Empirical Properties of Closed and Open Economy DSGE Models of the Euro Area

Malin Adolfson
Sveriges Riksbank

Stefan Laséen
Sveriges Riksbank

Jesper Lindé
IIES and Sveriges Riksbank

Mattias Villani*
Sveriges Riksbank and Stockholm University

September 1, 2005

Abstract

In this paper, we compare the empirical properties of closed and open economy DSGE models estimated on Euro area data. The comparison is made along several dimensions; we examine the models in terms of their marginal likelihoods, forecasting performance, variance decompositions, and their transmission mechanisms of monetary policy.

Keywords: Open economy; Closed economy; DSGE model; Monetary policy; Forecasting; Bayesian inference.

JEL Classification Numbers: E40; E52; C11.

1. Introduction

Since the pioneering work of Smets and Wouters (2003), the interest in academia and central banks for developing and estimating dynamic stochastic general equilibrium (DSGE) models of the macroeconomy have grown considerably. In more recent work, Smets and Wouters (2004) have shown that closed economy dynamic general equilibrium models augmented with nominal and real frictions have forecasting properties in line with best practice time series models (i.e., Bayesian VARs).

In this paper, we contrast a closed economy DSGE model with a model that accounts for open economy aspects. Our DSGE model extends the closed economy model of Christiano, Eichenbaum and Evans (2005) by incorporating open economy elements such as incomplete exchange rate pass-through and imperfect international financial integration. The closed economy version of the model differ slightly from Smets and Wouters' (2003) model in that it includes the working capital channel (i.e., firms borrow money from a financial intermediary to finance their wage bill), and a stochastic unit root technology shock as in Altig et al. (2003), which enables us to work with trending data.

We estimate open and closed economy versions of this model on data for the Euro area during the period $1980Q1-2002Q4$. Our interest in modeling the Euro area as an open economy stem

*Address: Sveriges Riksbank, SE-103 37 Stockholm, Sweden. E-mails: malin.adolfson@riksbank.se, stefan.laseen@riksbank.se, jesper.linde@riksbank.se, mattias.villani@riksbank.se.

We would like to thank participants at the conference "Dynamic Macroeconomic Theory" held in Copenhagen June 11-13, 2004, for helpful comments and discussions. The views expressed in this paper are solely the responsibility of the authors and should not be interpreted as reflecting the views of the Executive Board of Sveriges Riksbank.

partly from the work of Lindé (2003), who shows that changes in net exports account for a substantial fraction of the variation in output after a monetary policy shock in a 10-variable vector autoregressive (VAR) model estimated on Euro area data. In contrast, Lindé finds that U.S. data imply that consumption and investment responses explain most of the fluctuation in output after a policy shock, while net exports only account for a small part. Consequently, it seems appropriate to model the U.S. as a closed economy but worth considering open economy aspects when estimating a model on Euro area data.

In the paper we adopt the assumption that foreign inflation, output and interest rate are exogenously given. This approximation is perhaps more suitable for a small open economy, but given the results by Lindé (2003) it is probably a less rudimentary statement than modeling the Euro area as a closed economy. In addition, there is some empirical support for this approximation. By estimating a VAR model with ten Euro area variables and three foreign variables ("rest of the world" inflation, output and interest rate), we find that the Euro area variables account for a small fraction of the variation in the foreign variables, around 10(20) percent at the one(five) year horizon.[1]

We compare the estimated open and closed economy models in terms of their marginal likelihoods, their forecasting performance, the underlying sources of fluctuations in each model (variance decompositions), and the implications for the monetary transmission channel (impulse responses).

The results show that there are no fundamental differences between the estimated parameters in the closed and open economy versions of the model. At a general level, the existence of nominal and real frictions is crucial for both models' ability to fit the data. However, there are some differences in the estimated degree of the nominal and real frictions, which have effects on the dynamics of the two models. Impulse response analysis to an unexpected increase in the interest rate (i.e. a positive monetary policy shock) reveal differences in the transmission mechanism of monetary policy in the open and closed economy settings. The exchange rate channel implies that inflation drops more heavily in the open economy model than in the closed economy version. For output, we find that the exchange rate channel is relatively unimportant, but there is nevertheless a substantial difference in the impulse responses, which is due to the differences in nominal and real rigidities in the two models.

The comparison of marginal likelihoods suggest that a closed economy version of the model gives a better description of the domestic macroeconomic development than the open economy model estimated on the same set of variables. Note though that a comparison cannot be made against the complete open economy model since this is estimated on a different and richer set of variables, also including, for example, the exchange rate, exports and imports.

Since we cannot compare the marginal likelihoods of the closed economy model and the open economy model estimated on the full set of variables, we evaluate the forecasting performance of the open and closed DSGE models using traditional univariate and multivariate out-of-sample measures of the forecast accuracy. It is not clear what can be expected from this comparison a priori. The larger open economy version of the model naturally has the potential of providing a more detailed description of the economy, but this may also be a drawback if some aspect of the open economy is poorly modelled. It is probably fair to say that the collective experience from macroeconomic forecasting is that smaller models tend to out-perform larger ones. The general finding in this paper is that adding open economy features to the model improves the predictions on some of the variables, e.g. output and employment, whereas for other variables, such as

[1] The identifying assumption in the analysis is that the Euro area shocks have no contemporaneous effects on the foreign variables. Moreover, it should be noticed that the results are not much affected by changing the lag-length (we experimented with 1-4 lags).

inflation and investment, the closed economy model gives more accurate forecasts. However, the multivariate accuracy measures, which takes the joint forecasting performance of all seven domestic variables into account, seems to propose the open economy model as the best forecasting tool for all horizons that we consider (1 to 16 quarters ahead).

We also find that the macroeconomic development is driven by very different disturbances in the two models. The variance decompositions show that in the open economy model, "open economy shocks" are of high relevance for explaining the fluctuations in output and inflation in the short- to medium term horizon. In the closed economy model, most of the variation is instead attributed to the two technology shocks (stationary and unit root) at the same horizons.

The remainder of the paper is organized as follows. In Section 2, we describe the open economy DSGE model and how to reduce it to obtain a closed economy setting. We discuss the theoretical components of the model as well as the estimation outcomes in the open and closed economy frameworks. Section 3 contains the results from the comparison of the two models. Section 4 provides some concluding remarks.

2. The estimated DSGE model

This section gives an overview of the model economy, and presents the key equations in the theoretical model. We will here discuss the model in its open economy form, but we explain in Section 2.2 how we parameterize it to obtain a closed economy specification.

The model is an open economy version of the DSGE model in Christiano et al. (2005) and Altig et al. (2003), developed in Adolfson, Laséen, Lindé and Villani (2005). As in the closed economy setup, households maximize a utility function consisting of consumption, leisure and cash balances. However, in our open economy model the households consume a basket consisting of domestically produced goods and imported goods. These products are supplied by domestic and importing firms, respectively. We allow the imported goods to enter both aggregate consumption as well as aggregate investment. This is needed when matching the joint empirical fluctuations in both imports and consumption since imports (and investment) are a lot more volatile than consumption.

Households can save in domestic bonds and/or foreign bonds and hold cash. This choice balances into an arbitrage condition pinning down expected exchange rate changes (i.e., an uncovered interest rate parity (UIP) condition). As in the closed economy model households rent capital to the domestic firms and decide how much to invest in the capital stock given capital adjustment costs. These are costs to adjusting the investment rate as well as costs of varying the utilization rate of the capital stock. Each household is a monopoly supplier of a differentiated labour service which implies that they can set their own wage. Wage stickiness is introduced through an indexation variant of the Calvo (1983) model.

