ELSEVIER

Journal of International Economics 72 (2007) 481 – 511

Journal of INTERNATIONAL ECONOMICS

www.elsevier.com/locate/econbase

Bayesian estimation of an open economy DSGE model with incomplete pass-through

Malin Adolfson [a], Stefan Laséen [a], Jesper Lindé [a,b,*], Mattias Villani [a,c]

[a] *Sveriges Riksbank, SE-103 37 Stockholm, Sweden*
[b] *CEPR, United Kingdom*
[c] *Stockholm University, Sweden*

Received 22 April 2005; received in revised form 10 December 2006; accepted 15 January 2007

Abstract

In this paper, we develop a dynamic stochastic general equilibrium (DSGE) model for an open economy, and estimate it on Euro area data using Bayesian estimation techniques. The model incorporates several open economy features, as well as a number of nominal and real frictions that have proven to be important for the empirical fit of closed economy models. The paper offers: i) a theoretical development of the standard DSGE model into an open economy setting, ii) Bayesian estimation of the model, including assessments of the relative importance of various shocks and frictions for explaining the dynamic development of an open economy, and iii) an evaluation of the model's empirical properties using standard validation methods.

Keywords: DSGE model; Open economy; Monetary policy; Nominal rigidities; Bayesian inference; Business cycle

JEL classification: E40; E47; E52; C11

1. Introduction

In this paper, we develop a dynamic stochastic general equilibrium (DSGE) model for an open economy and estimate it on Euro area data. We extend the closed economy DSGE model of Christiano et al. (2005) by incorporating open economy aspects. Our model combines elements of

* Corresponding author. Sveriges Riksbank, SE-103 37 Stockholm, Sweden. Tel.: +46 70 24 66 171; fax: +46 8 21 05 31.
E-mail address: jesper.linde@riksbank.se (J. Lindé).

0022-1996/$ - see front matter
doi:10.1016/j.jinteco.2007.01.003

their closed economy setting with some of the features and findings in the New Open Economy Macroeconomics literature.[1]

Following Christiano et al. (2005), a number of nominal and real frictions such as sticky prices, sticky wages, variable capital utilization, capital adjustment costs and habit persistence are included in the theoretical model. We also allow for incomplete exchange rate pass-through in both the import and export sectors by including nominal price rigidities (i.e., local currency price stickiness), following, for example, Smets and Wouters (2002). The relevance of these frictions will be empirically determined in the estimation procedure. Apart from introducing the exchange rate channel, we also include a working capital channel (i.e., firms borrow money from a financial intermediary to finance part of their wage bill). Examining the role of the working capital channel is of particular interest, since Christiano et al. (2005) obtain a low estimated degree of price stickiness when allowing for working capital in matching the impulse responses after a monetary policy shock. In contrast, Smets and Wouters (2003, 2005) obtain a much higher degree of estimated price stickiness in a model without the working capital channel.

As in Altig et al. (2003), we include a stochastic unit-root technology shock in the model which induces a common stochastic trend in aggregate quantities. This allows us to use data in the estimation that has not been pre-processed (e.g. detrended). Compared to Smets and Wouters (2003, 2005), we also allow for a larger set of structural shocks, mainly due to the open economy aspects of our model. We perform relative model comparisons using Bayesian posterior densities to assess the importance of the various frictions and shocks for explaining business cycle fluctuations in the open economy.

We estimate the open economy model on Euro area data using Bayesian estimation techniques.[2] Smets and Wouters (2003, 2005) have shown that large-scale closed economy DSGE models can be successfully estimated using Bayesian methods. To simplify the analysis, we adopt the assumption that foreign inflation, output and interest rate are exogenously given. There is, however, substantial evidence in favor of this assumption. First, by estimating a VAR model with ten Euro area variables (inflation, output, interest rate, exchange rate, exports, imports, real wage, consumption, investment and employment) and three foreign variables ("rest of the world" inflation, output and interest rate), we find that the Euro area variables only account for a small fraction of the variation in the foreign variables (around 10% (20%) at the one- (five-) year horizon).[3] These findings are also supported by de Walque et al. (2005) who find small spillover effects in a joint structural analysis of business cycles in the Euro area, the US and the rest of the world. Second, to check the sensitivity of

[1] Important contributions to the theoretical literature on monetary policy in open economies are, among others, Corsetti and Pesenti (2001), Galí and Monacelli (2005) and Kollmann (2001). Earlier work on estimating more simple small open economy models includes Ambler et al. (2004), Justiniano and Preston (2004), and Lubik and Schorfheide (2005). de Walque et al. (2005) and Rabanal and Tuesta (2006) have recently estimated multi-country DSGE models.

