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WORKING PAPER NO. 171

AN ESTIMATED STOCHASTIC DYNAMIC GENERAL EQUILIBRIUM MODEL OF THE EURO AREA

BY FRANK SMETS
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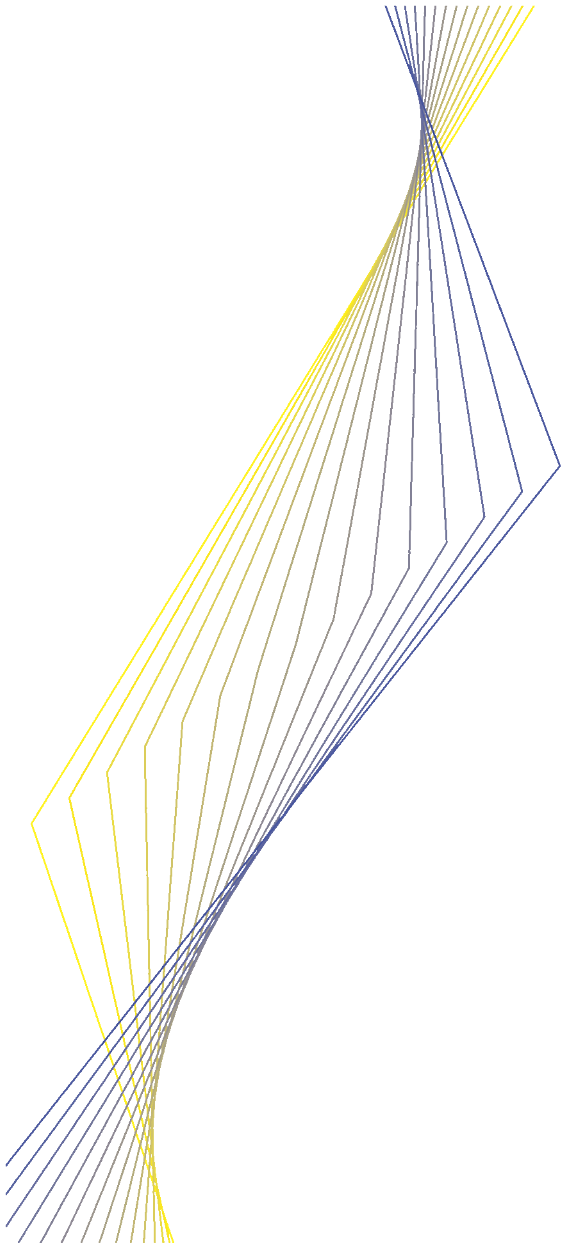

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AN ESTIMATED STOCHASTIC DYNAMIC GENERAL EQUILIBRIUM MODEL OF THE EURO AREA

BY FRANK SMETS AND RAF WOUTERS*

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Abstract

This paper develops and estimates a stochastic dynamic general equilibrium (SDGE) model with sticky prices and wages for the euro area. The model incorporates various other features such as habit formation, costs of adjustment in capital accumulation and variable capacity utilisation. It is estimated with Bayesian techniques using seven key macro-economic variables: GDP, consumption, investment, prices, real wages, employment and the nominal interest rate. The introduction of ten orthogonal structural shocks (including productivity, labour supply, investment, preference, cost-push and monetary policy shocks) allows for an empirical investigation of the effects of such shocks and of their contribution to business cycle fluctuations in the euro area. Using the estimated model, the paper also analyses the output (real interest rate) gap, defined as the difference between the actual and model-based potential output (real interest rate).

Key words: SDGE models; monetary policy; euro area

JEL-classification: E4-E5

Non-technical summary:

With the adoption of the euro and the start of the single monetary policy in EMU, there has been an increased need to understand the determinants of developments in the main aggregate euro area macro-economic time series. In this paper we, first, develop a stochastic dynamic general equilibrium (SDGE) model for the euro area, which features a number of frictions that appear to be necessary to capture the empirical persistence in the main euro area macro-economic data. Many of these frictions have become quite standard in the SDGE literature. The model exhibits both sticky nominal prices and wages that adjust following a staggered Calvo mechanism. The introduction of partial indexation of the prices and wages that can not be re-optimised results in a more general dynamic inflation and wage specification that will also depend on past inflation. The model incorporates a variable capital utilisation, where the cost of adjusting the utilisation rate is expressed in terms of consumption goods. This tends to smooth the adjustment of the rental rate of capital in response to changes in output. Costs of adjusting the capital stock are expressed as a function of the change in investment, rather than the level of investment as is commonly done. Finally, external habit formation in consumption is used to introduce the necessary empirical persistence in the consumption process.

Next, we estimate the SDGE model using Bayesian estimation techniques. For that we introduce a full set of structural shocks to the various structural equations. Next to two “supply” shocks, a productivity and a labour supply shock, we add three “demand” shocks (a preference shock, a shock to the investment adjustment cost function, and a government consumption shock), three “cost-push” shocks (modelled as shocks to the mark-up in the goods and labour markets and a shock to the required risk premium on capital) and two monetary policy shocks. We estimate the parameters of the model and the stochastic processes governing the structural shocks using seven key macro-economic time series in the euro area: real GDP, consumption, investment, the GDP deflator, the real wage, employment and the nominal short-term interest rate. Following recent developments in Bayesian estimation techniques, we estimate the model by minimising the posterior distribution of the model parameters based on the linearised state-space representation of the SDGE model.

Several results are worth highlighting. First, we compare the empirical performance of the SDGE model with those of standard and Bayesian Vector Autoregressions (VARs) estimated on the same data set and find, on the basis of the marginal likelihood and the Bayes factors, that the estimated SDGE model is performing better than standard VARs and at least as well as the best BVAR we consider. This suggests that the current generation of SDGE models with sticky prices and wages is sufficiently rich to capture the stochastics and the dynamics in the data, as long as a sufficient number of structural shocks is considered. These models can therefore provide a useful tool for monetary policy analysis in an empirically plausible set-up.

Second, the estimation procedure yields a plausible set of estimates for the structural parameters of the sticky price and wage SDGE model. In contrast to some of the results for the US, we find that there is a considerable degree of price stickiness in the euro area. This feature appears to be important to account for the empirical persistence of euro area inflation in spite of the presence of sticky wages and variable capacity utilisation which tend to introduce stickiness in real wages and marginal costs. Another important parameter, which empirically does not appear to be pinned down very precisely, is the elasticity of labour supply. We estimate this elasticity to be relatively high, which has important implications for how the natural output level responds to the various structural shocks.

Third, we analyse the effects of the various structural shocks on the euro area economy (and the uncertainty surrounding those effects). Overall, we find that qualitatively those effects are in line with the existing evidence. For example, a temporary monetary policy tightening, associated with a temporary increase in the nominal and real interest rate, has a hump-shaped negative effect on both output and inflation. Similarly, a positive productivity shock leads to a gradual increase in output, consumption, investment and the real wage, but has a negative impact on employment as documented for the United States in other studies. One feature of the impulse responses to the various "demand" shocks which may be less in line with existing evidence is the strong crowding out effect. This effect is accentuated by the high estimated elasticity of labour supply.

Fourth, the introduction and estimation of a set of orthogonal structural shocks allows us to examine the relative contribution of the various shocks to the empirical dynamics of the macro economic time series in the euro area. Overall, there are three structural shocks that explain a significant fraction of output, inflation and interest rates at the medium to long-term horizon: the preference shock, the labour supply shock and the monetary policy shock. In addition, the price mark-up shock is an important determinant of inflation, but not of output, while the productivity shock determines about 10% of output variations, but not of inflation.

Finally, as an illustration we also use the model to calculate the potential output level and real interest rate and the corresponding gaps. We define the efficient output level as the output level that is driven by "supply and demand" shocks when prices and wages are flexible. We show that the confidence bands around these estimated gaps (and in particular the real interest rate gap) are quite large.

1. Introduction

In this paper we present and estimate a stochastic dynamic general equilibrium (SDGE) model for the euro area using a Bayesian approach. Following Christiano, Eichenbaum and Evans (CEE, 2001) the model features a number of frictions that appear to be necessary to capture the empirical persistence in the main euro area macro-economic data. Many of these frictions have become quite standard in the SDGE literature. Following Kollmann (1997) and Erceg, Henderson and Levin (2000), the model exhibits both sticky nominal prices and wages that adjust following a Calvo mechanism. However, the introduction of partial indexation of the prices and wages that can not be re-optimised results in a more general dynamic inflation and wage specification that will also depend on past inflation. Following Greenwood, Hercowitz, and Huffmann (1988) and King and Rebelo (2000) the model incorporates a variable capital utilisation rate. This tends to smooth the adjustment of the rental rate of capital in response to changes in output. As in CEE (2001), the cost of adjusting the utilisation rate is expressed in terms of consumption goods. We also follow CEE (2001) by modelling the cost of adjusting the capital stock as a function of the change in investment, rather than the level of investment as is commonly done. Finally, external habit formation in consumption is used to introduce the necessary empirical persistence in the consumption process (See Fuhrer (2000) and McCallum and Nelson (1999)).

While the model used in this paper has many elements in common with that used in CEE (2001), the analysis differs mainly in the number of structural shocks we introduce and the methodology for estimating the SDGE model. We introduce a full set of structural shocks to the various structural equations.[1] Next to two "supply" shocks, a productivity and a labour supply shock, we add three "demand" shocks (a preference shock, a shock to the investment adjustment cost function, and a government consumption shock), three "cost-push" shocks (modelled as shocks to the mark-up in the goods and labour markets and a shock to the required risk premium on capital) and two monetary policy shocks. We estimate the parameters of the model and the stochastic processes governing the structural shocks using seven key macro-economic time series in the euro area: real GDP, consumption, investment, the GDP deflator, the real wage, employment and the nominal short-term interest rate. Following recent developments in Bayesian estimation techniques (see, e.g., Geweke (1999) and Schorfheide (2002)), we estimate the model by minimising the posterior distribution of the model parameters based on the linearised state-space representation of the SDGE model.

Several results are worth highlighting. First, we compare the empirical performance of the SDGE model with those of standard and Bayesian Vector Autoregressions (VARs) estimated on the same data set and find, on the basis of the marginal likelihood and the Bayes factors, that the estimated SDGE model is performing better than standard VARs and at least as well as the best BVAR we consider. This suggests that the current generation of SDGE models with sticky prices and wages (as, for example, analysed in

[1] CEE (2001) only consider the effects of a monetary policy shock.

CEE, 2001) is sufficiently rich to capture the stochastics and the dynamics in the data, as long as a sufficient number of structural shocks is considered. These models can therefore provide a useful tool for monetary policy analysis in an empirically plausible set-up.

Second, the estimation procedure yields a plausible set of estimates for the structural parameters of the sticky price and wage SDGE model. In contrast to the results of CEE (2001) for the US, we find that there is a considerable degree of price stickiness in the euro area. This feature appears to be important to account for the empirical persistence of euro area inflation in spite of the presence of sticky wages and variable capacity utilisation which tend to introduce stickiness in real wages and marginal costs. At this point it is not clear whether this difference is a result of structural differences between the US and the euro area, differences in the underlying structural model or differences in the estimation methodology.[2] Another important parameter, which empirically does not appear to be pinned down very precisely, is the elasticity of labour supply. We estimate this elasticity to be relatively high, which has important implications for how the natural output level responds to the various structural shocks.

Third, we analyse the effects of the various structural shocks on the euro area economy (and the uncertainty surrounding those effects). Overall, we find that qualitatively those effects are in line with the existing evidence. For example, a temporary monetary policy tightening, associated with a temporary increase in the nominal and real interest rate, has a hump-shaped negative effect on both output and inflation as in Peersman and Smets (2000). Similarly, a positive productivity shock leads to a gradual increase in output, consumption, investment and the real wage, but has a negative impact on employment as documented for the United States in Gali (1999). One feature of the impulse responses to the various "demand" shocks which may be less in line with existing evidence is the strong crowding out effect. This effect is accentuated by the high estimated elasticity of labour supply.

Fourth, the introduction and estimation of a set of orthogonal structural shocks allows us to examine the relative contribution of the various shocks to the empirical dynamics of the macro economic time series in the euro area. Overall, there are three structural shocks that explain a significant fraction of output, inflation and interest rates at the medium to long-term horizon: the preference shock, the labour supply shock and the monetary policy shock. In addition, the price mark-up shock is an important determinant of inflation, but not of output, while the productivity shock determines about 10% of output variations, but not of inflation.

Finally, as an illustration we also use the model to calculate the potential output level and real interest rate and the corresponding gaps. We define the efficient output level as the output level that is driven by "supply and demand" shocks when prices and wages are flexible. We show that the confidence bands around these estimated gaps (and in particular the real interest rate gap) are quite large.

The rest of the paper is structured as follows. Section 2 presents the derivation of the linearised model. In Section 3, we, first, discuss the estimation methodology, then, present the main results and, finally,

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2 Another hypothesis is that due to heterogeneity in the persistence of the national inflation rates in the countries that form the euro area, the use of aggregate euro area inflation data induces an upward bias in the estimated persistence of inflation.

compare the empirical performance of the estimated SDGE model with that of various VARs. In Section 4, we analyse the impulse responses of the various structural shocks and their contribution to the developments in the euro area economy. Section 5 discusses how the economy would respond under flexible prices and wages and derives a corresponding output and real interest rate gap. Finally, Section 6 reviews some of the main conclusions that we can draw from the analysis and contains suggestions for further work.

2. An SDGE model for the euro area

In this section we derive and present the linearised SDGE model that we estimate in Section 3. The model is an application of the real business cycle (RBC) methodology to an economy with sticky prices and wages.[3] Households maximise a utility function with three arguments (goods, money and leisure) over an infinite life horizon. Consumption appears in the utility function relative to a time-varying external habit variable.[4] 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 allocate wealth among cash on the one hand and riskless bonds on the other hand. Households also 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.[5] 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 can not be freely set, 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 this Section we sketch out the main building blocks.

2.1 The household sector

There is a continuum of households indicated by index τ. Households differ in that they supply a differentiated type of labour. So, each household has a monopoly power over the supply of its labour. Each household τ maximises an intertemporal utility function given by:

$$(1) \qquad E_0 \sum_{t=0}^{\infty} \beta^t U_t^{\tau}$$

where β is the discount factor and the instantaneous utility function is separable in consumption, labour (leisure) and real balances:

---

3 This model is a version of the model considered in Kollmann (1997) and features monopolistic competition in both the goods and labour markets. A similar model was discussed in Dombrecht and Wouters (2000). A closed economy version is analysed in Erceg, Henderson and Levin (2000). In addition, several features of CEE (2001) are introduced.

4 Habit depends on lagged aggregate consumption which is unaffected by any one agent's decisions. Abel (1990) calls this the "catching up with the Joneses" effect.

5 See King and Rebelo (2000).

(2) $$U_t^{\tau} = \varepsilon_t^B \left(\frac{1}{1-\sigma_c} \left(C_t^{\tau} - H_t \right)^{1-\sigma_c} - \frac{\varepsilon_t^L}{1+\sigma_l} \left(\ell_t^{\tau} \right)^{1+\sigma_l} + \frac{\varepsilon_t^M}{1-\sigma_m} \left(\frac{M_t^{\tau}}{P_t} \right)^{1-\sigma_m} \right)$$

Utility depends positively on the consumption of goods, C_t^{τ}, relative to an external habit variable, H_t, positively on real cash balances, M_t^{τ} / P_t and negatively on labour supply ℓ_t^{τ}. 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, and σ_m represents the inverse of the elasticity of money holdings with respect to the interest rate.

Equation (2) above also contains three preference shocks: ε_t^B represents a general shock to preferences that affects the intertemporal substitution of households (preference shock); ε_t^L represents a shock to the labour supply and ε_t^M is a money demand shock.

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

(3) $$H_t = h\,C_{t-1}$$

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

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

Households hold their financial wealth in the form of cash balances M_t and 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) $$Y_t^{\tau} = (w_t^{\tau} l_t^{\tau} + A_t^{\tau}) + (r_t^k z_t^{\tau} K_{t-1}^{\tau} - \Psi(z_t^{\tau}) K_{t-1}^{\tau}) + Div_t^{\tau}$$

Total income consists of three components: labour income plus the net cash inflow from participating in state-contingent securities ($w_t^{\tau} l_t^{\tau} + A_t^{\tau}$); 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}).

Following CEE (2001), we assume that there exist state-contingent securities that insure the households against variations in household specific labour income. As a result, the first component in the household's income will be equal to aggregate labour income and the marginal utility of wealth will be identical across different types of households.[6]

[6] See CEE (2001) for a more complete analysis.

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:

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

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:[7]

(7) $$\lambda_t = \varepsilon_t^b \left(C_t - H_t\right)^{-\sigma_c}$$

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

The demand for cash that follows from the household's optimisation problem is given by:

(8) $$\varepsilon_t^M \left(\frac{M_t}{P_t}\right)^{-\sigma_m} = \left(C_t - H_t\right)^{-\sigma_c} - \frac{1}{1+i_t}$$

Real cash holdings depend positively on consumption (relative to the habit) with an elasticity equal to σ_c / σ_m and negatively on the nominal interest rate. In what follows we will take the nominal interest rate as the central bank's policy instrument. Due to the assumption that consumption and cash holdings are additively separable in the utility function, cash holding will not enter in any of the other structural equations. Equation (8) then becomes completely recursive to the rest of the system of equations.[8]

2.1.2 Labour supply decisions and the wage setting equation

Households act as price-setters in the labour market. Following Kollmann (1997) and Erceg, Henderson and Levin (2000), 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

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

8 In the rest of the paper, we will ignore equation (8). In future work we intend to examine the implications of more general money demand functions for the behaviour of money in this kind of SDGE models. See Casares (2001), Ireland (2001) and Andres, Lopez-Salido and Valles (2002) for models in which money balances enter the aggregate demand equation. Nelson (2002) and CEE (2001) consider costs in adjusting cash balances. In that case, expectations of future marginal utility of consumption and the nominal interest rate enter the money demand equation, which allows for a potentially more interesting informational role for money balances.

near future. In addition, we allow for a partial 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:

(9) $$W_t^{\tau} = \left(\frac{P_{t-1}}{P_{t-2}} \right)^{\gamma_w} W_{t-1}^{\tau}$$

where γ_w is the degree of wage indexation. When $\gamma_w = 0$, there is no indexation and the wages that can not be re-optimised remain constant. When $\gamma_w = 1$, there is perfect indexation to past inflation.

Households set their nominal wages to maximise their intertemporal objective function subject to the intertemporal budget constraint and the demand for labour which is determined by:

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

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

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

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

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

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

where U_{t+i}^l is the marginal disutility of labour and U_{t+i}^C is the marginal utility of consumption. Equation (13) 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).[9] 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 (12), the law of motion of the aggregate wage index is given by:

---

9 Standard RBC models typically assume an infinite supply elasticity of labour in order to obtain realistic business cycle properties 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.

$$(W_t)^{-1/\lambda_{w,t}} = \xi \left(W_{t-1} \left(\frac{P_{t-1}}{P_{t-2}} \right)^{\gamma_w} \right)^{-1/\lambda_{w,t}} + (1-\xi)(\tilde{w}_t)^{-1/\lambda_{w,t}} \tag{14}$$

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)).[10]

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:

$$K_t = K_{t-1}[1-\tau] + \left[1 - S\left(\varepsilon_t^I I_t / I_{t-1}\right)\right] I_t , \tag{15}$$

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.[11] $S(.)$ 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 investment cost function, which is assumed to follow a first-order autoregressive process with an IID-Normal error term: $\varepsilon_t^I = \rho_I \varepsilon_{t-1}^I + \eta_t^I$.[12]

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

$$Q_t = E_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t} \left(Q_{t+1}(1-\tau) + z_{t+1} r_{t+1}^k - \Psi(z_{t+1}) \right) \right] , \tag{16}$$

$$Q_t S'\left(\frac{\varepsilon_t^I I_t}{I_{t-1}}\right) \frac{\varepsilon_t^I I_t}{I_{t-1}} + \beta E_t Q_{t+1} \frac{\lambda_{t+1}}{\lambda_t} S'\left(\frac{\varepsilon_{t+1}^I I_{t+1}}{I_t}\right)\left(\frac{\varepsilon_{t+1}^I I_{t+1}}{I_t}\right) \frac{I_{t+1}}{I_t} = 1 \tag{17}$$

$$r_t^k = \Psi'(z_t) \tag{18}$$

---

[10] 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).

[11] See CEE (2001).

[12] See, Keen (2002) for a recent SDGE model with sticky prices in which one of the shocks comes from changes in costs of adjusting investment.

Equation (16) 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.

The first order condition for the utilisation rate (18) 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.[13]

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 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:

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

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:

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

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:

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[13] Another assumption which will tend to have the same effect is that capital is perfectly mobile between firms. This is a rather 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.