Domestic production follows a Cobb-Douglas function in capital and labour, and is exposed to stochastic technology growth as in Altig et al. (2003). The firms (domestic, importing and exporting) all produce differentiated goods and set prices according to an indexation variant of the Calvo model. By including nominal rigidities in the importing and exporting sectors we allow for short-run incomplete exchange rate pass-through to both import and export prices.[2] In what follows we provide the optimization problems of the different firms and the households, and describe the behavior of the central bank.

[2] Since there are neither any distribution costs in the import and export sectors nor an endogenous pricing to market behaviour among the firms, there would be complete pass-through in the absence of nominal rigidities.

2.1. Model

The model economy includes four different categories of operating firms. These are domestic goods firms, importing consumption, importing investment, and exporting firms, respectively. Within each category there is a continuum of firms that each produces a differentiated good. The domestic goods firms produce their goods out of capital and labour inputs, and sell them to a retailer which transforms the intermediate products into a homogenous final good that in turn is sold to the households. The final domestic good is a composite of a continuum of i differentiated goods, each supplied by a different firm, which follows the constant elasticity of substitution (CES) function

$$Y_t = \left[\int_0^1 (Y_{i,t})^{\frac{1}{\lambda_t^d}} \, di \right]^{\lambda_t^d}, 1 \leq \lambda_t^d < \infty, \tag{1}$$

where λ_t^d is a stochastic process that determines the time-varying markup in the domestic goods market. The demand for firm i's differentiated product, $Y_{i,t}$, follows

$$Y_{i,t} = \left(\frac{P_{i,t}^d}{P_t^d} \right)^{-\frac{\lambda_t^d}{\lambda_t^d - 1}} Y_t. \tag{2}$$

The domestic production is exposed to unit root technology growth as in Altig et al. (2003). The production function for intermediate good i is given by

$$Y_{i,t} = z_t^{1-\alpha} \epsilon_t K_{i,t}^{\alpha} H_{i,t}^{1-\alpha} - z_t \phi, \tag{3}$$

where z_t is a unit-root technology shock, ϵ_t is a covariance stationary technology shock, and $H_{i,t}$ denotes homogeneous labour hired by the i^{th} firm. Notice that $K_{i,t}$ is not the physical capital stock, but rather the capital services stock, since we allow for variable capital utilization in the model. A fixed cost $z_t \phi$ is included in the production function. We set this parameter so that profits are zero in steady state, following Christiano et al. (2005).

We allow for working capital by assuming that a fraction ν of the intermediate firms' wage bill has to be financed in advance. Cost minimization yields the following nominal marginal cost for intermediate firm i:

$$MC_t^d = \frac{1}{(1-\alpha)^{1-\alpha}} \frac{1}{\alpha^{\alpha}} (R_t^k)^{\alpha} \left[W_t (1 + \nu (R_{t-1} - 1)) \right]^{1-\alpha} \frac{1}{(z_t)^{1-\alpha}} \frac{1}{\epsilon_t}, \tag{4}$$

where R_t^k is the gross nominal rental rate per unit of capital services, R_{t-1} the gross nominal (economy wide) interest rate, and W_t the nominal wage rate per unit of aggregate, homogeneous, labour $H_{i,t}$.

Each of the domestic goods firms is subject to price stickiness through an indexation variant of the Calvo (1983) model. Since we have a time-varying inflation target in the model we allow for partial indexation to the current inflation target, but also to last period's inflation rate in order to allow for a lagged pricing term in the Phillips curve. Each intermediate firm faces in any period a probability $(1 - \xi_d)$ that it can reoptimize its price. The reoptimized price is denoted $P_t^{d,new}$.[3] The different firms maximize profits taking into account that there might not

[3] For the firms that are not allowed to reoptimize their price, we adopt the indexation scheme $P_{t+1}^d = \left(\pi_t^d\right)^{\kappa_d} \left(\bar{\pi}_{t+1}^c\right)^{1-\kappa_d} P_t^d$ where κ_d is an indexation parameter.

be a chance to optimally change the price in the future. Firm i therefore faces the following optimization problem when setting its price

$$\max_{P_t^{d,new}} \mathrm{E}_t \sum_{s=0}^{\infty} (\beta\xi_d)^s \upsilon_{t+s}[((\pi_t^d \pi_{t+1}^d ... \pi_{t+s-1}^d)^{\kappa_d} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c ... \bar{\pi}_{t+s}^c)^{1-\kappa_d} P_t^{d,new}) Y_{i,t+s} \\ - MC_{i,t+s}^d (Y_{i,t+s} + z_{t+s}\phi^j)], \tag{5}$$

where the firm is using the stochastic discount factor $(\beta\xi_d)^s \upsilon_{t+s}$ to make profits conditional upon utility. β is the discount factor, and υ_{t+s} the marginal utility of the households' nominal income in period $t+s$, which is exogenous to the intermediate firms. π_t^d denotes inflation in the domestic sector, $\bar{\pi}_t^c$ a time-varying inflation target of the central bank and $MC_{i,t}^d$ the nominal marginal cost.

The first order condition of the profit maximization problem in equation (5) yields the following log-linearized Phillips curve:

$$\begin{aligned} \left(\widehat{\pi}_t^d - \widehat{\bar{\pi}}_t^c\right) = {} & \frac{\beta}{1+\kappa_d\beta}\left(\mathrm{E}_t \widehat{\pi}_{t+1}^d - \rho_\pi \widehat{\bar{\pi}}_t^c\right) + \frac{\kappa_d}{1+\kappa_d\beta}\left(\widehat{\pi}_{t-1}^d - \widehat{\bar{\pi}}_t^c\right) \\ & - \frac{\kappa_d\beta(1-\rho_\pi)}{1+\kappa_d\beta}\widehat{\bar{\pi}}_t^c + \frac{(1-\xi_d)(1-\beta\xi_d)}{\xi_d(1+\kappa_d\beta)}\left(\widehat{mc}_t^d + \widehat{\lambda}_t^d\right), \end{aligned} \tag{6}$$

where a hat denotes log-linearized variables (i.e., $\hat{X}_t = dX_t/X$).

We now turn to the import and export sectors. There is a continuum of importing consumption and investment firms that each buys a homogenous good at price P_t^* in the world market, and converts it into a differentiated good through a brand naming technology. The exporting firms buy the (homogenous) domestic final good at price P_t^d and turn this into a differentiated export good through the same type of brand naming. The nominal marginal cost of the importing and exporting firms are thus $S_t P_t^*$ and P_t^d/S_t, respectively. The differentiated import and export goods are subsequently aggregated by an import consumption, import investment and export packer, respectively, so that the final import consumption, import investment, and export good is each a CES composite according to the following:

$$C_t^m = \left[\int_0^1 \left(C_{i,t}^m\right)^{\frac{1}{\lambda_t^{mc}}} di\right]^{\lambda_t^{mc}}, \qquad I_t^m = \left[\int_0^1 \left(I_{i,t}^m\right)^{\frac{1}{\lambda_t^{mi}}} di\right]^{\lambda_t^{mi}}, \qquad X_t = \left[\int_0^1 \left(X_{i,t}\right)^{\frac{1}{\lambda_t^{x}}} di\right]^{\lambda_t^{x}}, \tag{7}$$

where $1 \leq \lambda_t^j < \infty$ for $j = \{mc, mi, x\}$ is the time-varying markup in the import consumption (mc), import investment (mi) and export (x) sector. By assumption the continuum of consumption and investment importers invoice in the domestic currency and exporters in the foreign currency. In order to allow for short-run incomplete exchange rate pass-through to import as well as export prices we therefore introduce nominal rigidities in the local currency price. This is modeled through the same type of Calvo setup as above. The price setting problems of the importing and exporting firms are completely analogous to that of the domestic firms in equation (5), and the demand for the differentiated import and export goods follow similar expressions as to equation (2). In total there is thus four specific Phillips curve relations determining inflation in the domestic, import consumption, import investment and export sectors.