[2] Lindé (2003) provides support for modelling the Euro area as an open economy by showing that "the rest of GDP" (i.e., output minus consumption and investment) moves significantly after a shock to monetary policy using a VAR on Euro area data. Since government expenditures are not cyclical, this suggests that fluctuations in net exports are important.

[3] The identifying assumption in the analysis is that Euro area shocks have no contemporaneous effects on the foreign variables.

our results, we have also estimated a specification of the DSGE model where we allow the Euro area variables to affect the foreign variables, both contemporaneously and with a lag. As could have been expected from the VAR analysis and the results in de Walque et al. (2005), the fit of the model is not improved by allowing for a feedback effect from the Euro area, and the parameter estimates in the DSGE, and thus the role of the various frictions and shocks, are essentially unaffected. For further details, the reader is referred to Adolfson et al. (2006).

To validate the fit of the estimated open economy DSGE model, we provide a thorough evaluation of the model's empirical properties. The estimated model is able to capture the volatility and persistence in the real exchange rate very well, which has turned out to be a difficult task without detrending the data (see, e.g., Bouakez, 2005, and the references therein). In addition, previous studies have not been able to match the dynamics of the real exchange rate without assuming unreasonable degrees of price rigidity. Our model, however, is able to replicate both the properties of the real exchange rate and the dynamics of the inflation differentials between the Euro area and the rest-of-the-world, using a reasonable degree of price stickiness and without detrending the data.[4] The key ingredient behind this ability of the model is that it embodies a set of time-varying markups (as suggested by Bouakez, 2005) that have rather persistent effects on the exchange rate dynamics, while generating much less fluctuations in quantities and prices. This finding is in line with the arguments of Duarte and Stockman (2005), and is attributed to the model setup which shares many of the features emphasized by Devereux and Engel (2002) as necessary to generate highly volatile exchange rates which are "disconnected" from the rest of the economy.[5]

Moreover, the model yields a high elasticity of substitution between domestic and imported goods. We find a preferred value in the range of 5 to 10 in the estimations. As shown by Obstfeld and Rogoff (2000), a high elasticity of substitution can explain the observed large home bias in trade. The typical estimates for the substitution elasticity between home and foreign goods are around 5 to 20 using micro data; see the references in Obstfeld and Rogoff (2000). However, using macro data, the estimates are usually considerably lower, in the range of 1.5–2, see e.g. Collard and Dellas (2002). We attribute our high estimate to the inclusion of both consumption and imports as observed variables when estimating the model.

The paper is organized as follows. In Section 2, the theoretical model is derived and described with particular emphasis on its open economy aspects and Section 3 contains a short description of the data used. In Section 4, we first discuss which parameters we have chosen to calibrate, and the prior distributions for the parameters we have chosen to estimate. Then, we report our estimation results and validate the model fit. The empirical properties of the estimated DSGE model are compared with the data using autocovariance functions. In Section 5, we explore the importance of nominal and real frictions in the model. Section 6 shows the impulse responses to a

[4] The model is able to match vector autocovariance functions for a large set of variables. In addition, in a companion paper (Adolfson et al., in press), we show that the forecasting ability of the model with respect to the real exchange rate and inflation, for example, compares favorably to Bayesian vector autoregressions (BVARs) and random walks, for example.

[5] Some of these features include (i) price stickiness in the import and export sectors, (ii) incomplete international financial markets, and (iii) stochastic deviations from the UIP condition (risk-premium shocks).

monetary policy shock and discusses the role of various shocks in explaining business cycles. Finally, Section 7 provides some conclusions.