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

2.2.2 Intermediate goods producers

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

(22) $$y_t^j = \varepsilon_t^a \tilde{K}_{j,t}^{\alpha} L_{j,t}^{1-\alpha} - \Phi ,$$

where ε_t^a is the productivity shock, $\tilde{K}_{j,t}$ 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 (11) and Φ is a fixed cost.

Cost minimisation implies:

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

Equation (23) 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:

(24) $$MC_t = \frac{1}{\varepsilon_t^a} W_t^{1-\alpha} r_t^{k\alpha} (\alpha^{-\alpha} (1-\alpha)^{-(1-\alpha)})$$

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

Nominal profits of firm j are then given by:

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

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

$(1-\xi_p)$. Following CEE (2001), prices of firms that do not receive a price signal are indexed to last period's inflation rate.[14] Profit optimisation by producers that are "allowed" to re-optimise their prices at time t results in the following first-order condition:

$$(26) \qquad E_t \sum_{i=0}^{\infty} \beta^i \xi_p{}^i \lambda_{t+i} y_{t+i}^j \left(\frac{\tilde{p}_t^j}{P_t} \left(\frac{(P_{t-1+i} / P_{t-1})}{P_{t+i} / P_t} \right)^{\gamma_p} - (1+\lambda_{p,t+i}) mc_{t+i} \right) = 0$$

Equation (26) 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 (21) implies that its law of motion is given by:

$$(27) \qquad (P_t)^{-1/\lambda_{p,t}} = \xi_p \left(P_{t-1} \left(\frac{P_{t-1}}{P_{t-2}} \right)^{\gamma_p} \right)^{-1/\lambda_{p,t}} + (1-\xi_p) \left(\tilde{p}_t^j \right)^{-1/\lambda_{p,t}} .$$

2.3 Market equilibrium

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

$$(30) \qquad Y_t = C_t + G_t + I_t + \psi(z_t) K_{t-1}$$

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. This rule will be discussed in the following sections of the paper. In order to maintain money market equilibrium, the money supply adjusts endogenously to meet the money demand at those interest rates.

In the capital market, equilibrium means that the government debt is held by domestic investors at the market interest rate R_t.

[14] 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.

2.4 The linearised model

For the empirical analysis of Section 3 we linearise the model equations described above around the non-stochastic steady state. Below we summarise the resulting linear rational expectations equations. The ^ above a variable denotes its log deviation from steady state. Variables dated at time t+1 refer to the rational expectation of those variables.

The *consumption equation* with external habit formation is given by:

$$(31) \qquad \hat{C}_t = \frac{h}{1+h}\hat{C}_{t-1} + \frac{1}{1+h}\hat{C}_{t+1} - \frac{1-h}{(1+h)\sigma_c}(\hat{R}_t - \hat{\pi}_{t+1}) + \frac{1-h}{(1+h)\sigma_c}(\hat{\varepsilon}_t^b - \hat{\varepsilon}_{t+1}^b)$$

When $h = 0$, this equation reduces to the traditional forward-looking consumption equation. With external habit formation, consumption depends on a weighted average of past and expected future consumption. Note that in this case the interest elasticity of consumption depends not only on the intertemporal elasticity of substitution, but also on the habit persistence parameter. A high degree of habit persistence will tend to reduce the impact of the real rate on consumption for a given elasticity of substitution.

The *investment equation* is given by:

$$(32) \qquad \hat{I}_t = \frac{1}{1+\beta}\hat{I}_{t-1} + \frac{\beta}{1+\beta}\hat{I}_{t+1} + \frac{\varphi}{1+\beta}\hat{Q}_t + \beta\hat{\varepsilon}_{t+1}^I - \hat{\varepsilon}_t^I$$

where $\varphi = 1/\bar{S}''$. 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 adjustment cost function, $\hat{\varepsilon}_t^I$, (also denoted a negative investment shock) temporarily reduces investment.

The corresponding *Q equation* is given by:

$$(33) \qquad \hat{Q}_t = -(\hat{R}_t - \hat{\pi}_{t+1}) + \frac{1-\tau}{1-\tau+\bar{r}^k}\hat{Q}_{t+1} + \frac{\bar{r}^k}{1-\tau+\bar{r}^k}\hat{r}_{t+1}^k + \eta_t^Q$$

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.[15] 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

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

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.[16]

The *capital accumulation equation* is standard:

$$\hat{K}_t = (1-\tau)\hat{K}_{t-1} + \tau\hat{I}_{t-1} \tag{34}$$

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

$$\hat{\pi}_t = \frac{\beta}{1+\beta\gamma_p}\hat{\pi}_{t+1} + \frac{\gamma_p}{1+\beta\gamma_p}\hat{\pi}_{t-1} + \frac{1}{1+\beta\gamma_p}\frac{(1-\beta\xi_p)(1-\xi_p)}{\xi_p}\left[\alpha\hat{r}_t^k + (1-\alpha)\hat{w}_t - \hat{\varepsilon}_t^a + \eta_t^p\right] \tag{35}$$

Inflation depends on past and expected future inflation and the current marginal cost, which itself is a function of the rental rate on capital, the real wage and the productivity parameter. When $\gamma_p = 0$, this equation reverts to the standard purely forward-looking Phillips curve. In other words, the degree of indexation determines how backward looking the inflation process is. 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, partial indexation of nominal wages results in the following real wage equation:

$$\begin{aligned}\hat{w}_t = {} & \frac{\beta}{1+\beta}\hat{w}_{t+1} + \frac{1}{1+\beta}\hat{w}_{t-1} + \frac{\beta}{1+\beta}\hat{\pi}_{t+1} - \frac{1+\beta\gamma_w}{1+\beta}\hat{\pi}_t + \frac{\gamma_w}{1+\beta}\hat{\pi}_{t-1} \\ & - \frac{1}{1+\beta}\frac{(1-\beta\xi_w)(1-\xi_w)}{(1+\frac{(1+\lambda_w)\sigma_L}{\lambda_w})\xi_w}\left[\hat{w}_t - \sigma_L\hat{L}_t - \frac{\sigma_c}{1-h}(\hat{C}_t - h\hat{C}_{t-1}) - \hat{\varepsilon}_t^L - \eta_t^w\right]\end{aligned} \tag{36}$$

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 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:

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

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

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

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

(38) $\hat{Y}_t = (1-\tau k_y - g_y)\hat{C}_t + \tau k_y \hat{I}_t + g_y \varepsilon_t^G = \phi \hat{\varepsilon}_t^a + \phi\alpha\hat{K}_{t-1} + \phi\alpha\psi\hat{r}_t^k + \phi(1-\alpha)\hat{L}_t$,

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.

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

(39)
$$\hat{R}_t = \rho\hat{R}_{t-1} + (1-\rho)\{\overline{\pi}_t + r_\pi(\hat{\pi}_{t-1} - \overline{\pi}_t) + r_Y\hat{Y}_t\} + r_{\Delta\pi}(\hat{\pi}_t - \hat{\pi}_{t-1}) + r_{\Delta y}(\hat{Y}_t - \hat{Y}_{t-1}) - r_a\eta_t^a - r_L\eta_t^L + \eta_t^R$$

The monetary authorities gradually respond to deviations of lagged inflation from an inflation objective. The parameter ρ captures the degree of interest rate smoothing. In addition, there is also a feedback effect from the current change in inflation, the current growth rate in output and current innovations in the technology and labour supply shock variables. The latter two shocks were introduced to capture changes in potential output. Finally, we assume that there are two monetary policy shocks: one is a persistent shock to the inflation objective ($\overline{\pi}_t$); the other is a temporary interest rate shock (η_t^R). The latter will also be denoted a monetary policy shock.

Equations (31) to (39) determine the nine endogenous variables: $\hat{\pi}_t$, $\hat{w}_t$, $\hat{K}_{t-1}$, $\hat{Q}_t$, $\hat{I}_t$, $\hat{C}_t$, $\hat{R}_t$, $\hat{r}_t^k$, $\hat{L}_t$ of our model. 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 (ε_t^a, ε_t^I, ε_t^b, $\hat{\varepsilon}_t^L$, ε_t^G), three "cost-push" shocks (η_t^w, η_t^p and η_t^Q) and two monetary policy shocks ($\overline{\pi}_t$ and η_t^R). The first set of shock variables are assumed to follow an independent first-order autoregressive stochastic process, whereas the second set are assumed to be IID independent processes.

3. Estimation results

In this section we, first, discuss how we estimate the structural parameters and the processes governing the ten structural shocks. Next, we present the main estimation results. Finally, we compare the empirical performance of the estimated SDGE model with a number of a-theoretical VARs.

3.1 Estimation methodology

There are various ways of estimating or calibrating the parameters of a linearised SDGE model. Geweke (1999) distinguishes between the weak and the strong econometric interpretation of SDGE models. The weak interpretation is closest in spirit to the original RBC programme developed by Kydland and Prescott (1982).[17] The parameters of an SDGE model are calibrated in such a way that selected theoretical moments given by the model match as closely as possible those observed in the data. One way of achieving this, is by minimising some distance function between the theoretical and empirical moments of interest. For example, recently, a number of researchers have estimated the parameters in monetary SDGE models by minimising the difference between an empirical and the theoretical impulse response to a monetary policy shock (Rotemberg and Woodford, 1998, and CEE, 2001). The advantage of this approach is that moment estimators are often more robust than the full-information estimators discussed below. In addition, these estimation methods allow the researcher to focus on the characteristics in the data for which the SDGE model, which is necessarily an abstraction of reality, is most relevant.

In contrast, the strong econometric interpretation attempts to provide a full characterisation of the observed data series. For example, following Sargent (1989), a number of authors have estimated the structural parameters of SDGE models using classical maximum likelihood methods.[18] These maximum likelihood methods usually consist of four steps. In the first step, the linear rational expectations model is solved for the reduced form state equation in its predetermined variables. In the second step, the model is written in its state space form. This involves augmenting the state equation in the predetermined variables with an observation equation which links the predetermined state variables to observable variables. In this step, the researcher also needs to take a stand on the form of the measurement error that enters the observation equations.[19] The third step consists of using the Kalman filter to form the likelihood function. In the final step, the parameters are estimated by maximising the likelihood function. Alternatively within this strong interpretation, a Bayesian approach can be followed by combining the likelihood function with prior distributions for the parameters of the model, to form the posterior density function. This posterior can then be optimised with respect to the model parameters either directly or through Monte-Carlo Markov-Chain (MCMC) sampling methods.[20]

The attractions of the strong econometric interpretation are clear. When successful, it provides a full characterisation of the data generating process and allows for proper specification testing and forecasting. Recently, the strong econometric interpretation has gained in attraction for three reasons. First, as is the case in this paper, the dynamics of various SDGE models have been enriched in order to be able to match not only the contemporaneous correlations in the observed data series, but also the serial correlation and

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[17] It is in line with Kydland and Prescott's (1996) emphasis on the fact that the model economy is intended to "mimic the world along a carefully specified set of dimensions".

[18] See, for example, the references in Ireland (1999).

[19] Recently, Ireland (1999) has suggested a way of combining the power of SDGE theory with the flexibility of vector autoregressive time-series models by proposing to model the residuals in the observation equations (which capture the movements in the data that the theory can not explain) as a general VAR proces. This proposed method admits that while SDGE models may be powerful enough to account for and explain many key features of the data, they remain too stylised to possibly capture all of the dynamics that can be found in the data. One problem with this approach is that if the "measurement" error is due to misspecification of the model, there is no reason why it should be uncorrelated with the structural shocks in the model. In this paper, we do not introduce measurement error.

[20] Recent examples of such a Bayesian approach are Otrok (2001), Fernandez-Villaverde and Rubio-Ramirez (2001) and Schorfheide (2002).

cross-covariances. Moreover, various shocks have been added, which avoids the singularity problem and allows for a better characterisation of the unconditional moments in the data. Second, as pointed out by Geweke (1999), the weak econometric interpretation of SDGE models is not necessarily less stringent than the strong interpretation: in spite of the focus on a restricted set of moments, the model is assumed to account for all aspects of the observed data series and these aspects are used in calculating the moments of interest. Third, computational methods have improved so that relatively large models can be solved quite efficiently. In this paper, we follow the strong econometric interpretation of SDGE models.

As in recent papers by Geweke (1998), Fernandez-Villaverde and Rubio-Ramirez (2001), Schorfheide (1999) and Landon-Lane (2000), we apply Bayesian techniques for basically two reasons. First, this approach allows one to formalise the use of prior information coming either from micro-econometric studies or previous macro-econometric studies and thereby makes an explicit link with the previous calibration-based literature. Second, the Bayesian approach provides a framework for evaluating fundamentally misspecified models on the basis of the marginal likelihood of the model or the Bayes' factor. As, for example, shown by Geweke (1998), the marginal likelihood of a model is directly related to the predictive density function. The prediction performance is a natural criterion for validating models for forecasting and policy analysis.[21]

In order to estimate the parameters of the SDGE model presented in section 2, we use data over the period 1970:1-1999:4 on seven key macro-economic variables in the euro area: real GDP, real consumption, real investment, the GDP deflator, real wages, employment and the nominal interest rate.[22] As we do not have good measures of the area-wide capital stock, the value of capital or the rental rate on capital, we will assume these variables are not observed. Moreover, because there is no consistent euro area data available on aggregate hours worked in the euro area, we need to use employment instead. As the employment variable is likely to respond more slowly to macro-economic shocks than total hours worked, we assume that in any given period only a constant fraction, ξ_e, of firms is able to adjust employment to its desired total labour input. The difference is taken up by (unobserved) hours worked per employer.[23] This gives rise to the following auxiliary equation for employment:

$$(40) \qquad \hat{E}_t = \beta \hat{E}_{t+1} + \frac{(1-\beta\xi_e)(1-\xi_e)}{\xi_e}(\hat{L}_t - \hat{E}_t)$$

where $\hat{E}_t$ denotes the number of people employed.

21 An additional advantage of the Bayesian approach is that the posterior distribution provides a complete characterisation of shock and parameter uncertainty, which is crucial for evaluating the usefulness of models for policy. Moreover, from a practical point of view, the use of prior distributions over the parameters makes the optimisation algorithm more stable. This is particular valuable when only relatively small samples of data are available. One drawback is that it can be very computationally intensive, as in general MCMC methods need to be used to draw from the posterior distribution. However, as shown in this paper even for relatively large sets of parameters current PCs can generate big samples in a relatively short period.

22 The data set used is the one constructed in Fagan et al (2001). All variables are treated as deviations around the sample mean. Real variables are detrended by a linear trend, while inflation and the nominal interest rate are detrended by the same linear trend in inflation.

23 As hours-worked is assumed to be completely flexible, the rigidity in employment does not affect the overall labour input.

As discussed above, the seven observable variables need to be explained in terms of ten structural shocks. In order to calculate the likelihood function of the observed data series, we use the Kalman filter as in Sargent (1989). This likelihood function needs to be combined with a prior density for the model parameters to obtain the posterior distribution of the parameters. Before discussing the results, we first discuss the choice of the prior distribution.

A number of parameters were kept fixed from the start of the exercise. This can be seen as a very strict prior. Most of these parameters can be directly related to the steady-state values of the state variables and could therefore be estimated from the means of the observable variables (or linear combinations of them). However, given that our data set is already demeaned, we can not pin them down in the estimation procedure. The discount factor, β, is calibrated to be 0.99, which implies an annual steady state real interest rate of 4%. The depreciation rate, τ, is set equal to 0.025 per quarter, which implies an annual depreciation on capital equal to 10 percent. We set $\alpha = 0.30$, which roughly implies a steady state share of labour income in total output of 70%. The share of steady-state consumption in total output is assumed to be 0.6, while the share of steady-state investment is assumed to be 0.22. This corresponds more or less to the average share of output and investment in total euro area output over the estimation period. It also implies a steady-state capital output ratio of about 2.2. In addition, we also need to fix the parameter capturing the mark-up in wage setting as this parameter is not identified. We set λ_w equal to 0.5, which is somewhat larger than the findings in the micro-econometric studies by Griffin (1996) based on US data.

The first three columns of Table 1 give an overview of our assumptions regarding the prior distribution of the other 34 estimated parameters. All the variances of the shocks are assumed to be distributed as an inverted Gamma distribution with a degree of freedom equal to 2. This distribution guarantees a positive variance with a rather large domain. The precise mean for the prior distribution was based on previous estimation outcomes and trials with a very weak prior. The distribution of the autoregressive parameters in the "supply and demand" shocks is assumed to follow a beta distribution with mean 0.85 and standard error 0.1. The beta distribution covers the range between 0 and 1, but a rather strict standard error was used to have a clear separation between the persistent and the non-persistent shocks. The technology, utility and price setting parameters were assumed to be either Normal distributed or Beta distributed (for the parameters that were restricted to the 0-1 range). The mean was set at values that correspond with other studies in the literature. The standard errors were set so that the domain covers a reasonable range of parameter values. For example, the mean of the Calvo parameters in the price and wage setting equations were set so that average length of the contract is about one year in line with some of the estimates of Gali, Gertler and Lopez-Salido (2001), but the standard error allows for variation between 3 quarters and 2 years. Similarly, the mean of the intertemporal elasticity of substitution is set equal to one, consistent with log preferences and the findings of Casares (2001) for the euro area. The elasticity of the capital utilisation cost function has a mean of 0.2, and includes in its domain the value of 0.1 suggested by King and Rebelo (2000). For some of the other parameters such as the elasticity of the cost of adjusting investment or the share of fixed costs in total production, we took as a starting point the values that were close to those estimated by CEE (2001) for the United States. A wide range of calibrations has been used for the inverse elasticity of labour supply. We took as a starting point a value of 2, which falls in between the relatively low elasticities that are typically estimated in the micro-labour literature and the larger elasticities typically used in SDGE models. Finally, the prior on the coefficients in the monetary policy reaction function are standard: a relatively high long-term coefficient on inflation helps to guarantee a unique solution path when solving the model, the lagged interest rate prior is set at 0.8, and the output reaction coefficient is set around a value that correspond with the Taylor coefficient of 0.5.

3.2 Parameter estimates

In addition to the prior distribution, Table 1 reports two sets of results regarding the parameter estimates. The first set contains the estimated posterior mode of the parameters, which is obtained by directly maximising the log of the posterior distribution with respect to the parameters, and an approximate standard error based on the corresponding Hessian. The second set reports the 5, 50 and 95 percentile of the posterior distribution of the parameters obtained through the Metropolis-Hastings sampling algorithm.[24] The latter is based on 100000 draws. Graph 1 summarises this information visually by plotting the prior distribution, the posterior distribution and the probability curve for a normal distribution with the posterior mode as mean and the corresponding Hessian-based estimate as standard error. In general, both distributions seem to give similar messages.

Overall, most parameters are estimated significantly different from zero. This is true for the standard errors of all the shocks, with the exception of the inflation objective shock, which does not seem to play much of a role. This will also be clear in the forecast error variance decomposition discussed below. With the exception of the productivity shock, all the persistent shocks are estimated to have an autoregressive parameter which is higher than the 0.85 assumed in the prior distribution.

Focusing on the four parameters characterising the degree of price and wage stickiness, we find that the indexation parameters are estimated to be smaller than assumed in the prior distribution. For example, the estimated price indexation parameter, $\gamma_p = 0.4$, implies that the weight on lagged inflation in the inflation equation is only 0.28. This is quite consistent with the results in Gali, Gertler and Lopez-Salido (2001). There is, however, a considerable degree of Calvo wage and price stickiness. The average duration of wage contracts is estimated to be one year, whereas the average duration of the price contracts is much longer at two and a half years. The greater stickiness in prices relative to wages is somewhat counterintuitive, but turns out to be a very robust outcome of the estimated model. In spite of our relatively tight prior on the Calvo price parameter the data prefer a much higher degree of stickiness. One important reason for the relatively higher degree of nominal stickiness in prices than in wages appears to be the underlying specification of the process driving marginal costs. Whereas individual households' marginal costs of supplying labour are upward-sloping (due to the individual marginal disutility of labour), we assumed that the marginal cost curve in the intermediate goods sector is flat and the same for all firms (due to constant returns to scale). For a given elasticity of prices to real marginal cost, this will

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[24] See Landon-Lane (1999) and Otrok (2001) for earlier applications of the MH algorithm to SDGE models and Geweke (1998) for a discussion of the various sampling algorithms.

tend to bias upward the estimate of Calvo price stickiness. Indeed, using a single equation GMM approach, Gali, Gertler and Lopez-Salido (2001) find the same high degree of nominal price stickiness for the euro area when they assume constant returns to scale. Only when they assume decreasing returns to scale and an upward-sloping marginal cost curve, Gali, Gertler and Lopez-Salido (2000) estimate a more reasonable degree of price stickiness that is comparable with what we estimate for wages.[25]

Our estimate of the intertemporal elasticity of substitution (1/σ) is less than one and close to the assumption made in much of the RBC literature which assumes an elasticity of substitution between a half and one. However, one needs to be careful when making such comparisons, as we have assumed external habit formation which turns out to be significant. The external habit stock is estimated to be 55% of past consumption, which is somewhat smaller than the estimates reported in CEE (2001). Disregarding the preference shocks, our consumption equation (31) can be written as:

$$\hat{C}_t = h\hat{C}_{t-1} - \frac{1-h}{\sigma_c}\sum_{i=0}^{\infty}(\hat{R}_{t+i} - \hat{\pi}_{t+1+i})$$

Our estimates of σ_c and h thus imply that an expected one percent increase in the short-term interest rate for four quarters has an impact on consumption of about 0.28.

