AN ESTIMATED DYNAMIC STOCHASTIC GENERAL EQUILIBRIUM MODEL OF THE EURO AREA

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Abstract
This paper develops and estimates a dynamic stochastic general equilibrium (DSGE) 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 utilization. It is estimated with Bayesian techniques using seven key macroeconomic variables: GDP, consumption, investment, prices, real wages, employment, and the nominal interest rate. The introduction of ten orthogonal structural shocks (including productivity, labor 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, we also analyze the output (real interest rate) gap, defined as the difference between the actual and model-based potential output (real interest rate). (JEL: E4, E5)

1. Introduction

In this paper we present and estimate a dynamic stochastic general equilibrium (DSGE) model for the euro area. 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 macroeconomic data. Many of these frictions have become quite standard in the DSGE 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 cannot be reoptimized results in a more general dynamic inflation and wage specification that will also depend on past inflation. Following

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Greenwood, Hercowitz, and Huffmann (1988) and King and Rebelo (2000) the model incorporates a variable capital utilization 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 utilization rate is expressed in terms of consumption goods. We also follow CEE (2001) by modeling 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).

Although the model used in this paper has many elements in common with that used in CEE (2001), the analysis differs in two main respects: the number of structural shocks that are introduced and the methodology for estimating the DSGE model. We introduce a full set of structural shocks to the various structural equations.[1] Next to five shocks arising from technology and preferences (a productivity shock, a labor supply shock, a shock to the household's discount factor, a shock to the investment adjustment cost function, and a government consumption shock), we add three "cost-push" shocks (modelled as shocks to the markup in the goods and labor 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 macroeconomic 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 2000), we estimate the model by minimizing the posterior distribution of the model parameters based on the linearized state-space representation of the DSGE model. The purpose of the estimation in this paper is twofold. First, it allows us to evaluate the ability of the new generation of New-Keynesian DSGE models to capture the empirical stochastics and dynamics in the data. In particular, we compare the predictive performance of the estimated DSGE model with that of Vector Autoregressions (VARs) estimated on the same data set. Such an empirical validation is important if those models are to be used for monetary policy analysis. Second, the estimated model is used to analyze the sources of business cycle movements in the euro area. Compared to the standard use of identified VARs for these purposes, our methodology provides a fully structural approach that has not been used before. The structural approach makes it easier to identify the various shocks in a theoretically consistent way. One potential

1. CEE (2001) only consider the effects of a monetary policy shock. They estimate a subset of the structural parameters using indirect inference methods by minimizing the distance between the estimated impulse responses of a monetary policy shock in an identified VAR and those based on the DSGE model. There are also small differences in the model specification. For example, we generalize the indexation mechanism in goods and labor markets to allow for partial indexation. This allows us to estimate the degree of "backward-looking-ness" in the inflation and wage equation. On the other hand, our model does not include an interest rate cost channel.

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drawback is that the identification is dependent on the structural model. Also for that reason, it is important that the model fits the data reasonably well.[2]

Several results of our analysis are worth highlighting. First, when comparing the empirical performance of the DSGE model with those of standard and Bayesian VARs, we find, on the basis of the marginal likelihood and the Bayes factors, that the estimated DSGE model is performing as well as standard and Bayesian VARs. This suggests that the current generation of DSGE models with sticky prices and wages is sufficiently rich to capture the time-series properties of 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 setup.

Second, the estimation procedure yields a plausible set of estimates for the structural parameters of the sticky price and wage DSGE model. In contrast to the results of CEE (2001) for the United States, 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 utilization that 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 United States and the euro area, differences in the underlying structural model, or differences in the estimation methodology.[3] Many of the other parameters, such as the intertemporal elasticity of consumption, the elasticity of the investment adjustment cost function, and the degree of habit formation in consumption are estimated to be in the same ballpark as those estimated for the U.S. economy. The elasticity of labor supply, another important parameter, does not appear to be pinned down very precisely by the data.

Third, we analyze the effects (and the uncertainty surrounding those effects) of the various structural shocks on the euro area economy. 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 (2001). 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 that may be less in line with existing evidence is the strong crowding-out effect. This is particularly the case for the government consumption shock. While the strong crowding-out effect of a

2. In this paper, we do not use the estimated model to evaluate monetary policy. One of the challenges in this respect is to develop an appropriate welfare criterion. We leave this for future research.

3. 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.

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government consumption shock is not in line with evidence for the United States over the post-Bretton Woods sample period (see, for example, Fatas and Mihov 2001), recent international evidence by Perotti (2002) shows that such effects are not uncommon in the more recent period and in other countries.

Fourth, regarding the relative contribution of the various shocks to the empirical dynamics of the macroeconomic time series in the euro area, we find that the labor supply and the monetary policy shock are the two most important structural shocks driving variations in euro area output. In contrast, the price markup shock (together with the monetary policy shock) is the most important determinant of inflation developments in the euro area.

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 potential output level as the output level that is driven by "preference and technology" 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 linearized model. In Section 3, we first discuss the estimation methodology, then present the main results and, finally, compare the empirical performance of the estimated DSGE model with that of various VARs. In Section 4, we analyze 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. A DSGE Model for the Euro Area

In this section we derive and present the linearized DSGE 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.[4] Households maximize a utility function with two arguments (goods and leisure (or labor)) over an infinite life horizon. Consumption appears in the utility function relative to a time-varying external habit variable.[5] Labor is differentiated over households, so that there is some monopoly power over wages that results in an explicit wage equation and allows for the introduction of sticky nominal wages

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

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

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à la Calvo (1983). Households rent capital services to firms and decide how much capital to accumulate given certain capital adjustment costs. As the rental price of capital goes up, the capital stock can be used more intensively according to some cost schedule.[6] Firms produce differentiated goods, decide on labor 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 cannot 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 the next 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 labor. So, each household has a monopoly power over the supply of its labor. Each household τ maximizes an intertemporal utility function given by:

$$E_0 \sum_{t=0}^{\infty} \beta^t U_t^{\tau} \tag{1}$$

where β is the discount factor and the instantaneous utility function is separable in consumption and labor (leisure):[7]

$$U_t^{\tau} = \varepsilon_t^b \left(\frac{1}{1-\sigma_c} (C_t^{\tau} - H_t)^{1-\sigma_c} - \frac{\varepsilon_t^L}{1+\sigma_l} (\ell_t^{\tau})^{1+\sigma_l} \right) \tag{2}$$

Utility depends positively on the consumption of goods, C_t^{τ}, relative to an external habit variable, H_t, and negatively on labor 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.

Equation (2) also contains two preference shocks: ε_t^b represents a shock to the discount rate that affects the intertemporal substitution of households (preference shock) and ε_t^L represents a shock to the labor supply. Both shocks are assumed to follow a first-order autoregressive process with an i.i.d.-normal error term: $\varepsilon_t^b = \rho_b \varepsilon_{t-1}^b + \eta_t^b$ and $\varepsilon_t^L = \rho_L \varepsilon_{t-1}^L + \eta_t^L$.

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

6. See King and Rebelo (2000).

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

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$$H_t = hC_{t-1} \tag{3}$$

Households maximize their objective function subject to an intertemporal budget constraint that is given by:

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

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

Household's total income is given by:

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

Total income consists of three components: labor 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 utilization ($r_t^k z_t^\tau K_{t-1}^\tau - \Psi(z_t^\tau)K_{t-1}^\tau$), 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 labor income. As a result, the first component in the household's income will be equal to aggregate labor income and the marginal utility of wealth will be identical across different types of households.[8]

The income from renting out capital services depends not only on the level of capital that was installed last period, but also on its utilization rate (z_t). As in CEE (2001), it is assumed that the cost of capital utilization is zero when capital utilization is one ($\psi(1) = 0$). Next we discuss each of the household decisions in turn.

2.1.1 Consumption and Savings Behavior. The maximization 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:

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

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:[9]

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

8. See CEE (2001) for a more complete analysis.

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

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

2.1.2 Labor Supply Decisions and the Wage Setting Equation. Households act as price-setters in the labor 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 that 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 reoptimized in the near future. In addition, we allow for a partial indexation of the wages that cannot be adjusted to past inflation. More formally, the wages of households that cannot reoptimize adjust according to:

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

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

Households set their nominal wages to maximize their intertemporal objective function subject to the intertemporal budget constraint and the demand for labor that is determined by:

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

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

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

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

This maximization problem results in the following markup equation for the reoptimized wage:

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

where U_{t+i}^l is the marginal disutility of labor and U_{t+i}^C is the marginal utility of consumption. Equation (12) shows that the nominal wage at time t of a

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household τ that is allowed to change its wage is set so that the present value of the marginal return to working is a markup over the present value of marginal cost (the subjective cost of working).[10] When wages are perfectly flexible ($\xi_w = 0$), the real wage will be a markup (equal to $1 + \lambda_{w,t}$) over the current ratio of the marginal disutility of labor and the marginal utility of an additional unit of consumption. We assume that shocks to the wage markup, $\lambda_{w,t} = \lambda_w + \eta_t^w$, are i.i.d.-normal around a constant.

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

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

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 utilization rate of already installed capital (z_t). Both actions are costly in terms of foregone consumption (see the intertemporal budget constraint (4) and (5)).[11] Households choose the capital stock, investment, and the utilization rate in order to maximize their intertemporal objective function subject to the intertemporal budget constraint and the capital accumulation equation, which is given by:

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

where I_t is gross investment, τ is the depreciation rate, and the adjustment cost function $S(\cdot)$ is a positive function of changes in investment.[12] $S(\cdot)$ 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

10. Standard RBC models typically assume an infinite supply elasticity of labor in order to obtain realistic business cycle properties for the behavior 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.

11. 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).

12. See CEE (2001).

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a first-order autoregressive process with an i.i.d.-normal error term: $\varepsilon_t^I = \rho_I \varepsilon_{t-1}^I + \eta_t^I$.[13]

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

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

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

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

Equation (15) states that the value of installed capital depends on the expected future value taking into account the depreciation rate and the expected future return as captured by the rental rate times the expected rate of capital utilization.

The first-order condition for the utilization rate (17) equates the cost of higher capital utilization 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 utilization is that it reduces the impact of changes in output on the rental rate of capital and therefore smooths the response of marginal cost to fluctuations in output.[14]

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.

13. See Keen (2001) for a recent DSGE model with sticky prices in which one of the shocks comes from changes in costs of adjusting investment.

14. Another assumption that 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.

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2.2.1 Final-Good Sector. The final good is produced using the intermediate goods in the following technology:

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

where y_t^j denotes the quantity of domestic intermediate good of type j that is used in final goods production, at date t. $\lambda_{p,t}$ is a stochastic parameter that determines the time-varying markup 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 i.i.d.-normal.

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

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

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

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

2.2.2 Intermediate Goods Producers. Each intermediate good j is produced by a firm j using the following technology:

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

where ε_t^a is the productivity shock (assumed to follow a first-order autoregressive process: $\varepsilon_t^a = \rho_a \varepsilon_{t-1}^a + \eta_t^a$), $\tilde{K}_{j,t}$ is the effective utilization 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 labor used by the firm given by (10) and Φ is a fixed cost.

Cost minimization implies:

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

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

$$MC_t = \frac{1}{\varepsilon_t^a} W_t^{1-\alpha} r_t^{k\alpha} (\alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}) \tag{23}$$

This implies that the marginal cost, too, is independent of the intermediate good produced. Nominal profits of firm j are then given by:

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

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

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 reoptimized in any particular period is constant and equal to $1 - \xi_p$. Following CEE (2001), prices of firms that do not receive a price signal are indexed to last period's inflation rate. In contrast to CEE (2001), we allow for partial indexation.[15] Profit optimization by producers that are "allowed" to reoptimize their prices at time t results in the following first-order condition:

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

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

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

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

2.3 Market Equilibrium

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

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

15. Erceg, Henderson, and Levin (2000) use indexation to the average steady-state inflation rate. Allowing for indexation of the nonoptimized prices on lagged inflation, results in a linearized 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 optimizing behavior 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 behavior. This will also have important consequences for the welfare evaluation of inflation costs.

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The capital rental market is in equilibrium when the demand for capital by the intermediate goods producers equals the supply by the households. The labor market is in equilibrium if firms' demand for labor equals labor 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 section. In the capital market, equilibrium means that the government debt is held by domestic investors at the market interest rate R_t.