2. The open economy DSGE model

We build on the work of Christiano et al. (2005) and extend their DSGE model to an open economy. As in their model, households maximize a utility function consisting of consumption, leisure and cash balances. However, in our open economy model, households consume and invest in baskets consisting of domestically produced and imported goods. We allow the imported goods to enter both aggregate consumption and investment. This is needed when matching the joint fluctuations in both imports and consumption, since imports are about three times as volatile as consumption in our data sample. 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. In what follows, we sketch the model set up for the different firms and households. We also describe the behavior of the central bank, the fiscal authority, and illustrate how the foreign economy develops.[6]

2.1. Firms

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

$$Y_t = \left[\int_0^1 (Y_{i,t})^{\frac{1}{\lambda_t^{\mathrm{d}}}} \mathrm{d}i\right]^{\lambda_t^{\mathrm{d}}}, 1 \leq \lambda_t^{\mathrm{d}} < \infty, \tag{2.1}$$

where λ_t^{d} is the time-varying markup in the domestic goods market. The production function for intermediate good i is given by

$$Y_{i,t} = z_t^{1-\alpha}\epsilon_t \mathrm{K}_{i,t}^{\alpha}\mathrm{H}_{i,t}^{1-\alpha} - \mathrm{z}_t\phi, \tag{2.2}$$

where z_t is a unit-root technology shock capturing world productivity, ϵ_t is a domestic covariance stationary technology shock, and $H_{i,t}$ denotes homogeneous labor hired by the ith firm. $K_{i,t}$ denotes capital services which differ from the physical capital stock, since we allow for variable capital utilization in the model. A fixed cost $z_t\phi$ is included in the production function and following Christiano et al. (2005), we set ϕ so that profits are zero in steady state.

We allow for working capital by assuming that a fraction v of the intermediate firms' wage bill must be financed in advance through loans from a financial intermediary. Cost minimization yields the following nominal marginal cost for intermediate firm i:

$$MC_t^{\mathrm{d}} = \frac{1}{(1-\alpha)^{1-\alpha}}\frac{1}{\alpha^{\alpha}}(R_t^k)^{\alpha}[W_t(1+v(R_{t-1}-1))]^{1-\alpha}\frac{1}{(z_t)^{1-\alpha}}\frac{1}{\epsilon_t}, \tag{2.3}$$

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, labor $H_{i,t}$.

[6] A detailed presentation of the model is provided in the working paper version of this paper, see Adolfson et al. (2005).

Each of the domestic goods firms is subject to price stickiness through an indexation variant of the Calvo (1983) model. Thus, in any period, each intermediate firm faces a probability $1-\xi_d$ that it can reoptimize its price. For those firms that are not allowed to reoptimize their price, we adopt the indexation scheme $P_{t+1}^{\mathrm{d}}=(\pi_t^{\mathrm{d}})^{\kappa_{\mathrm{d}}}(\bar{\pi}_{t+1}^c)^{1-\kappa_{\mathrm{d}}}P_t^{\mathrm{d}}$ where κ_{d} is an indexation parameter. Since the central bank has a time-varying inflation target ($\bar{\pi}_t^c$) 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. The process for the inflation target is defined in Eq. (2.13). The first-order condition of the profit maximization problem yields the following log-linearized Phillips curve:

$$\begin{aligned}(\hat{\pi}_t^{\mathrm{d}}-\hat{\bar{\pi}}_t^c) = {} & \frac{\beta}{1+\kappa_{\mathrm{d}}\beta}(E_t\hat{\pi}_{t+1}^{\mathrm{d}}-\rho_\pi\hat{\bar{\pi}}_t^c)+\frac{\kappa_{\mathrm{d}}}{1+\kappa_{\mathrm{d}}\beta}(\hat{\pi}_{t-1}^{\mathrm{d}}-\hat{\bar{\pi}}_t^c)-\frac{\kappa_{\mathrm{d}}\beta(1-\rho_\pi)}{1+\kappa_{\mathrm{d}}\beta}\hat{\bar{\pi}}_t^c \\ & +\frac{(1-\xi_{\mathrm{d}})(1-\beta\xi_{\mathrm{d}})}{\xi_{\mathrm{d}}(1+\kappa_{\mathrm{d}}\beta)}(\widehat{mc}_t^d+\hat{\lambda}_t^{\mathrm{d}}),\end{aligned} \tag{2.4}$$

where a hat denotes log-deviation from steady-state (i.e., $\hat{X}_t=\ln X_t-\ln X$), and $\hat{\pi}_t^{\mathrm{d}}$ denotes inflation in the domestic sector.