In the model economy there is also a continuum of households which attain utility from consumption, leisure and real cash balances. The preferences of household j are given by

$$\mathrm{E}_0^j \sum_{t=0}^{\infty} \beta^t \left[\zeta_t^c \ln(C_{j,t} - bC_{j,t-1}) - \zeta_t^h A_L \frac{(h_{j,t})^{1+\sigma_L}}{1+\sigma_L} + A_q \frac{\left(\frac{Q_{j,t}}{z_t P_t^d}\right)^{1-\sigma_q}}{1-\sigma_q}\right], \tag{8}$$

where $C_{j,t}$, $h_{j,t}$ and $Q_{j,t}/P_t^d$ denote the j^{th} household's levels of aggregate consumption, labour supply and real cash holdings, respectively. Consumption is subject to habit formation through $bC_{j,t-1}$, such that the household's marginal utility of consumption is increasing in the quantity of goods consumed last period. ζ_t^c and ζ_t^h are AR(1) preference shocks to consumption and labour supply, respectively. To make cash balances in equation (8) stationary when the economy is growing they are scaled by the unit root technology shock z_t. Households consume a basket of domestically produced goods and imported products which are supplied by the domestic and importing consumption firms, respectively. Aggregate consumption is assumed to be given by the following constant elasticity of substitution (CES) function:

$$C_t = \left[(1-\omega_c)^{1/\eta_c}\left(C_t^d\right)^{(\eta_c-1)/\eta_c} + \omega_c^{1/\eta_c}\left(C_t^m\right)^{(\eta_c-1)/\eta_c}\right]^{\eta_c/(\eta_c-1)}, \tag{9}$$

where C_t^d and C_t^m are consumption of the domestic and imported good, respectively. ω_c is the share of imports in consumption, and η_c is the elasticity of substitution across consumption goods.

The households invest in a basket of domestically produced goods and imported investment goods to form the physical capital stock, and decide how much capital services to rent to the domestic firms, given capital adjustment costs. These are costs to adjusting the investment rate as well as costs of varying the utilization rate of the physical capital stock. The households can increase their capital stock by investing in additional physical capital (I_t), taking one period to come in action, or by directly increasing the utilization rate of the capital at hand ($u_t = K_t/\bar{K}_t$). The capital accumulation equation for the physical capital stock ($\bar{K}_t$) is given by

$$\bar{K}_{t+1} = (1-\delta)\bar{K}_t + \Upsilon_t\left(1-\tilde{S}\left(I_t/I_{t-1}\right)\right)I_t, \tag{10}$$

where $\tilde{S}\left(I_t/I_{t-1}\right)$ determines the investment adjustment costs through the estimated parameter $\tilde{S}''$, and Υ_t is a stationary investment-specific technology shock. Total investment is assumed to be given by a CES aggregate of domestically produced goods and imported investment goods (I_t^d and I_t^m, respectively) according to

$$I_t = \left[(1-\omega_i)^{1/\eta_i}\left(I_t^d\right)^{(\eta_i-1)/\eta_i} + \omega_i^{1/\eta_i}\left(I_t^m\right)^{(\eta_i-1)/\eta_i}\right]^{\eta_i/(\eta_i-1)}, \tag{11}$$

where ω_i is the share of imports in investment, and η_i is the elasticity of substitution across investment goods.

Further, along the lines of Erceg, Henderson and Levin (2000), each household is a monopoly supplier of a differentiated labour service which implies that they can set their own wage. After having set their wage, households inelastically supply the firms' demand for labour at the going wage rate. Each household sells its labour to a firm which transforms household labour into a homogenous good that is demanded by each of the domestic goods producing firms. Wage stickiness is introduced through the Calvo (1983) setup, with partial indexation to last period's CPI inflation rate, the current inflation target and the technology growth. Household j reoptimizes its nominal wage rate $W_{j,t}^{new}$ according to the following

$$\begin{gathered}\max_{W_{j,t}^{new}} \quad \mathrm{E}_t \textstyle\sum_{s=0}^{\infty}\left(\beta\xi_w\right)^s \left[-\zeta_{t+s}^h A_L \frac{\left(h_{j,t+s}\right)^{1+\sigma_L}}{1+\sigma_L} + \right. \\ \left. \upsilon_{t+s}\frac{\left(1-\tau_{t+s}^y\right)}{\left(1+\tau_{t+s}^w\right)}\left(\left(\pi_t^c \ldots \pi_{t+s-1}^c\right)^{\kappa_w}\left(\bar{\pi}_{t+1}^c \ldots \bar{\pi}_{t+s}^c\right)^{(1-\kappa_w)}\left(\mu_{z,t+1} \ldots \mu_{z,t+s}\right)W_{j,t}^{new}\right)h_{j,t+s}\right],\end{gathered} \tag{12}$$

where ξ_w is the probability that a household is not allowed to reoptimize its wage, τ_t^y a labour income tax, τ_t^w a pay-roll tax (paid for simplicity by the households), and $\mu_{z,t} = z_t/z_{t-1}$ is the growth rate of the permanent technology level.[4]

The households can save in domestic bonds and foreign bonds, and also hold cash. This choice balances into an arbitrage condition pinning down expected exchange rate changes (i.e., an uncovered interest rate parity condition). To ensure a well-defined steady-state in the model, we assume that there is a premium on the foreign bond holdings which depends on the aggregate net foreign asset position of the domestic households, following, e.g., Lundvik (1992) and Benigno (2001):

$$\Phi(a_t, \tilde{\phi}_t) = \exp(-\tilde{\phi}_a(a_t - \bar{a}) + \tilde{\phi}_t), \tag{13}$$

where $A_t \equiv (S_t B_t^*)/(P_t z_t)$ is the net foreign asset position, and $\tilde{\phi}_t$ is a shock to the risk premium.

The budget constraint for the households is given by

$$\begin{aligned} & M_{t+1} + S_t B_{t+1}^* + P_t^c C_t \left(1+\tau_t^c\right) + P_t^i I_t + P_t a(u_t) \overline{K}_t \\ = \\ & R_{t-1}\left(M_t - Q_t\right) + Q_t + R_{t-1}^* \Phi(a_{t-1}, \widetilde{\phi}_{t-1}) S_t B_t^* \\ & + \left(1-\tau_t^k\right) R_t^k u_t \bar{K}_t + \left(1-\tau_t^y\right) \frac{W_t}{1+\tau_t^w} h_t + \left(1-\tau_t^k\right) \Pi_t \\ & -\tau_t^k \left[\left(R_{t-1}-1\right)\left(M_t - Q_t\right) + \left(R_{t-1}^* \Phi(a_{t-1}, \widetilde{\phi}_{t-1}) - 1\right) S_t B_t^* + B_t^* \left(S_t - S_{t-1}\right)\right] \\ & + TR_t + D_t, \end{aligned} \tag{14}$$

where the right-hand side describes the resources at disposal. The households earn interest on the amount of nominal domestic assets that are not held as cash, $M_t - Q_t$. They can also save in foreign bonds B_t^*, which pay a risk-adjusted pre-tax gross interest rate of $R_{t-1}^* \Phi(a_{t-1}, \widetilde{\phi}_{t-1})$. S_t is the nominal exchange rate (foreign currency per unit of domestic currency), R_t^k the gross nominal rental rate of capital, and W_t the nominal wage rate. The households earn income from renting capital and labour services (K_t and h_t) to the intermediate firms, where u_t denotes the varying capital utilization rate and $\bar{K}_t$ the physical capital stock. They pay taxes on consumption (τ_t^c), capital income (τ_t^k), labour income (τ_t^y), and on the pay-roll (τ_t^w). Π_t denotes profits, TR_t lump-sum transfers from the government, and D_t the household's net cash income from participating in state contingent securities at time t. The right hand side describes how the households spend their resources on consumption and investment goods, priced at P_t^c and P_t^i respectively, on future bond holdings, and pay the cost of varying the capital utilization rate $P_t a(u_t)\bar{K}_t$, where $a(u_t)$ is the utilization cost function.

