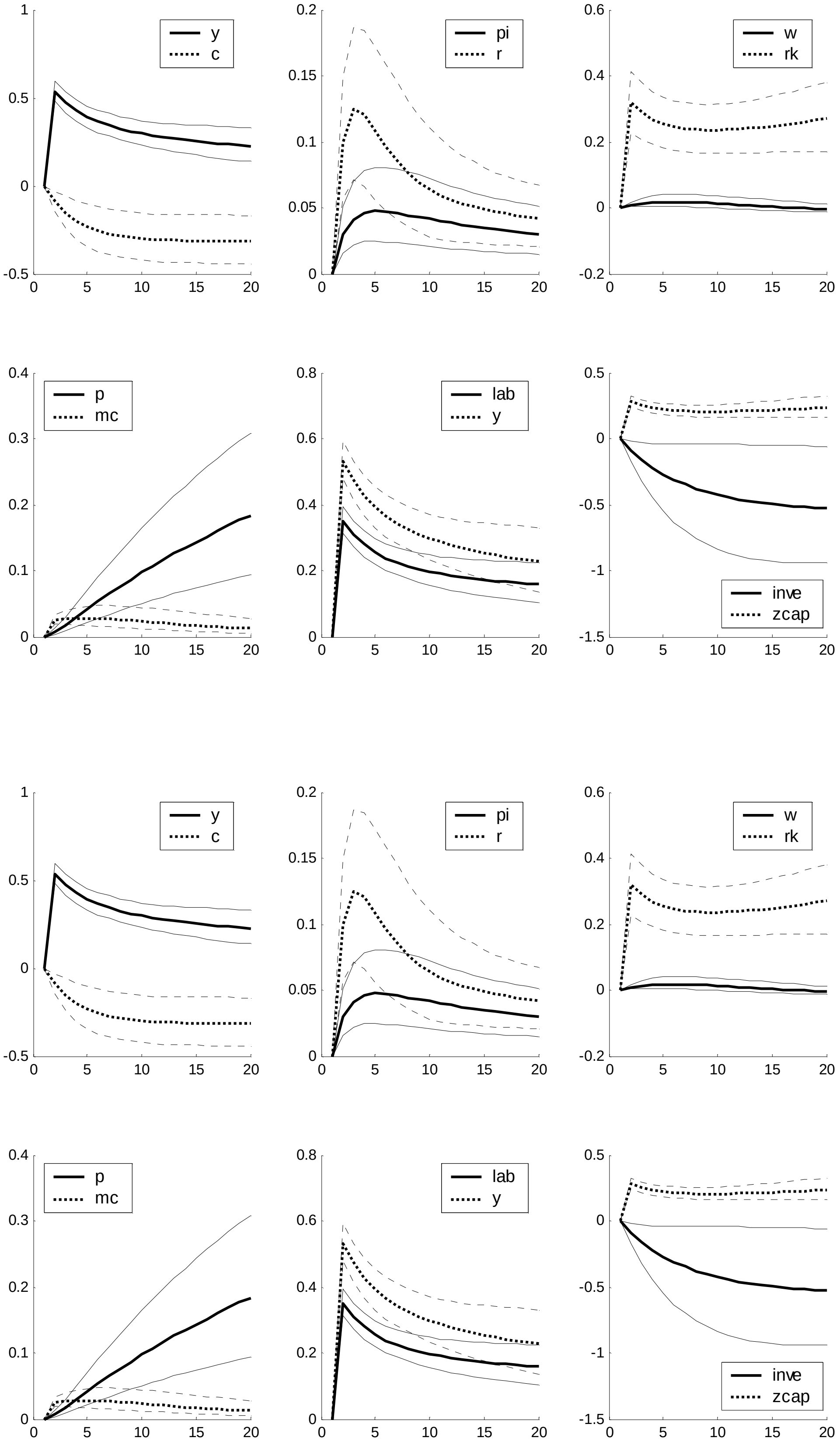
Graph 6: Impulse response of a productivity shock: sticky price (upper 6) and flexible price (lower 6)