We now turn to the import and export sectors. There is a continuum of importing consumption and investment firms which 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 technology. The nominal marginal cost of the importing and exporting firms is thus $S_tP_t^*$ and P_t^{d}/S_t, respectively, where S_t is the nominal exchange rate (domestic currency per unit of foreign currency). The differentiated import and export goods are subsequently aggregated by an import consumption, an import investment and an export packer, respectively, so that the final import consumption, import investment and export good each constitutes a CES composite according to the following:

$$C_t^{\mathrm{m}}=\left[\int_0^1(C_{i,t}^{\mathrm{m}})^{\frac{1}{\lambda_t^{\mathrm{mc}}}}\mathrm{d}i\right]^{\lambda_t^{\mathrm{mc}}},\qquad I_t^{\mathrm{m}}=\left[\int_0^1(I_{i,t}^{\mathrm{m}})^{\frac{1}{\lambda_t^{\mathrm{mi}}}}\mathrm{d}i\right]^{\lambda_t^{\mathrm{mi}}},\qquad X_t=\left[\int_0^1(X_{i,t})^{\frac{1}{\lambda_t^{\mathrm{x}}}}\mathrm{d}i\right]^{\lambda_t^{\mathrm{x}}}, \tag{2.5}$$

where $1\leq\lambda_t^j<\infty$ for $j=\{\mathrm{mc, mi, x}\}$ is the time-varying markup in the import consumption (mc), import investment (mi) and export (x) sector. By assumption, importers and exporters invoice in local currency. To allow for short-run incomplete exchange rate pass-through to import and export prices, we introduce nominal rigidities in the local currency price, following Smets and Wouters (2002), for example.[7] This is modeled through the same type of Calvo setup as described above. The price setting problems of the importing and exporting firms are completely analogous to those of the domestic firms. In total, there are thus four specific Phillips curve relations determining inflation in the domestic, import consumption, import investment and export sectors, all having the same structure as Eq. (2.4).

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

The domestic economy is assumed to be small in relation to the foreign economy and plays a negligible part in aggregate foreign consumption and investment. Foreign demand for (aggregate) domestic consumption and investment goods, C_t^x and I_t^x, respectively, is given by

$$C_t^{\mathrm{x}} = \left[\frac{P_t^{\mathrm{x}}}{P_t^*}\right]^{-\eta_f} C_t^*, \qquad I_t^{\mathrm{x}} = \left[\frac{P_t^{\mathrm{x}}}{P_t^*}\right]^{-\eta_f} I_t^*, \tag{2.6}$$

where C_t^*, I_t^* and P_t^* denote foreign consumption, investment and price level, respectively.[8] To allow for temporary different degrees of technological progress domestically and abroad, we introduce a stationary asymmetric technology shock $\tilde{z}_t^*=z_t^*/z_t$, where z_t^* is the total technology level abroad, when defining aggregate demand for export goods. We will treat $\tilde{z}_t^*$ as a stationary shock, implying that $\mu_z=\mu_z^*$, which together with our assumption that $\pi=\pi^*$ in turn induces a stationary real exchange rate in the model.

2.2. Households

There is a continuum of households which maximizes utility subject to a standard budget constraint. The preferences of household j are given by

$$E_0^j \sum_{t=0}^{\infty} \beta^t \left[\zeta_t^c \ln\left(C_{j,t}-bC_{j,t-1}\right)-\zeta_t^h A_L \frac{\left(h_{j,t}\right)^{1+\sigma_L}}{1+\sigma_L} + A_q \frac{\left(\frac{Q_{j,t}}{z_t P_t^{\mathrm{d}}}\right)^{1-\sigma_q}}{1-\sigma_q}\right], \tag{2.7}$$

where $C_{j,t}$, $h_{j,t}$ and $Q_{j,t}/P_t^{\mathrm{d}}$ denote the jth household's levels of aggregate consumption, labor 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 today is affected by the quantity of goods consumed in the last period. ζ_t^c and ζ_t^h are persistent preference shocks to consumption and labor supply, respectively. To make real cash balances stationary when the economy is growing, they are scaled by the unit root technology shock, z_t. Aggregate consumption is assumed to be given by a constant elasticity of substitution (CES) function, consisting of domestically produced goods and imported products (which are supplied by the domestic and importing consumption firms, respectively):

$$C_t = \left[(1-\omega_c)^{1/\eta_c}\left(C_t^{\mathrm{d}}\right)^{(\eta_c-1)/\eta_c} + \omega_c^{1/\eta_c}\left(C_t^{\mathrm{m}}\right)^{(\eta_c-1)/\eta_c}\right]^{\eta_c/(\eta_c-1)}, \tag{2.8}$$