2.4 The Linearized Model

For the empirical analysis of Section 3 we linearize the model equations described previously around the nonstochastic steady state. Next we summarize the resulting linear rational expectations equations. The $\hat{}$ above a variable denotes its log deviation from steady state.

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

$$\hat{C}_t = \frac{h}{1+h}\hat{C}_{t-1} + \frac{1}{1+h}E_t\hat{C}_{t+1} - \frac{1-h}{(1+h)\sigma_c}(\hat{R}_t - E_t\hat{\pi}_{t+1}) + \frac{1-h}{(1+h)\sigma_c}(\hat{\varepsilon}^b_t - E_t\hat{\varepsilon}^b_{t+1}) \tag{28}$$

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:

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

where $\varphi = 1/\bar{S}''$. As discussed in CEE (2001), modeling 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, $\hat{\varepsilon}^I_t$, (also denoted as a negative investment shock) temporarily reduces investment.

The corresponding *Q equation* is given by:

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

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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.[16] We assume that this equity premium shock follows an i.i.d.-normal process. In a fully fledged model, the production of capital goods and the associated investment process could be modelled in a separate sector. In such a case, imperfect information between the capital producing borrowers and the financial intermediaries could give rise to a stochastic external finance premium. For example, in Bernanke, Gertler, and Gilchrist (1998), the deviation from the perfect capital market assumptions generates deviations between the return on financial assets and equity that are related to the net worth position of the firms in their model. Here, we implicitly assume that the deviation between the two returns can be captured by a stochastic shock, whereas the steady-state distortion due to such informational frictions is zero.[17]

The *capital accumulation equation* is standard:

$$\hat{K}_t = (1 - \tau)\hat{K}_{t-1} + \tau\hat{I}_{t-1} \tag{31}$$

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

$$\begin{aligned}\hat{\pi}_t = {} & \frac{\beta}{1 + \beta\gamma_p} E_t\hat{\pi}_{t+1} + \frac{\gamma_p}{1 + \beta\gamma_p}\hat{\pi}_{t-1} \\ & + \frac{1}{1 + \beta\gamma_p}\frac{(1 - \beta\xi_p)(1 - \xi_p)}{\xi_p}[\alpha\hat{r}_t^k + (1 - \alpha)\hat{w}_t - \hat{\varepsilon}_t^a + \eta_t^p]\end{aligned} \tag{32}$$

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-markup 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:

16. This is the only shock that is not directly related to the structure of the economy.

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

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

The real wage is a function of expected and past real wages and the expected, current, and past inflation rate where the relative weight depends on the degree of indexation of the nonoptimized 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 labor market. The size of this effect will be greater, the smaller the degree of wage rigidity, the lower the demand elasticity for labor and the lower the inverse elasticity of labor supply (the flatter the labor supply curve).

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

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

where $\psi = \psi'(1)/\psi''(1)$ is the inverse of the elasticity of the capital utilization cost function.

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

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

where k_y is the steady state capital-output ratio, g_y the steady-state government spending-output ratio and ϕ is 1 plus the share of the fixed cost in production. We assume that the government spending shock follows a first-order autoregressive process with an i.i.d.-normal error term: $\varepsilon_t^G = \rho_G \varepsilon_{t-1}^G + \eta_t^G$. Finally, the model is closed by adding the following empirical monetary policy reaction function:

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

The monetary authorities follow a generalized Taylor rule by gradually responding to deviations of lagged inflation from an inflation objective (normalized to be zero) and the lagged output gap defined as the difference between actual and potential output (Taylor 1993). Consistently with the DSGE model, potential output is defined as the level of output that would prevail under flexible price

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and wages in the absence of the three "cost-push" shocks.[18] The parameter ρ captures the degree of interest rate smoothing. In addition, there is also a short-run feedback from the current changes in inflation and the output gap. Finally, we assume that there are two monetary policy shocks: one is a persistent shock to the inflation objective ($\bar{\pi}_t$), which is assumed to follow a first-order autoregressive process ($\bar{\pi}_t = \rho_\pi \bar{\pi}_{t-1} + \eta_t^\pi$); the other is a temporary i.i.d.-normal interest rate shock (η_t^R). The latter will also be denoted a monetary policy shock. Of course, it is important to realize that there was no single monetary authority during most of the sample period that we will use in estimating equation (36). However, Gerlach and Schnabel (2000) have shown that since the early 1990s average interest rates in the euro area can be characterized quite well by a Taylor rule. This is in line with the findings of Clarida, Gali, and Gertler (1998) that a Taylor-type monetary policy reaction function is able to describe the behavior of both the Bundesbank, which acted as the de facto anchor of the European exchange rate mechanism, and the French and Italian central banks since the early 1980s.

Equations (28) to (36) 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 behavior 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, ε_t^L, ε_t^G), three "cost-push" shocks (η_t^w, η_t^p, and η_t^Q), and two monetary policy shocks ($\bar{\pi}_t$ and η_t^R). As discussed before, 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 i.i.d.-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 DSGE model with a number of nontheoretical VARs.

3.1 Estimation Methodology

There are various ways of estimating or calibrating the parameters of a linearized DSGE model. Geweke (1999) distinguishes between the weak and the strong econometric interpretation of DSGE models. The weak interpretation is closest in spirit to the original RBC program developed by Kydland and Prescott

18. See Section 5 for a discussion of this output gap concept. In practical terms, we expand the model consisting of Equations (28) to (36) with a flexible-price-and-wage version in order to calculate the model-consistent output gap.

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(1982).[19] The parameters of an DSGE 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 minimizing some distance function between the theoretical and empirical moments of interest. For example, recently, a number of researchers have estimated the parameters in monetary DSGE models by minimizing 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 next. In addition, these estimation methods allow the researcher to focus on the characteristics in the data for which the DSGE model, which is necessarily an abstraction of reality, is most relevant.

In contrast, the strong econometric interpretation attempts to provide a full characterization of the observed data series. For example, following Sargent (1989), a number of authors have estimated the structural parameters of DSGE models using classical maximum likelihood methods.[20] 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 that 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.[21] The third step consists of using the Kalman filter to form the likelihood function. In the final step, the parameters are estimated by maximizing 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 optimized with respect to the model parameters either directly or through Monte-Carlo Markov-Chain (MCMC) sampling methods.[22]

The attractions of the strong econometric interpretation are clear. When successful, it provides a full characterization of the data-generating process and

19. 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."

20. See, for example, the references in Ireland (1999).

21. Recently, Ireland (1999) has suggested a way of combining the power of DSGE 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 process. This proposed method admits that while DSGE models may be powerful enough to account for and explain many key features of the data, they remain too stylized 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.

22. Recent examples of such a Bayesian approach are Otrok (2001), Fernandez-Villaverde and Rubio-Ramirez (2001), and Schorfheide (2000).

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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 DSGE 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 cross-covariances. Moreover, various shocks have been added, which avoids the singularity problem and allows for a better characterization of the unconditional moments in the data. Second, as pointed out by Geweke (1999), the weak econometric interpretation of DSGE 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 DSGE models. As in recent papers by Geweke (1998), Fernandez-Villaverde and Rubio-Ramirez (2001), Schorfheide (2000), and Landon-Lane (2000), we apply Bayesian techniques for two reasons. First, this approach allows one to formalize the use of prior information coming either from microeconometric studies or previous macroeconometric studies and thereby makes an explicit link with the previous calibration-based literature. Second, from a practical point of view, the use of prior distributions over the structural parameters makes the highly nonlinear optimization algorithm more stable. This is particularly valuable when only relatively small samples of data are available, as is the case with euro area time series.[23]

In order to estimate the parameters of the DSGE model presented in Section 2, we use data over the period 1980:2–1999:4 on seven key macroeconomic variables in the euro area: real GDP, real consumption, real investment, the GDP deflator, real wages, employment, and the nominal interest rate.[24] As we do not have good measures of the area-wide capital stock, the value of capital or the rental rate on capital, we 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 macroeconomic shocks than total hours worked, we assume that in any given period only a constant fraction,

23. The Bayesian approach also provides a framework for evaluating fundamentally misspecified models. This can be done 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. One drawback is that it can be very computationally intensive, as MCMC methods generally 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.

24. The data set used is the one constructed in Fagan, Henry, and Mestre (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. This data set starts in 1970. We use the 1970s to initialize our estimates.

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ξ_e, of firms is able to adjust employment to its desired total labor input. The difference is taken up by (unobserved) hours worked per employer.[25] This gives rise to the following auxiliary equation for employment:

$$\hat{E}_t = \beta \hat{E}_{t+1} + \frac{(1 - \beta\xi_e)(1 - \xi_e)}{\xi_e} (\hat{L}_t - \hat{E}_t) \tag{37}$$

where $\hat{E}_t$ denotes the number of people employed.[26]

The fact that the model contains ten structural shocks and there are only seven observable variables raises a general identification issue. For example, without further restrictions, it may be difficult to separately identify the labor supply and the wage markup shocks that both enter equation (33).[27] Identification is achieved by assuming that each of the structural shocks are uncorrelated and that four of the ten shocks, the three "cost-push" shocks, and the temporary monetary policy shock, follow a white noise process. This allows us to distinguish those shocks from the persistent "technology and preference" shocks and the inflation objective shock. As discussed next, the autoregressive parameter of the latter shocks has a relatively strict prior distribution with a mean of 0.85 and a standard error of 0.10, clearly distinguishing them from the white noise 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 is then combined with a prior density for the structural parameters to obtain the posterior distribution of the parameters. Before discussing the estimation 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 viewed 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 cannot 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 percent. 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 labor income in total output of 70 percent. The share of steady-state consump-

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

26. Obviously, this is only a shortcut. In future research, we intend to investigate more in detail the theoretical and empirical determinants of the extensive and intensive margin of the labor supply and demand decisions.

27. Note, however, that while the "technology and preference" shocks affect potential output, the "cost-push" shocks do not. As discussed in Section 5, the underlying argument is that "cost-push" shocks refer to inefficient variations in the natural level of output due to market imperfections and as such should not be accommodated by monetary policy. As a result, the policy-controlled interest rate will respond differently to, say, a labor supply shock and a wage markup shock, because they affect the output gap differently.

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tion 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 markup 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 microeconometric studies by Griffin (1996) based on U.S. data.

The first three columns of Table 1 give an overview of our assumptions regarding the prior distribution of the other 32 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 "technology and preference" 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 nonpersistent 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 typically set at values that correspond to those in 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 (2001a), but the standard error allows for variation between three quarters and two years. Similarly, the mean of the intertemporal elasticity of substitution is set equal to 1, consistent with log preferences and the findings of Casares (2001) for the euro area. The elasticity of the capital utilization 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 labor 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 microlabor literature and the larger elasticities typically used in DSGE models. Finally, the priors on the means of the coefficients in the monetary policy reaction function are standard: a relatively high long-term coefficient on inflation (1.7) helps to guarantee a unique solution path when solving the model; the prior on the lagged interest rate is set at 0.8, and the prior on the output gap reaction coefficient corresponds to the Taylor coefficient of 0.5.