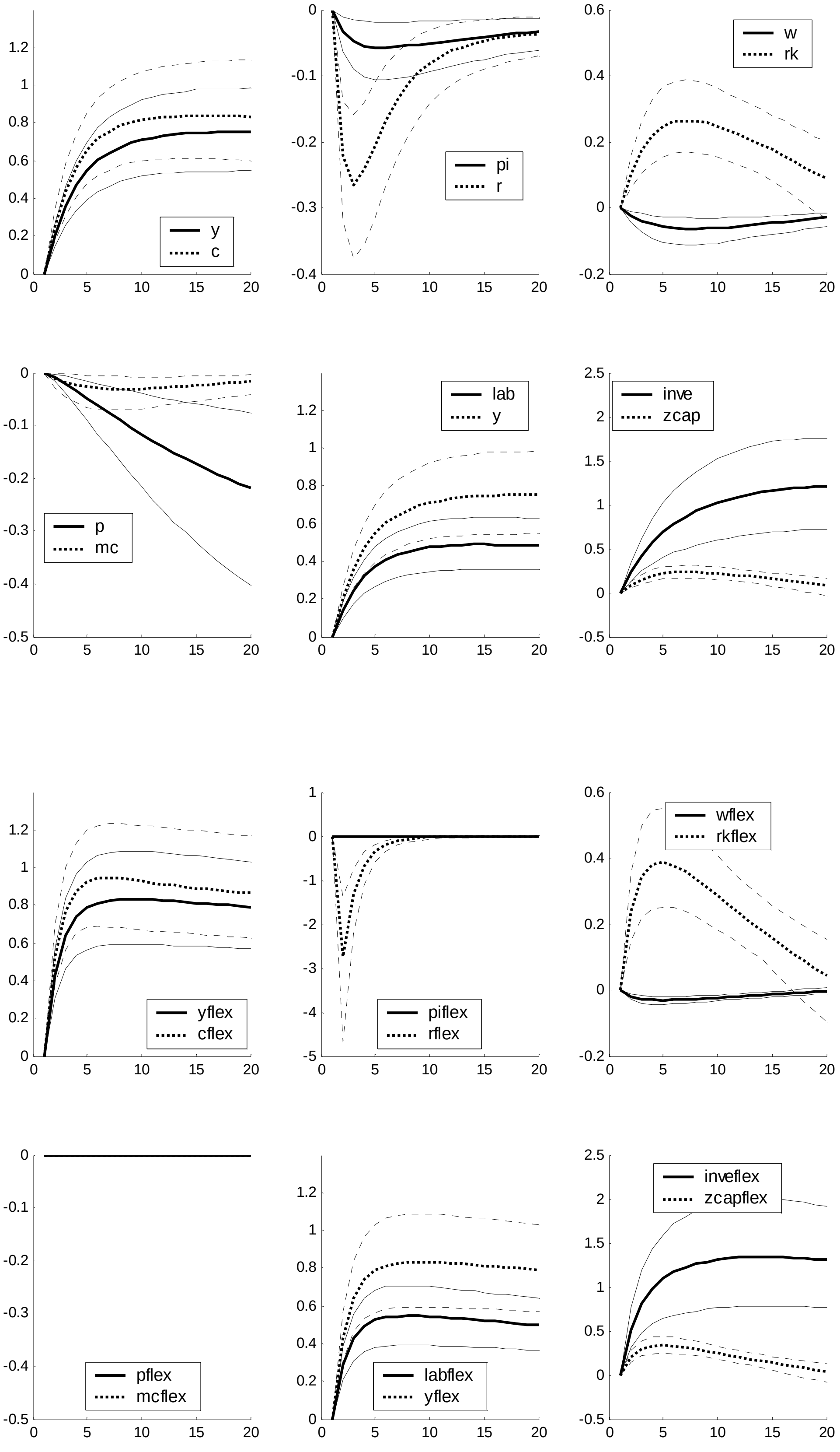
Graph 7: Impulse response of a preference shock: sticky price (upper 6) and flexible price (lower 6)



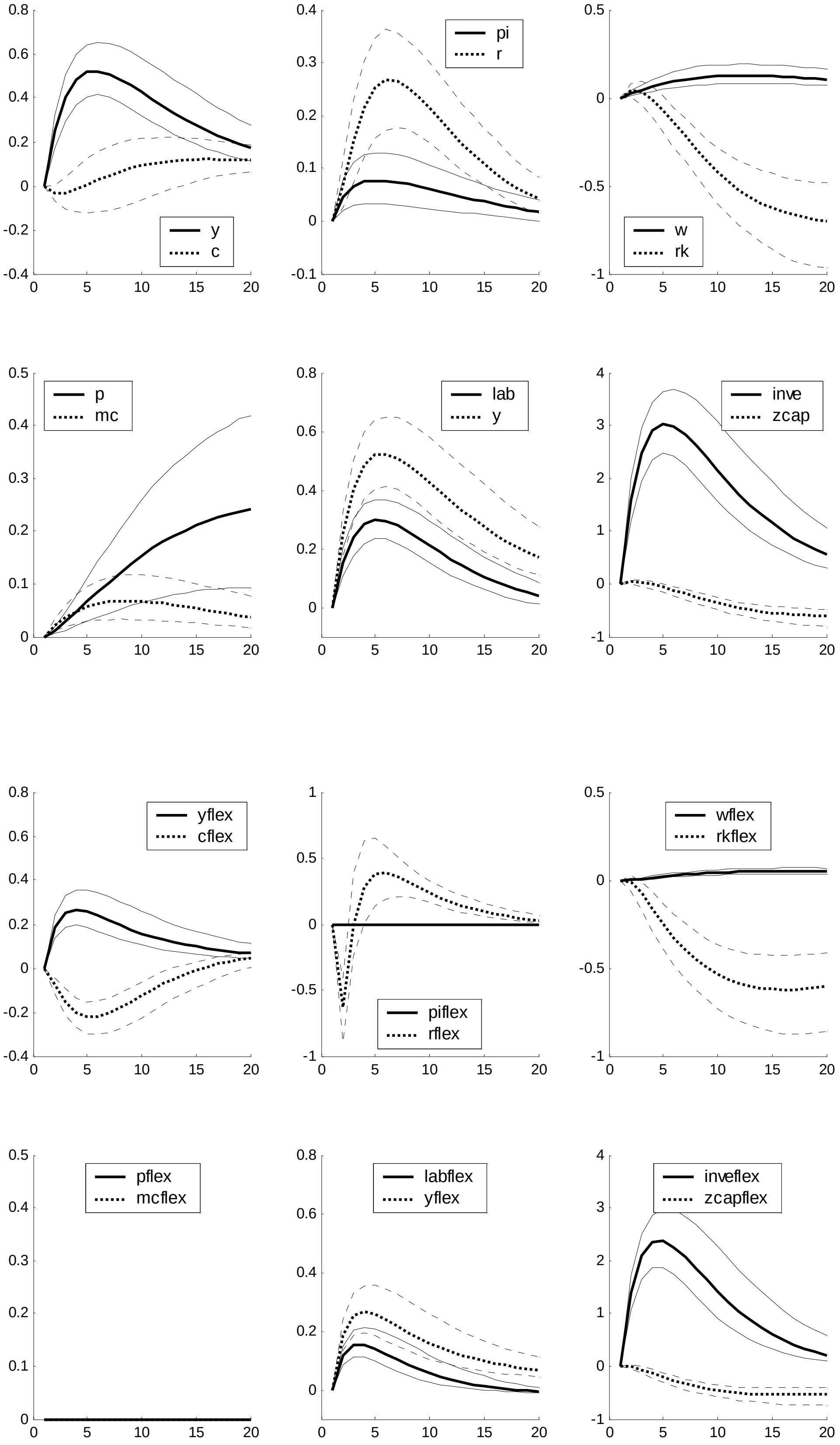