The estimate of the adjustment cost parameter is very similar to the one estimated in CEE (2001).[26] It implies that investment increases by about 0.2 percent following a one percent increase in the current price of installed capital. Also the estimates for the fixed cost parameter and the elasticity of the cost of adjusting capacity utilisation are in line with the results in CEE (2001). In contrast to our previous results, the estimate of σ_l is around 1 and relatively small. This implies a relatively large elasticity of the labour supply. However, this parameter is not very precisely estimated.

Finally, our estimation delivers plausible parameters for the long and short-run reaction function of the monetary authorities. Obviously, as there was no single monetary policy in the euro area over the estimation period, these results need to be taken with a grain of salt. The estimates imply that in the long run the response of interest rates to inflation was greater than one and close to the value suggested by Taylor (1993), thereby satisfying the so-called Taylor principle. Also the response to output is similar to the one suggested by Taylor (1993). In addition, we also find a significant positive short-term reaction to the current change in inflation and the current real growth rate and a negative response to a positive productivity shock and labour supply shock. Finally, in agreement with the large literature on estimated interest rate rules, we also find evidence of a substantial degree of interest rate smoothing.

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[25] One way of introducing an upward-sloping marginal cost curve is to assume that the capital stock is firm-specific as in Woodford (2000).

[26] Table 1 reports $1/\varphi = \bar{S}''$.

3.3 Assessing the empirical performance of the estimated SDGE model

3.3.1 Comparing the estimated SDGE model with VARs

The discussion in the previous section shows that the model is able to deliver reasonable and significant estimates of the underlying parameters. In this Section, we analyse how well our estimated model does compared to a-theoretical VAR models run on the same data set. As mentioned above, one advantage of the Bayesian approach used in this paper is that it provides a framework for comparing and choosing between fundamentally misspecified models. Such a comparison can be done on the basis of the marginal likelihood of the model.[27]

The marginal likelihood of a model A is defined as:

(41) $$M = \int_{\theta} p(\theta \mid A) p(Y_T \mid \theta, A) \; d\theta$$

where $p(\theta \mid A)$ is the prior density for model A and $p(Y_T \mid \theta, A)$ is the probability density function or the likelihood function of the observable data series, Y_T, conditional on model A and parameter vector θ. By integrating out the parameters of the model, the marginal likelihood of a model gives an indication of the overall likelihood of the model given the data.

The Bayes factor between two models *i* and *j* is then defined as

(42) $$B_{ij} = \frac{M_i}{M_j}$$

Moreover, prior information can be introduced in the comparison by calculating the posterior odds:

(43) $$PO_i = \frac{p_i M_i}{\sum_j p_j M_j}$$

where p_i is the prior probability that is assigned to model *i*. If one is agnostic about which of the various models is more likely, the prior should weigh all models equally.

The marginal likelihood of a model (or the Bayes factor) is directly related to the predictive density or likelihood function of a model, given by:

(44) $$\hat{p}_{T+1}^{T+m} = \int_{\theta} p(\theta \mid Y_T, A) \prod_{t=T+1}^{T+m} p(y_t \mid Y_T, \vartheta, A) \; d\theta \; ,$$

as $\hat{p}_0^T = M_T$.

Therefore, the marginal likelihood of a model also reflects the prediction performance of a model. Similarly, the Bayes factor compares the models' ability to predict out of sample.

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[27] See Landon-Lane (1998), Geweke (1999) and Schorfheide (2002).

Geweke (1998) discusses various ways to calculate the marginal likelihood of a model.[28] Table 2 presents the results of applying these methods to the SDGE model and various VARs. The upper part of the Table compares the SDGE model with three standard VAR models of lag order one to three, estimated using the same seven observable data series. The lower part of Table 2 compares the SDGE model with Bayesian VARs estimated using the well-known Minnesota prior.[29] In both cases, the results show that the SDGE model has the highest marginal probability. According to the prediction error interpretation of the Bayes factor, this implies that the SDGE model does the best job in predicting the seven variables over the period 1980:2 to 1999:4.

Focusing on the standard VARs, the VAR(1) and VAR(2) models have a similar marginal probability, while the VAR(3) does worst. This ordering is similar using the Laplace transformation to approximate the posterior distribution around the mode.[30] The positive results for the SDGE model relative to the VAR(3) model in terms of the marginal likelihood are in contrast with the RMSE-results and the likelihood statistics for both models. The interpretation in terms of predictive error explains this result: the extremely high number of parameters estimated for the VAR(3) model relative to the small sample period (especially for the starting period) implies a much higher parameter uncertainty and this results in a larger out-of-sample prediction error of the VAR(3) model. Of course, this result is dependent on the relatively small size of the observation period. For larger samples the natural disadvantage of the larger VAR(3) model will be offset to a greater extent by its extra explanatory power. This problem for the VAR(3) (and to a lesser extent the VAR(2)) can be partially overcome by estimating the corresponding BVAR with a Minnesota prior. Indeed, the lower part of Table 2 shows that in this case the BVAR(3) is the preferred model compared to the other BVAR models and the BVAR(3) model does almost as well as the SDGE model.[31]

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[28] If, as in our case, an analytical calculation of the posterior distribution is not possible, one has to be able to make drawings from the posterior distribution of the model. If the distribution is known and easily drawn from, independent draws can be used. If that is not possible, various MCMC methods are available. Geweke (1998) presents different posterior simulation methods (acceptance and importance sampling, Gibbs sampler and the Metropolis-Hastings algorithm used in this paper). Given these samples of the posterior distribution, Geweke (1998) also proposes different methods to calculate the marginal likelihood necessary for model comparison (a method for importance sampling and for MH algorithm, a method for the Gibbs sampler, and the modified harmonic mean that works for all sampling methods). Schorfheide (1999) also uses a Laplace approximation to calculate the marginal likelihood. This method applies a standard correction to the posterior evaluation at the posterior mode to approximate the marginal likelihood. So it does not use any sampling method but starts from the evaluation at the mode of the posterior. Furthermore, in the case of VAR-models the exact form of the distribution functions for the coefficients and the covariance matrix is known, and exact (and Monte Carlo integration) recursive calculation of the posterior probability distribution and the marginal likelihood using the prediction error decomposition is possible.

[29] See Doan, Litterman and Sims (1984).

[30] The likelihood values of the Laplace approximation are significant lower than the sampling results at least for the VAR models (the difference seems to become larger with the number of parameters in the model). For the VAR models, the approximation errors for the results based on the MH-algorithm and the importance sampling relative to the exact calculations of the marginal likelihood based on the prediction error decomposition is very small. For the SDGE model the MH and the importance sampling based approximations of the marginal likelihood deviate strongly. This difference tends to increase with the step size for the MH algorithm. As the modified harmonic mean is not sensitive to the step size, it is the preferred statistic.

[31] This result also illustrates that it can be very useful to use the SDGE model as prior information for larger VAR systems (See Del Negro and Schorfheide, 2002). These priors should be more informative than the random walk hypothesis used in the Minnesota prior.

Overall, the posterior odds suggest that the SDGE model outperforms most of the VAR models and does at least as well as the BVAR(3) model. These results show that the current generation of New-Keynesian SDGE models with sticky prices and wages and endogenous persistence in consumption and investment are able to capture the main features of the euro area data, as long as one is willing to entertain enough structural shocks to capture the stochastics.[32]

3.3.2 Comparison of empirical and model-based cross-covariances

Traditionally SDGE models are validated by comparing the model-based variances and covariances with those in the data. In this Section, we therefore calculate the cross covariances between the seven observed data series implied by the model and compare these with the empirical cross covariances. The empirical cross-covariances are based on a VAR(3) estimated on the data sample of 115 observations covering the period 1971:q2 - 1999:q4. In order to be consistent, the model-based cross-covariances are also calculated by estimating a VAR(3) on 10.000 random samples of 115 observations generated from the SDGE model (100 runs for a selection of 100 parameter draws from the posterior sample). Graph 2 summarises the results of this exercise. The full lines represent the median (bold) and the 5% and 95% intervals for the covariance sample of the SDGE model. The dotted line gives the empirical cross-covariances based on the VAR(3) model estimated on the observed data. Generally, the data covariances fall within the error bands, suggesting that the model is indeed able to mimick the cross-covariances in the data. However, the error bands are quite large, indicating that that there is a large amount of uncertainty surrounding the model-based cross-covariances. It is worth noting that these large error bands are often neglected in more traditional calibration exercises of SDGE models, in which models are often rejected on the basis of an informal comparison of model-based and empirical moments. It appears that the uncertainty coming from the short sample, is significantly higher than that coming from parameter uncertainty.

Looking more closely, there are a number of cross-correlations where the discrepancies between the model-based cross-covariances and the empirical ones are somewhat larger. In particular, the cross-correlations with the interest rate do not seem to be fully satisfactory. The estimated variance of the interest rate is too small; the model seems to have problems fitting the negative correlation between

32 There have been a number of other attempts to compare estimated SDGE models with VARs. However, in most of these cases the SDGE model is clearly rejected. For example, Schorfheide (2002) obtains an extremely low Bayes factor for SDGE models relative to VAR models, and he concludes that SDGE models fail to give an acceptable specification of the data. The models also yield an unsatisfactory empirical presentation of the correlation coefficients and impulse response functions. This application is, however, limited to relatively small models with two shocks (a productivity shock and a monetary policy shock) and tested on two variables (inflation and output-growth). Bergin (2002), using classical likelihood methods, finds evidence in favour of a open economy SDGE model when a general covariance matrix between the shocks is allowed. The results of Ireland (1999) also indicate that the performance of structural models can approach the unconstrained VAR if sufficient flexibility for the shocks is allowed. In the case of Ireland these shocks are however treated as observation errors, so that they are separated from the structural models. Kim (2000) estimates a four variable model, and find evidence that the SDGE model does as good as a VAR(1) model. Rabanal and Rubio-Ramirez (2002) compare different SDGE models but do not compare these outcomes with a VAR model. Fernandez-Villaverde and Rubio-Ramarez (2001) compare a Dynamic Equilibrium model of the cattle cycle and compare it with different types of VAR models. They find that the structural model can easily beat a standard VAR model, but not a BVAR model with Minnesota prior.

current interest rates and future output and inflation; and it underestimates the positive correlation between current activity and future interest rates.[33]

4. What structural shocks drive the euro area economy?

In this Section we use the estimated SDGE model to analyse the impulse responses to the various structural shocks and the contribution of those shocks to the business cycle developments in the euro area economy.

4.1 Impulse response analysis

Graphs 3 to 12 plot the impulse responses to the various structural shocks. Note that these impulse responses are obtained with the estimated monetary policy reaction function. The impulse responses to each of the ten structural shocks are calculated for a selection of 1000 parameters from the posterior sample of 100000. The graphs plot the median response together with the 5 and 95 percentiles. Overall, it turns out that the median response is very similar to the mean and the mode of the responses.

Graph 3 shows that, following a positive *productivity shock*, output, consumption and investment rise, while employment falls. Also the utilisation rate of capital falls. As pointed out by Gali (1999), the fall in employment is consistent with estimated impulse responses of identified productivity shocks in the US and is in contrast to the predictions of the standard RBC model without nominal rigidities. Due to the rise in productivity, the marginal cost falls on impact. As monetary policy does not respond strongly enough to offset this fall in marginal cost, inflation falls gradually. The estimated reaction of monetary policy on a productivity shock is in line with similar results for the US as presented in Ireland (1999) and Gali, Lopez-Salido and Valles (2000) (at least for the pre-Volcker period). Finally, note that the real wage only gradually rises following the positive productivity shock.[34]

Graph 4 shows the effects of a positive *labour supply shock*. The qualitative effects of this supply shock on output, inflation and the interest rate are very similar to those of a positive productivity shock. Due to the higher persistence of the labour supply shock, the real interest rate is, however, not significantly affected. The main qualitative differences are that, first, employment also rises in line with output and, second, that the real wage falls significantly. It is this significant fall in the real wage that leads to a fall in the marginal cost and a fall in inflation. A qualitatively very similar impulse response is obtained with a negative *wage mark-up shock* (Graph 5). In this case, however, the real interest rate rises and real wages and marginal costs fall more on impact. The impact of a negative *price mark-up shock* on output, inflation and interest rates is very similar, but the effect on the real marginal cost, real wages and the rental rate of capital is opposite (Graph 6).

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33 This appears to be a general problem of sticky-price models. See King and Watson (1996) and Keen (2001).

34 See also Francis and Ramey (2001).

Turning to some of the demand shocks, it is clear that in all cases real interest rates rise. Graph 7 shows that a positive *preference shock*, while increasing consumption and output significantly, has a significant crowding-out effect on investment. The increase in capacity necessary to satisfy increased demand is delivered by an increase in the utilisation of installed capital and an increase in employment. As typically strong accelerator effects are found in empirical impulse responses, this points to a potential problem in the underlying model. Increased consumption demand puts pressure on the prices of production factors: both the rental rate on capital and the real wage rise, putting upward pressure on the marginal cost and inflation. Similarly, an investment boom driven by a temporary reduction in the cost of installing capital (Graph 8) has quite strong crowding-out effects on consumption. However, in this case the fall in consumption increases the marginal utility of working, leading to a greater willingness of households to work. As a result the effects on real wages, marginal costs and prices are insignificant. If the investment boom is much more temporary (e.g. due to temporary negative *equity premium shock*, Graph 9), then the crowding-out effect is smaller, and again, in this case, real wages, the marginal cost and prices rise. Finally, the strong crowding-out effects are also clear in response to a *government spending shock* (Graph 10). In this case, both consumption and investment fall significantly. While the rental rate on capital rises, real wages are again not affected very much because of the greater willingness of households to work.

Finally, Graphs 11 and 12 plot the effects of the two monetary policy shocks. The temporary shock leads to a rise in the nominal and real short-term interest rate. This leads to a hump-shaped fall in output, consumption and investment. In line with the stylised facts following a monetary policy shock, real wages fall. The maximum effect on investment is about three times as large as that on consumption. Overall, these effects are consistent with the evidence on the euro area, although the price effects in the model are somewhat larger than those estimated in some identified VARs (e.g. Peersman and Smets, 2001).

The effects of a persistent change in the inflation objective are strikingly different in two respects. First, there is no liquidity effect, as nominal interest rates start falling immediately as a result of the reduced inflation expectations. This is in line with the arguments made in Gali (2000) that the presence (or lack thereof) of a liquidity effect following a monetary policy shock will depend on the persistence of the shock. Second, because the change in policy is implemented gradually and expectations have time to adjust, the output effects of the change in inflation are much smaller.

4.2 Variance decomposition

The contribution of each of the structural shocks to the forecast error variance of the endogenous variables at various horizons (short run: 1 year; medium run: 2.5 years, long run: 25 years) is shown in Table 3. Let us first focus on the determinants of output. At the one-year horizon, output variations are driven primarily by the preference shock and the monetary policy shock. In the medium term, both of these shocks continue to dominate, but the two supply shock (productivity and labour supply) together also account for about 20% of the forecast error variance. In the long run, the labour supply shock dominates, but somewhat surprisingly the monetary policy shock still accounts for about one fourth of the forecast error in output. The monetary policy shock works mainly through investment. The price and wage mark-up shocks do not seem to matter for output variability.

That both "supply shocks", the productivity and labour shock, account for only 37 percent in the long run seems to run counter to the results from identified VAR studies that those shocks account for most of the long-run variance (E.g. Shapiro and Watson, 1989 and Blanchard and Quah, 1989). However, it should be noted that in those studies it is assumed that only supply shocks affect output in the long run. The limited importance of productivity shocks (maximum 12% of forecast error variance in output) confirms the conjecture made in Gali (2000) that the negative correlation between output and employment in response to a productivity shock raises serious doubts about the quantitative significance of productivity shocks as a source of aggregate fluctuations in industrialised countries. As will become clear in the discussion of the historical decomposition, the importance of the monetary policy shocks is mainly due to the dismal performance of monetary policy in the 1970s.

Turning to the determinants of inflation, we find that in the short run variations in inflation are mainly driven by price mark-up shocks. To some extent, this finding is not very surprising. Empirically, inflation is a quite volatile process, but at the same time we estimate inflation to be a very sluggish process, which only very gradually responds to current and expected changes in the marginal cost. It is therefore not very surprising that one needs quantitatively important "cost push" shocks to account for the short-run behaviour of volatile prices. Of course, these shocks could capture a whole range of shocks that are not accounted for in the stylised model such as changes in oil prices, terms-of-trade shocks, changes in taxes, etc. In the medium and long run, preference shocks and labour supply shocks both account for about 20% of the variation in inflation, whereas monetary policy shocks also account for about 15%. It is also important to note that this decomposition does not say anything about the fundamentally monetary nature of inflation in the long run. As the steady state of our model is deterministic (even changes in the inflation objective are ultimately temporary), it is to be expected that the long-run variance will be determined by temporary shocks.

Under the estimated reaction function, the nominal interest rate is mainly determined by the preference shock, the labour supply shock and the monetary policy shock. Summarising these results, there are three structural shocks that explain a significant fraction of output, inflation and interest rates at the medium to long-term horizon: the preference shock, the labour supply shock and the monetary policy shock. In addition, the price mark-up shock is an important determinant of inflation, but not of output, while the productivity shock determines about 10% of output variations, but not inflation.

It is worth noting that while productivity shocks explain an important part of the variance in employment in the short run, it is mainly the labour supply shock that plays an important role in the long run. Also worth noting is that while the wage mark-up shock explains a lot of the variation in real wages in the short run, the preference and labour supply shocks account for most of it in the medium to long run. Finally, as indicated before the inflation objective shock plays no role.

4.3 Historical decomposition

Graphs 13 and 14 summarise the historical contribution of the various structural shocks to output and inflation developments in the euro area. This decomposition is based on our best estimates of the various shocks. While obviously such a decomposition must be treated with caution, it helps in understanding how the estimated model interprets specific movements in the observed data and therefore can shed some light on its plausibility.[35]

Focusing on the decomposition of inflation first, it is clear that in line with the results from the variance decomposition the short-run variability in inflation is mostly accounted for by "cost-push" shocks. In part these shocks seem to come from oil price changes. However, the secular part in inflation is mostly driven by monetary policy shocks and "supply and demand" shocks. Monetary policy has clearly contributed quite significantly to the surge in inflation in the 1970s and its stabilisation from 1980s onward. The various "supply" and "demand" shocks, and in particular the preference and labour supply shock, lead to a clear cyclical pattern in inflation with peaks in 1982 and 1992 and troughs in 1979, 1987 and 1999.

The relative role of the various shocks during the 1970s is also clear from the decomposition of output. While loose monetary policy contributed to offsetting the fall in output due to negative supply and demand shocks in the 1970s, it contributed very little to output variations in the 1980s and 1990s. Most of the variation in output since the mid 1980s seems to be due to the various supply and demand shocks, although the monetary policy tightening during the ERM crisis of 1992 has contributed somewhat to the 1993 recession.

5. Output and interest rate gaps: an application

In a simple benchmark New-Keynesian model with only nominal price rigidities and no "mark-up" shocks, Woodford (2002) has pointed out that optimal monetary policy will be able to replicate the flexible price equilibrium, thereby restoring the first best. In such a model, the output gap or the real interest rate gap, both defined as deviations from their flexible price level, are useful indicators for optimal monetary policy.[36] Due to the presence of both nominal price and wage rigidities and the occurrence of price and wage mark-up shocks, this will no longer be the case in our model. However, in a model with both nominal price and wage rigidities, Erceg, Henderson and Levin (2000) have shown that targeting a weighted average of price and wage inflation, or of price inflation and the output gap, defined as the deviation of actual output from its flexible price level, comes close to optimal monetary policy.

In Erceg, Henderson and Levin (2000) and Woodford (2002), all shocks are coming from technologies and preferences. As a result, in the absence of other steady-state distortions, the flexible price output and real interest rate level is also the efficient output and real interest rate level and can thus be seen as the

[35] It needs to be mentioned that while the sample in Graphs 13 and 14 starts in the early 1970s, the first nine years of the sample are used for the initialisation of the Kalman filter and are not used to estimate the structural parameters. Given the large monetary policy shocks, doing so would probably have implications for the stability of the policy rule.