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TABLE 1. PARAMETER ESTIMATES

	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	0.4	2*	0.598	0.113	0.469	0.624	0.874	0.639
σ inflation objective shock	Inv gamma	0.02	2*	0.017	0.008	0.012	0.025	0.085	0.033
σ cons. preference shock	Inv gamma	0.2	2*	0.336	0.096	0.237	0.392	0.631	0.407
σ government spending shock	Inv gamma	0.3	2*	0.325	0.026	0.292	0.333	0.385	0.335
σ labor supply shock	Inv gamma	1.00	2*	3.520	1.027	2.313	3.674	5.845	3.818
σ investment shock	Inv gamma	0.10	2*	0.085	0.030	0.060	0.105	0.196	0.113
σ interest rate shock	Inv gamma	0.10	2*	0.081	0.023	0.060	0.089	0.125	0.090
σ equity premium shock	Inv gamma	0.40	2*	0.604	0.063	0.514	0.608	0.727	0.613
σ price markup shock	Inv gamma	0.15	2*	0.160	0.016	0.140	0.164	0.197	0.165
σ wage markup shock	Inv gamma	0.25	2*	0.289	0.027	0.256	0.295	0.346	0.297
ρ productivity shock	Beta	0.85	0.10	0.823	0.065	0.697	0.815	0.910	0.811
ρ inflation objective shock	Beta	0.85	0.10	0.924	0.088	0.658	0.865	0.970	0.855
ρ cons. preference shock	Beta	0.85	0.10	0.855	0.035	0.772	0.842	0.894	0.838
ρ government spending shock	Beta	0.85	0.10	0.949	0.029	0.900	0.945	0.977	0.943
ρ labor supply shock	Beta	0.85	0.10	0.889	0.052	0.773	0.891	0.952	0.881

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ρ investment shock	Beta	0.85	0.10	0.927	0.022	0.864	0.913	0.946	0.910
investment adj cost	Normal	4.00	1.5	6.771	1.026	5.148	6.920	8.898	6.962
σ consumption utility	Normal	1.00	0.375	1.353	0.282	0.959	1.371	1.902	1.391
h consumption habit	Beta	0.70	0.10	0.573	0.076	0.464	0.595	0.713	0.592
σ labor utility	Normal	2.00	0.75	2.400	0.589	1.603	2.491	3.481	2.503
Fixed cost	Normal	1.45	0.25	1.408	0.166	1.169	1.407	1.693	1.417
Calvo employment	Beta	0.50	0.15	0.599	0.050	0.513	0.598	0.673	0.597
Capital util. adj. cost	Normal	0.20	0.075	0.169	0.075	0.062	0.175	0.289	0.201
Calvo wages	Beta	0.75	0.05	0.737	0.049	0.662	0.742	0.824	0.742
Calvo prices	Beta	0.75	0.05	0.908	0.011	0.888	0.905	0.922	0.905
Indexation wages	Beta	0.75	0.15	0.763	0.188	0.455	0.745	0.930	0.728
Indexation prices	Beta	0.75	0.15	0.469	0.103	0.309	0.472	0.670	0.477
r inflation	Normal	1.70	0.10	1.684	0.109	1.526	1.688	1.844	1.688
r d(inflation)	Normal	0.30	0.10	0.140	0.053	0.072	0.151	0.237	0.151
r lagged interest rate	Beta	0.80	0.10	0.961	0.014	0.932	0.958	0.974	0.956
r output-gap	Normal	0.125	0.05	0.099	0.041	0.037	0.095	0.169	0.098
r d(output-gap)	Normal	0.0625	0.05	0.159	0.027	0.119	0.156	0.201	0.158

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

Note: In the case of the consumption preference, government spending, investment, and the three mark-up shocks, the estimated standard deviation reported in the table does not correspond to the standard deviation of the corresponding shocks in Equations (28) to (36) due to a different normalization of those shocks in the estimation procedure. This normalization does not affect any of the other results reported in this paper and is available from the authors upon request.

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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 maximizing 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 5th, 50th, and 95th percentile of the posterior distribution of the parameters obtained through the Metropolis-Hastings sampling algorithm.[28] The latter is based on 100,000 draws.[29] Figure 1 summarizes 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 to be 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 next. The persistent shocks are estimated to have an autoregressive parameter that lies between 0.82 (for the productivity shock) and 0.95 for the government spending shock.

Focusing on the four parameters characterizing the degree of price and wage stickiness, we find that the indexation parameters are estimated to be equal to or smaller than the means assumed in their prior distribution. For example, the estimated price indexation parameter, $\gamma_p = 0.46$, implies that the weight on lagged inflation in the inflation equation is only 0.31. This is quite consistent with the results in Gali, Gertler, and Lopez-Salido (2001a). 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 labor are upward-sloping (due to the individual marginal disutility of labor), the marginal cost curve in the intermediate goods sector is assumed to be flat and the same for all firms (due to constant returns to scale). For a given

28. See Landon-Lane (1998) and Otrok (2001) for earlier applications of the MH algorithm to DSGE models and Geweke (1998) for a discussion of the various sampling algorithms.

29. A sample of 100,000 draws was sufficient to ensure the convergence of the MH sampling algorithm. A technical appendix which contains some standard convergence diagnostics is available from the authors upon request.

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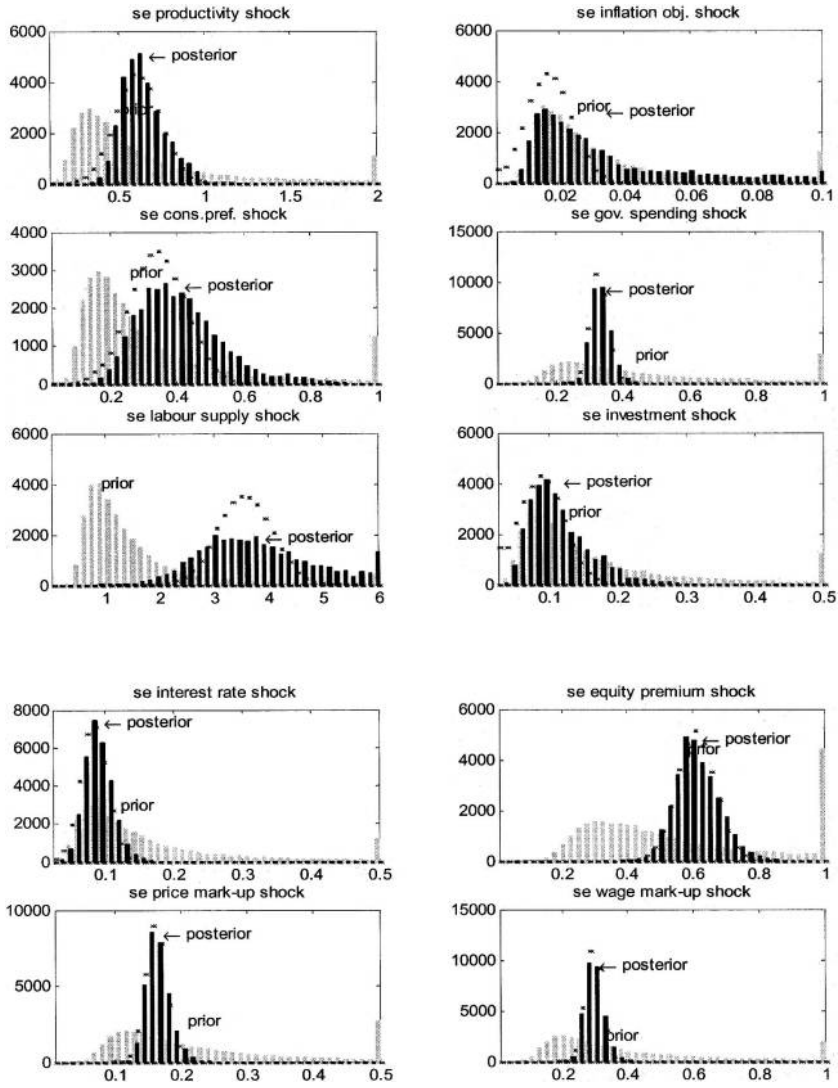


FIGURE 1A. Estimated Parameter Distribution

elasticity of prices to real marginal cost, this will tend to bias upward the estimate of Calvo price stickiness. Indeed, using a single equation GMM approach, Gali, Gertler, and Lopez-Salido (2001a) 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 (2001a) estimate a more

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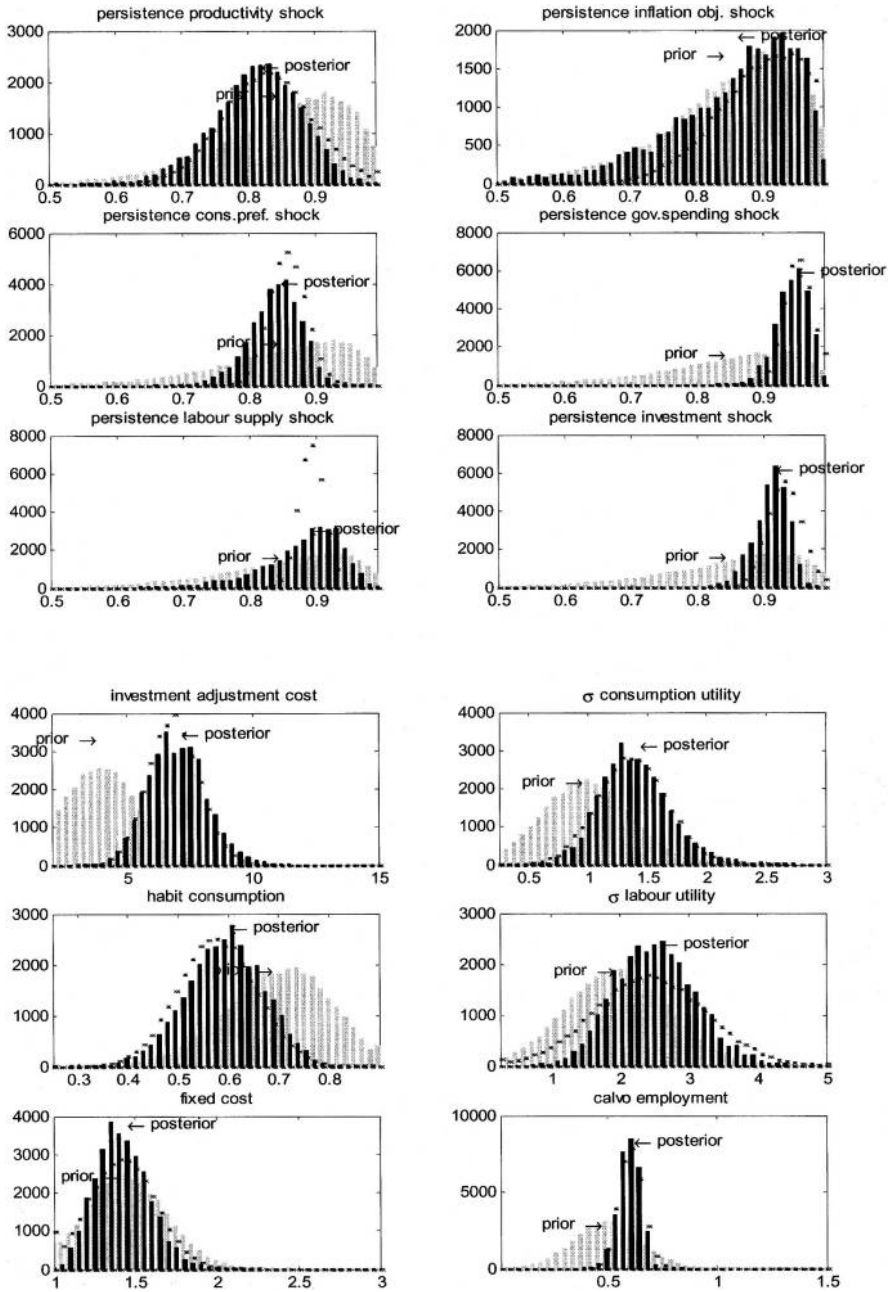