Graph 8: Impulse response of a public spending shock: sticky price (upper 6) and flexible price (lower 6)



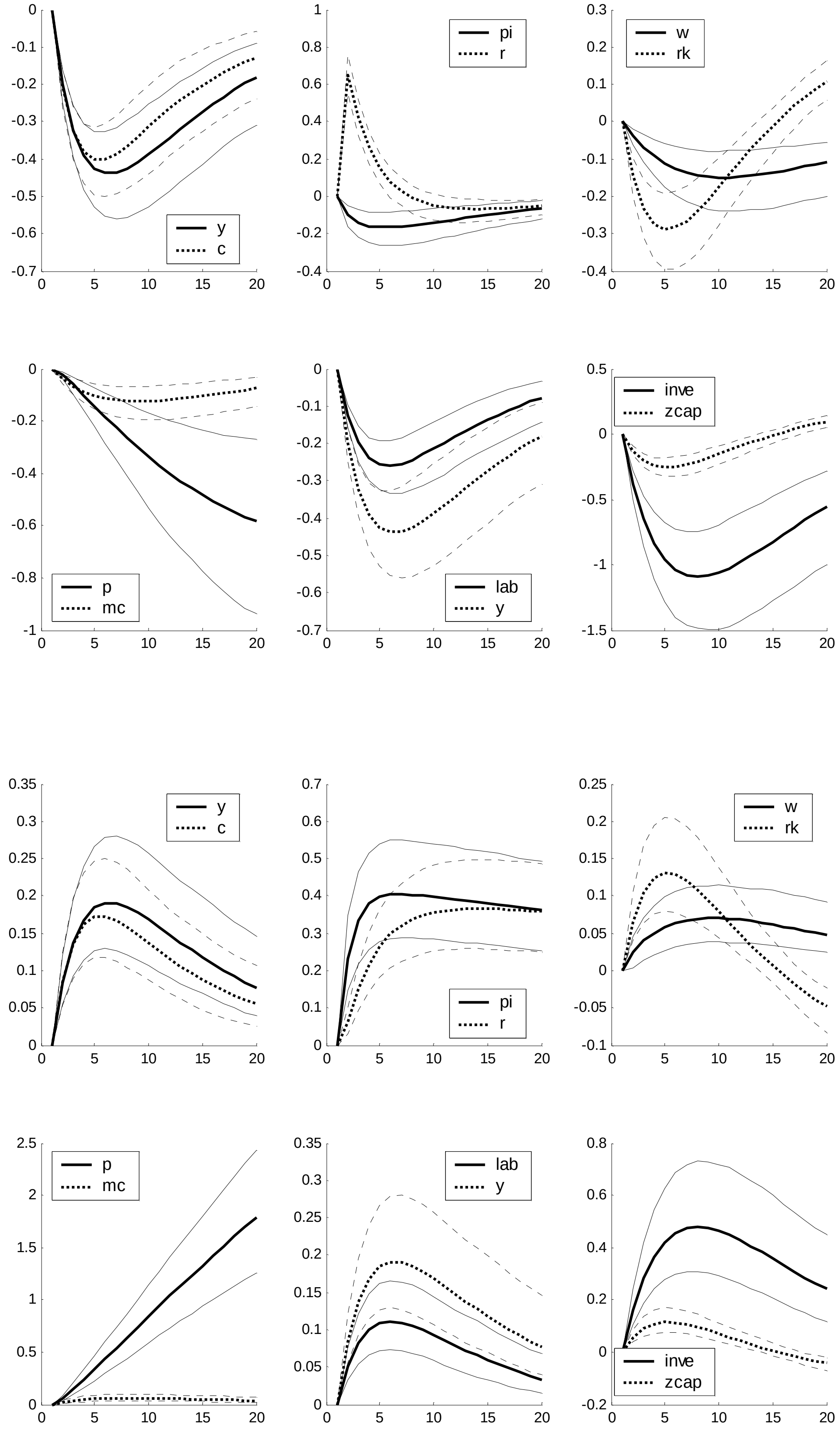