[36] See also the discussion in Neiss and Nelson (2001) and Gali (2000).

appropriate target level of output or of the real interest rate. In our application, we have assumed that at least three shocks are due to stochastic variations in inefficient mark-ups: the wage mark-up, the price mark-up and the equity premium shock. As these shocks give rise to inefficient variations in the flexible-price-and-wage level of output, one can argue that monetary authorities should not accommodate such variations and instead try to keep output at its efficient level. The target or potential level of output can then be defined as the flexible-price-and-wage level of output that would arise in the absence of mark-up shocks. Of course, in this case mark-up shocks will give rise to a trade-off between inflation stabilisation and output gap stabilisation.

Graphs 15 to 19 show the impulse responses to the five "supply and demand" shocks when prices and wages are flexible. There is no point in discussing monetary policy in this set-up, as monetary policy will be neutral. We simply assume that monetary policy stabilises the price level.

With flexible prices and wages, output jumps up immediately and much more strongly in response to a productivity shock (Graph 15). In line with higher productivity, real wages jump up immediately, stabilising the real marginal cost. Higher output is produced by a higher capital utilisation and an increase in the capital stock, while employment actually falls as households reduce their labour supply in line with the fall in the marginal utility of consumption. The natural interest rate temporarily falls. A positive labour supply shock has very similar effects on output and the natural real interest rate (Graph 16). The main difference is that now employment increases, while real wages hardly change. The latter contrasts with the sticky price outcome, in which real wages fall quite substantially.

The striking thing about the effects of a positive preference shock is that the natural output level responds strongly negatively (Graph 17). This is mainly due to the fact that higher consumption reduces the marginal benefit from working and therefore leads to a fall in labour supply (or a rise in the real wage). This reduces the marginal product of capital, which together with the rise in the natural real interest rate, has a strong negative impact on investment. In contrast, a positive investment shock leads to a rise in output and only a limited crowding out of consumption (Graph 18), while the natural real interest rate falls temporarily. A similar pattern is observed in response to a positive government spending shock (Graph 19).

Overall, it appears that the natural output level responds quite significantly not only to the "supply" shocks, but also to the "demand" shocks, as does the natural real interest rate. Somewhat surprisingly, the real wage does not move very much in response to the various shocks, with the exception of the productivity shock. To understand these effects in the flexible-price-and-wage economy, it is useful to look at the equilibrium in the labour market. This will be determined by equation (37) and the conditions that the real wage equals the marginal rate of substitution of households and the marginal product of labour. This give rise to the following labour supply and demand equations:

(45) $$\hat{L}_t^d = -\frac{1+\psi(1-\alpha)}{\alpha}\hat{w}_t + \frac{1+\psi}{\alpha}\hat{\varepsilon}_t^a$$

(46) $$\hat{L}_t^s = \frac{1}{\sigma_L}\hat{w}_t - \frac{\sigma_c}{\sigma_L(1-h)}(\hat{C}_t - \hat{C}_{t-1}) + \frac{1}{\sigma_L \hat{\varepsilon}_t^l}$$

Note that under the estimated parameters both the labour demand and the labour supply schedule will be relatively flat. The labour demand schedule (45) is flat because of the low estimated elasticity of the cost of adjusting capacity utilisation, while the labour supply schedule (46) is flat because of the high estimate of the labour supply elasticity. As a result, the initial effects of shifts in both schedules (e.g. due to a labour supply shock or a productivity shock) on the real wage will be limited, while the employment effects will be strong. Additional effects on the labour market come from the corresponding changes in consumption, which have a strong negative effect on labour supply. In the case of a productivity shock, this will reduce the positive employment effect and reinforce the positive real wage effect as is clear in Graph 15. In contrast, in the case of a labour supply shock, it will tend to limit both the positive employment effect and the negative real wage effect. Due to the strong consumption effect on labour supply, also "demand" shocks can have a relatively strong impact on employment and the output level.

Graphs 20 and 21 plot the historical estimate of the potential output level and the associated real interest rate, defined as the output level and real interest rate that would prevail under flexible prices and wages in the absence of mark-up shocks (together with the 5 and 95 percentiles).[37] A number of general observations are worth making. First, it appears that potential output is smoother than the associated real interest rate. Moreover, while the confidence bands around both the output and the interest rate gap are quite large, this is particularly problematic for the real interest rate gap, which is hardly significant over the sample period. This suggests that the real interest rate gap may be a poor guide for monetary policy. Second, estimated potential output according to the SDGE model is very different from traditional estimates which rely on a smoothed trend through output. It appears that there was a quite dramatic fall in potential output from 1973 to 1975. This gave rise to a significant positive output gap during most of the 1970s and the early 1980s, which coincided with the rise in inflation. From 1982 onward potential output has gradually risen to a higher level with a dip in the early 1990s. As a result there is still a substantial negative output gap at the end of 1999. The upper panel of Graph 19 shows that most of the long-term variation in potential output seems to be due to labour supply developments. Third, the real interest rate associated with potential output appears to covary much more with the actual estimated real interest rate, but is more volatile. According to the real interest rate gap, monetary policy was relatively tight during the last seven years of the 1990s, although most recently the gap seems to have closed.

6. Conclusions

Recently a new generation of small-scale monetary business cycle models generally referred to as New-Keynesian or New Neoclassical Synthesis models have been developed (Goodfriend and King (1997), Rotemberg and Woodford (1997) and Clarida, Gali and Gertler (1999)). Gali (2000) highlights some of the new findings, ideas or features of these models relative to the traditional Keynesian literature. The monetary SDGE model used in this paper shares the essential features of this class of models (in

[37] Our gap differs from the gap that is calculated in Gali, Gertler and Lopez-Salido (2002) and Neiss and Nelson (2001) in the sense that those papers implicitly assume that there are no mark-up shocks.

particular the sticky, but forward-looking price setting). Following Christiano, Eichenbaum and Evans (2001), our model also features a relatively large number of additional frictions that are necessary to capture the empirical persistence and covariances in the main macro-economic data of the euro area. These frictions include sticky, but forward-looking nominal wage setting, variable capital utilisation, adjustment costs in capital accumulation and habit formation in consumption. Finally, the model also includes a full set of structural shocks -- two “supply” shocks (a productivity and labour supply shock), three “demand” shocks (a preference, an investment and a government spending shock), three mark-up shocks (a price and wage mark-up shock and an equity premium shock) and two monetary policy shocks --, to account for the stochastics in the empirical data. These extensions of the canonical two-equation model allow us to (i) estimate with Bayesian techniques the model parameters using the main euro area macro data on output, inflation, real wages, investment, consumption, the short-term interest rate and employment; (ii) examine the sources of business cycle dynamics in the euro area; and (iii) analyse some of the new features of this class of models, highlighted by Gali (2000), in an empirically plausible set-up. Regarding the latter, it is worth recalling what we have learned from performing this exercise.

The forward-looking behaviour of inflation. The parameter estimates in this paper suggest that there is a considerable degree of price and wage stickiness in the euro area. As a result, prices respond only slowly to changes in expected marginal costs, while wages adjust only slowly to deviations from their efficient levels. Both price and wage inflation also depend to some extent on past inflation which introduces a backward-looking component. Nevertheless, the forward-looking component clearly dominates, in particular in the price setting equation.

The concept of the output gap (and interest rate gap). In the canonical model of Woodford (1999), the concept of the output gap – defined as the deviation of actual output from its flexible price and wage equilibrium value – plays a central role, both as a force driving underlying developments in inflation (through its effect on marginal cost) and as a policy target. A similar role can also be assigned to the real interest rate gap (Neiss and Nelson (2000), Woodford (2000)). In our estimated model which features a larger number of shocks arising from both technologies and preferences and inefficient mark-ups, it is less clear what the appropriate output gap is from a monetary policy perspective. Clearly, all “non-monetary” shocks will potentially affect output and the real rate in a flexible price and wage economy. We argue that for monetary policy purposes, the appropriate estimate of potential output should only take into account that part of the natural level of output that is driven by shocks arising from preferences and technologies. Following this definition, we derive a model-based output and real interest rate gap and show that there is considerable uncertainty around it.

The transmission of monetary policy shocks and the liquidity effect. Our estimates of the effects of a *temporary* monetary policy shock are very much in line with the existing evidence for the euro area (e.g. Peersman and Smets, 2000). It leads to a rise in the nominal and real interest rate, a hump-shaped fall in output, consumption and investment with the latter responding significantly stronger and a gradual fall in marginal costs and prices. However, the effects of a *persistent* monetary policy shock are strikingly different in two respects. First, in line with the arguments made in Gali (2000) there is no liquidity effect as the fall in the nominal component outweighs the rise in the real component of the short-term interest rate. Second, because the change in policy is credible and implemented gradually, expectations have time to adjust and the output effects are much smaller. These findings underline the importance of forward-looking pricing behaviour and the persistence of the shocks for assessing the effects of monetary policy changes.

The transmission of non-monetary shocks. Gali (1999) emphasised that in models with sticky prices, unless monetary policy is sufficiently accommodating, employment is likely to drop in the short run in response to a favourable productivity shock. Our estimates of the effect of a positive productivity shock confirm this significant negative effect on employment under the estimated policy reaction function. It is worth noting that due to the high estimated labour supply elasticity, productivity shocks have a negative effect on employment even in the flexible price and wage economy. Gali (2000) also conjectured that the empirical procyclicality of employment raised serious doubts about the quantitative significance of productivity shocks as a source of aggregate fluctuations. Our results indeed suggest that, in contrast to many identified VAR studies, the productivity shocks only account for 10 percent of the long-run output variance. Instead, preference shocks, labour supply shocks and monetary policy shocks (in particular in the 1970s) are the most important source of variation in output, inflation and interest rates.

Overall, the results presented in this paper show that an estimated version of the SDGE model with sticky prices and wages can be used for monetary policy analysis in an empirically plausible set-up. At the same time, the analysis in this paper needs to be further improved in a number of dimensions.

When estimating the model, we have implicitly assumed that the agents in the economy have perfect information regarding the shocks hitting the economy. A more realistic assumption would be to estimate the model under the assumption that those agents (like the econometrician) only observe the observable variables. An interesting question is then to what extent imperfect information regarding the nature of the monetary policy shocks could account for the empirical persistence in the inflation process (as, for example, in Erceg and Levin (2000)). Second, the robustness of the estimation results to various perturbations in the structure of the model needs to be examined. As in CEE (2001), it would be interesting to see which of the various frictions are crucial for capturing the persistence and covariances in the data. Also a further examination and identification of the various structural shocks would be interesting. Third, in this paper we have not analysed optimal monetary policy. A deeper analysis of the appropriate welfare function and the various trade-offs faced by the monetary authorities in the context of this model would be very welcome.

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Table 1: Estimated parameters

	Prior distribution			Estimated maximum posterior		Posterior distribution MH			
	type	mean	st. error	mode	st.error (Hessian)	5%	median	95%	mean
σ productivity shock	inv gamma	0.40	2 *	0.589	0.131	0.444	0.612	0.873	0.628
σ inflation obj. shock	inv gamma	0.02	2 *	0.016	0.007	0.011	0.023	0.069	0.028
σ cons.pref. shock	inv gamma	0.20	2 *	0.247	0.083	0.173	0.297	0.571	0.324
σ gov.spending shock	inv gamma	0.30	2 *	0.325	0.026	0.290	0.329	0.378	0.331
σ labour supply shock	inv gamma	1.00	2 *	1.354	0.504	0.997	1.658	2.603	1.709
σ investment shock	inv gamma	0.10	2 *	0.101	0.033	0.074	0.129	0.247	0.140
σ interest rate shock	inv gamma	0.10	2 *	0.116	0.019	0.102	0.129	0.158	0.129
σ equity premium shock	inv gamma	0.40	2 *	0.603	0.058	0.520	0.611	0.718	0.614
σ price mark-up shock	inv gamma	0.15	2 *	0.160	0.016	0.139	0.162	0.192	0.163
σ wage mark-up shock	inv gamma	0.25	2 *	0.279	0.026	0.246	0.285	0.331	0.286
ρ productivity shock	beta	0.85	0.10	0.834	0.067	0.712	0.828	0.912	0.822
ρ inflation obj. shock	beta	0.85	0.10	0.924	0.088	0.658	0.865	0.970	0.847
ρ cons.pref. shock	beta	0.85	0.10	0.905	0.028	0.817	0.886	0.931	0.882
ρ gov. spending shock	beta	0.85	0.10	0.966	0.022	0.912	0.956	0.982	0.952
ρ labour supply shock	beta	0.85	0.10	0.962	0.019	0.916	0.955	0.980	0.952
ρ investment shock	beta	0.85	0.10	0.939	0.026	0.856	0.917	0.961	0.914
investment adj cost	Normal	4.00	1.5	5.911	1.005	4.321	5.974	7.973	6.048
σ consumption utility	Normal	1.00	0.375	1.607	0.292	1.126	1.608	2.106	1.613
h consumption habit	beta	0.70	0.10	0.541	0.077	0.416	0.552	0.681	0.551
σ labour utility	Normal	2.00	0.75	0.755	0.817	0.439	1.188	2.365	1.265
fixed cost	Normal	1.45	0.25	1.488	0.207	1.199	1.487	1.835	1.499
calvo employment	beta	0.50	0.15	0.593	0.054	0.503	0.596	0.671	0.593
capital util. adj.cost	Normal	0.20	0.075	0.169	0.075	0.062	0.175	0.289	0.175
calvo wages	beta	0.75	0.05	0.763	0.039	0.690	0.758	0.817	0.756
calvo prices	beta	0.75	0.05	0.910	0.011	0.890	0.909	0.927	0.909
indexation wages	beta	0.75	0.15	0.656	0.195	0.383	0.663	0.900	0.655
indexation prices	beta	0.75	0.15	0.408	0.102	0.268	0.425	0.597	0.429
r inflation	Normal	1.70	0.10	1.658	0.102	1.537	1.661	1.821	1.668
r d(inflation)	Normal	0.30	0.10	0.199	0.052	0.134	0.221	0.313	0.222
r lagged interest rate	beta	0.80	0.10	0.942	0.015	0.901	0.931	0.946	0.928
r output	Normal	0.125	0.05	0.148	0.041	0.079	0.143	0.215	0.144
r d(output)	Normal	0.0625	0.05	0.173	0.025	0.131	0.173	0.219	0.174
r ε productivity shock	Normal	0.0625	0.05	0.096	0.029	0.043	0.086	0.137	0.088
r ε labour supply	Normal	0.0625	0.05	0.047	0.026	0.007	0.030	0.063	0.031

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

Table 2: Empirical evaluation of the SDGE-model

Summary of the model statistics : VAR - BVAR - SDGE

	VAR(3)	VAR(2)	VAR(1)	SDGE-model
RMSE in sample from T0+1:T with OLS estimates 1:T				
y	0.42	0.44	0.50	0.53
pi	0.20	0.21	0.23	0.23
r	0.12	0.12	0.13	0.14
lab	0.19	0.20	0.22	0.21
w	0.48	0.51	0.54	0.57
cons	0.42	0.44	0.48	0.58
inv	1.03	1.08	1.17	1.24

Posterior probability approximation T0+1:T

	VAR(3)	VAR(2)	VAR(1)	SDGE-model
Prediction error decomposition[1]	-303.42	-269.11	-269.18	
Laplace approximation	-315.65	-279.77	-273.55	-266.43
Modified harmonic mean[2]	-305.92	-270.28	-268.41	-266.15
Bayes factor rel. to SDGE model	0.00	0.02	0.10	1.00
Prior probabilities	0.25	0.25	0.25	0.25
Posterior odds rel. to SDGE model	0.00	0.01	0.09	0.89

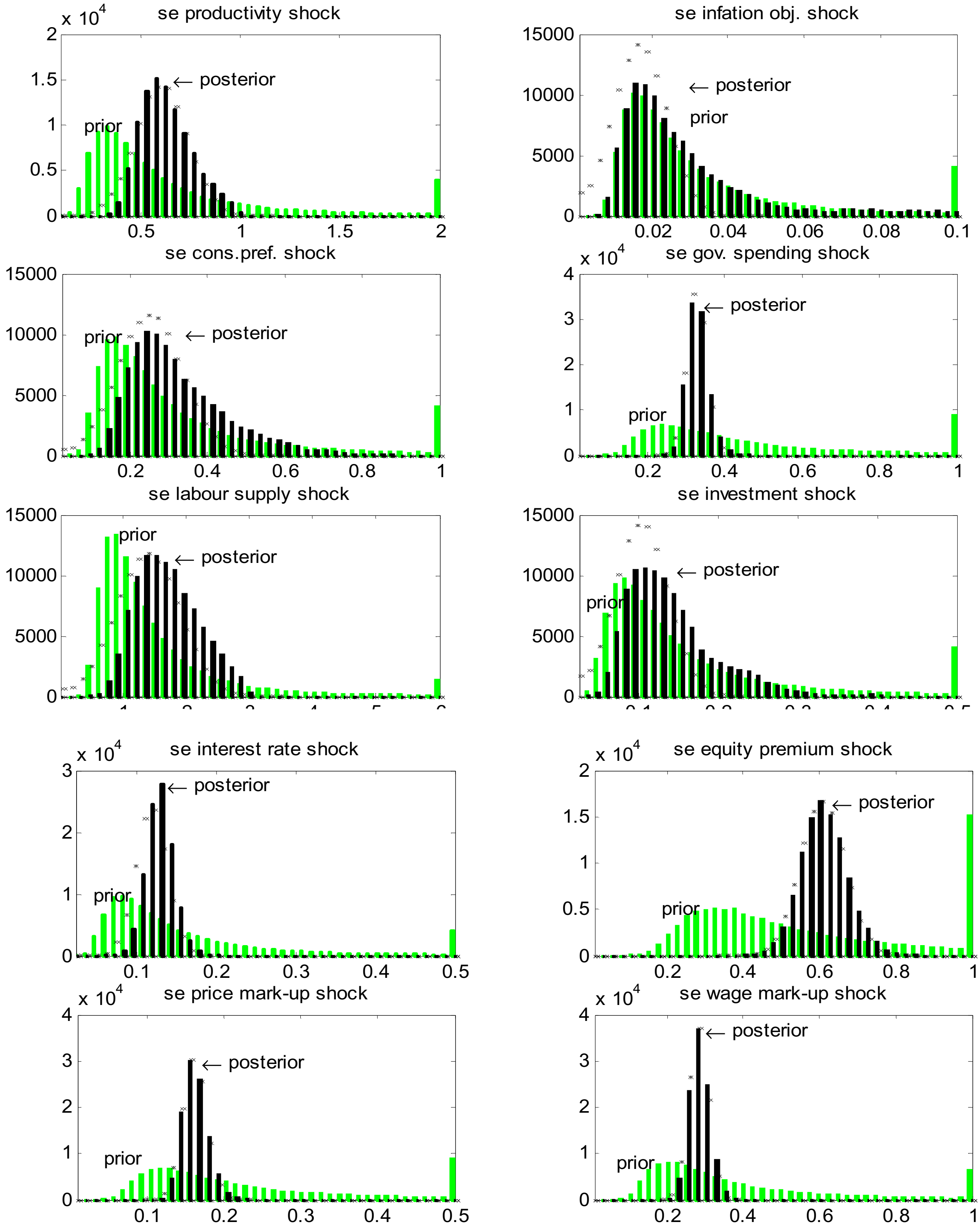
	BVAR(3)	BVAR(2)	BVAR(1)	SDGE
Modified harmonic mean[2]	-266.71	-268.71	-290.00	-266.15
Bayes factor rel. to SDGE model	0.57	0.08	0.00	1.00
Prior probabilities	0.25	0.25	0.25	0.25
Posterior odds rel. to SDGE model	0.35	0.05	0.00	0.61