FIGURE 1B. Estimated Parameter Distribution

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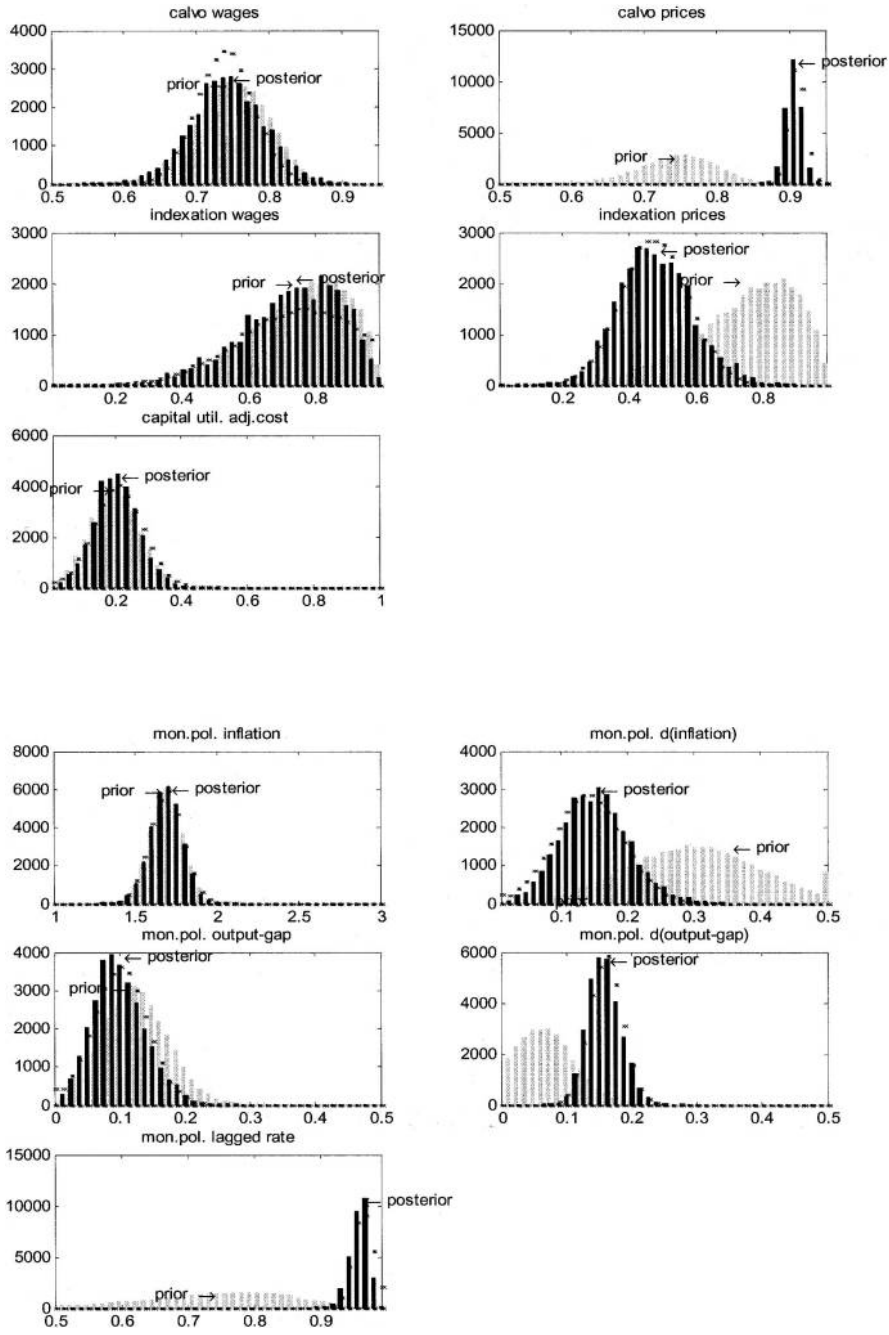


FIGURE 1C. Estimated Parameter Distribution

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reasonable degree of price stickiness that is comparable with what we estimate for wages.[30]

Our estimate of the intertemporal elasticity of substitution ($1/\sigma$) is less than 1 and close to the assumption made in much of the RBC literature that assumes an elasticity of substitution between 1/2 and 1. However, one needs to be careful when making such comparisons, as our model features external habit formation that turns out to be significant. The external habit stock is estimated to be about 57 percent of past consumption, which is somewhat smaller than the estimates reported in CEE (2001).

Disregarding the preference shocks, our consumption Equation (28) can be written as:

$$\hat{C}_t = h\hat{C}_{t-1} - \frac{1-h}{\sigma_c}\sum_{i=0}^{\infty}(\hat{R}_{t+i} - \hat{\pi}_{t+1+i}) \tag{38}$$

Our estimates of σ_c and h thus imply that an expected 1 percent increase in the short-term interest rate for four quarters has an impact on consumption of about 0.30.

The estimate of the adjustment cost parameter is very similar to the one estimated in CEE (2001).[31] It implies that investment increases by about 0.2 percent following a 1 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 utilization are in line with the results in CEE (2001). The estimate of σ_l is around 2.5, implying an intermediate estimate of the elasticity of labor supply. However, this estimate did not prove to be very robust across specifications.

Finally, our estimation delivers plausible parameters for the long- and short-run reaction function of the monetary authorities, broadly in line with those proposed by Taylor (1993). Obviously, as there was no single monetary policy in the euro area over most of 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 1, 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 output gap. Finally, in agreement with the large literature on estimated interest rate rules, we also find evidence of a substantial degree of interest rate smoothing.

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

31. Table 1 reports $1/\varphi = \bar{S}''$.

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3.3 Assessing the Empirical Performance of the Estimated DSGE Model

3.3.1 Comparing the Estimated DSGE Model with VARs. The discussion in the previous section shows that the model is able to deliver reasonable and significant estimates of the model parameters. In this section, we analyze how well our estimated model does compared to nontheoretical VAR models estimated on the same data set. As discussed in Geweke (1999), the Bayesian approach used in this paper provides a framework for comparing and choosing between fundamentally misspecified models on the basis of the marginal likelihood of the model.[32]

The marginal likelihood of a model A is defined as:

$$M = \int_{\theta} p(\theta|A)\, p(Y_T|\theta, A) d\theta \tag{39}$$

where $p(\theta|A)$ is the prior density for model A and $p(Y_T|\theta, A)$ 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

$$B_{ij} = \frac{M_i}{M_j} \tag{40}$$

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

$$PO_i = \frac{p_i M_i}{\sum_j p_j M_j} \tag{41}$$

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:

$$\hat{p}_{T+1}^{T+m} = \int_{\theta} p(\theta|Y_T, A) \prod_{t=T+1}^{T+m} p(y_t|Y_T, \vartheta, A) d\theta, \tag{42}$$

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

Therefore, the marginal likelihood of a model also reflects its prediction

32. See also Landon-Lane (1998) and Schorfheide (2000).

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TABLE 2. ESTIMATION STATISTICS

Summary of the model statistics: VAR—BVAR—DSGE				
	VAR(3)	VAR(2)	VAR(1)	DSGE-model
In sample RMSE (80:2–99:4)				
Y	0.42	0.44	0.50	0.54
π	0.20	0.21	0.23	0.21
R	0.12	0.12	0.13	0.12
E	0.19	0.20	0.22	0.21
w	0.48	0.51	0.54	0.57
C	0.42	0.44	0.48	0.60
I	1.03	1.08	1.17	1.26
Posterior probability approximation (80:2–99:4)				
	VAR(3)	VAR(2)	VAR(1)	DSGE-model
Prediction error decomposition[1]	−303.42	−269.11	−269.18	
Laplace approximation	−315.65	−279.77	−273.55	−269.59
Modified harmonic mean[2]	−305.92	−270.28	−268.41	−269.20
Bayes factor rel. to DSGE model	0.00	0.34	2.20	1.00
Prior probabilities	0.25	0.25	0.25	0.25
Posterior odds	0.00	0.10	0.62	0.28
	BVAR(3)	BVAR(2)	BVAR(1)	DSGE
Prediction error decomposition[2]	−266.71	−268.71	−290.00	−269.20
Bayes factor rel. to DSGE model	12.06	1.63	0.00	1.00
Prior probabilities	0.25	0.25	0.25	0.25
Posterior odds	0.82	0.11	0.00	0.07

[1] Posterior probability computed recursively using the prediction error decomposition (treating 1970s given).
[2] Posterior probability approximation via sampling: MC for the VAR, Gibbs for the BVAR, MH for the DSGE model.

performance. Similarly, the Bayes factor compares the models' abilities to predict out of sample.

Geweke (1998) discusses various ways to calculate the marginal likelihood of a model.[33] Table 2 presents the results of applying some of these methods to the DSGE model and various VARs. The upper part of the table compares the DSGE model with three standard VAR models of lag order 1 to 3, estimated

33. 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 (2000) 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.

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using the same seven observable data series. The lower part of Table 2 compares the DSGE model with Bayesian VARs estimated using the well-known Minnesota prior.[34] In both cases, the results show that the marginal likelihood of the estimated DSGE model is very close to that of the best VAR models. This implies that the DSGE model does at least as good a job as the VAR models 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.[35] The marginal likelihood of the DSGE model is larger than that of the VAR(2) and VAR(3) model and very close to that of the VAR(1) model. This is somewhat in contrast with the RMSE-results reported in the upper panel of Table 2. An interpretation in terms of predictive errors 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 both the BVAR(2) and BVAR(3) model do somewhat better than the DSGE model.[36] Nevertheless, the posterior odds suggest that even in this case one cannot reject the DSGE model at conventional confidence intervals. These results show that the current generation of New-Keynesian DSGE 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 quite well, as long as one is willing to entertain enough structural shocks to capture the stochastics.[37]

34. See Doan, Litterman, and Sims (1984).

35. The likelihood values of the Laplace approximation are significantly 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 DSGE 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.

36. This result also illustrates that it can be very useful to use the DSGE 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.

37. There have been a number of other attempts to compare estimated DSGE models with VARs. However, in most of these cases the DSGE model is clearly rejected. For example, Schorfheide (2000) obtains an extremely low Bayes factor for DSGE models relative to VAR models, and he

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3.3.2 Comparison of Empirical and Model-Based Cross-Covariances. Traditionally DSGE 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 covering the period 1971:2–1999:4. 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 DSGE model (100 runs for a selection of 100 parameter draws from the posterior sample). Figure 2 summarizes the results of this exercise. The full lines represent the median (bold) and the 5 percent and 95 percent intervals for the covariance sample of the DSGE 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 mimic the cross-covariances in the data. However, the error bands are quite large, indicating 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 DSGE 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 current interest rates and future output and inflation; and it underestimates the positive correlation between current activity and future interest rates.[38]

concludes that DSGE 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 (2003), using classical likelihood methods, finds evidence in favor of a open economy DSGE 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 finds evidence that the DSGE model does as good as a VAR(1) model. Rabanal and Rubio-Ramirez (2001) compare different DSGE models but do not compare these outcomes with a VAR model. Fernandez-Villaverde and Rubio-Ramirez (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.

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

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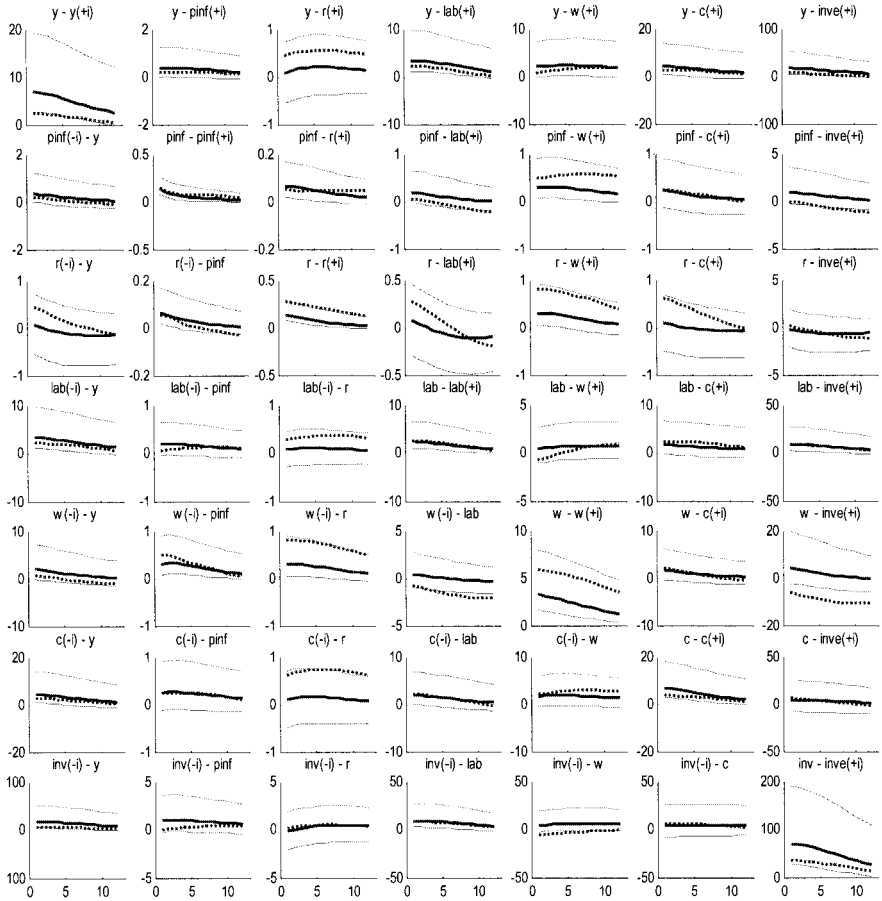


FIGURE 2. Comparison of Cross-Covariances of the DSGE-Model and the Data

4. What Structural Shocks Drive the Euro Area Economy?

In this section we use the estimated DSGE model to analyze 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