Graph 9: Impulse response of a labour supply shock: sticky price (upper 6) and flexible price (lower 6)



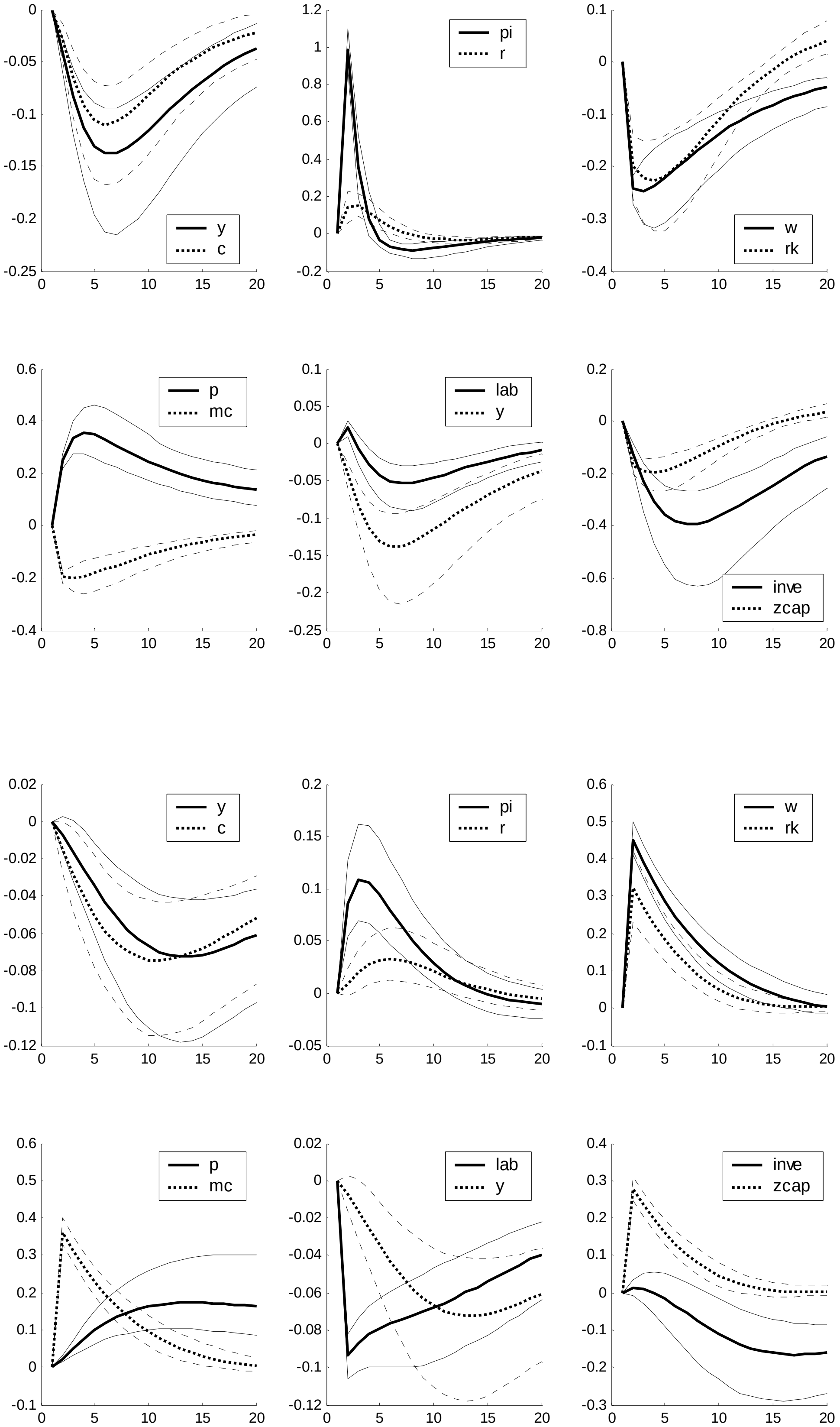
Graph 10: Impulse response of a