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 can increase their capital services (K_t) by investing (I_t) in additional physical capital ($\bar{K}_t$), taking one period to come into action, or by directly increasing the utilization rate of the physical capital stock at hand ($K_t=u_t\bar{K}_t$). Both operations undertake a cost. The capital accumulation equation is given by

$$\bar{K}_{t+1} = (1-\delta)\bar{K}_t + \Upsilon_t(1-\tilde{S}(I_t/I_{t-1}))I_t, \tag{2.9}$$

[8] By assuming that the elasticity (η_f) is the same for consumption and investment in Eq. (2.6), we can use foreign output ($Y_t^*=C_t^*+I_t^*$) as the only "demand variable", and consequently avoid taking a stand on how much of the exporting goods are used for consumption and investment purposes, respectively.

where $\tilde{S}\,(I_t/I_{t-1})$ 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 domestic and imported investment goods (I_t^{d} and I_t^{m}, respectively) according to

$$I_t=\left[(1-\omega_i)^{1/\eta_i}\left(I_t^{\mathrm{d}}\right)^{(\eta_i-1)/\eta_i}+\omega_i^{1/\eta_i}\left(I_t^{\mathrm{m}}\right)^{(\eta_i-1)/\eta_i}\right]^{\eta_i/(\eta_i-1)}, \tag{2.10}$$

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

In addition to accumulating physical capital and holding cash, households can save in domestic and foreign bonds. The choice between domestic and foreign bond holdings 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 Schmitt-Grohé and Uribe (2001):

$$\Phi(a_t,\tilde{\phi}_t)=\exp(-\tilde{\phi}_a(a_t-\overline{a})+\tilde{\phi}_t), \tag{2.11}$$

where $a_t\equiv(S_tB_t^*)/(P_tz_t)$ is the net foreign asset position, and $\tilde{\phi}_t$ is a shock to the risk premium. This implies that domestic households are charged a premium over the (exogenous) foreign interest rate R_t^* if the domestic economy as a whole is a net borrower ($B_t^*<0$), and receive a lower remuneration on their savings if the domestic economy is a net lender ($B_t^*>0$).

Further, along the lines of Erceg et al. (2000), each household is a monopoly supplier of a differentiated labor service which implies that it can set its own wage. Wage stickiness is introduced through the Calvo (1983) setup, with partial indexation to the CPI inflation rate in the previous period, the current inflation target and the current permanent technology growth rate. $1-\xi_w$ is the probability that household j is allowed to reoptimize its wage, $W_{j,t}$. For those households that are not allowed to reoptimize, the indexation scheme is $W_{j,t+1}=(\pi_t^c)^{\kappa_w}(\overline{\pi}_{t+1}^c)^{(1-\kappa_w)}\mu_{z,t+1}W_{j,t}$, where κ_w is the indexation parameter, and $\mu_{z,t}=z_t/z_{t-1}$ is the growth rate of the permanent technology level.

2.3. Central bank

Rather than assuming that monetary policy aims at optimizing a specific loss function, we approximate the behavior of the central bank with an instrument rule. Following Smets and Wouters (2003), the central bank is assumed to adjust the short-term interest rate in response to the CPI inflation rate, the time-varying inflation target, the output gap (measured as actual minus trend output[9]), the real exchange rate ($\hat{x}_t\equiv\hat{S}_t+\hat{P}_t^*-\hat{P}_t^c$), and the lagged interest rate. Although instrument rules are not based on optimizing behavior, they appear to perform well from an empirical viewpoint, and from a welfare perspective, it is not obvious that these rules perform

[9] An alternative specification is to define the output target in terms of the output level that would have prevailed in the absence of nominal rigidities as in Smets and Wouters (2003). This model consistent output gap would probably come closer to optimal monetary policy (see Woodford, 2003, for further discussion). However, Del Negro et al. (in press) 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.