Figures 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 1,000 parameters from the posterior sample of

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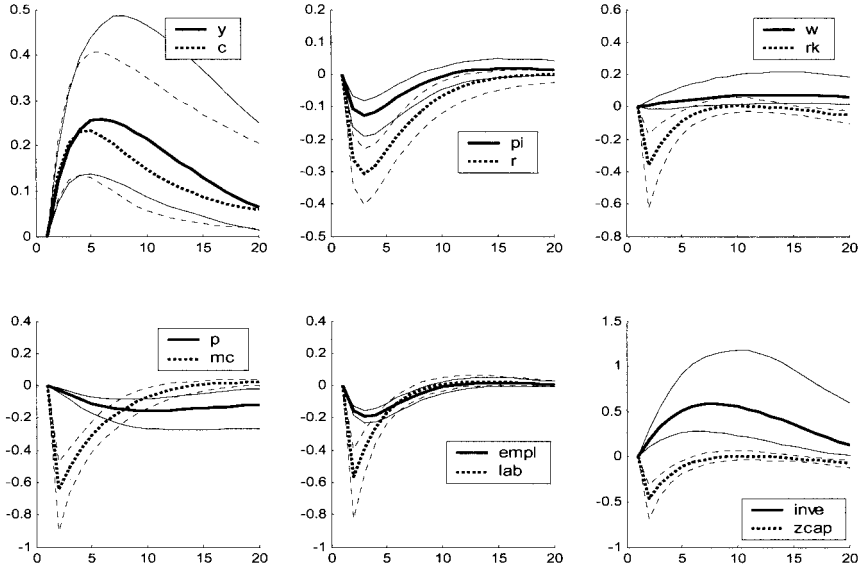


FIGURE 3. Productivity Shock

100,000. The figures plot the median response together with the 5th and 95th percentiles.[39]

Figure 3 shows that, following a positive productivity shock, output, consumption, and investment rise, while employment falls. Also the utilization 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 United States 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 but not very strongly. The estimated reaction of monetary policy on a productivity shock is in line with similar results for the United States as presented in Ireland (1999) and Gali, Lopez-Salido, and Valles (2003) (at least for the pre-Volcker period). Finally, note that the real wage rises only gradually and not very significantly following the positive productivity shock.[40]

Figure 4 shows the effects of a positive labor 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. 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

39. In general, the median response turns out to be very similar to the mean and the mode of the responses.

40. See also Francis and Ramey (2001).

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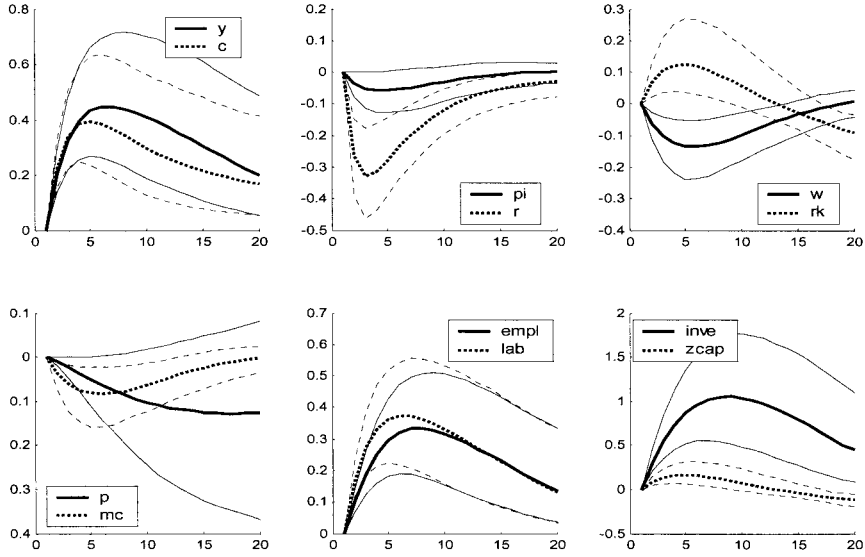


FIGURE 4. Labor Supply Shock

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 markup shock (Figure 5). In this case, however, the real interest rate rises reflecting the fact

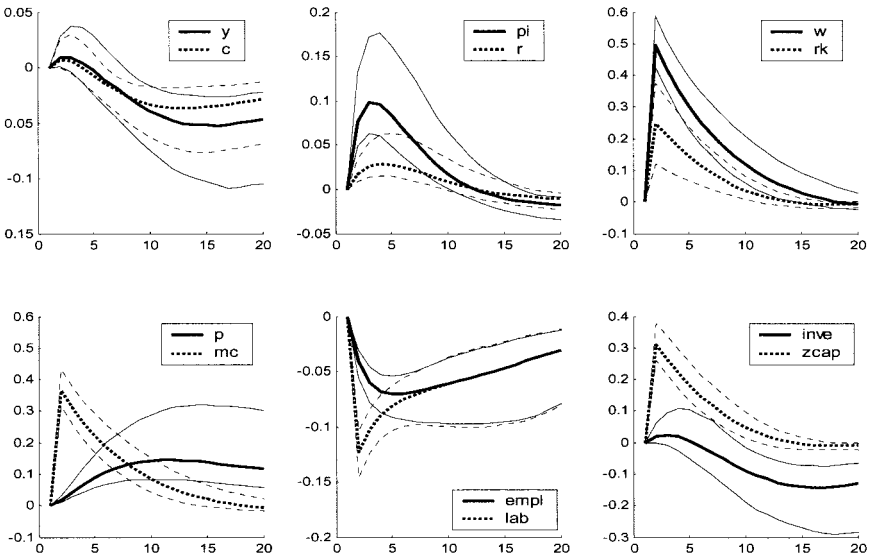


FIGURE 5. Wage Markup Shock

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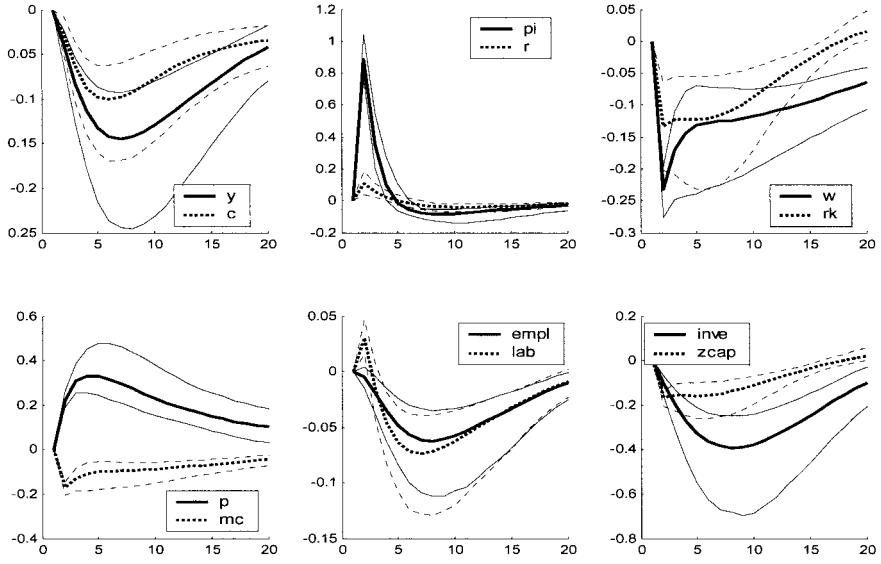


FIGURE 6. Price Markup Shock

that the wage markup shock creates a trade-off between inflation and output gap stabilization. Real wages and marginal costs fall more on impact. The impact of a negative price markup 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 (Figure 6).

Turning to some of the "demand" shocks, it is clear that in all cases increased overall demand puts upward pressure on real factor prices, real marginal cost, and inflation. In order to stem these inflationary pressures, real interest rate eventually rise in all cases. Figure 7 shows that a positive preference shock, while increasing consumption and output significantly, has a significant negative crowding-out effect on investment. The increase in capacity necessary to satisfy increased demand is delivered by an increase in the utilization 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. The ultimate effect of a preference shock on inflation is relatively small. An investment boom driven by a temporary reduction in the cost of installing capital (Figure 8) similarly leads to a strong expansion of output and employment, but has no significant effect on consumption. Due to the higher estimated persistence of the investment shock, the effects on marginal cost and inflation are more significant than in the case of the preference shock. Qualitatively similar impulse responses are derived following a temporary negative equity premium shock (Figure 9), but in this case the effects on output, employment and investment are much more short-lived and

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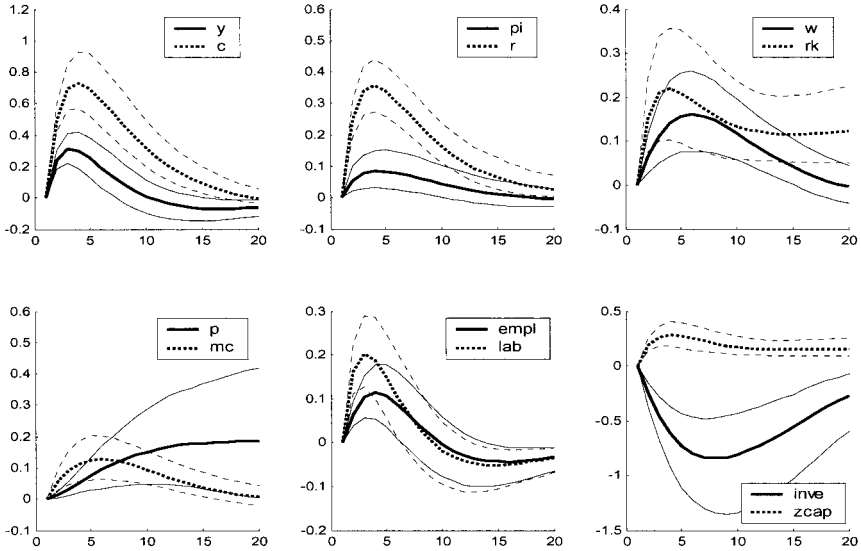


FIGURE 7. Preference Shock

the resulting effects on real wages, the marginal cost and prices much more limited. Finally, strong crowding-out effects are particularly clear in response to a government spending shock (Figure 10). In this case, both consumption and

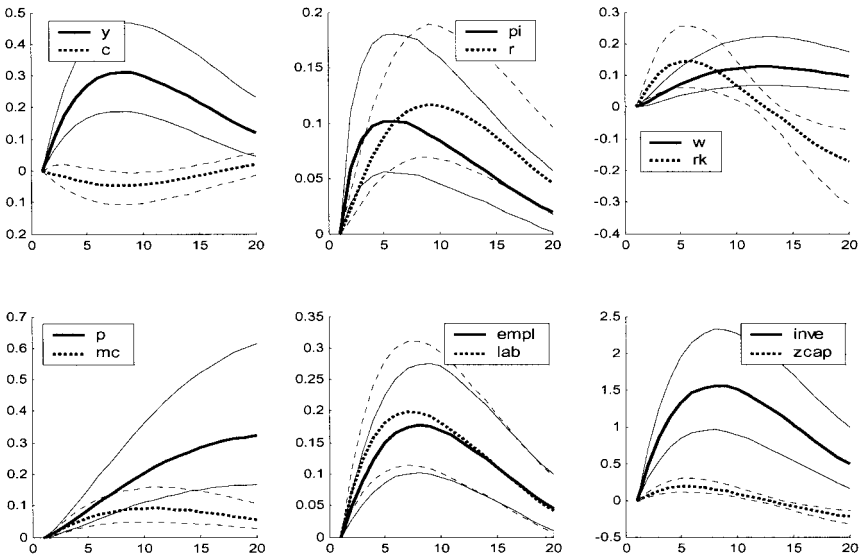


FIGURE 8. Investment Shock

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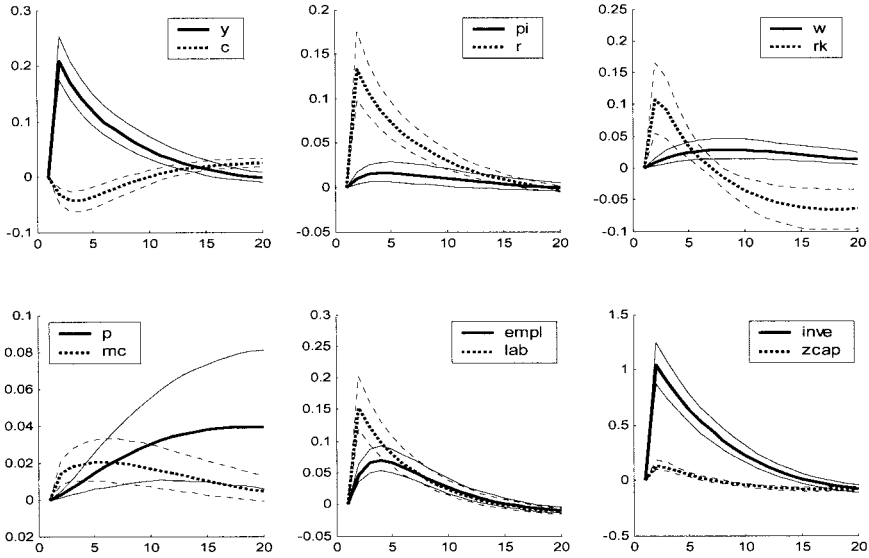