investment shock: sticky price (upper 6) and flexible price (lower 6)



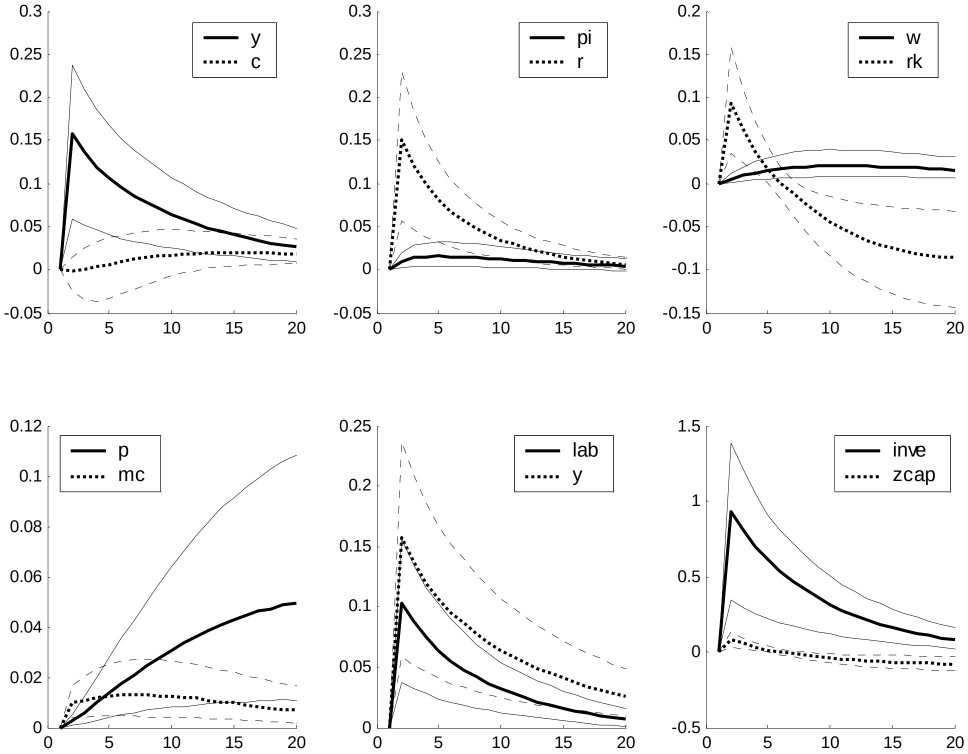
Graph 11: Impulse response of an interest rate shock (upper 