substantially worse than optimal rules.[10] Thus, monetary policy is approximated with the following (log-linearized) instrument rule

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1-\rho_R)[\hat{\bar{\pi}}_t^c + r_\pi(\hat{\pi}_{t-1}^c - \hat{\bar{\pi}}_t^c) + r_y \hat{y}_{t-1} + r_x \hat{x}_{t-1}] + r_{\Delta\pi}\Delta\hat{\pi}_t^c + r_{\Delta y}\Delta\hat{y}_t + \varepsilon_{R,t}, \tag{2.12}$$

where $\varepsilon_{R,t}$ is an uncorrelated monetary policy shock.

2.4. Shock processes

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

$$\hat{\varsigma}_t = \rho_\varsigma \hat{\varsigma}_{t-1} + \varepsilon_{\varsigma,t}, \quad \varepsilon_{\varsigma,t} \overset{\text{iid}}{\sim} N(0, \sigma_\varsigma^2), \tag{2.13}$$

where $\varsigma_t = \{\mu_{z,t}, \epsilon_t, \lambda_t^j, \zeta_t^c, \zeta_t^h, \Upsilon_t, \tilde{\phi}_t, \varepsilon_{R,t}, \hat{\bar{\pi}}_t^c, \tilde{z}_t^*\}, \mu_{z,t} \equiv \frac{z_t}{z_{t-1}}$, and $j = \{d, mc, mi, x\}$.

2.5. Government

The government in this economy collects tax revenues resulting from taxes on capital income τ_t^{k}, labor income τ_t^{y}, consumption τ_t^{c}, and payroll τ_t^{w}, and spends resources on government consumption of the final domestic good, G_t. The resulting fiscal surplus/deficit plus the seigniorage are assumed to be transferred back to the households in a lump-sum fashion. Consequently, there is no government debt. The fiscal policy variables (τ_t^k, τ_t^y, τ_t^c, τ_t^w, and HP-detrended G_t) are assumed to follow an identified VAR model with two lags and an uninformative prior.

2.6. Foreign economy

Foreign prices, $\hat{\pi}_t^*$, output (HP-detrended), $\hat{y}_t^*$, and the interest rate $\hat{R}_t^*$ are exogenously given by an identified VAR model with four lags estimated with an informative prior.[11] Given our assumption of equal substitution elasticities in foreign consumption and investment (see footnote 8), these three variables suffice to describe the foreign economy in our model setup.

3. Data

To estimate the model, we use quarterly Euro area data for the period 1970:1–2002:4 and match the following fifteen variables: the GDP deflator, the real wage, consumption, investment, the real exchange rate, the short-run interest rate, employment, GDP, exports, imports, the consumption deflator, the investment deflator, foreign output, foreign inflation and the foreign interest

[10] Onatski and Williams (2004) find that instrument rules perform relatively well compared to optimal rules in the Smets and Wouters (2003) model, and that they are more robust to different parameter estimates.

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

rate.[12] For the Euro area, there is no (official) data on aggregate hours worked and we therefore use employment E_t in the estimations.[13]

To calculate the likelihood function of the observed variables, we apply the Kalman filter.[14] As in Altig et al. (2003), the non-stationary technology shock induces a common stochastic trend in the real variables of the model. To make these variables stationary, we use first differences[15] and derive the state space representation for the following vector of observed variables

$$\begin{aligned}\tilde{Y}_t = [\pi_t \quad \Delta \ln (W_t/P_t) \quad \Delta \ln C_t \quad \Delta \ln I_t \quad \hat{x}_t \quad R_t \quad \hat{E}_t \quad \Delta \ln Y_t \ \ldots \\ \Delta \ln \tilde{X}_t \quad \Delta \ln \tilde{M}_t \quad \pi_t^{\mathrm{def},c} \quad \pi_t^{\mathrm{def},i} \quad \Delta \ln Y_t^* \quad \pi_t^* \quad R_t^*]'.\end{aligned} \tag{3.1}$$