FIGURE 9. Equity Premium Shock

investment fall significantly. While the rental rate on capital rises, real wages are not much affected because of the greater willingness of households to work. The estimated model shares the failure of standard RBC models to account for a

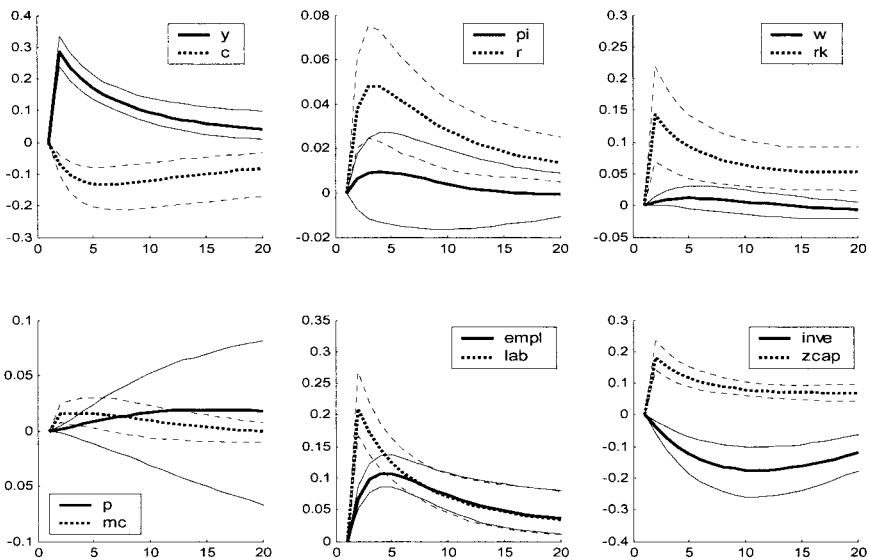


FIGURE 10. Government Spending Shock

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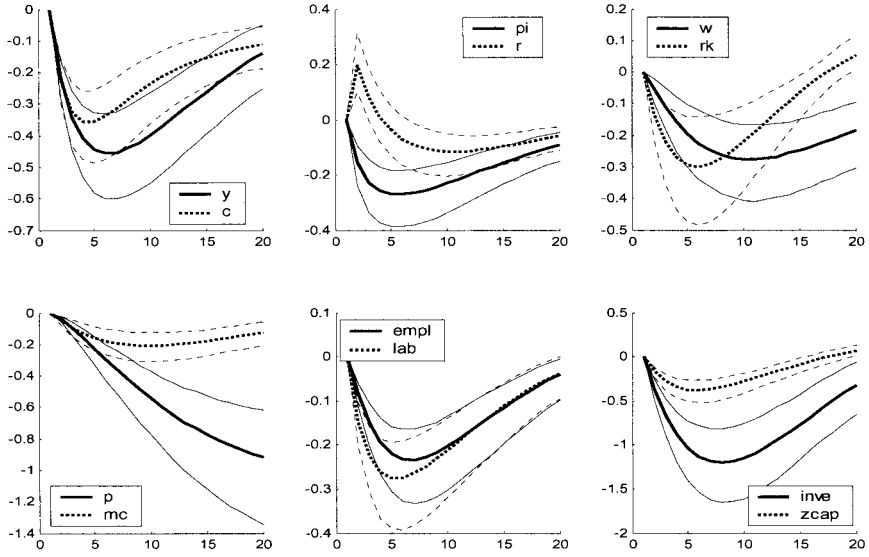


FIGURE 11. Monetary Policy Shock

positive effect of government expenditures on private consumption and investment as documented for the United States in Fatas and Mihov (2001) and Blanchard and Perotti (2002). However, Perotti (2002) shows that the response of consumption and investment is often insignificant or even negative in other countries and also fell in the United States in the post-1980 period.

Finally, Figures 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 stylized 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 output and 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 increasing immediately as a result of the increased 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 monetary policy 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.

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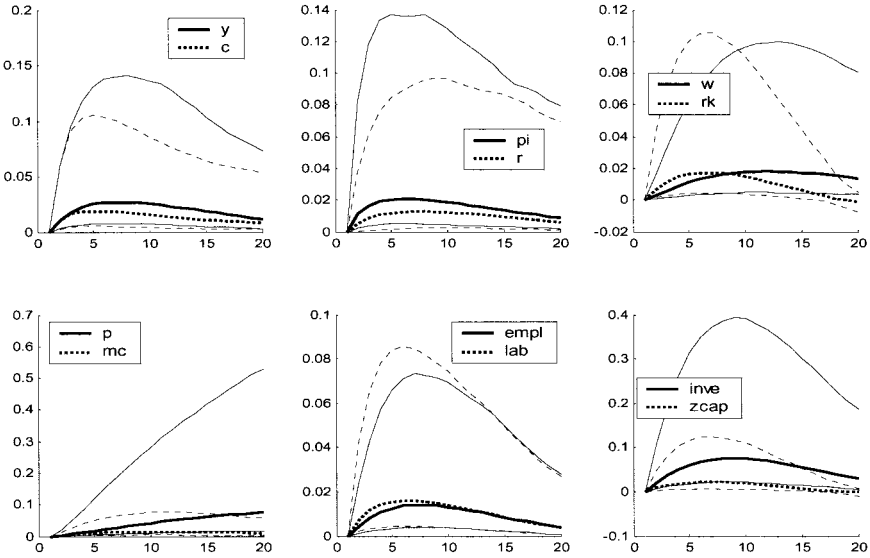


FIGURE 12. Inflation Objective Shock

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; and long run: 25 years) is reported in Table 3. Let us first focus on the determinants of output. Beyond the very short-term horizon, output variations are driven primarily by the labor supply and the monetary policy shocks. Both shocks also explain a significant fraction of the variance in consumption and investment. In the very short run, both the preference and the government spending shock have a significant effect on output, but these effects are relatively short-lived. In contrast, the contribution of the productivity and the investment shock builds up as the horizon lengthens, with the former accounting for about 10 percent and the latter for about 15 percent of the medium-term forecast variance in output. The price and wage markup shocks do not seem to matter for output variability.

That both "supply shocks," the productivity and labor shock, account for only 40 percent of the variance of output 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 confirms the conjecture made in Gali (2000) that the negative correlation between output and employment in response to a productivity shock

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TABLE 3. VARIANCE DECOMPOSITION

		C	I	Y	E	π	W	R
t = 0	Productivity shock	0.05	0.02	0.05	0.40	0.01	0.00	0.26
	Inflation objective shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Preference shock	0.63	0.04	0.19	0.07	0.00	0.01	0.23
	Government spending shock	0.01	0.00	0.25	0.08	0.00	0.00	0.01
	Labor supply shock	0.15	0.06	0.16	0.21	0.00	0.01	0.29
	Investment shock	0.00	0.13	0.03	0.04	0.01	0.00	0.00
	Interest rate shock	0.14	0.08	0.16	0.13	0.03	0.01	0.11
	Equity premium shock	0.00	0.65	0.15	0.04	0.00	0.00	0.07
	Price markup shock	0.00	0.01	0.00	0.00	0.94	0.17	0.04
	Wage markup shock	0.00	0.00	0.00	0.03	0.01	0.79	0.00
	Forecast error variance	0.37	1.64	0.29	0.05	0.05	0.30	0.02
t = 4	Productivity shock	0.06	0.05	0.09	0.15	0.04	0.00	0.24
	Inflation objective shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Preference shock	0.56	0.11	0.12	0.05	0.02	0.08	0.36
	Government spending shock	0.02	0.00	0.08	0.05	0.00	0.00	0.01
	Labor supply shock	0.19	0.15	0.28	0.39	0.01	0.07	0.30
	Investment shock	0.00	0.32	0.10	0.09	0.04	0.02	0.02
	Interest rate shock	0.15	0.19	0.27	0.21	0.22	0.12	0.03
	Equity premium shock	0.00	0.16	0.04	0.02	0.00	0.00	0.03
	Price markup shock	0.01	0.02	0.02	0.01	0.65	0.11	0.01
	Wage markup shock	0.00	0.00	0.00	0.02	0.02	0.60	0.00
	Forecast error variance	3.56	18.94	2.66	0.82	0.09	1.13	0.09
t = 10	Productivity shock	0.07	0.05	0.09	0.07	0.03	0.01	0.19
	Inflation objective shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Preference shock	0.50	0.12	0.06	0.02	0.02	0.09	0.36
	Government spending shock	0.03	0.00	0.05	0.04	0.00	0.00	0.01
	Labor supply shock	0.23	0.17	0.32	0.48	0.01	0.07	0.28
	Investment shock	0.00	0.36	0.14	0.13	0.06	0.06	0.06
	Interest rate shock	0.16	0.21	0.29	0.22	0.35	0.29	0.07
	Equity premium shock	0.00	0.06	0.02	0.01	0.00	0.00	0.03
	Price markup shock	0.01	0.02	0.03	0.01	0.50	0.10	0.01
	Wage markup shock	0.00	0.00	0.00	0.02	0.02	0.37	0.00
	Forecast error variance	5.72	55.81	5.81	1.99	0.12	2.17	0.12
t = 100	Productivity shock	0.07	0.05	0.08	0.05	0.03	0.03	0.17
	Inflation objective shock	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Preference shock	0.41	0.12	0.05	0.03	0.02	0.06	0.33
	Government spending shock	0.05	0.01	0.04	0.04	0.00	0.00	0.01
	Labor supply shock	0.27	0.18	0.33	0.49	0.01	0.05	0.27
	Investment shock	0.02	0.38	0.16	0.14	0.07	0.11	0.09
	Interest rate shock	0.17	0.20	0.28	0.20	0.40	0.40	0.10
	Equity premium shock	0.00	0.05	0.02	0.01	0.00	0.00	0.02
	Price markup shock	0.01	0.02	0.03	0.01	0.45	0.09	0.01
	Wage markup shock	0.00	0.00	0.00	0.02	0.02	0.25	0.00
	Forecast error variance	7.21	82.66	7.87	2.72	0.13	3.36	0.14

raises serious doubts about the quantitative significance of productivity shocks as a source of aggregate fluctuations in industrialized countries. One factor that may explain the important role of the labor supply and monetary policy shocks in driving output is that both those shocks can explain the significant positive correlation between output, consumption, investment, and employment in the

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data. As will become clear in the discussion of the historical decomposition, the relatively large contribution of monetary policy shocks to the variance in output, is mainly due to the disinflation period of the early 1980s and the ERM crisis of 1992–1993.

Turning to the determinants of inflation, we find that at all horizons variations in inflation are mainly driven by price markup shocks. Empirically, inflation is a quite volatile process. At the same time inflation is estimated to respond only very sluggishly 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 behavior of volatile prices. Of course, these shocks could capture a whole range of shocks that are not accounted for in the stylized model such as changes in oil prices, terms-of-trade shocks, changes in taxes, etc. In the medium to long run, monetary policy shocks also account for about 20 to 40 percent of the inflation variance.