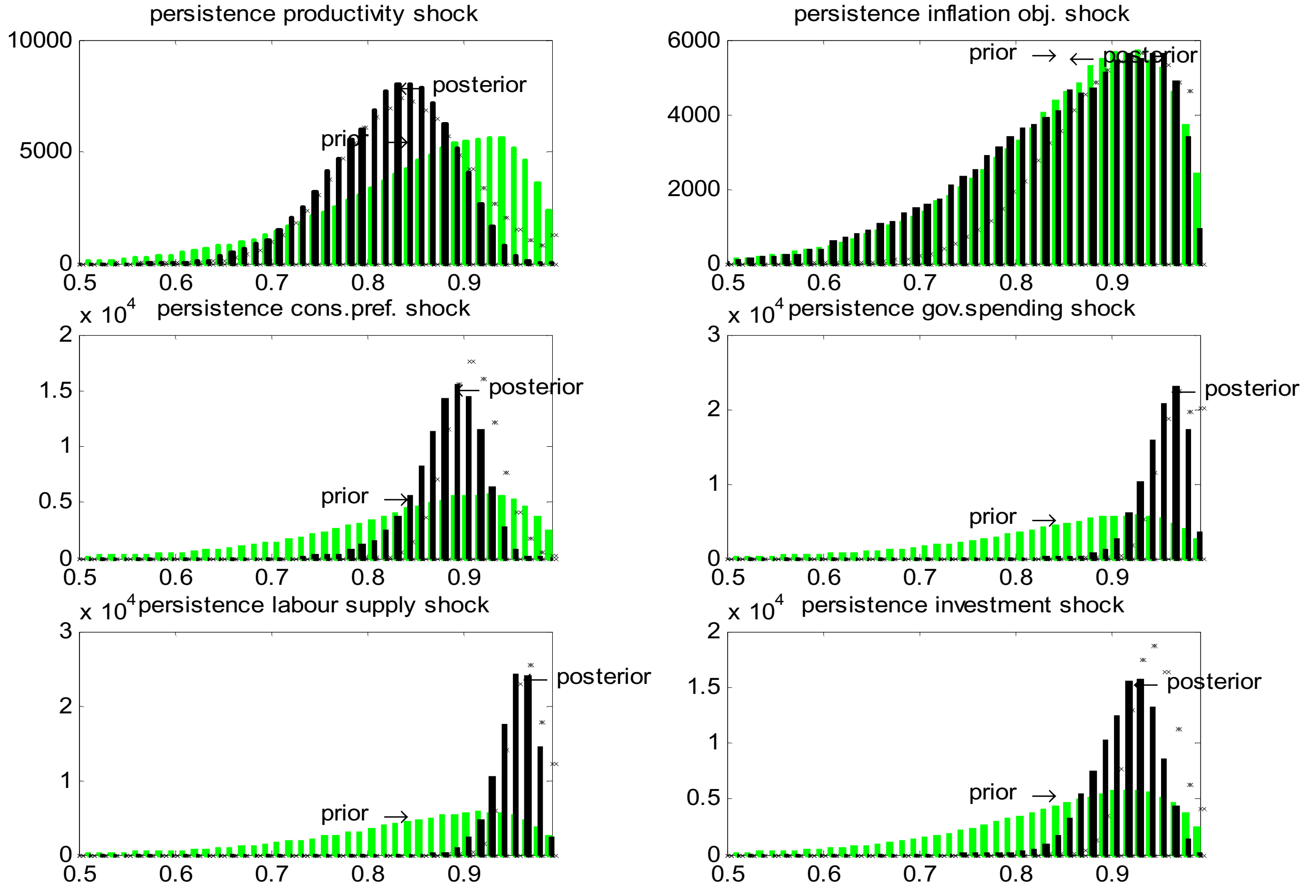
[1] Posterior probability computed recursively using the prediction error decomposition (treating first T0 obs given)
[2] Posterior probability approximation via sampling: MC for the VAR, Gibbs for the BVAR, MH for the SDGE model

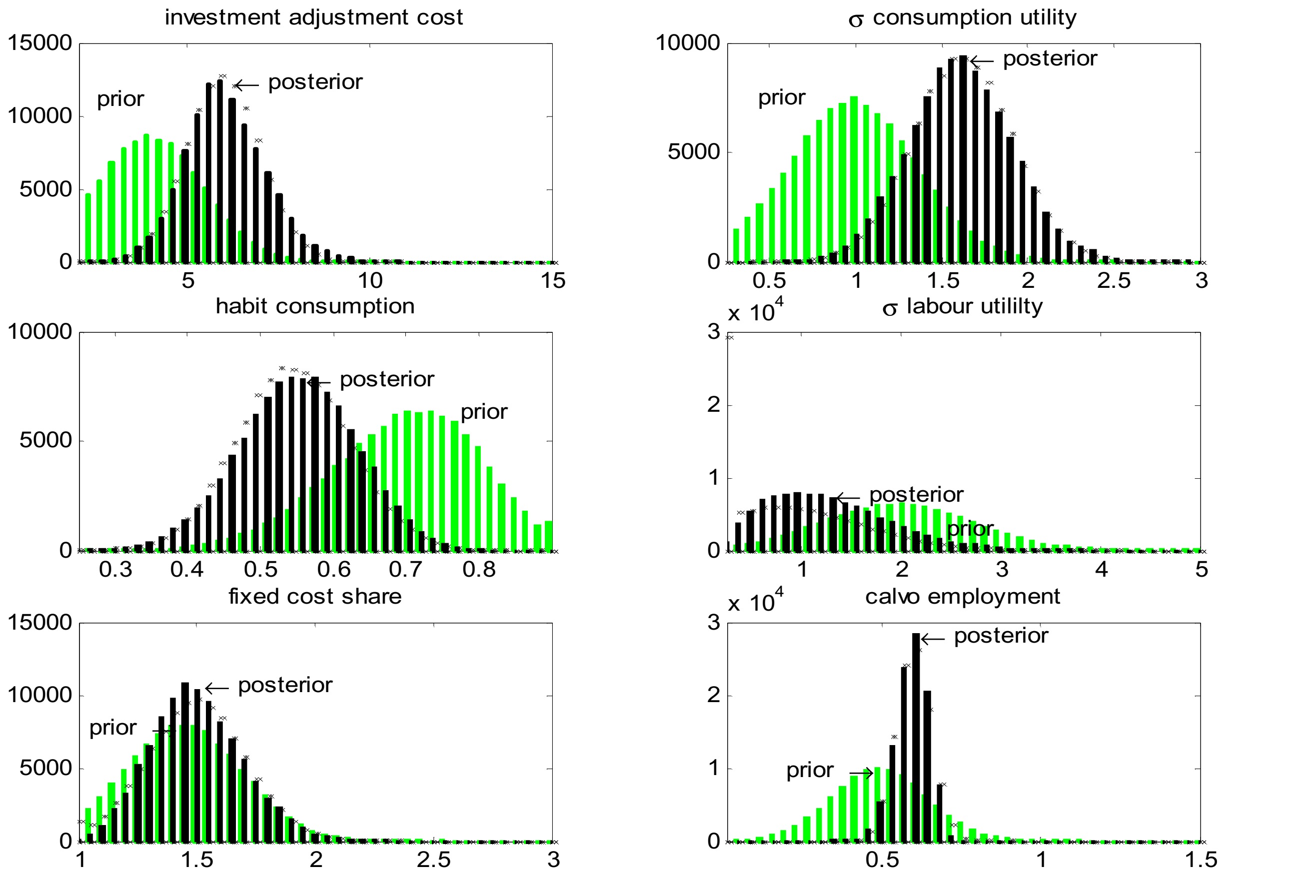
Table 3: Forecast error variance decomposition using the estimated SDGE model

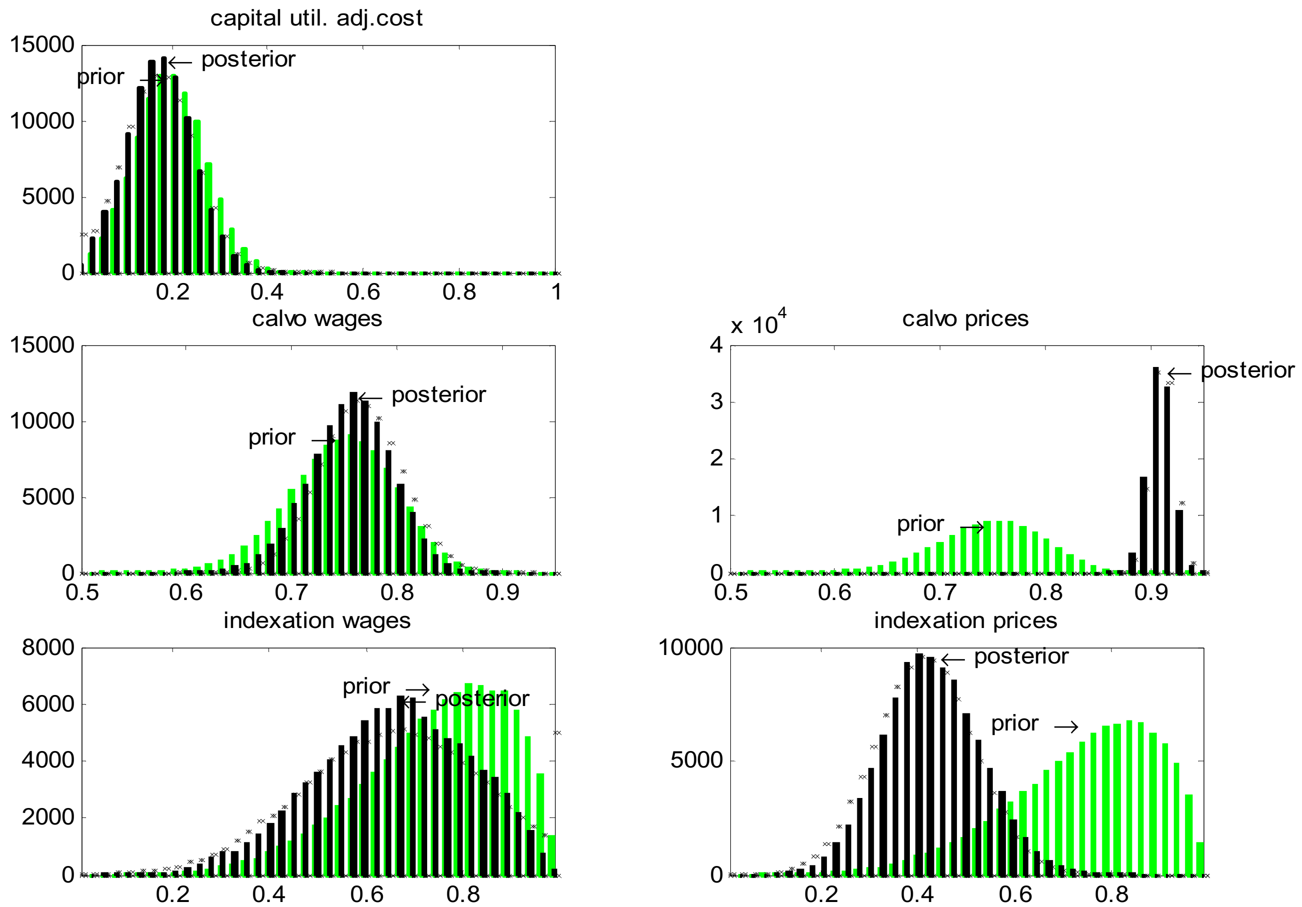
		C	I	Y	E	π	W	R
t = 0	productivity shock	0.02	0.02	0.03	0.60	0.01	0.00	0.11
	inflation objective shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	preference shock	0.75	0.02	0.38	0.11	0.03	0.07	0.19
	gov. spending shock	0.04	0.02	0.20	0.05	0.00	0.00	0.06
	labour supply shock	0.03	0.00	0.02	0.04	0.03	0.02	0.19
	investment shock	0.05	0.11	0.00	0.01	0.00	0.00	0.00
	interest rate shock	0.11	0.10	0.19	0.11	0.02	0.01	0.30
	equity premium shock	0.00	0.73	0.18	0.04	0.00	0.00	0.07
	price mark-up shock	0.00	0.01	0.01	0.00	0.91	0.16	0.07
	wage mark-up shock	0.00	0.00	0.00	0.03	0.00	0.74	0.00
		0.40	1.39	0.23	0.05	0.05	0.29	0.02
t = 4	productivity shock	0.03	0.06	0.08	0.38	0.01	0.01	0.06
	inflation objective shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	preference shock	0.73	0.06	0.39	0.12	0.16	0.33	0.50
	gov. spending shock	0.04	0.04	0.05	0.04	0.02	0.01	0.02
	labour supply shock	0.04	0.00	0.04	0.13	0.14	0.10	0.21
	investment shock	0.06	0.34	0.02	0.04	0.01	0.02	0.01
	interest rate shock	0.09	0.26	0.34	0.22	0.10	0.07	0.12
	equity premium shock	0.00	0.22	0.06	0.03	0.00	0.00	0.05
	price mark-up shock	0.01	0.02	0.02	0.01	0.54	0.07	0.03
	wage mark-up shock	0.00	0.00	0.00	0.03	0.01	0.38	0.00
		3.96	13.05	1.76	0.53	0.09	1.51	0.07
t = 10	productivity shock	0.03	0.07	0.12	0.20	0.01	0.02	0.04
	inflation objective shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	preference shock	0.69	0.10	0.26	0.06	0.20	0.42	0.53
	gov. spending shock	0.05	0.04	0.03	0.05	0.04	0.02	0.02
	labour supply shock	0.06	0.01	0.09	0.27	0.21	0.16	0.24
	investment shock	0.08	0.41	0.06	0.11	0.01	0.03	0.03
	interest rate shock	0.09	0.26	0.38	0.25	0.14	0.11	0.08
	equity premium shock	0.00	0.08	0.03	0.02	0.00	0.00	0.03
	price mark-up shock	0.01	0.02	0.03	0.01	0.39	0.04	0.02
	wage mark-up shock	0.00	0.00	0.00	0.03	0.01	0.19	0.00
		6.87	39.22	3.48	1.16	0.13	3.48	0.11
t = 100	productivity shock	0.03	0.07	0.10	0.09	0.02	0.05	0.04
	inflation objective shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	preference shock	0.55	0.14	0.16	0.06	0.18	0.37	0.46
	gov. spending shock	0.06	0.03	0.06	0.11	0.05	0.04	0.02
	labour supply shock	0.20	0.08	0.27	0.46	0.24	0.20	0.29
	investment shock	0.07	0.41	0.10	0.11	0.01	0.03	0.08
	interest rate shock	0.08	0.20	0.26	0.14	0.16	0.15	0.08
	equity premium shock	0.00	0.05	0.02	0.01	0.00	0.00	0.03
	price mark-up shock	0.01	0.02	0.02	0.01	0.33	0.04	0.01
	wage mark-up shock	0.00	0.00	0.00	0.01	0.01	0.12	0.00
		9.42	71.70	6.29	2.65	0.16	5.25	0.14

Graph 1: Prior and posterior distributions of the model parameters

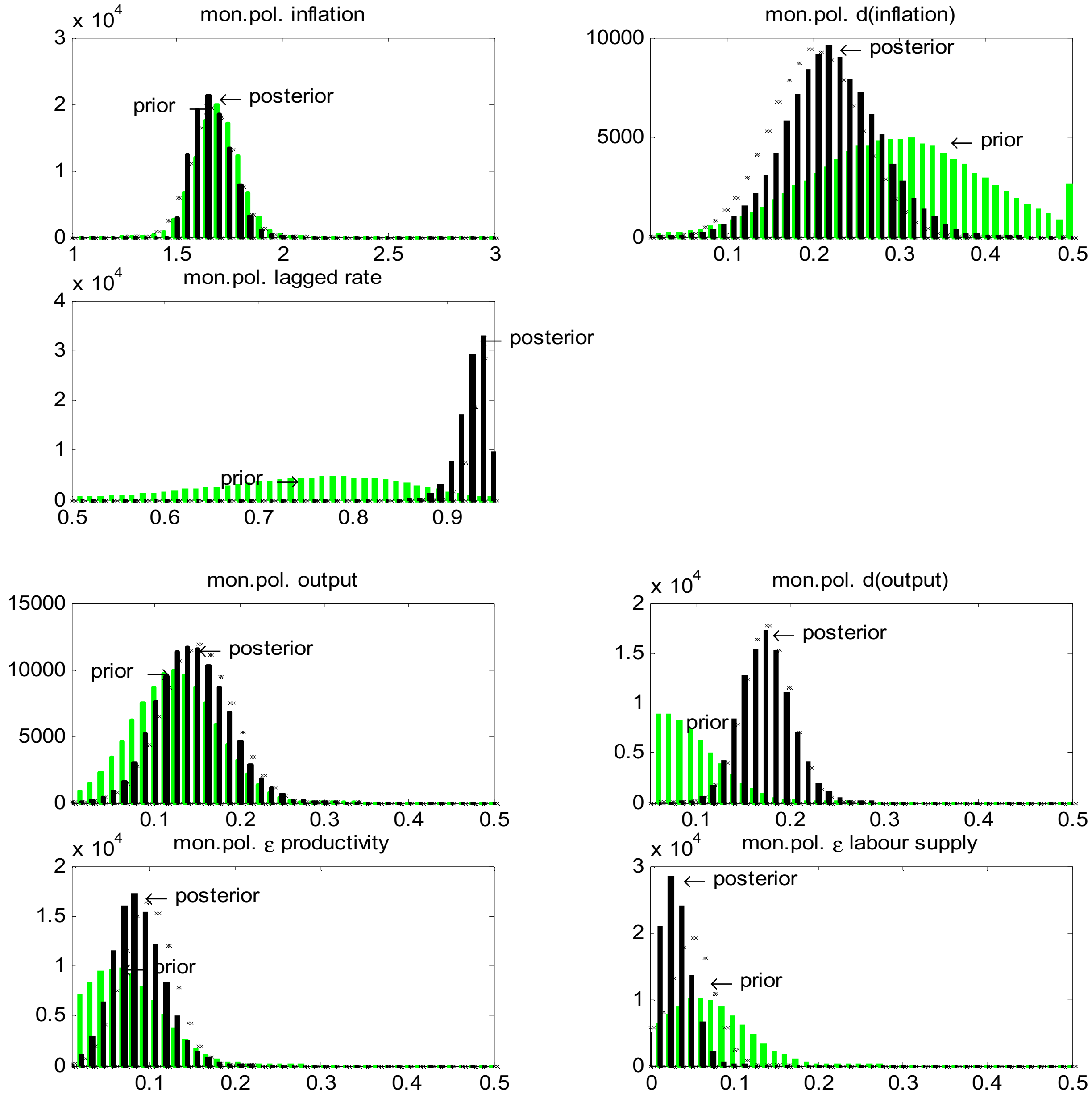



persistence productivity shock
prior
posterior
persistence inflation obj. shock
prior
posterior
x 10^4 persistence cons.pref. shock
prior
posterior
x 10^4 persistence gov.spending shock
prior
posterior
x 10^4 persistence labour supply shock
prior
posterior
x 10^4 persistence investment shock
prior
posterior


investment adjustment cost
prior
posterior
σ consumption utility
prior
posterior
habit consumption
prior
posterior
x 10^4 σ labour utililty
prior
posterior
fixed cost share
prior
posterior
x 10^4 calvo employment
prior
posterior

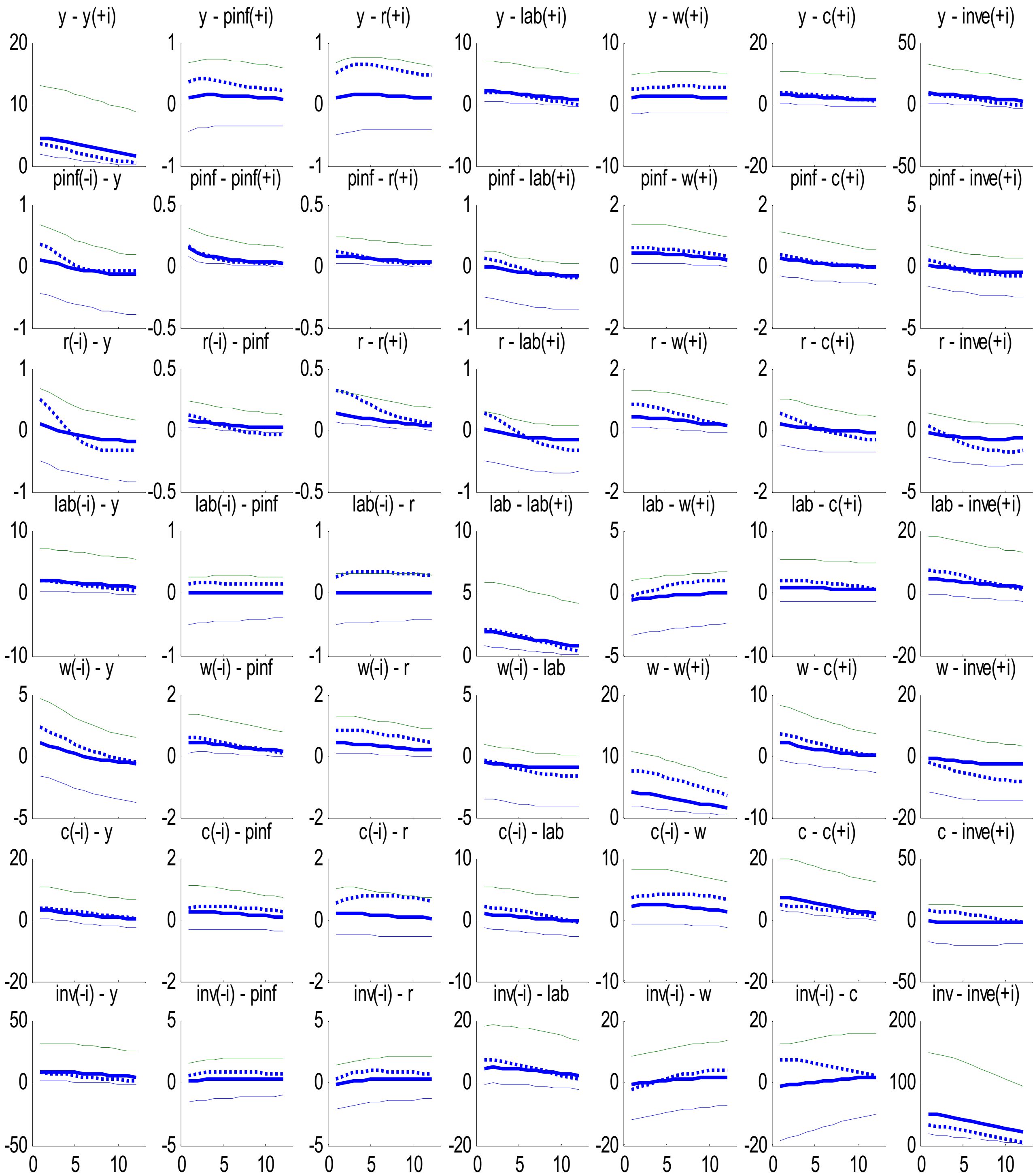


capital util. adj.cost
prior
posterior
calvo wages
prior
posterior
calvo prices
x 10^4
prior
posterior
indexation wages
prior
posterior
indexation prices
posterior
prior


mon.pol. inflation
x 10^4
prior
← posterior
mon.pol. d(inflation)
← posterior
← prior
mon.pol. lagged rate
x 10^4
posterior
prior
mon.pol. output
prior
posterior
mon.pol. d(output)
x 10^4
posterior
prior
mon.pol. ε productivity
x 10^4
posterior
prior
mon.pol. ε labour supply
x 10^4
posterior
prior