In comparison with the previous literature, we have chosen to work with a large number of variables, to be able to identify the estimated parameters in a satisfactory way. The foreign variables are included in the estimation because they enable identification of the asymmetric technology shock ($\tilde{z}_t^*$) and are informative about the parameters governing the propagation of foreign impulses to the domestic economy.[16]

---

[12] The data set we employ is the AWM data described in detail by Fagan et al. (2005). The AWM data set includes foreign output and prices, but not foreign interest rates. Therefore, we use the Fed funds rate as a proxy for R_t^*. The foreign output (prices) series is computed as a weighted average of the GDP (GDP deflator) series for the U.S., the United Kingdom, Japan and Switzerland with weights of 0.646, 0.230, 0.102 and 0.022, respectively. The exchange rate in the AWM is the ECB's official effective exchange rate for the 12 main trading partners of the Euro area with weights based on 1995–1997 manufactured goods trade (see Adolfson et al., 2006). Unfortunately, the export and import series in the AWM data set consist of intra- as well as extra-area trade. However, it was not possible to obtain sufficiently long series (1970Q1–2002Q4) only including trade with non-Euro area countries that were also consistent with the other variables in the data set.

[13] Since employment is likely to respond more slowly to shocks than hours worked, we model employment using Calvo-rigidity (following Smets and Wouters, 2003):

$$\Delta \hat{E}_t = \beta E_t \Delta \hat{E}_{t+1} + \frac{(1-\xi_e)(1-\beta\xi_e)}{\xi_e}(\hat{H}_t - \hat{E}_t),$$

where $1-\xi_e$ is the fraction of firms that can adjust the level of employment to the preferred amount of total labor input.

[14] We use the period 1970:1–1979:4 to compute a prior of the state for the unobserved variables, and then use the period 1980:1–2002:4 for inference.

[15] We have also experimented with an alternative strategy which exploits the fact that the real variables contain the same stochastic trend as output. In this case, the vector with observed variables is defined as

$$\begin{aligned}\tilde{Y}_t = [\pi_t \quad \ln (W_t/P_t) - \ln Y_t \quad \ln C_t - \ln Y_t \quad \ln I_t - \ln Y_t \quad \hat{x}_t \quad R_t \quad \hat{E}_t \quad \Delta \ln Y_t \ \ldots \\ \ln \tilde{X}_t - \ln Y_t \quad \ln \tilde{M}_t - \ln Y_t \quad \pi_t^{\mathrm{def},c} \quad \pi_t^{\mathrm{def},i} \quad \ln Y_t^* - \ln Y_t \quad \pi_t^* \quad R_t^*]'.\end{aligned}$$

As can be seen in Adolfson et al. (2005, in press), the estimation results for the model with this vector of observable variables are very similar to those reported here.

[16] In the state-space representation of the model, which links the theoretical model to the observed data, we add the unit-root world productivity shock and the stationary asymmetric (or foreign) technology shocks to the business cycle component of foreign output in order to obtain the observed level of foreign GDP. This enables us to identify the stationary asymmetric technology shock, since the process for detrended foreign output is identified from the VAR and the unit root world productivity process also from domestic quantities.