Somewhat surprisingly, other shocks together typically account for less than 15 percent of the variance in inflation. One of the main reasons why technology and preference shocks do not affect inflation very significantly, is that under the estimated monetary policy reaction function, interest rates respond quite strongly to those shocks, thereby helping to close the output gap and to avoid inflationary or deflationary pressures that may otherwise arise. Indeed, Table 3 shows that the nominal interest rate is mainly determined by the preference shock, the labor supply shock, and the productivity shock. This highlights the fact that the relative importance of the various shocks as sources of business cycle fluctuations in output and inflation will very much depend on the monetary policy regime. In contrast, monetary policy shocks only account for maximum 10 percent of the forecast variance in nominal interest rates. Finally, as indicated before the inflation objective, shock plays no role.

4.3 Historical Decomposition

Figures 13 and 14 summarize 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.[41]

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 contrast, the secular part in

41. It needs to be mentioned that while the sample in Figures 13 and 14 starts in the early 1970s, the first nine years of the sample are used for the initialization 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.

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inflation is mostly driven by monetary policy shocks. According to our model, monetary policy was the predominant factor behind the surge in inflation in the 1970s and its stabilization from the late 1970s onward. Finally, the run-up in inflation in the late 1980s and early 1990s is attributed to the various "supply" and "demand" shocks.

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 "markup" 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.[42] Our analysis differs from Woodford's analysis in two important ways. First, due to the presence of both nominal price and wage rigidities, it will no longer be possible for monetary policymakers to restore the flexible-price equilibrium in our model. However, Erceg, Henderson, and Levin (2000) have shown that in this case targeting a weighted average 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. Second, 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 level and can thus be seen as the appropriate target level. In our model, we have assumed that three shocks are due to stochastic variations in inefficient markups: the wage markup, the price markup, 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. Accordingly, we have defined the target or potential level of output as the flexible-price-and-wage level of output that would arise in the absence of such markup shocks. Of course, in this case markup shocks will give rise to a trade-off between inflation stabilization and output gap stabilization. In the rest of this section, we first briefly discuss the response of the flexible price economy

42. See also the discussion in Neiss and Nelson (2001) and Gali (2000).

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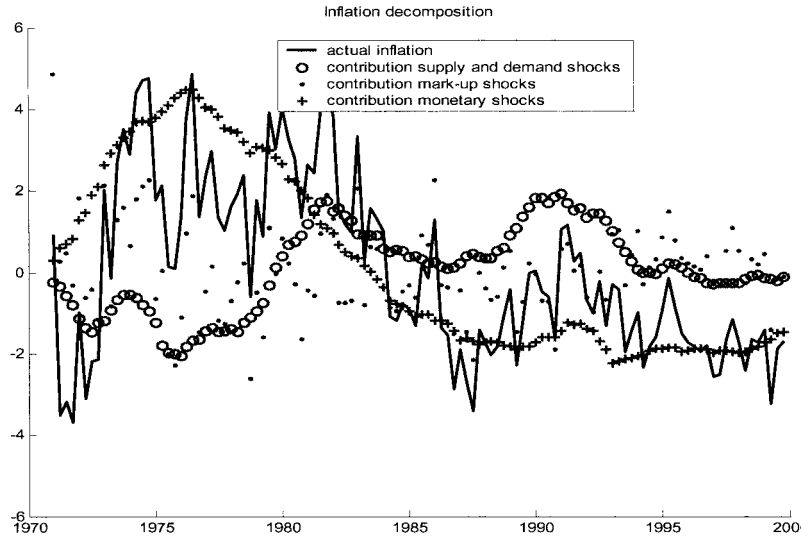


FIGURE 13. Inflation Decomposition

to the five preference and technology shocks. Next, we calculate the output and real interest rate gap as defined before.

Figures 15 to 19 show the impulse responses to the five technology and preference shocks when prices and wages are flexible. There is no point in

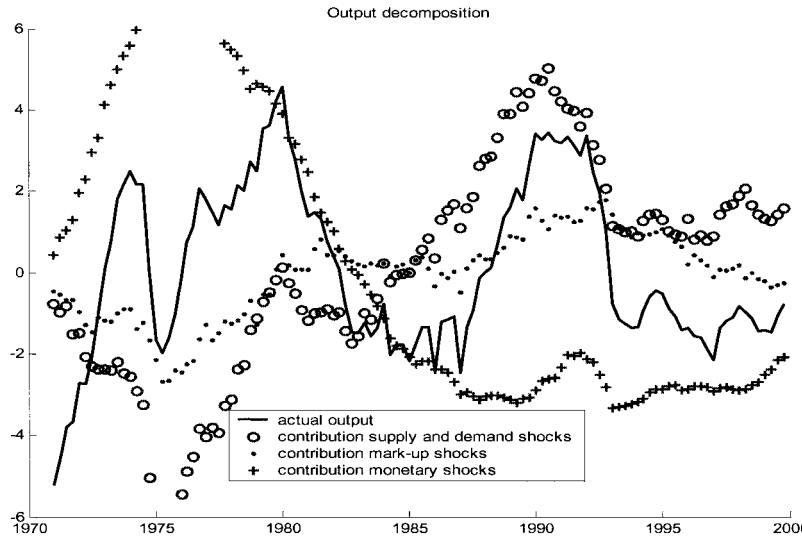


FIGURE 14. Output Decomposition

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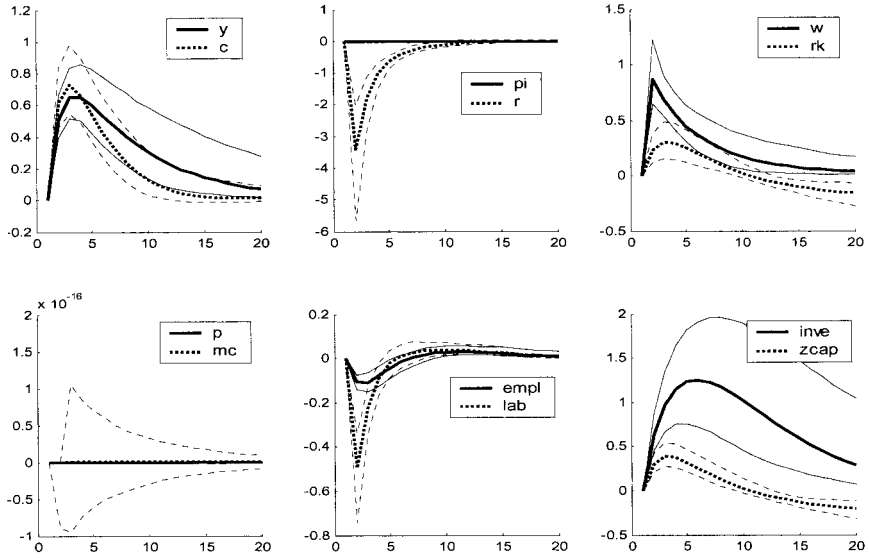


FIGURE 15. Productivity Shock: Flexible Price-Wage Model

discussing monetary policy in this setup, as monetary policy will be neutral. We simply assume that monetary policy stabilizes the price level.

With flexible prices and wages, output jumps up immediately and much more strongly in response to a productivity shock (Figure 15). In line with higher productivity, real wages jump up immediately, stabilizing the real marginal cost. Higher output is produced by a higher capital utilization and an increase in the capital stock, while employment actually falls as households reduce their labor supply in line with the fall in the marginal utility of consumption. The natural interest rate temporarily falls. A positive labor supply shock has very similar effects on output and the natural real interest rate (Figure 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 significantly. Comparing the flexible-price outcome in Figure 15 and 16 with the sticky-price outcome in Figure 3 and 4, it is clear that both shocks create a negative output gap. In that sense, we can loosely speaking call them "supply" shocks.

The striking thing about the effects of a positive preference shock is that the natural output level responds strongly negatively (Figure 17). This is mainly due to the fact that higher consumption reduces the marginal benefit from working and therefore leads to a fall in labor 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 a more limited

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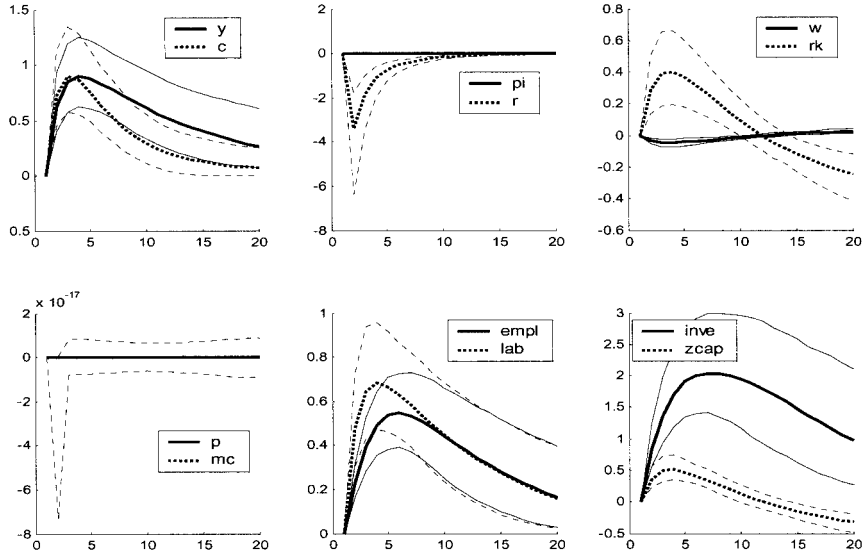


FIGURE 16. Labor Supply Shock: Flexible Price and Wage Model

crowding out of consumption (Figure 18), while the natural real interest rate falls temporarily. A similar pattern is observed in response to a positive government spending shock (Figure 19). Comparing the flexible-price output

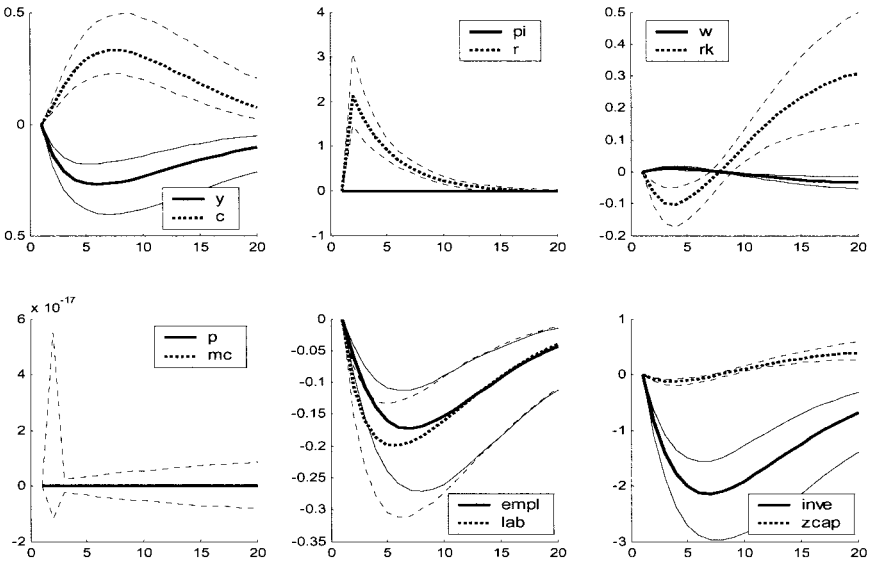


FIGURE 17. Preference Shock: Flexible Price and Wage Model

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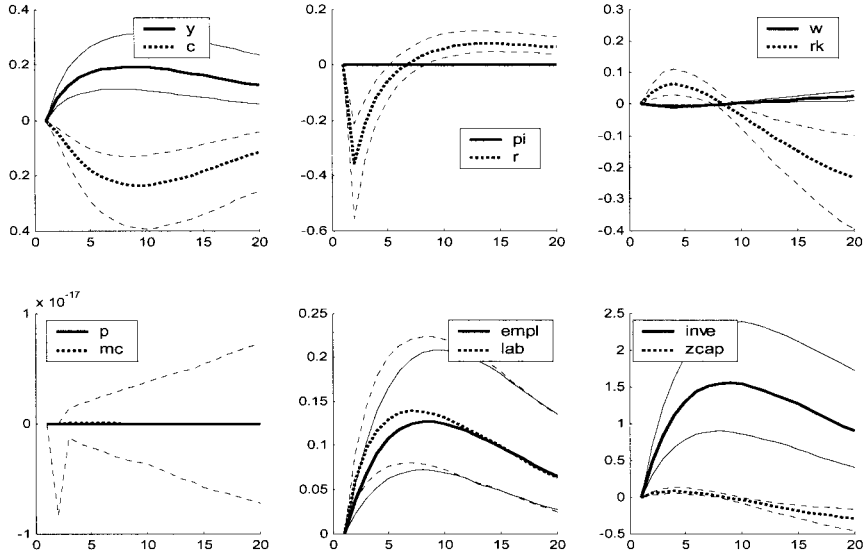


FIGURE 18. Investment Shock: Flexible Price and Wage Model

effects of those three shocks with the corresponding output effects under sticky prices and wages in Section 4.1, it is clear that those "demand" shocks create a positive output gap.