Following Smets and Wouters (2003), monetary policy is approximated with the following instrument rule (expressed in log-linearized terms)

$$\begin{aligned} \widehat{R}_t &= \rho_R \widehat{R}_{t-1} + (1-\rho_R)\left[\widehat{\bar{\pi}}_t^c + r_\pi\left(\hat{\pi}_{t-1}^c - \widehat{\bar{\pi}}_t^c\right) + r_y \hat{y}_{t-1} + r_x \hat{x}_{t-1}\right] \\ & \quad + r_{\Delta\pi}\left(\hat{\pi}_t^c - \hat{\pi}_{t-1}^c\right) + r_{\Delta y} \Delta \hat{y}_t + \varepsilon_{R,t}, \end{aligned} \tag{15}$$

where $\varepsilon_{R,t}$ is an uncorrelated monetary policy shock. Thus, the central bank is assumed to adjust the short term interest rate in response to deviations of CPI inflation from the time-varying inflation target $\left(\hat{\pi}_t^c - \widehat{\bar{\pi}}_t^c\right)$, the output gap ($\hat{y}_t$, measured as actual minus trend output), the real exchange rate ($\hat{x}_t$) and the interest rate set in the previous period. In addition, note that the nominal interest rate adjusts directly to the inflation target. The output target used by

[4] For the households that are not allowed to reoptimize, the indexation scheme is $W_{j,t+1} = \left(\pi_t^c\right)^{\kappa_w} \left(\bar{\pi}_{t+1}^c\right)^{(1-\kappa_w)} \mu_{z,t+1} W_{j,t}^{new}$, where κ_w.

the central bank is here defined to be the trend level of output. An alternative specification is to define the output target in terms of the level output that would have prevailed in the absence of nominal rigidities. This model consistent output gap would to a larger extent probably come closer to optimal monetary policy (see Woodford, 2003, for further discussion). However, Del Negro et al. (2004) show that a rule using the trend output gap is preferred over a rule with the model consistent output gap, when estimating a closed economy DSGE model on US data.

To clear the final goods market, the foreign bond market, and the loan market, the following three constraints must hold in equilibrium:

$$C_t^d + I_t^d + G_t + C_t^x + I_t^x \leq z_t^{1-\alpha} \epsilon_t K_t^\alpha H_t^{1-\alpha} - z_t \phi - a(u_t) \bar{K}_t, \tag{16}$$

$$S_t B_{t+1}^* = S_t P_t^x \left(C_t^x + I_t^x\right) - S_t P_t^* \left(C_t^m + I_t^m\right) + R_{t-1}^* \Phi(a_{t-1}, \widetilde{\phi}_{t-1}) S_t B_t^*, \tag{17}$$

$$\nu W_t H_t = \mu_t M_t - Q_t, \tag{18}$$

where C_t^x and I_t^x are the foreign demand for export goods, P_t^* the foreign price level, and $\mu_t = M_{t+1}/M_t$ is the monetary injection by the central bank. When defining the demand for export goods, we introduce a stationary asymmetric technology shock $\tilde{z}_t^* = z_t^*/z_t$, where z_t^* is the permanent technology level abroad, to allow for different degrees of technological progress domestically and abroad.

The structural shock processes in the model is given in log-linearized form by the univariate representation

$$\hat{x}_t = \rho_x \hat{x}_{t-1} + \varepsilon_{x,t}, \qquad \varepsilon_{x,t} \overset{iid}{\sim} N\left(0, \sigma_x^2\right)$$

where $x = \{\ \mu_{z,t}, \epsilon_t, \lambda_t^j, \zeta_t^c, \zeta_t^h, \Upsilon_t, \tilde{\phi}_t, \varepsilon_{R,t}, \bar{\pi}_t^c, \tilde{z}_t^*\}$ and $j = \{d, mc, mi, x\}$.

Lastly, to simplify the analysis we adopt the assumption that the foreign prices, output (HP-detrended) and interest rate are exogenously given by an identified VAR(4) model.[5] The fiscal policy variables - taxes on capital income, labour income, consumption, and the pay-roll, together with (HP-detrended) government expenditures - are assumed to follow an identified VAR(2) model.[6]

To compute the equilibrium decision rules, we proceed as follows. First, we stationarize all quantities determined in period t by scaling with the unit root technology shock z_t. Then, we log-linearize the model around the constant steady state and calculate a numerical solution with the AIM algorithm developed by Anderson and Moore (1985).

2.2. Estimation

To estimate the model we use quarterly Euro area data for the period 1970Q1-2002Q4. The data set employed here was first constructed by Fagan et al. (2001).[7] In order to be able to identify the 51 parameters in the open economy model we use data on the following 15 variables in the estimation: the domestic inflation rate π_t; the growth rates in the real wage $\Delta\overline{w}_t$ (Δ denotes the first difference operator), consumption Δc_t, investment Δi_t, GDP Δy_t, exports $\Delta\widetilde{X}_t$, imports $\Delta\widetilde{M}_t$; the short-run interest rate R_t; employment E_t; the growth rates in the consumption deflator $\pi_t^{def,c}$ and the investment deflator $\pi_t^{def,i}$; the real exchange rate x_t; foreign inflation π_t^*;

[5] The reason why we include foreign output HP-detrended and not in growth rates in the VAR is that the level of foreign output enters the model (e.g., in the aggregate resource constraint).

[6] It should be noted that Adolfson et al. (2005) report that the fiscal shocks have small dynamic effects in the model. This is because households are Ricadian and infinitively lived. Moreover, these shocks are transitory and do not generate any wealth effects. Finally, the fiscal shocks are estimated to have relatively small variance.

[7] The Fagan data set includes foreign (i.e., rest of the world) output and inflation, but not a foreign interest rate. We therefore use the Fed funds rate as a proxy for R_t^*.

the foreign interest rate R_t^*; and the growth rate in foreign output Δy_t^*.[8] Including a large set of variables facilitates identification of the underlying structural parameters in the economy. For instance, inclusion of the consumption and investment deflators along with the domestic and foreign GDP deflators implies that we can extract information about the unobserved import markup shocks. Unfortunately, as we adopt the assumption that firms in the export sector set prices in foreign currency, we are not able obtain appropriate data for export prices. This implies that the export price markup shock series will be weakly identified compared to other parts of the model. The reason for modeling the real variables in growth rates is that the unit root technology shock induces a common stochastic trend in the levels of these variables. Although the parameters in the exogenous foreign VAR are pre-estimated, we still include the foreign variables as observables in the estimation for two reasons. First, they enable identification of the asymmetric technology shock, as the foreign VAR is estimated using HP-detrended foreign output and we include actual foreign output growth as observable in the estimation.[9] Second, they are informative about the parameters governing the propagation of foreign impulses to the domestic economy. 13 structural shocks are estimated, out of which 11 follow AR(1) processes and two are white noise processes. Although we match 15 variables, this procedure does not involve singularity problems since 8 shocks are included as pre-estimated in the model (5 fiscal and 3 foreign). To calculate the likelihood function of the observed variables we apply the Kalman filter where we use the period 1970Q1-1979Q4 to form a prior on the unobserved state variables in 1979Q4, and then use the period 1980Q1-2002Q4 for inference.