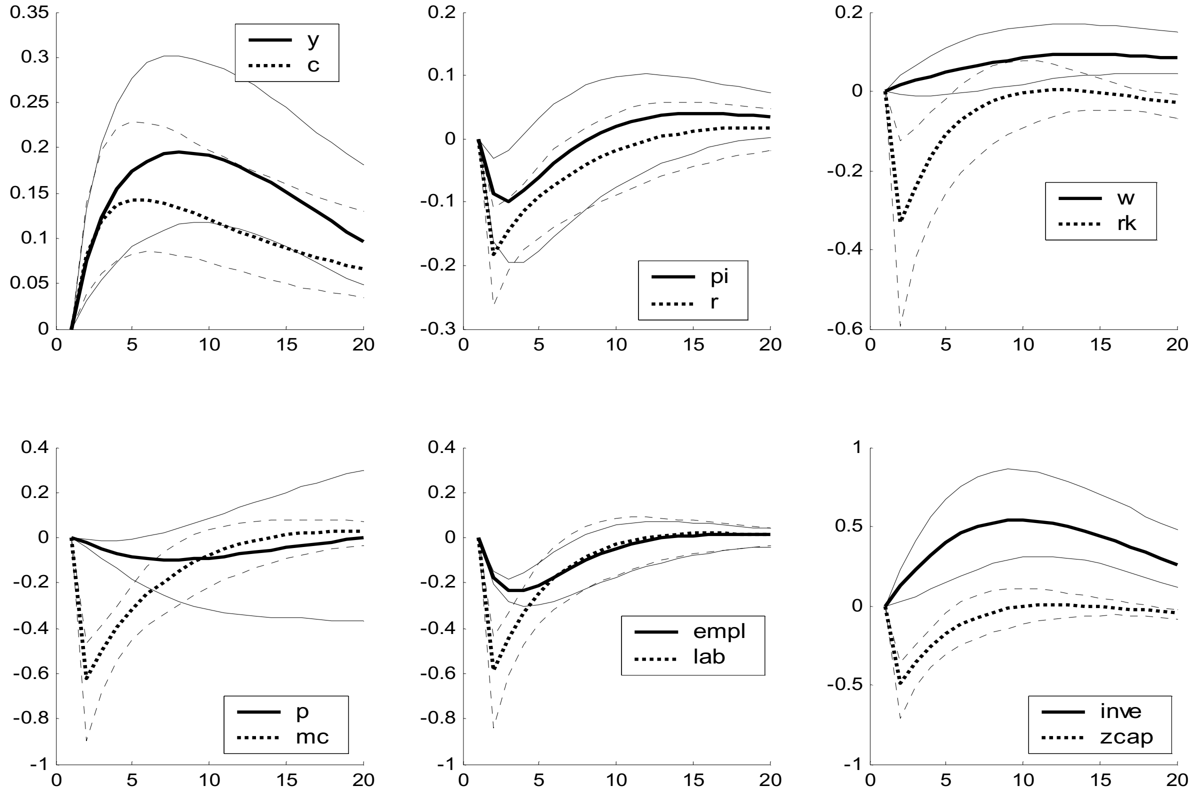
Graph 2:

Comparison of cross-covariances of the SDGE-model and the data



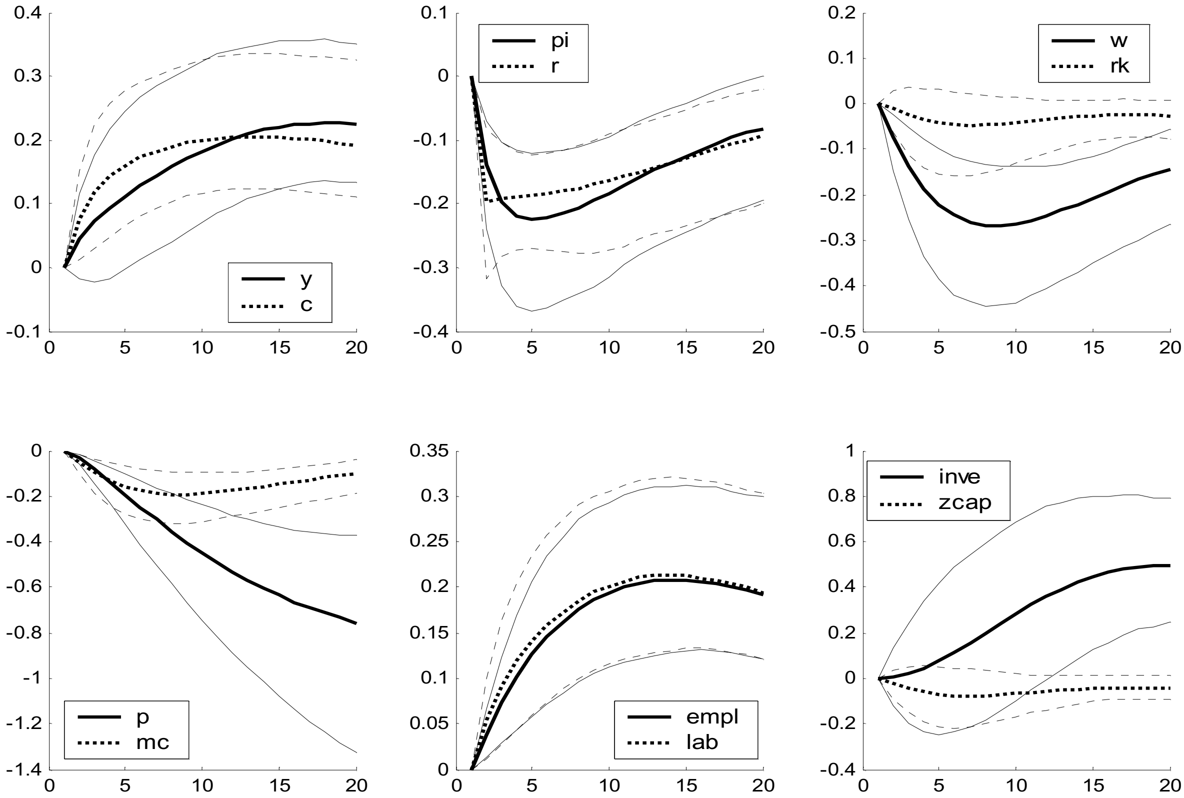
Graph 3

Productivity shock



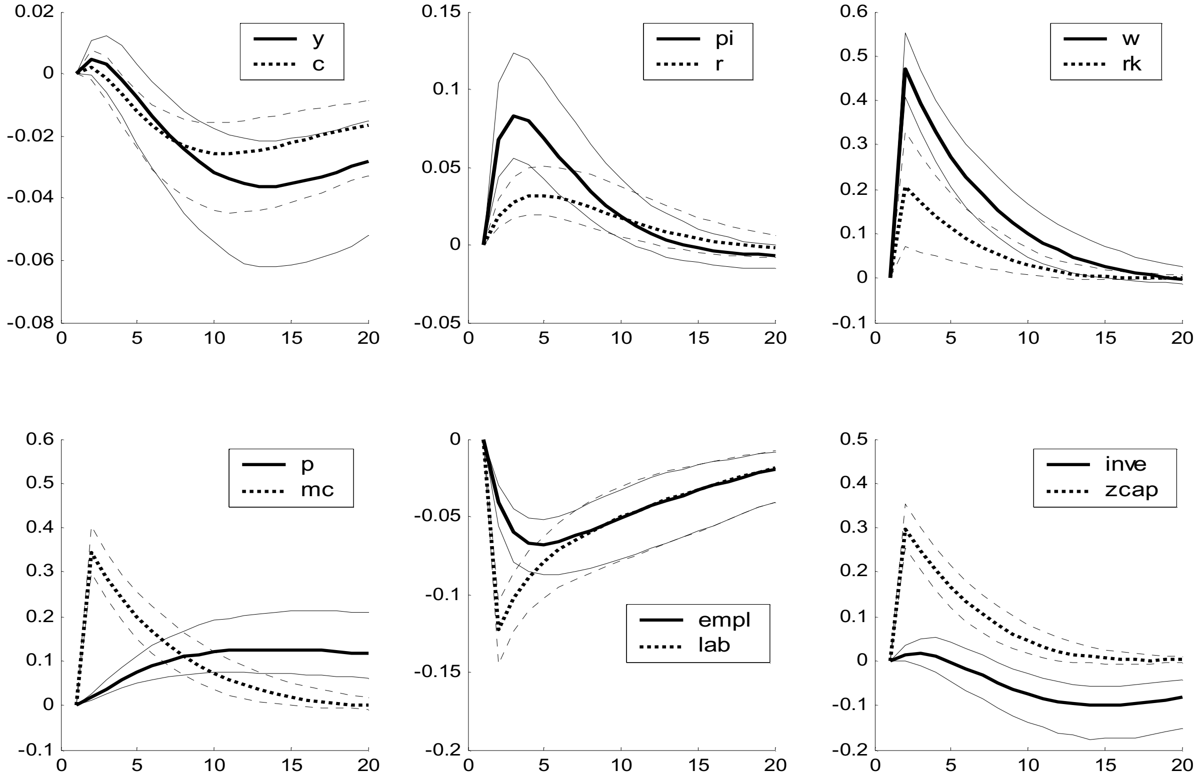
Graph 4:

Labour supply shock



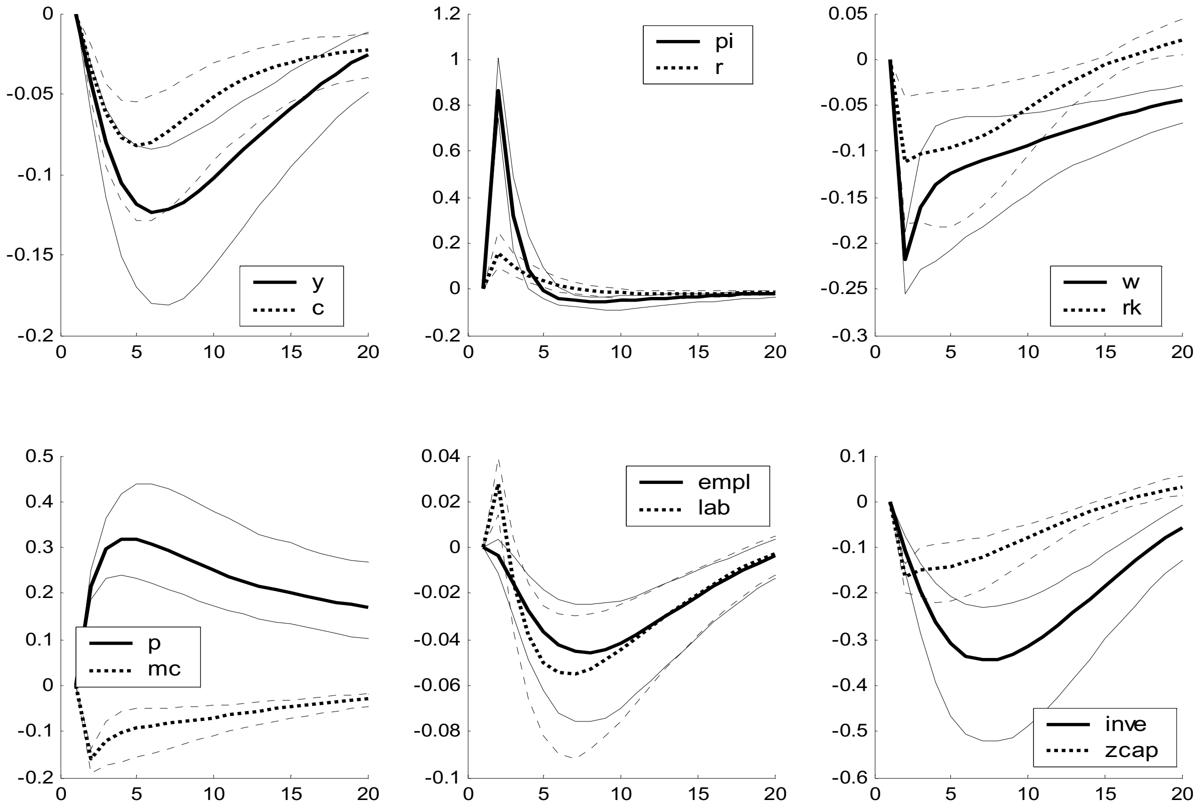
Graph 5:

Wage mark-up shock



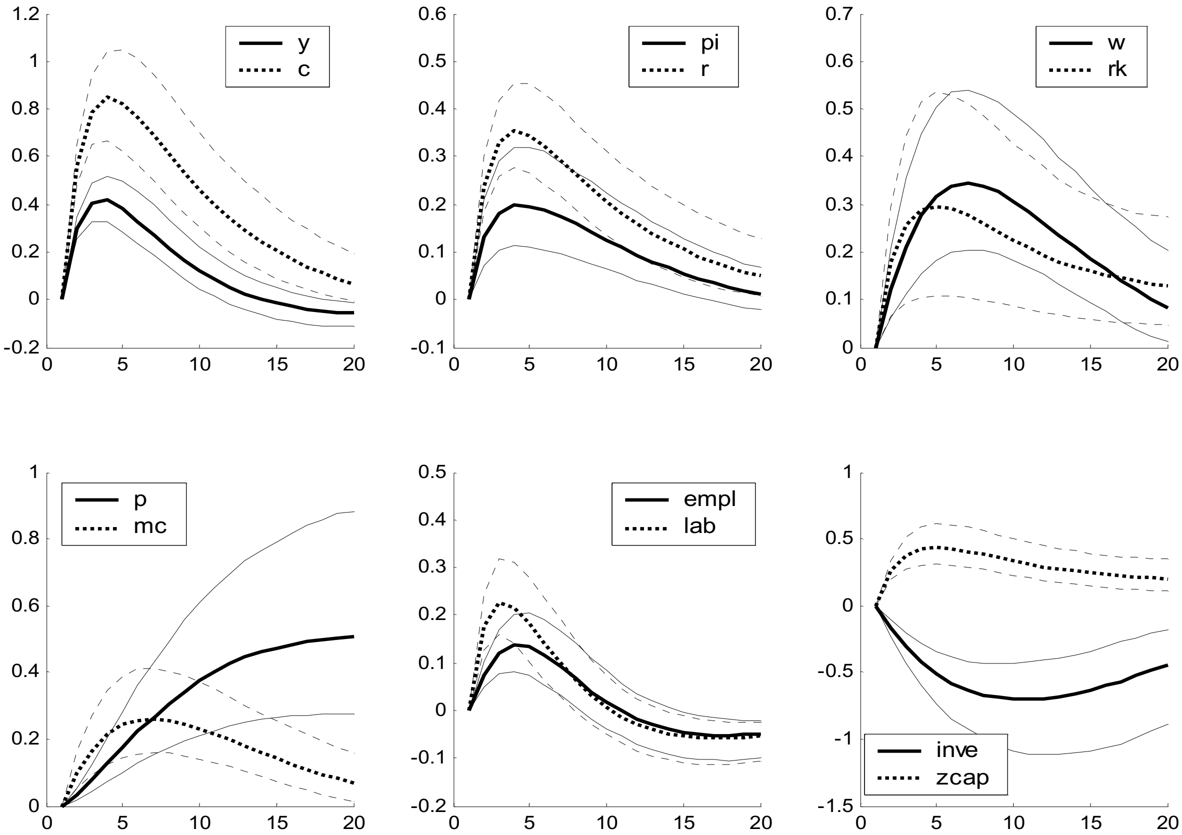
Graph 6:

Price mark-up shock



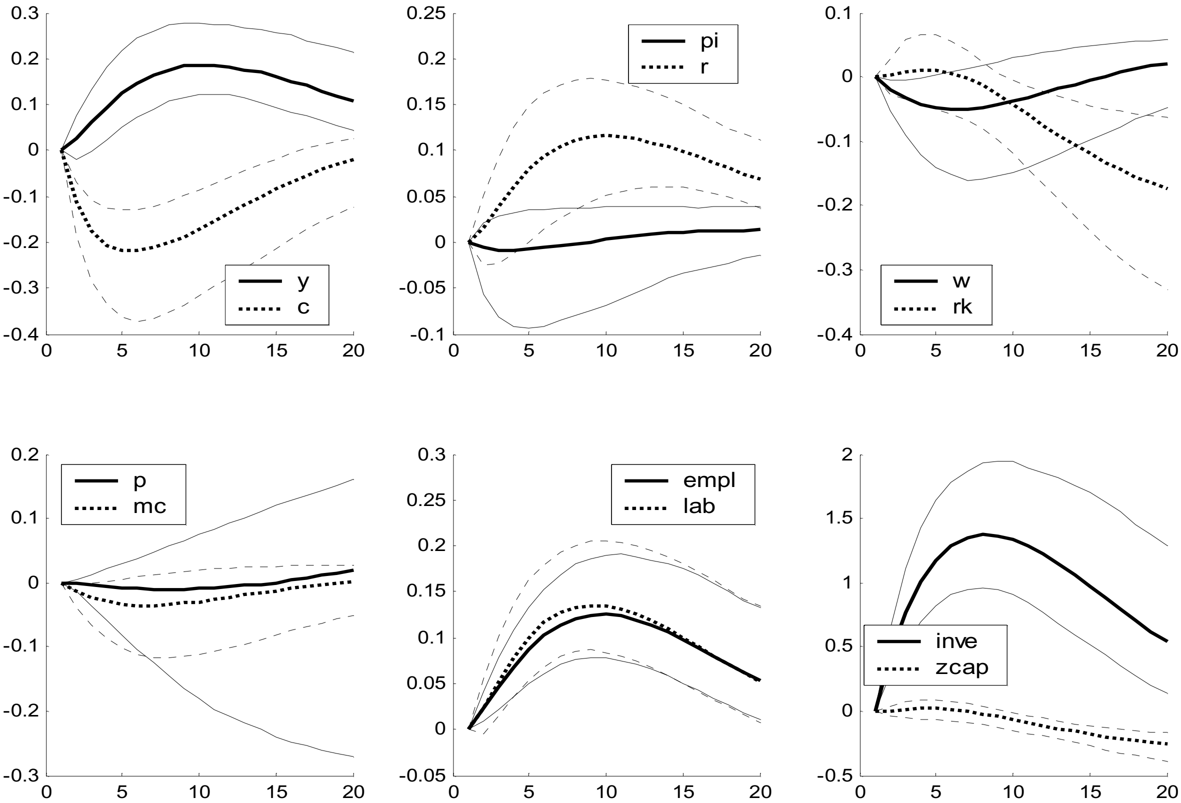
Graph 7:

Preference shock



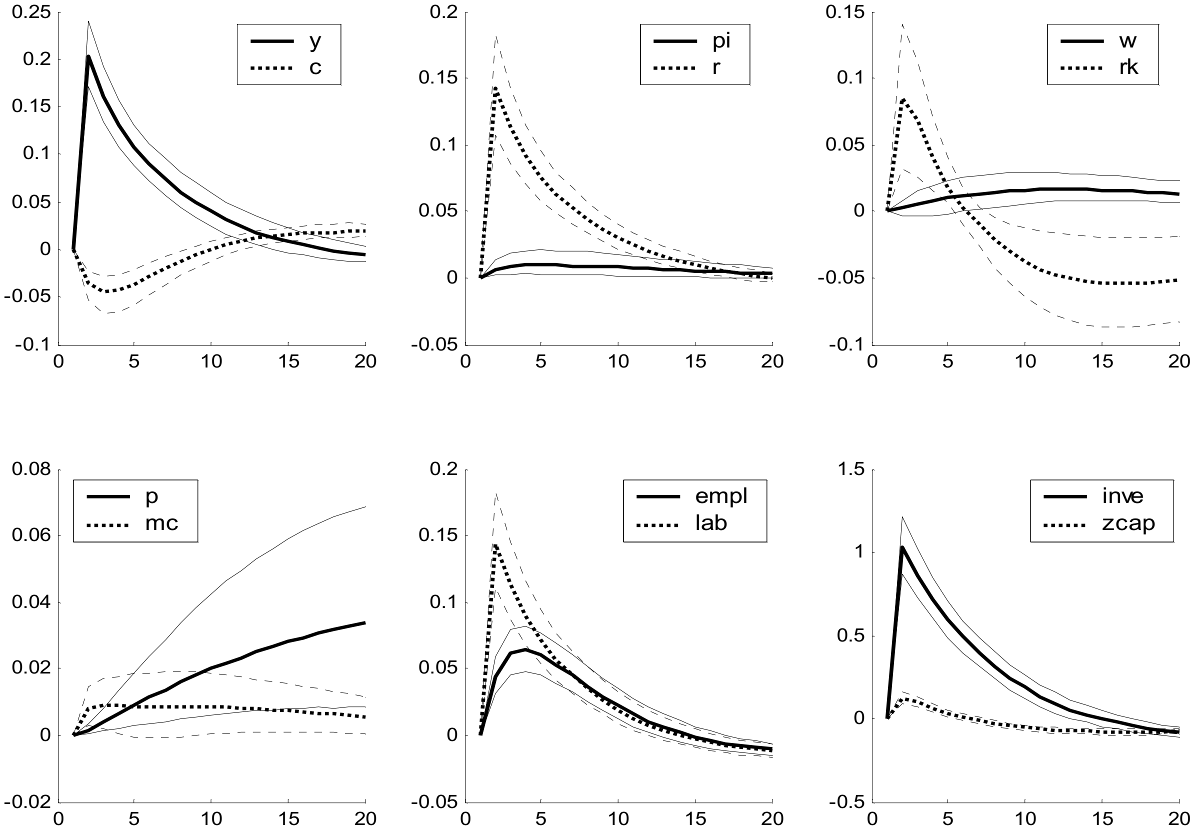
Graph 8:

Investment shock



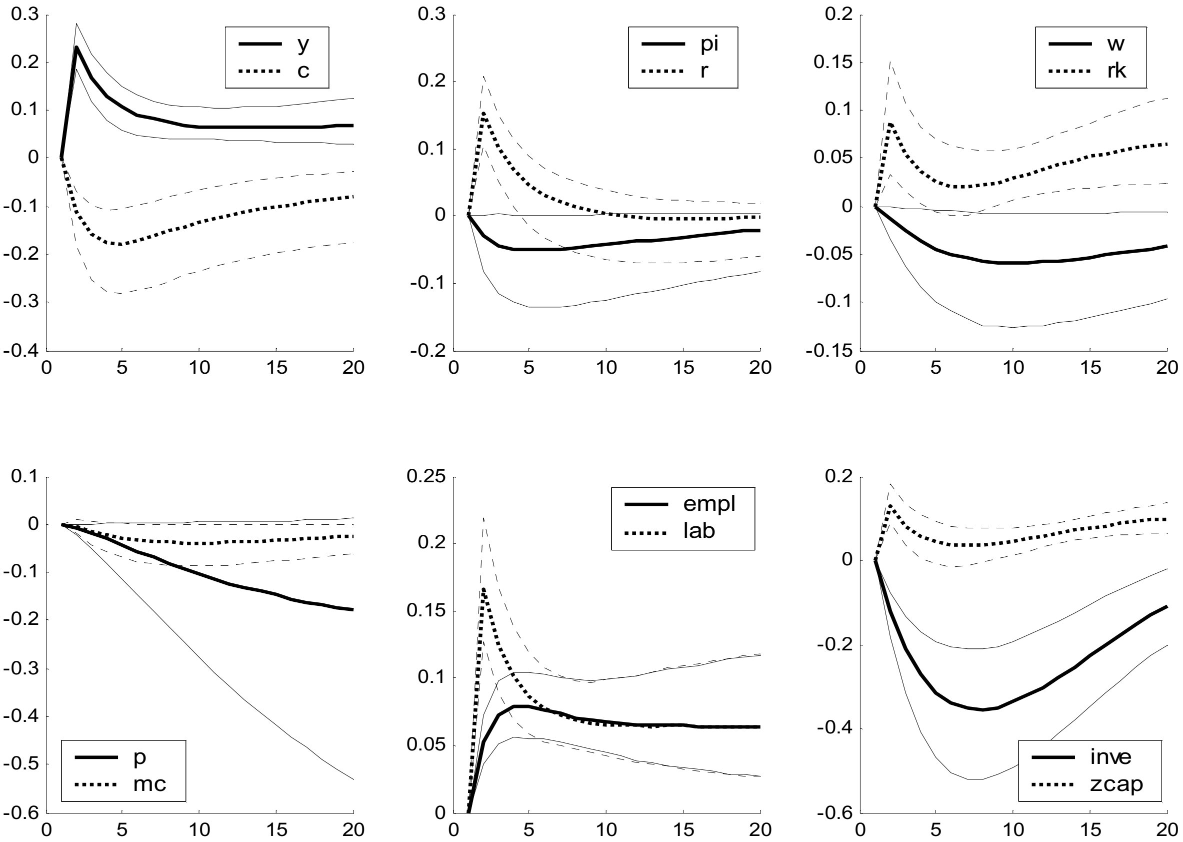
Graph 9:

Equity premium shock



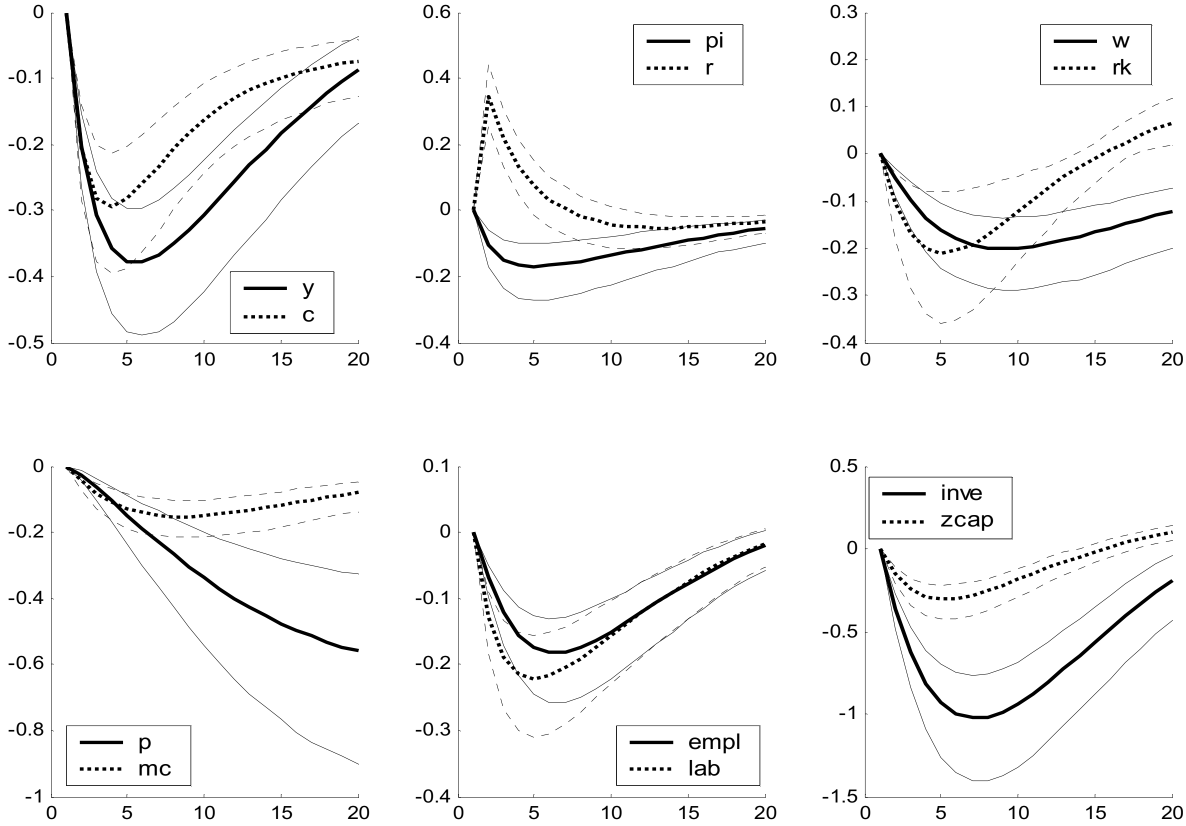
Graph 10:

Government spending shock



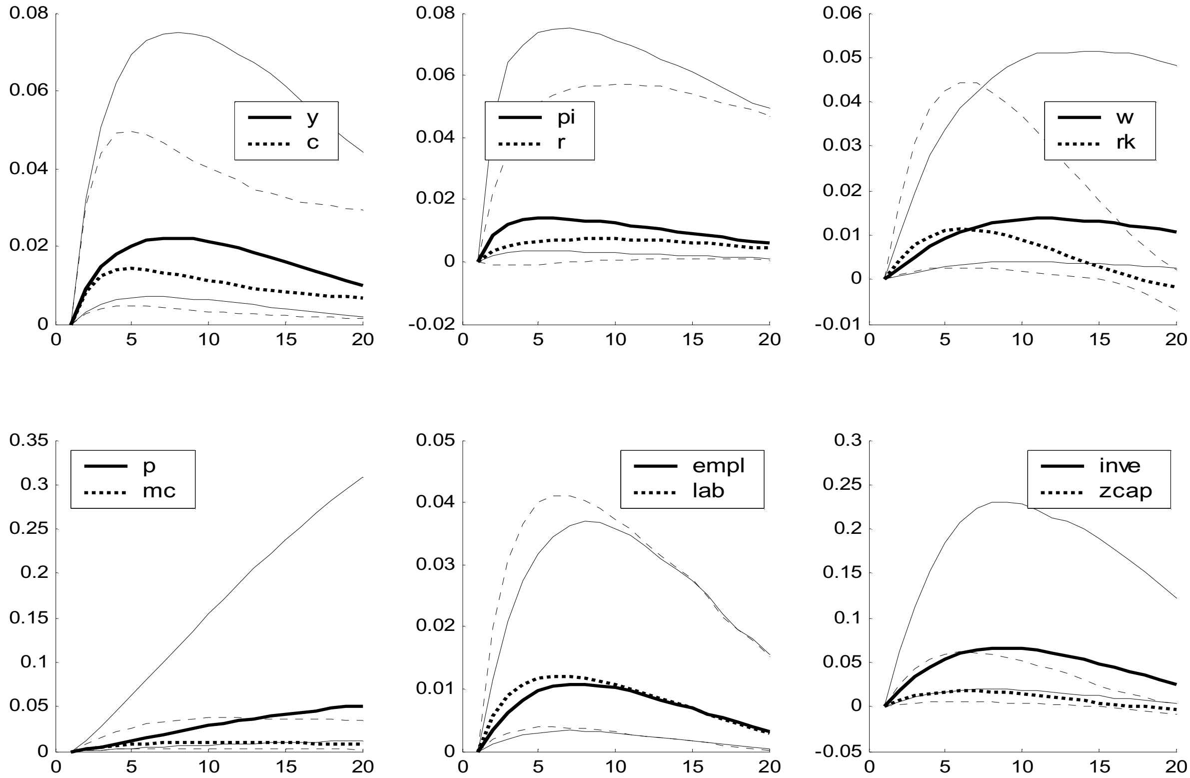
Graph 11:

Monetary policy shock

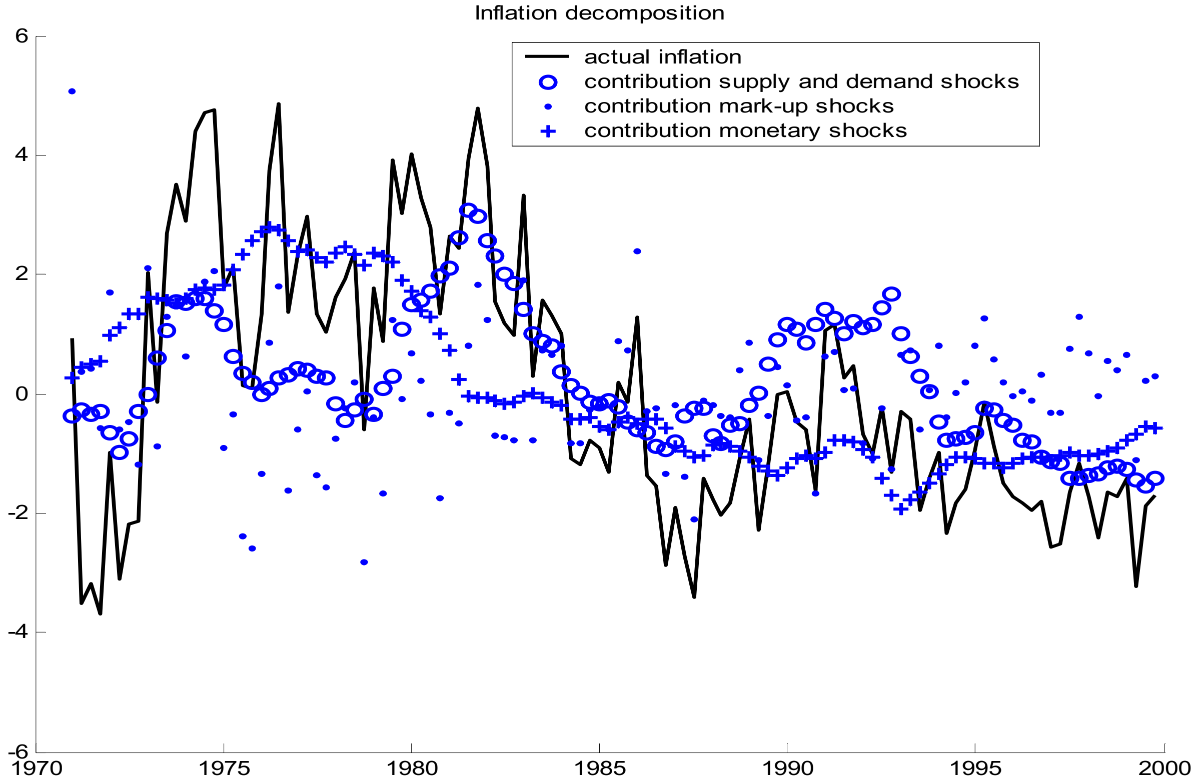


Graph 12

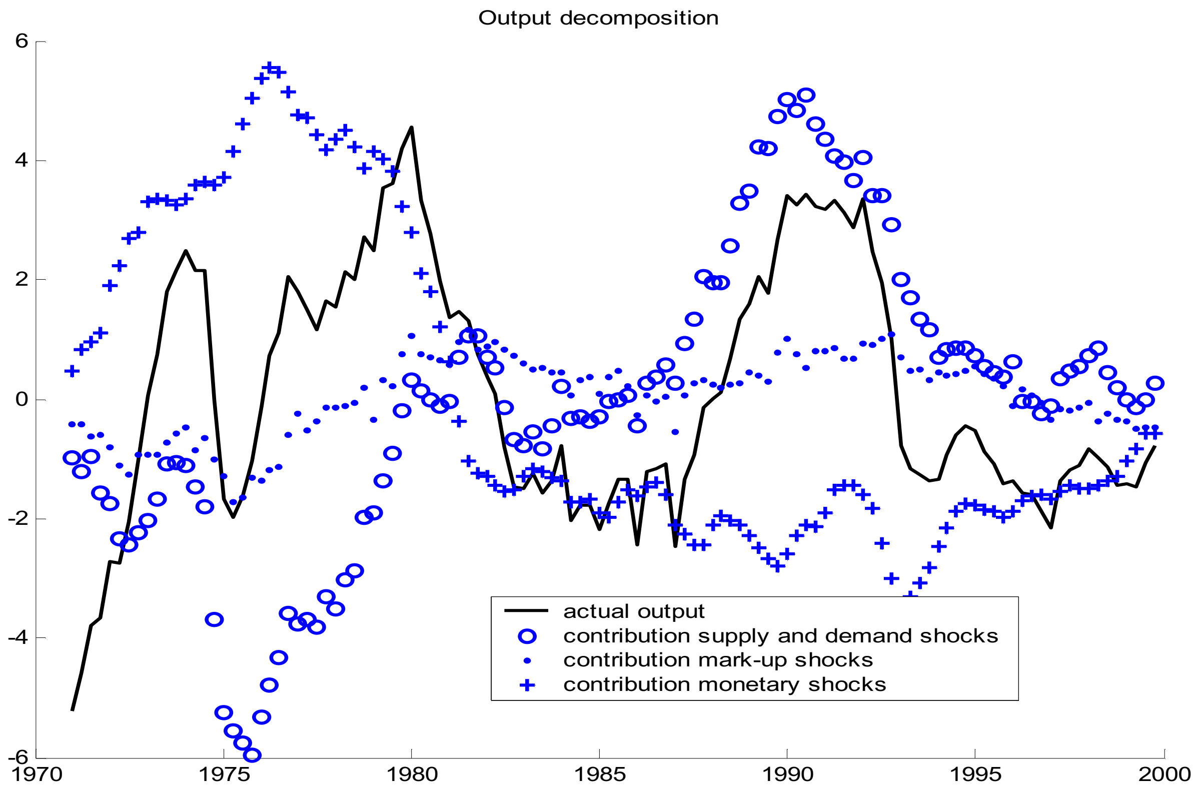
Inflation objective shock



Graph 13 + 14



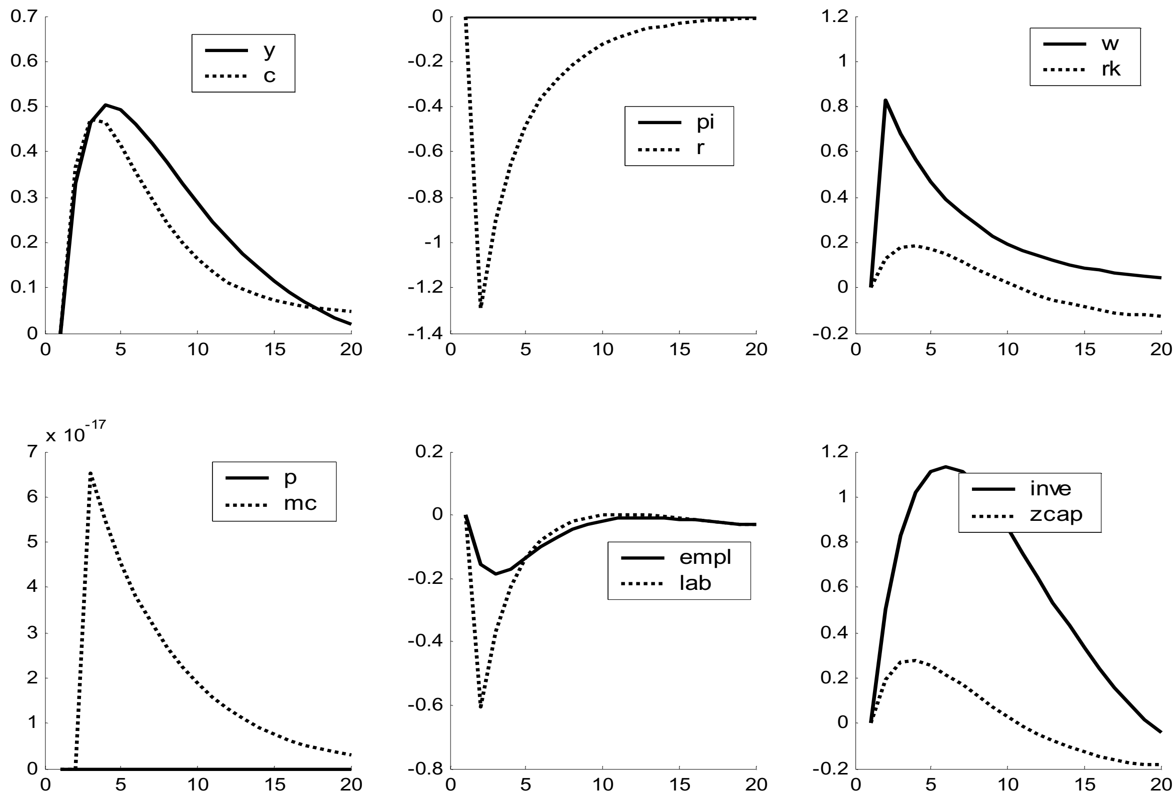
Inflation decomposition
actual inflation
contribution supply and demand shocks
contribution mark-up shocks
contribution monetary shocks
6
4
2
0
-2
-4
-6
1970
1975
1980
1985
1990
1995
2000