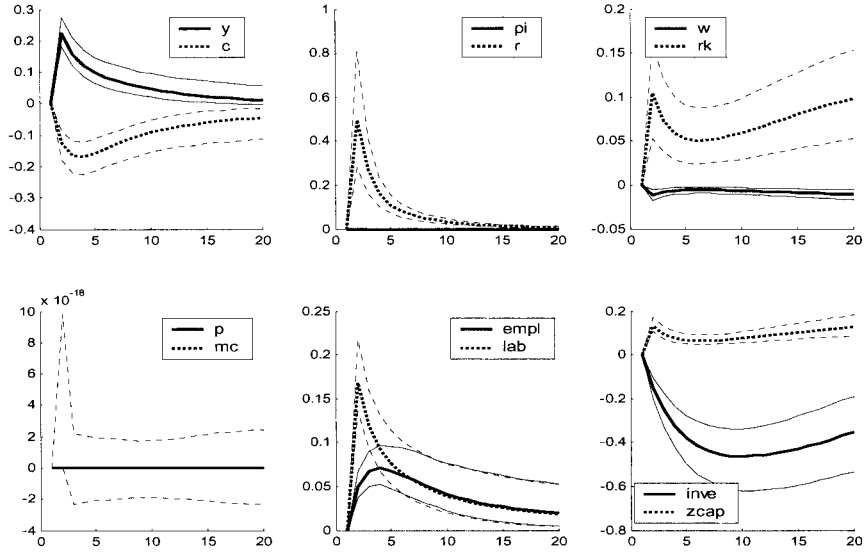


FIGURE 19. Government Spending Shock: Flexible Price and Wage Economy

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Overall, it appears that the natural output level responds quite significantly not only to the "supply," but also to the "demand" shocks, as does the natural real interest rate. 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 labor market. This will be determined by Equation (34) and the conditions that the real wage equals the marginal rate of substitution of households and the marginal product of labor. This gives rise to the following labor supply and demand equations:

$$\hat{L}_t^d = -\frac{1+\psi(1-\alpha)}{\alpha}\hat{w}_t + \frac{1+\psi}{\alpha}\hat{\varepsilon}_t^a + \hat{K}_{t-1} \tag{43}$$

$$\hat{L}_t^s = \frac{1}{\sigma_L}\hat{w}_t - \frac{\sigma_c}{\sigma_L(1-h)}(\hat{C}_t - \hat{C}_{t-1}) + \frac{1}{\sigma_L}\hat{\varepsilon}_t^l. \tag{44}$$

Note that under the estimated parameters the labor demand schedule (43) will be relatively steep because of the low estimated elasticity of the cost of adjusting capacity utilization. As a result, shifts in the labor supply schedule due to a labor supply shock or changes in consumption will have only limited effects on the real wage, while the employment effects will be strong.

Figures 20 and 21 plot the historical estimate of the potential output level and the associated real interest rate and the corresponding gaps together with the 5th and 95th percentiles (lower panel).[43] A number of general observations are worth making. First, it appears that potential output is much 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 DSGE model is very different from traditional estimates which rely on a smoothed trend through output. It appears that there was a fall in potential output from 1973 to 1975 and again during the late 1970s and early 1980s. 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 Figure 20 shows that most of the long-term variation in potential output seems to be due to labor supply developments. Third, the real interest rate associated with potential output appears to covary much more with the actual estimated interest rate, but is more volatile. According to the real interest rate

43. Our gap differs from the gap that is calculated in Gali, Gertler, and Lopez-Salido (2001b) and Neiss and Nelson (2001) in the sense that those papers implicitly assume that there are no markup shocks.

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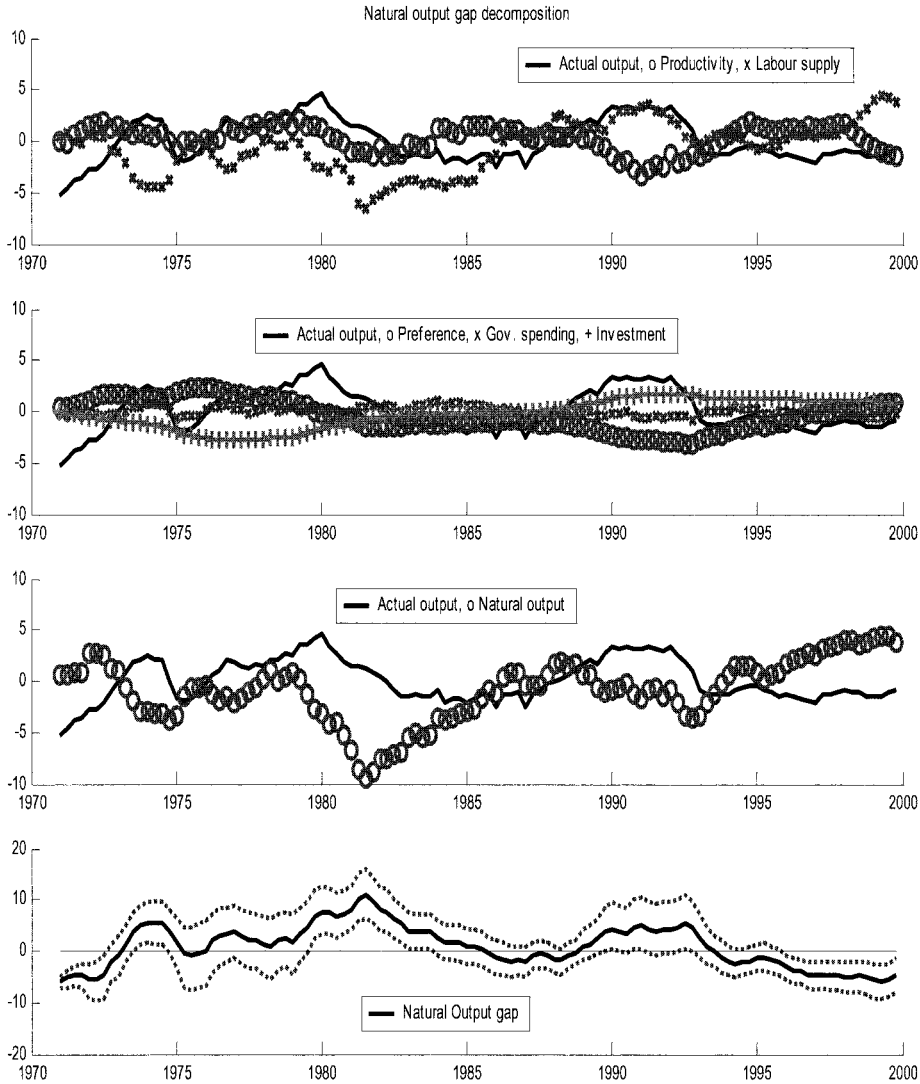


FIGURE 20. Natural Output Gap Decomposition

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

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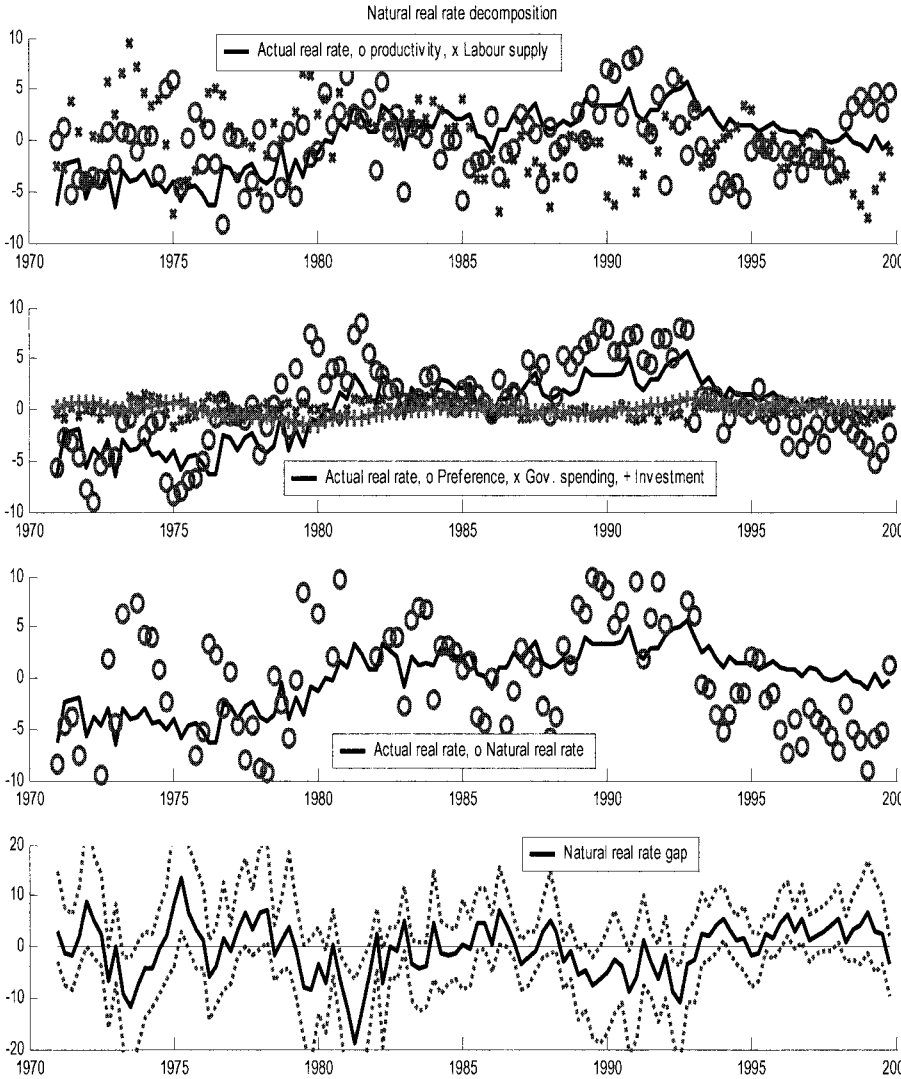


FIGURE 21. Natural Real Rate Decomposition

models have been developed (Goodfriend and King 1997, Rotemberg and Woodford 1998, 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 DSGE model used in this paper shares the essential features of this class of models (in particular the sticky, but forward-looking price setting). Following CEE (2001), our model also features a relatively large number of additional frictions that are

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necessary to capture the empirical persistence and covariances in the main macroeconomic data of the euro area. These frictions include sticky, but forward-looking nominal wage setting, variable capital utilization, 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 labor supply shock), three "demand" shocks (a preference, an investment, and a government spending shock), three markup shocks (a price and wage markup 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 (1) 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; (2) examine the sources of business cycle dynamics in the euro area; and (3) analyze some of the new features of this class of models, highlighted by Gali (2000), in an empirically plausible setup. Regarding the latter, it is worth recalling what we have learned from performing this exercise.

The Forward-Looking Behavior 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 that 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 2001; Woodford 2000). In our estimated model that features a larger number of shocks arising from both technologies and preferences and inefficient markups, it is less clear what the appropriate output gap is from a monetary policy perspective. Clearly, all "nonmonetary" 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.

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The Transmission of Monetary Policy Shocks and the Liquidity Effect. Our estimates of the effects of a *temporary* monetary policy shock are in line with the existing evidence for the euro area (e.g., Peersman and Smets 2001). 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 behavior and the persistence of the shocks for assessing the effects of monetary policy changes.

The Transmission of Nonmonetary Shocks. Gali (1999) emphasized 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 favorable 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 labor 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 account for less than 10 percent of the long-run output variance. Instead, labor supply shocks and monetary policy shocks are the most important source of variation in output.

Overall, the results presented in this paper show that an estimated version of the DSGE model with sticky prices and wages can be used for monetary policy analysis in an empirically plausible setup. 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 examina-

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tion and identification of the various structural shocks would be interesting. Third, in this paper we have not analyzed 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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