To get a closed economy version of the model we must establish that the consumption and investment baskets only consist of domestically produced goods. That is, we set $\omega_c = \omega_i = 0$ and $\eta_c = \eta_i = \infty$.[10] The 29 parameters pertaining to the domestic economy are then estimated by matching the 'domestic' variables (π_t, Δc_t, Δi_t, Δy_t, $\Delta \overline{w}_t$, R_t, E_t).

A number of parameters are kept fixed throughout the estimation procedure of both the closed and open economy versions of the model. Most of these parameters can be related to the steady-state values of the observed variables in the model, and are therefore calibrated to match the sample mean of these.[11]

Table 1 shows the assumptions for the prior distribution of the estimated parameters. The location of the prior distribution corresponds to a large extent to those in Smets and Wouters (2003) and the findings in Altig et al. (2003) on U.S. data. For more details about our choice

[8] There is no (official) data on aggregate hours worked, $\hat{H}_t$, available for the euro area. Therefore, we use employment $\hat{E}_t$ in our estimations. Since employment is likely to respond more slowly to shocks than hours worked, we model employment using Calvo-rigidity (following Smets and Wouters, 2003): $\Delta \hat{E}_t = \beta E_t \Delta \hat{E}_{t+1} + \frac{(1-\xi_e)(1-\beta\xi_e)}{\xi_e}\left(\hat{H}_t - \hat{E}_t\right)$. For reasons discussed in greater detail in Adolfson et al. (2005), we also take out a linear trend in employment and the excess trend in imports and exports relative to the trend in GDP prior to estimation.

[9] We measure actual foreign output in the state-space representation as the sum of detrended foreign output, domestic productivity and the asymmetric technology shock. This enables us to identify the asymmetric technology shock since the process for detrended foreign output is identified from the VAR and the process for domestic productivity from domestic quantities.

[10] In addition, we set $\lambda_{mc} = \lambda_{mi} = 1$, $\xi_{mc} = \xi_{mi} = \xi_x = 0$, $\widetilde{\phi} = 0$, and $r_x = 0$ to ensure that all relative prices are unity and that the effects of the three foreign VAR shocks, the asymmetric technology shock and the three import and export markup shocks are zero.

[11] The calibrated parameters are set to the following: the money growth $\mu = 1.01$; the discount factor $\beta = 0.999$; the depreciation rate $\delta = 0.013$; the capital share in production $\alpha = 0.29$; the share of imports in consumption and investment $\omega_c = 0.31$ and $\omega_i = 0.55$, respectively; the steady-state tax rates on labour income and consumption $\tau^y = 0.177$ and $\tau^c = 0.125$, respectively; government expenditures-output ratio 0.20. For reasons discussed in greater detail in Adolfson et al. (2005), we also set the substitution elasticity between domestic and imported goods $\eta_c = 5$ and the capital utilization parameter $\sigma_a = 10^6$.

of prior distributions, see Adolfson et al. (2005). Note that we use the same prior distribution for the 29 domestic parameters in both the open and closed economy settings.

The joint posterior distribution of all estimated parameters is obtained in two steps. First, the posterior mode and Hessian matrix evaluated at the mode is computed by standard numerical optimization routines. Second, the Hessian matrix is used in the Metropolis-Hastings algorithm to generate a sample from the posterior distribution (see Smets and Wouters (2003), and the references therein, for details).

3. Comparing the models

In Table 1 we report the posterior mode and marginal likelihoods for the closed and open economy versions of the model. There are no fundamental differences between the estimated parameters in the two models; in both the closed and open economy specifications nominal and real frictions are found to be of critical importance for the models' adaptability to the data. There are, however, some differences that have effects on the dynamics of the two models. The nominal frictions in terms of the price and wage stickinesses are somewhat smaller in the open economy model. As an example, the domestic price stickiness is 0.88 in the open economy setting compared to 0.90 in the closed economy model. This implies an average duration of domestic price contracts of 8 and 10 quarters, respectively, under the traditional assumption that the households own the capital stock. If we instead assume that capital is specific to each firm, we can reinterpret our estimates of the price stickiness parameter to imply an average duration of about 4.5 quarters (see Altig et al., 2004) in the open economy model.

In contrast, the real frictions, in terms of habit formation and investment adjustment costs, are larger in the open economy setting than in the closed economy model. In the open economy model the habit formation parameter b is estimated to be 0.69 compared to 0.63 in the closed economy version. Naturally, this implies that the real variables respond less to disturbances in the open economy model compared to the closed economy model, while nominal variables react more heavily in the former. Compared to Christiano et al. (2005) who estimate their model by matching the impulse response functions to a monetary policy shock, DSGE models that are estimated to match all the variability in the data typically imply a somewhat higher degree of nominal and real frictions. This is case here as well as in Smets and Wouters (2003).

Figure 1 displays the impulse responses to a monetary policy shock in the open and closed economy models. In general, the impulse response functions show a hump-shaped pattern with the maximum impact of a policy shock occurring after about one year in both the closed and open economy models. However, the magnitude of the responses differ considerably. For instance, domestic inflation reacts more to a monetary policy shock in the open economy setting (solid) than in the closed economy model, whereas the response of output is stronger in the closed economy model (dashed). To examine if these differences are due to the exchange rate channel in the transmission mechanism of monetary policy or discrepancies in the dynamics of the two models (i.e., the parameter differences discussed above), we also display the responses from a closed economy version with parameters taken from the estimated full open economy model. The difference between the open economy and closed economy models with the same domestic parameters (solid and dotted lines, respectively) can thus be attributed to the exchange rate channel. However, we see from Figure 1 that most of the difference between the closed and open economy models for output cannot be ascribed to the exchange rate channel, instead it is mostly due to the different parameter estimates in the two models. For inflation, the exchange rate channel is most important around the peak, and less relevant at longer horizons. It should also be noted that net exports fall considerably after the appreciation of the real exchange rate.

A marginal likelihood comparison (see, e.g., Smets and Wouters (in press)) of the open and closed economy versions of the model is not straightforward since the closed economy version only includes a subset of the 15 observed variables in the estimation. One approach is to compare the marginal likelihood of the closed econony model, $p_c(x_c)$, where x_c denotes the subset of closed economy variables, to the marginal likelihood of the closed economy variables in the open economy model, which we denote by $p_o(x_c)$. Another approach is to compare the marginal likelihood of x_c conditional on the open economy variables, x_o, using the open economy model. Since $p_o(x_c|x_o) = p_o(x_c, x_o)/p_o(x_o)$, and $p_o(x_c, x_o)$ is already available from the estimation on the full set of variables, the latter approach boils down to computing the marginal likelihood of x_o in the open economy model. A problem with both these approaches is that the model is at best weakly identified if only a subset of the data is used for estimation. Even though we have well defined prior distributions on the model parameters to aid identification, a vague prior on the underlying unobserved state variables in combination with the complex nature of the DSGE model resulted in numerically unstable marginal likelihoods.[12] We have therefore chosen another route for computing the marginal likelihood of the closed economy variables in the open economy model, where the 22 parameters pertaining to the open economy are calibrated and only the 29 domestic parameters are estimated. The parameters referring to the open economy are calibrated to their posterior mode values from the full estimation on all 15 variables (see Table 1).