6) and inflation objective shock (lower 6)



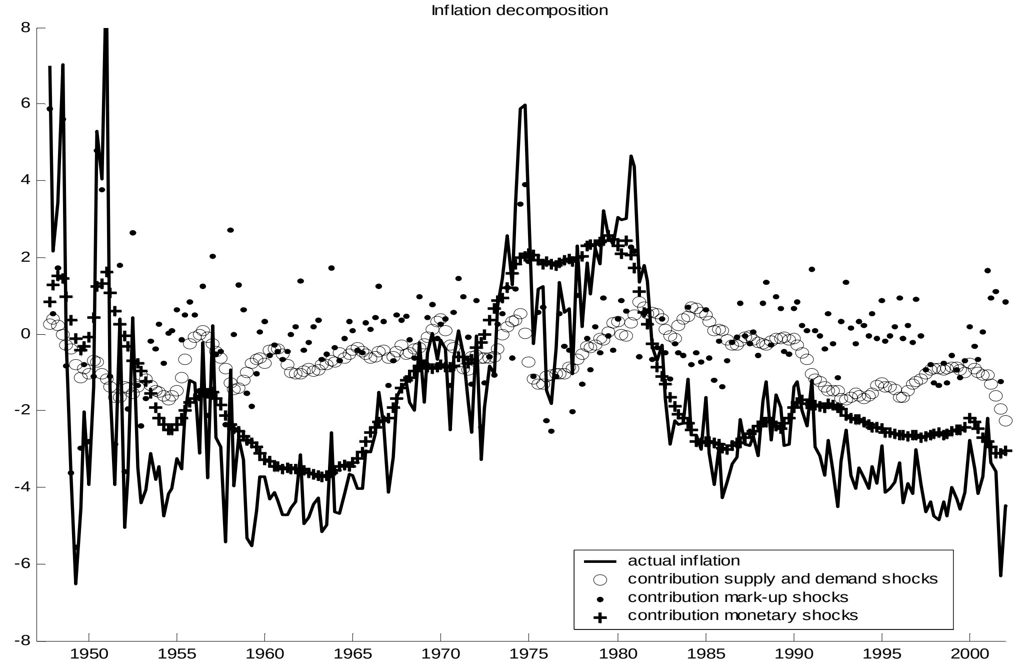
Graph 10: Impulse response of a price mark-up shock (upper 6) and a wage mark-up shock (lower 6)