Output decomposition
actual output
contribution supply and demand shocks
contribution mark-up shocks
contribution monetary shocks
6
4
2
0
-2
-4
-6
1970
1975
1980
1985
1990
1995
2000

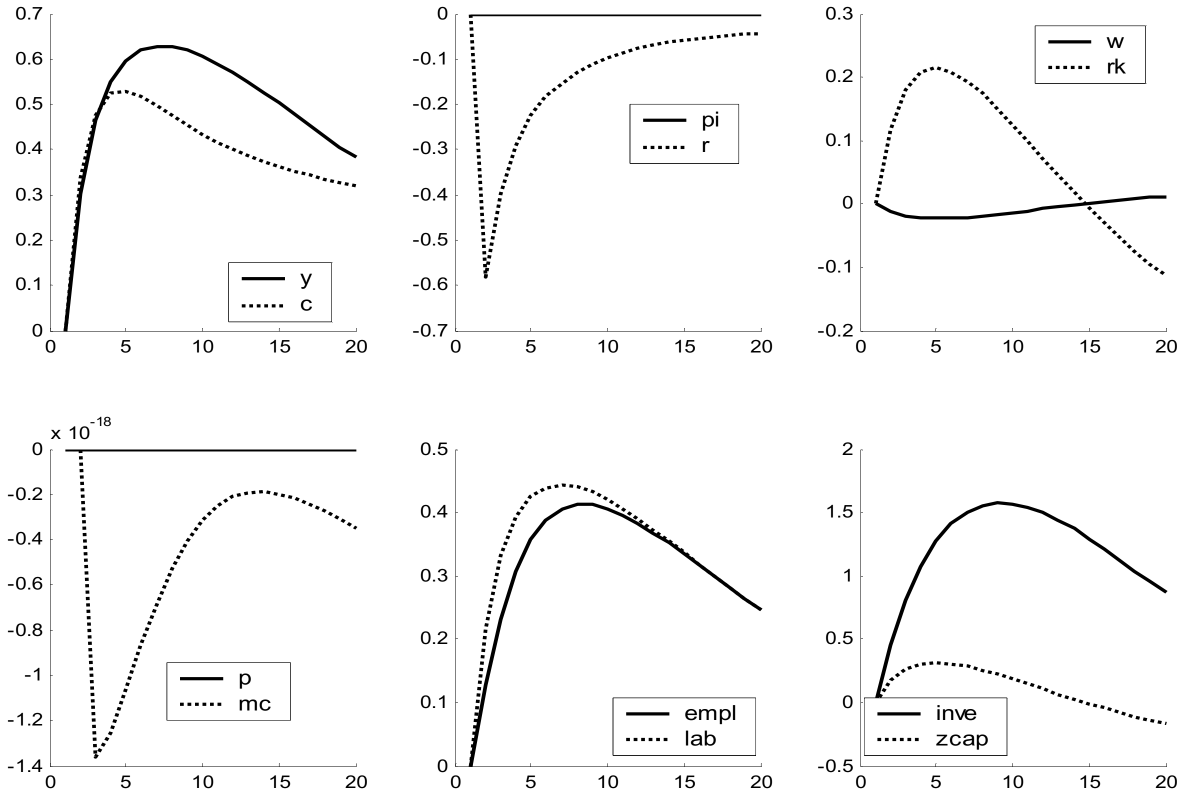
Graph 15:

Productivity shock : flexible price-wage model



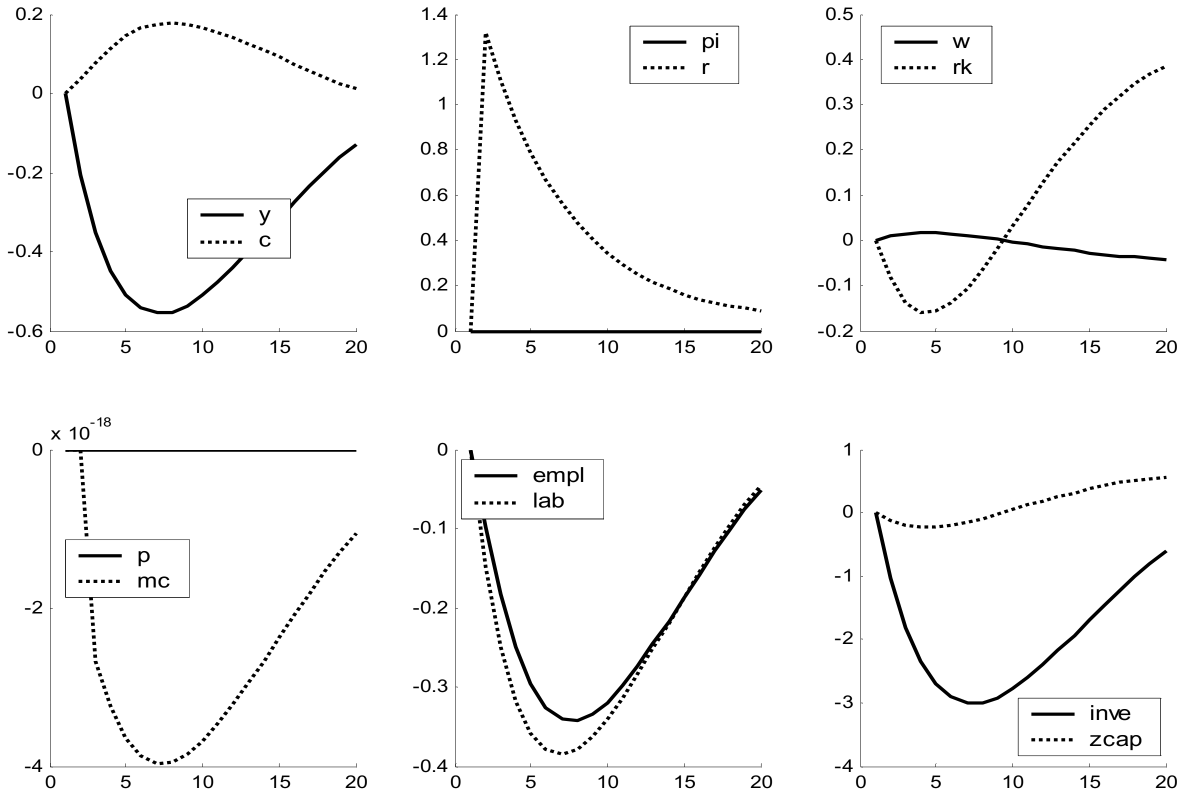
Graph 16:

Labour supply shock: flexible price and wage model



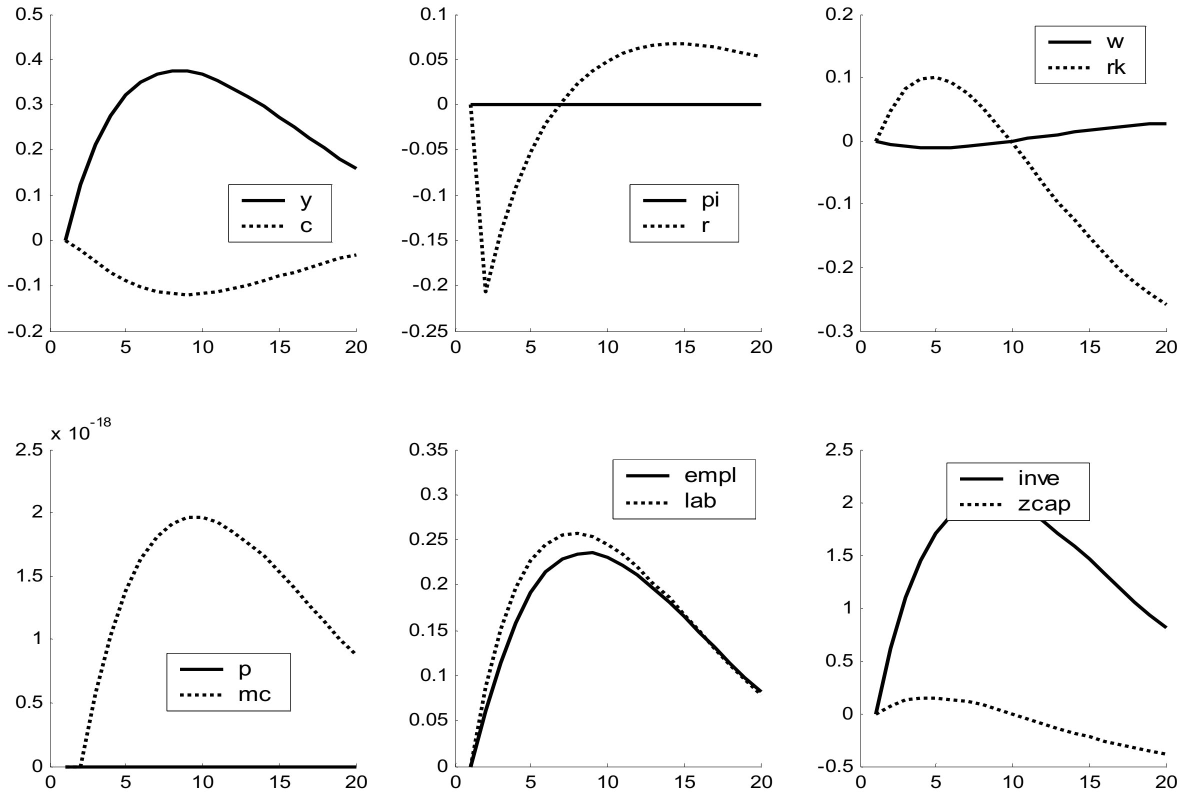
Graph 17:

Preference shock: flexible price and wage model



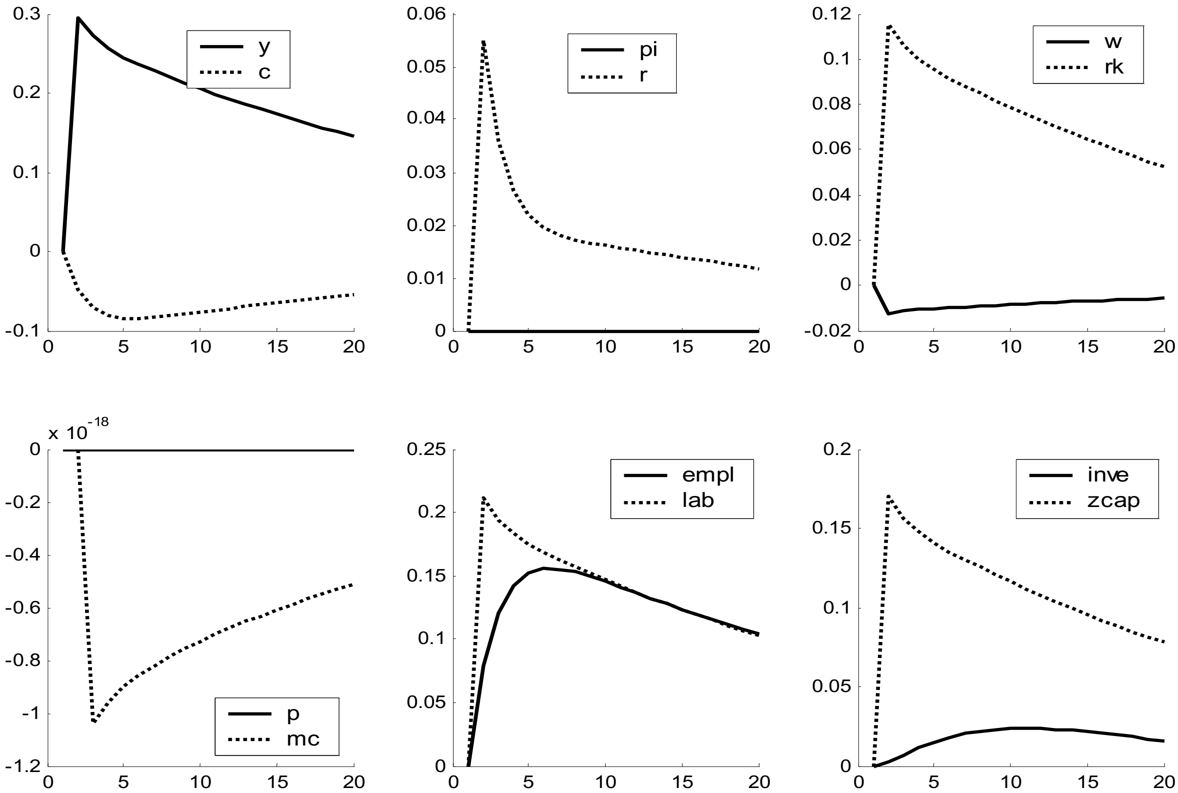
Graph 18:

Investment shock: flexible price and wage model

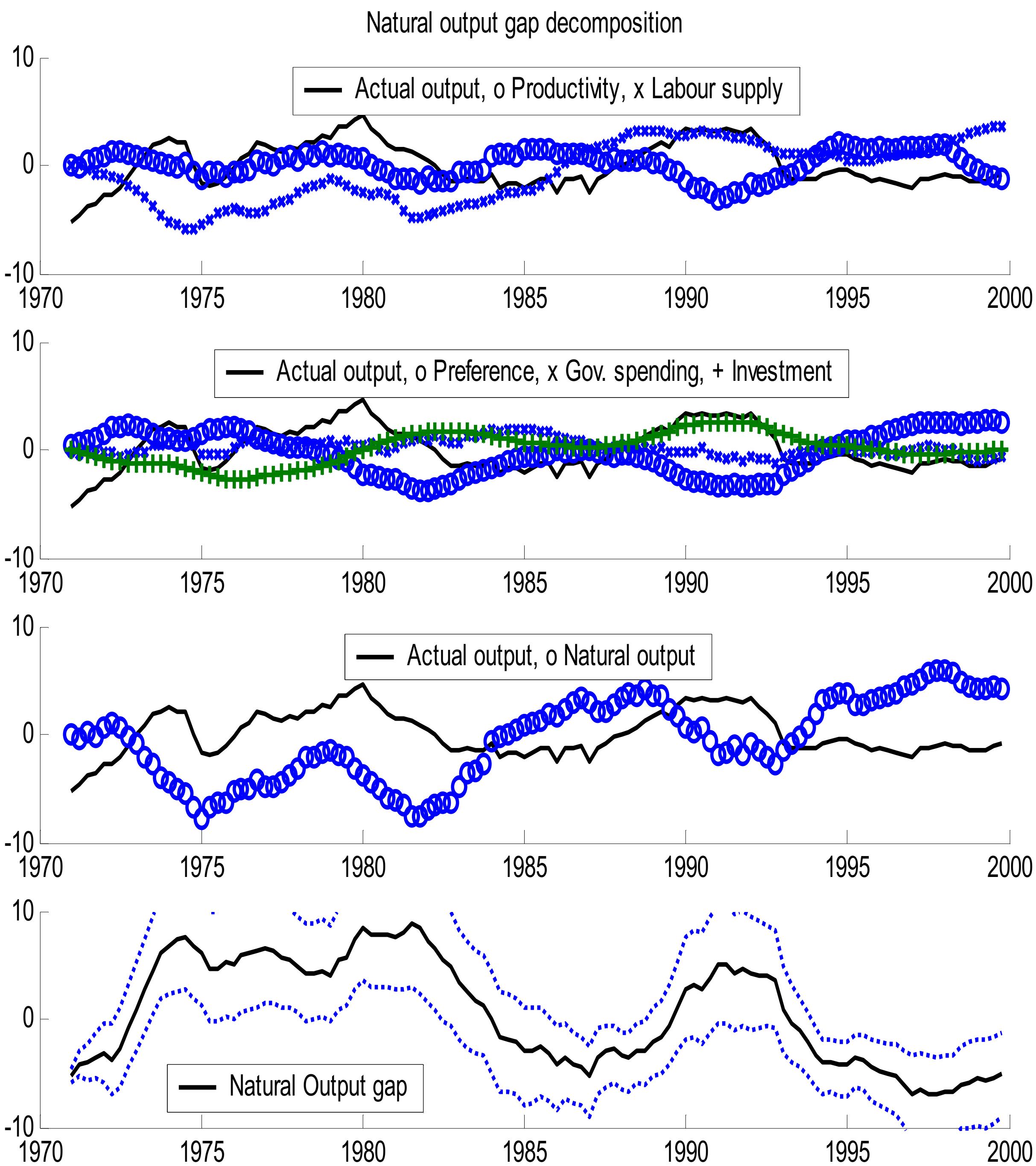


Graph 19:

Government spending shock: flexible price and wage model

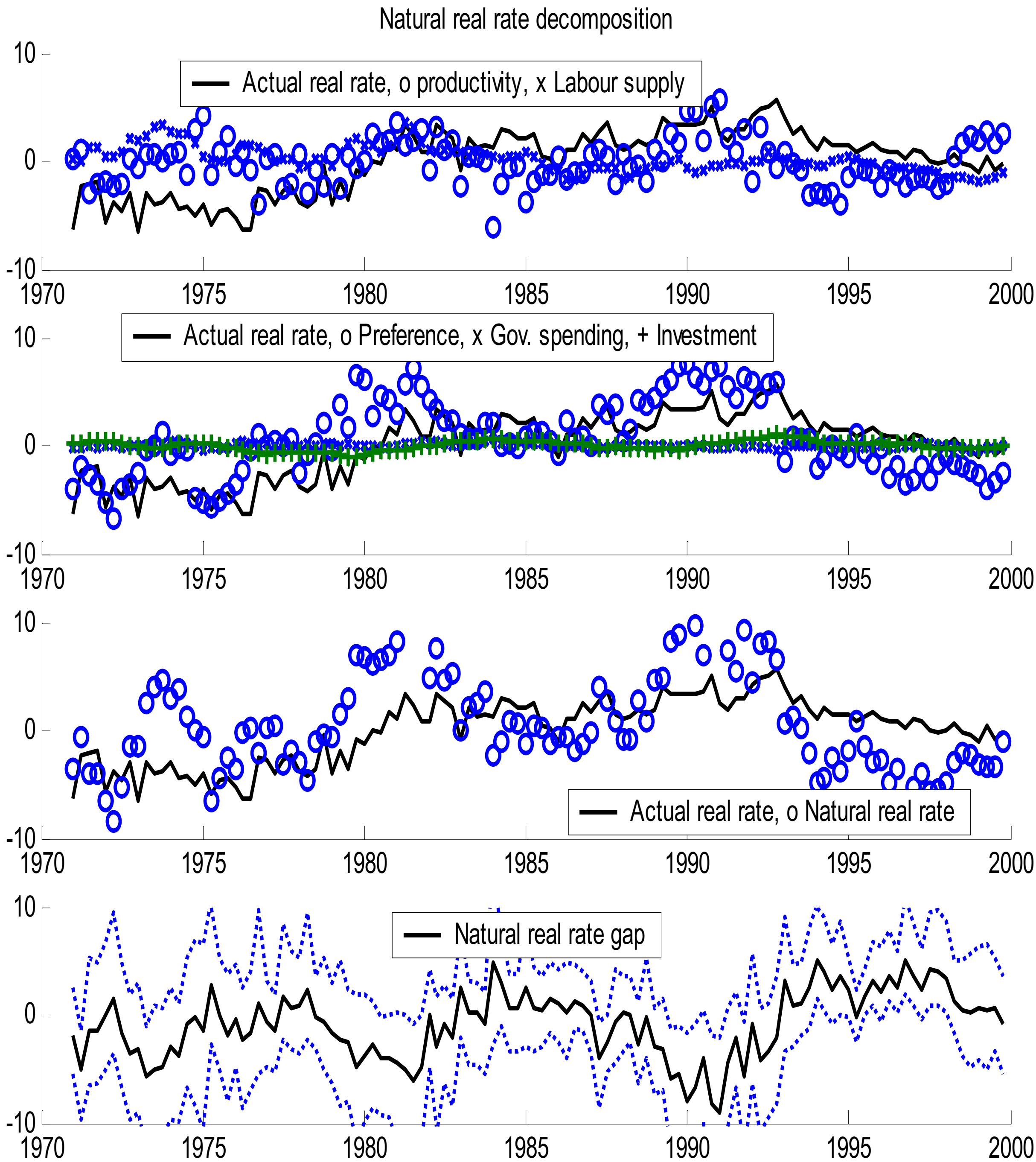


Graph 20



Natural output gap decomposition
Actual output, o Productivity, x Labour supply
10
0
-10
1970
1975
1980
1985
1990
1995
2000
Actual output, o Preference, x Gov. spending, + Investment
Actual output, o Natural output
Natural Output gap

Graph 21


Natural real rate decomposition
Actual real rate, o productivity, x Labour supply
Actual real rate, o Preference, x Gov. spending, + Investment
Actual real rate, o Natural real rate
Natural real rate gap
10
0
-10
1970
1975
1980
1985
1990
1995
2000

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