The marginal likelihood seems to speak in favour of the closed economy model. The Bayes factor on the open economy model estimated on seven variables is about 0.002, which indicates that the closed economy model provides a better description of the seven domestic variables during $1980Q1 - 2002Q4$. In the light of the well known sensitivity of the marginal likelihood in non-linear models to the choice of prior distribution, the difference in marginal likelihoods of the two seven-variable models in Table 1 should not be over-emphasized. This is especially relevant here since the two compared models differ by as much as 22 parameters. Considering also the fact that we are unable to compare the closed economy version of the model with the full open economy model estimated on all 15 variables, leads us to examine the robustness of these results using other modes of model evaluation, such as out-of-sample forecasting precision.

The left panel in Table 2 shows the forecasting performance of the open and closed economy models in terms of root mean squared errors of the seven domestic variables on various horizons over the time period $1994Q1 - 2002Q4$.[13] The open economy model does slightly worse in terms of the (domestic) inflation forecasts in the medium to long-term horizons, but surpasses the long-term closed economy forecasts on output. The multivariate statistics (i.e., the log determinant of the mean square forecast error matrix of the domestic variables and the log predictive score (LPDS)) reported in the right panel in Table 2, however, indicate that the open economy model performs better on all horizons when the projections of all seven variables are jointly taken into account. The log determinant statistic measures the multivariate point forecast accuracy while the LPDS measures the plausibility of the observed outcomes with respect to the predictive distribution as a whole.

Finally, Table 3 summarizes the results from the variance decomposition of the seven domestic variables at four and 20 quarters horizon using the posterior mode estimates of the parameters.[14]

[12] Even though the results varied between simulations, the two approaches both indicate a fairly strong preference for the closed economy model.

[13] The forecasts are generated by sequentially expanding the sample in each quarter, and re-estimating the parameters every year.

[14] To save space we only report two horizons. The results from other horizons can be obtained from the authors upon request.

As could be expected from the parameter estimates in Table 1, we see that the role of various shocks for explaining the macroeconomic fluctuations differ between the two models. In the closed economy model, the two "traditional" technology shocks, i.e., the unit root and stationary technology shocks, are much more important. At the one year horizon they account for 55 and 35 percent of the fluctuations in inflation and output, respectively. After five years they account for about 70 percent of the fluctuations in output, which is line with the results in the early RBC literature, and somewhat higher than the corresponding number reported by Smets and Wouters (2003). In contrast, in the open economy specification the effects of unit root technology shocks are in line with the VAR evidence in Altig et al. (2004) and Galí and Rabanal (2004). The difference in the role of unit root technology shocks in the two specifications is that in the open economy version other shocks are assigned a more prominent role in order for the model to account for the joint behaviour of inflation, output, export, import and the real exchange rate. At the five year horizon, we notice that the importing markup shocks come out as an important source of the variation in output. In particular, the import investment markup shock turns up as very important. The reason for this is that the import investment markup shock has a very strong and persistent effect on the real exchange rate, which in turn influences output. Even if we conjectured in our discussion of Figure 1 that the exchange rate channel was not the main mechanism for understanding the transmission of monetary policy shocks, it is still sufficiently important for generating substantial output effects after a markup shock to import investment goods.

4. Concluding remarks

In the very last years, the monetary policy literature have witnessed a revival in estimation and implementation of DSGE models in monetary policy analysis. In this paper, we compared the empirical properties of the closed economy benchmark DSGE model with an open economy version developed by Adolfson et al. (2005). By and large, the estimation results display many similarities. That is, nominal and real frictions are of crucial importance for the empirical adaptability of both models. Despite the general similarity, the specific details of the estimation results suggest some differences in the monetary transmission channel. Equally important, we find that the sources of macroeconomic fluctuations in the two versions of the model differ considerably. In the open economy version of the model we find a larger role for "open-economy" shocks in order to account for the joint fluctuations in "domestic" and "open economy" variables (e.g., output and the real exchange rate, respectively). In terms of the models' forecasting performance of the development of the seven key macrovariables; inflation, the real wage, employment, nominal interest rate, consumption, investment and output, we find the two models to perform about equally well, with a slight edge for the open economy model.

Throughout the analysis, we maintain the assumption that the spillover effects from the Euro area shocks to the foreign economy are zero. This assumption is defended on the basis of a simple VAR analysis, which suggests that the spillover effects are small in the short- to medium run. However, it would be of interest to extend the analysis in this paper to multi-country models allowing for such effects. Very recent and preliminary contributions of Adjémain et al. (2004) and Walque and Wouters (2004) estimate multi-country models of the Euro area and the U.S.. These papers, however, maintain the implicit assumption that no countries outside these two currency areas influence or are affected by fluctuations in the U.S. and the Euro area. This assumption is a short-cut as is the case with our zero-spillover assumption.

Finally, the different sources behind aggregate fluctuations in the two models can be expected to have effects on the conduct of monetary policy in the open and closed economy settings, respectively. We leave for future work to analyze the implications for optimal monetary policy.

References

Adjémain, Stéphane, Matthieu Darracq Pariès and Frank Smets (2004) Structural Analysis of US and EA Business Cycles. Manuscript, European Central Bank.

Adolfson, Malin, Stefan Laséen, Jesper Lindé and Mattias Villani (2005) Bayesian Estimation of an Open Economy DSGE Model with Incomplete Pass-Through. Working Paper No. 179, Sveriges Riksbank.

Altig, David, Lawrence Christiano, Martin Eichenbaum and Jesper Lindé (2003) The Role of Monetary Policy in the Propagation of Technology Shocks. Manuscript, Northwestern University.

Altig, David, Lawrence Christiano, Martin Eichenbaum and Jesper Lindé (2004) Firm-Specific Capital, Nominal Rigidities and the Business Cycle. Working Paper No. 176, Sveriges Riksbank.

Anderson, Gary and George Moore (1985) A Linear Algebraic Procedure for Solving Linear Perfect Foresight Models. *Economics Letters* 17(3), 247-252.

Benigno, Pierpaolo (2001) Price Stability with Imperfect Financial Integration. Manuscript, New York University.

Calvo, Guillermo (1983) Staggered Prices in a Utility Maximizing Framework. *Journal of Monetary Economics* 12, 383-398.

Christiano, Lawrence, Martin Eichenbaum and Charles Evans (2005) Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy. *Journal of Political Economy* 113(1), 1-45.

Del Negro, Marco, Frank Schorfheide, Frank Smets and Raf Wouters (2004), "On the Fit and Forecasting Performance of New Keynesian Models", CEPR Discussion Paper No. 4848.

Erceg, Christopher, Dale Henderson and Andrew Levin (2000) Optimal Monetary Policy with Staggered Wage and Price Contracts. *Journal of Monetary Economics* 46(2), 281-313.

Fagan, Gabriel, Jerome Henry and Ricardo Mestre (2001) An Area-Wide Model (AWM) for the Euro Area. Working Paper No. 42. European Central Bank.

Galí, Jordi and Pau Rabanal (2004) Technology Shocks and Aggregate Fluctuations: How Well Does the RBC Model Fit Postwar U.S. Data? In Gertler, Mark and Kenneth Rogoff (eds.), *NBER Macroeconomics Annual 2004*, pp. 225-288. Cambridge, MA: MIT Press.