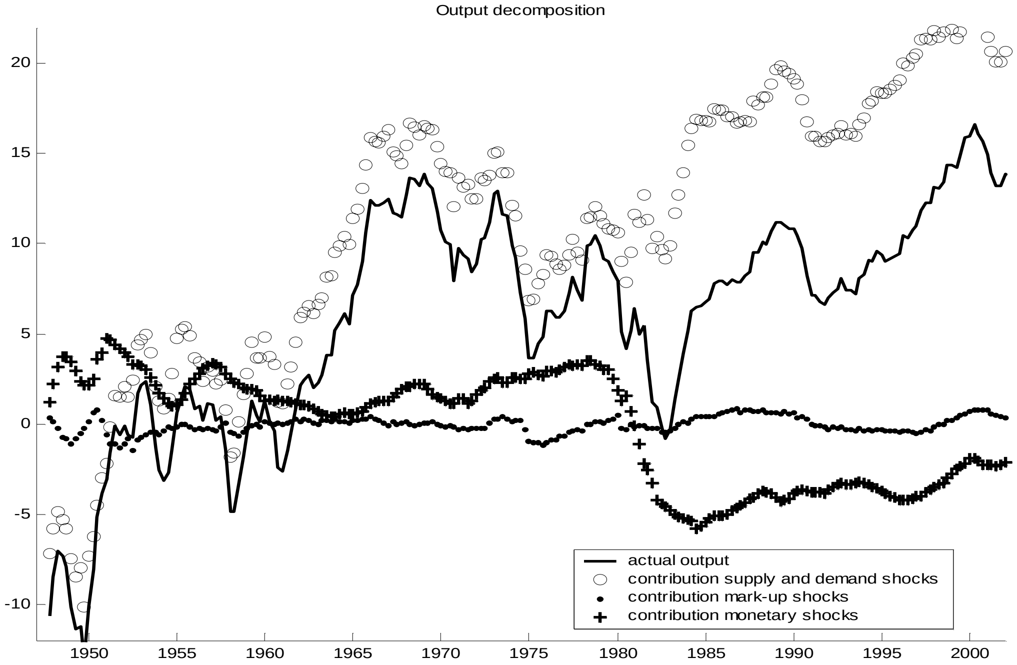


Graph 13: Impulse response of a equity price mark-up shock

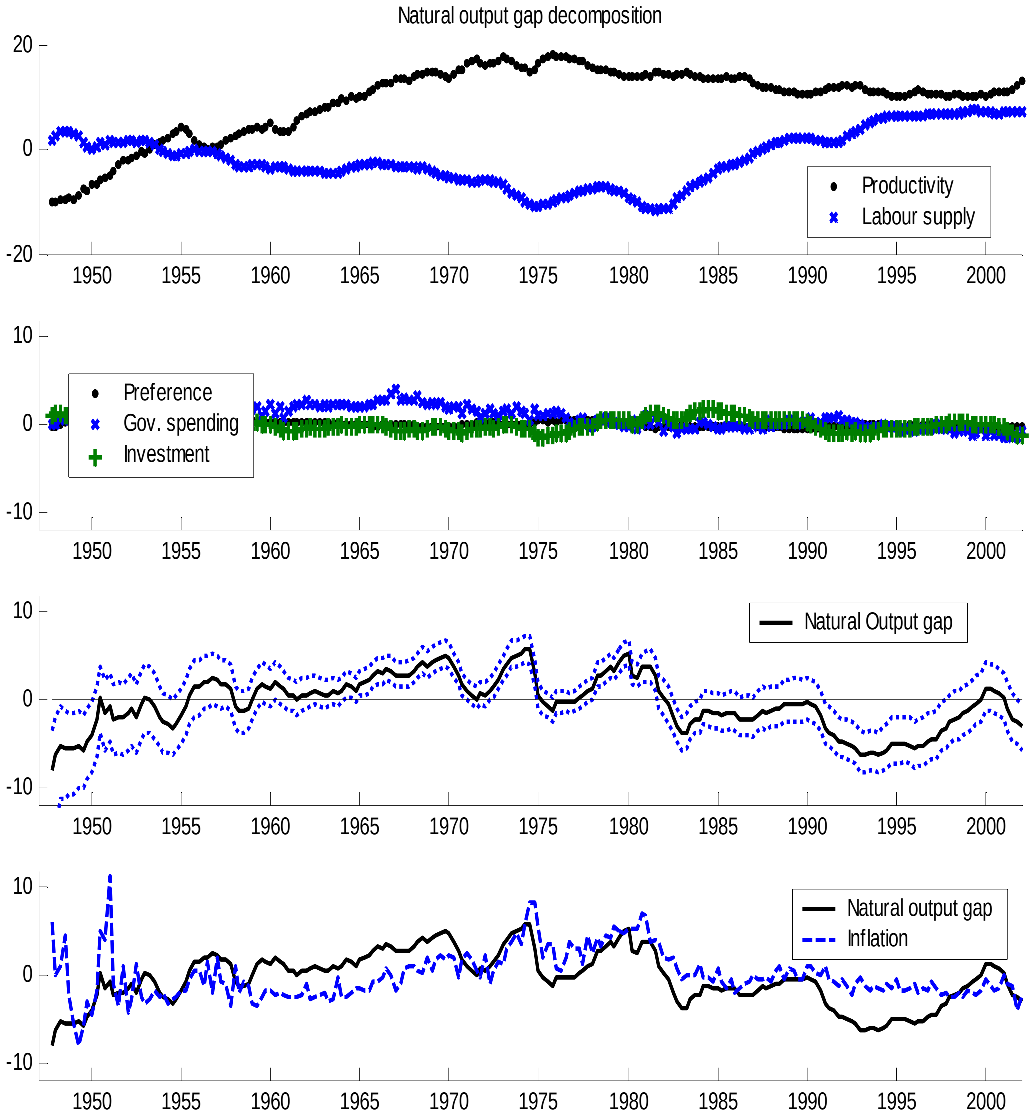


Graph 14: Historical decomposition of inflation and output





Graph 15: Natural output level and Output gap



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