Lindé, Jesper (2003) Comment on "The Output Composition Puzzle: A Difference in the Monetary Transmission Mechanism in the Euro Area and U.S." by Ignazio Angeloni, Anil K Kasyap, Benoît Mojon and Daniele Terlizzese. *Journal of Money, Credit and Banking* 35(6), 1309-1318.

Lundvik, Petter (1992) Foreign Demand and Domestic Business Cycles: Sweden 1891-1987. In *Business Cycles and Growth*, pp.61-96. Monograph Series No. 22, Institute for International Economic Studies, Stockholm University.

Smets, Frank and Raf Wouters (2003) An Estimated Stochastic Dynamic General Equilibrium Model of the Euro Area. *Journal of the European Economic Association* 1(5), 1123-1175.

Smets, Frank and Raf Wouters (2004) Forecasting with a Bayesian DSGE Model. An Application to the Euro Area. Working Paper No. 389, European Central Bank.

Smets, Frank and Raf Wouters (in press) Comparing Shocks and Frictions in US and Euro Area Business Cycles: A Bayesian DSGE Approach. *Journal of Applied Econometrics.*

Walque, Grégory de, and Raf Wouters (2004) An Open Economy DSGE Model Linking the Euro Area and the US Economy. Manuscript, National Bank of Belgium.

Woodford, Michael (2003) *Interest and Prices: Foundations of a Theory of Monetary Policy.* Princeton: Princeton University Press.

Table 1: Prior and posterior distributions

Parameter		Prior distribution			Sample period 1980Q1-2002Q4 Posterior distribution					
					Open (15 var.)		Closed (7 var.)		Open (7 var.)	
		type	mean*	std.dev. /df	mode	std. dev. (Hessian)	mode	std. dev. (Hessian)	mode	std. dev. (Hessian)
Calvo wages	ξ_w	beta	0.675	0.050	0.697	0.047	0.738	0.042	0.707	0.048
Calvo domestic prices	ξ_d	beta	0.675	0.050	0.883	0.015	0.904	0.017	0.881	0.034
Calvo import cons. prices	ξ_{mc}	beta	0.500	0.100	0.463	0.059			calib. to 0.463	
Calvo import inv. prices	ξ_{mi}	beta	0.500	0.100	0.740	0.040			calib. to 0.740	
Calvo export prices	ξ_x	beta	0.500	0.100	0.639	0.059			calib. to 0.639	
Calvo employment	ξ_e	beta	0.675	0.100	0.792	0.022	0.796	0.022	0.802	0.026
Indexation wages	κ_w	beta	0.500	0.150	0.516	0.160	0.201	0.031	0.188	0.088
Index. domestic prices	κ_d	beta	0.500	0.150	0.212	0.066	0.392	0.142	0.352	0.141
Index..import cons. prices	κ_{mc}	beta	0.500	0.150	0.161	0.074			calib. to 0.161	
Index..import inv. prices	κ_{mi}	beta	0.500	0.150	0.187	0.079			calib. to 0.187	
Indexation export prices	κ_x	beta	0.500	0.150	0.139	0.072			calib. to 0.139	
Markup domestic	λ^d	inv. gamma	1.200	2	1.168	0.053	1.196	0.068	1.188	0.069
Markup imported cons.	λ^{mc}	inv. gamma	1.200	2	1.619	0.063			calib. to 1.619	
Markup imported invest.	λ^{mi}	inv. gamma	1.200	2	1.226	0.088			calib to. 1.226	
Investment adj. cost	$\tilde{S}''$	normal	7.694	1.500	8.732	1.370	6.705	1.518	8.053	1.423
Habit formation	b	beta	0.650	0.100	0.690	0.048	0.629	0.051	0.668	0.045
Subst. elasticity invest.	η_i	inv. gamma	1.500	4	1.669	0.273			calib. to 1.669	
Subst. elasticity foreign	η_f	inv. gamma	1.500	4	1.460	0.098			calib. to 1.460	
Technology growth	μ_z	trunc. normal	1.006	0.0005	1.005	0.000	1.005	0.001	1.006	0.001
Capital income tax	τ_k	beta	0.120	0.050	0.137	0.042	0.250	0.042	0.232	0.044
Labour pay-roll tax	τ_w	beta	0.200	0.050	0.186	0.050	0.190	0.051	0.186	0.050
Risk premium	$\tilde{\phi}$	inv. gamma	0.010	2	0.145	0.047			calib. to 0.145	
Unit root tech. shock	ρ_{μ_z}	beta	0.850	0.100	0.723	0.106	0.894	0.035	0.891	0.038
Stationary tech. shock	ρ_{ε}	beta	0.850	0.100	0.909	0.030	0.974	0.009	0.956	0.027
Invest. spec. tech shock	ρ_{Υ}	beta	0.850	0.100	0.750	0.041	0.458	0.094	0.537	0.118
Asymmetric tech. shock	$\rho_{\tilde{z}^*}$	beta	0.850	0.100	0.993	0.002			calib. to 0.993	
Consumption pref. shock	ρ_{ζ^c}	beta	0.850	0.100	0.935	0.029	0.978	0.008	0.983	0.006
Labour supply shock	ρ_{ζ^h}	beta	0.850	0.100	0.675	0.062	0.513	0.096	0.476	0.089
Risk premium shock	$\rho_{\tilde{\phi}}$	beta	0.850	0.100	0.991	0.008			calib. to 0.991	
Imp. cons. markup shock	$\rho_{\lambda^{mc}}$	beta	0.850	0.100	0.978	0.016			calib. to 0.978	
Imp. invest. markup shock	$\rho_{\lambda^{mi}}$	beta	0.850	0.100	0.974	0.015			calib. to 0.974	
Export markup shock	ρ_{λ^x}	beta	0.850	0.100	0.894	0.045			calib. to 0.894	
Unit root tech. shock	σ_{μ_z}	inv. gamma	0.200	2	0.130	0.025	0.138	0.029	0.153	0.033
Stationary tech. shock	σ_{ε}	inv. gamma	0.700	2	0.452	0.082	0.444	0.078	0.440	0.080
Invest. spec. tech. shock	σ_{Υ}	inv. gamma	0.200	2	0.424	0.046	0.562	0.073	0.539	0.083
Asymmetric tech. shock	$\sigma_{\tilde{z}^*}$	inv. gamma	0.200	2	0.203	0.031			calib. to 0.203	
Consumption pref. shock	σ_{ζ^c}	inv. gamma	0.200	2	0.151	0.031	0.130	0.029	0.132	0.028
Labour supply shock	σ_{ζ^h}	inv. gamma	0.050	2	0.095	0.015	0.094	0.015	0.095	0.014
Risk premium shock	$\sigma_{\tilde{\phi}}$	inv. gamma	0.400	2	0.130	0.023			calib. to 0.130	
Domestic markup shock	σ_{λ^d}	inv. gamma	0.300	2	0.130	0.012	0.143	0.014	0.141	0.015
Imp. cons. markup shock	$\sigma_{\lambda^{mc}}$	inv. gamma	0.300	2	2.548	0.710			calib. to 2.548	
Imp. invest. markup shock	$\sigma_{\lambda^{mi}}$	inv. gamma	0.300	2	0.292	0.079			calib. to 0.292	
Export markup shock	σ_{λ^x}	inv. gamma	0.300	2	0.977	0.214			calib. to 0.977	
Monetary policy shock	σ_R	inv. gamma	0.150	2	0.133	0.013	0.145	0.015	0.143	0.016
Inflation target shock	$\sigma_{\bar{\pi}^c}$	inv. gamma	0.050	2	0.044	0.012	0.042	0.012	0.043	0.012
Interest rate smoothing	ρ_R	beta	0.800	0.050	0.874	0.021	0.892	0.024	0.877	0.022
Inflation response	r_{π}	normal	1.700	0.100	1.710	0.067	1.728	0.090	1.729	0.047
Diff. infl response	$r_{\Delta\pi}$	normal	0.300	0.100	0.317	0.059	0.319	0.070	0.341	0.065
Real exch. rate response	r_x	normal	0.000	0.050	-0.009	0.008			calib. to -0.009	
Output response	r_y	normal	0.125	0.050	0.078	0.028	0.065	0.035	0.077	0.026
Diff. output response	$r_{\Delta\pi}$	normal	0.0625	0.050	0.116	0.028	0.100	0.026	0.084	0.037
Log marginal likelihood					-1909.34		-638.00		-644.52	

*Note: For the inverse gamma distribution, the mode and the degrees of freedom are reported. Also, for the parameters $\lambda^d, \lambda^{mc}, \lambda^{mi}, \eta_i, \eta_f$ and μ_z the prior distributions are truncated at 1. The posterior samples of 550,000 draws were generated from the posterior of which the first 50,000 draws were discarded as burn-in.

Table 2: Forecast accuracy

Horizon	Model	Univariate Root mean squared errors: Domestic inflation	Real wage	Consum ption	Invest-ment	Interest rate	Employ-ment	Output	Multivariate: Log deter-minant statistic	Log predictive density score
1Q	Open economy	**0.194**	0.514	**0.368**	1.646	**0.423**	**0.213**	0.328	**-21.475**	**7.114**
	Closed economy	0.200	**0.464**	0.370	**1.333**	0.466	0.258	**0.313**	-21.140	9.341
4Q	Open economy	0.634	2.451	**0.775**	6.270	1.273	**0.467**	1.242	-8.708	**22.949**
	Closed economy	**0.622**	**1.952**	0.931	**3.568**	**1.192**	0.778	**1.011**	**-8.717**	27.592
8Q	Open economy	1.318	2.919	**0.939**	6.098	2.164	**0.897**	1.329	**-8.127**	**26.667**
	Closed economy	**1.045**	**2.156**	1.102	**3.853**	**1.668**	1.803	**1.250**	-6.985	30.434
12Q	Open economy	1.743	2.821	**0.973**	4.689	2.849	**1.346**	**1.160**	**-6.322**	**29.314**
	Closed economy	**1.313**	**2.161**	1.053	**3.956**	**2.163**	2.883	1.229	-6.126	33.449
16Q	Open economy	1.808	2.415	**0.998**	4.252	3.142	**2.034**	**1.038**	**-7.053**	**30.643**
	Closed economy	**1.371**	**1.870**	1.043	**4.021**	**2.489**	3.803	1.137	-7.038	34.378

Note: The results are based on rolling forecasts from 1994Q1-2002Q3. Forecast distributions are generated from sub-sampling 500 draws from the full posterior distribution of the estimated parameters (re-estimated every year) using 100 shock sequences for each draw. The log determinant statistic is the logarithm of the determinant of the mean squared forecast error (MSFE) matrix. The log predictive density score (LPDS) equals the average of (-2 times) the logarithm of the predictive density $p_t(x_{t+h})$ over the evaluation period. Bold numbers indicate the best forecasting model for each measure.

Table 3: Variance decompositions

4 quarters	Domestic inflation		Real wage		Consumption		Investment		Interest rate		Employment		Output	
	Open	Closed	Open	Closed	Open	Closed	Open	Closed	Open	Closed	Open	Closed	Open	Closed
Stationary technology	0.137	0.279	0.057	0.101	0.049	0.082	0.019	0.003	0.068	0.179	0.101	0.195	0.046	0.044
Unit root technology	0.078	0.239	0.199	0.332	0.089	0.325	0.052	0.188	0.036	0.220	0.025	0.180	0.107	0.316
Consumtion preference	0.069	0.015	0.054	0.049	0.327	0.267	0.073	0.081	0.125	0.076	0.142	0.132	0.119	0.107
Labour supply	0.288	0.143	0.460	0.347	0.094	0.044	0.037	0.025	0.131	0.087	0.127	0.060	0.088	0.036
Domestic markup	0.032	0.034	0.047	0.075	0.024	0.036	0.013	0.042	0.026	0.032	0.023	0.038	0.025	0.040
Investment specific technology	0.001	0.043	0.056	0.036	0.030	0.001	0.504	0.403	0.187	0.088	0.188	0.123	0.234	0.195
Monetary policy	0.067	0.059	0.038	0.047	0.098	0.172	0.060	0.183	0.101	0.177	0.104	0.189	0.104	0.182
Inflation target	0.142	0.168	0.005	0.001	0.024	0.054	0.018	0.062	0.079	0.121	0.023	0.059	0.025	0.060
Fiscal variables	0.017	0.020	0.011	0.011	0.012	0.019	0.005	0.013	0.014	0.020	0.020	0.023	0.016	0.020
Import consumption markup	0.085		0.022		0.023		0.049		0.007		0.019		0.024	
Import investment markup	0.007		0.014		0.120		0.094		0.050		0.061		0.034	
Risk premium	0.030		0.005		0.004		0.036		0.052		0.037		0.040	
Asymmetric technology	0.007		0.000		0.002		0.004		0.006		0.001		0.001	
Export markup	0.022		0.022		0.092		0.007		0.068		0.089		0.087	
Foreign variables	0.020		0.009		0.011		0.027		0.049		0.040		0.050	
20 quarters														
Stationary technology	0.018	0.298	0.086	0.173	0.058	0.154	0.040	0.200	0.052	0.256	0.016	0.071	0.058	0.173
Unit root technology	0.085	0.251	0.342	0.582	0.177	0.406	0.117	0.424	0.096	0.290	0.051	0.253	0.222	0.534
Consumtion preference	0.081	0.031	0.108	0.082	0.200	0.209	0.096	0.132	0.147	0.071	0.192	0.297	0.048	0.071
Labour supply	0.023	0.038	0.027	0.015	0.120	0.051	0.083	0.100	0.105	0.053	0.224	0.157	0.121	0.071
Domestic markup	0.003	0.002	0.012	0.016	0.001	0.005	0.001	0.005	0.003	0.001	0.002	0.003	0.000	0.005
Investment specific technology	0.200	0.100	0.235	0.072	0.228	0.096	0.055	0.017	0.143	0.090	0.016	0.052	0.150	0.050
Monetary policy	0.006	0.017	0.038	0.052	0.025	0.052	0.013	0.082	0.008	0.029	0.034	0.109	0.023	0.065
Inflation target	0.231	0.233	0.015	0.000	0.002	0.011	0.002	0.020	0.173	0.184	0.009	0.019	0.002	0.015
Fiscal variables	0.026	0.030	0.010	0.008	0.021	0.016	0.009	0.019	0.023	0.025	0.035	0.040	0.017	0.016
Import consumption markup	0.220		0.062		0.043		0.240		0.080		0.080		0.098	
Import investment markup	0.042		0.035		0.081		0.265		0.102		0.272		0.200	
Risk premium	0.017		0.013		0.007		0.010		0.004		0.001		0.014	
Asymmetric technology	0.017		0.006		0.002		0.014		0.010		0.002		0.005	
Export markup	0.022		0.004		0.032		0.031		0.035		0.058		0.031	
Foreign variables	0.010		0.007		0.005		0.024		0.019		0.008		0.011	

Figure 1: Impulse responses from a monetary policy shock