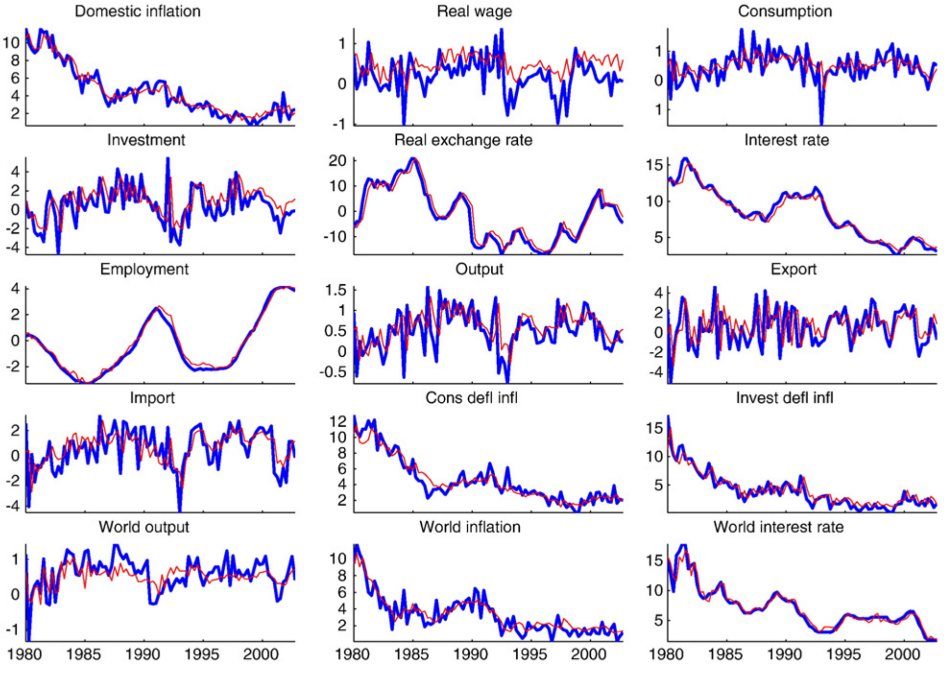

Fig. 1. Data (thick) and one-sided predicted values from the model (thin).

We use raw data without demeaning, with the following exceptions. First, we take out a linear trend from the employment series and second, since the import and export to output ratios are increasing during the sample period, we decided to remove the excessive trend of import and export, to make the export and import shares stationary (see Adolfson et al., 2005, for further details). For all other variables, we use the actual series (seasonally adjusted with the X12-method). Note that employment and the real exchange rate are measured as percentage deviations around the mean. In Fig. 1, the thick line depicts the data we match with the model.

It should be noted that the consumption and investment aggregates in the model are CES composites of domestic and imported goods. This is not the way these aggregates are measured in the data. This needs to be accounted for when constructing the measurement equation in the state-space representation of the model; see Adolfson et al. (2005) for details.

4. Estimation

Bayesian inference starts out from a prior distribution that describes the available information prior to observing the data used in the estimation. The observed data is subsequently used to update the prior, via Bayes' theorem, to the posterior distribution of the model's parameters which can be summarized in the usual measures of location (e.g. mode or mean) and spread (e.g. standard deviation and probability intervals).

4.1. Calibrated parameters

A number of parameters are kept fixed throughout the estimation procedure (i.e., having infinitely strict priors). We choose to calibrate the parameters we think are weakly identified by

Table 1

Parameter	Description	Value	Parameter	Description	Value
(a) Calibrated parameters					
β	Discount factor	0.999	ω_i	Imported investment share	0.55
α	Capital share in production	0.29	ω_c	Imported consumption share	0.31
η_c	Substitution elasticity (C_t^{d} and C_t^{m})	5.00	ν	Share of wage in advance	1.00
σ_a	Capital utilization cost parameter	10^6	τ_y	Labor income tax	0.177
μ	Money growth rate (quarterly)	1.01	τ_c	Value added tax	0.125
σ_L	Labor supply elasticity	1.00	$\rho_{\bar{\pi}}$	Inflation target persistence	0.975
δ	Depreciation rate	0.013	g_r	G/Y ratio	0.204
λ_w	Wage markup	1.05			
(b) Implied steady state relationships					
$\bar{\pi}$	Steady state inflation rate (percent)	2.02	$\tilde{X}/Y=\tilde{M}/Y$	Export/Import output ratio	0.25
R	Nominal interest rate (percent)	5.30	$S_t=S_{t+1}$	Nominal exchange rate	1.00
C/Y	Consumption–output ratio	0.58	A	Net foreign assets	0.00
I/Y	Investment–output ratio	0.22	X	Real exchange rate	1.00

Note: The steady state is affected by some parameters that are estimated, e.g. μ_z, λ_{d}, $\lambda_{\mathrm{m},c}$ and $\lambda_{\mathrm{m},i}$, which implies that the steady state values differ somewhat between the prior and the posterior. The table reports the implied values given by these parameters evaluated at the prior mode.

the variables included in $\tilde{Y}_t$. Most of these parameters can be related to the steady state values of the observed variables in the model, and are therefore calibrated so as to match their sample mean. Table 1 reports the calibrated parameters along with the implied steady state values of some key variables.[17]

Since we lack data on capital-income taxes as well as pay-roll taxes, we approximate these with AR(1) processes, and set the persistence parameters ρ_{τ^k} and ρ_{τ^w} to 0.9. The standard deviations for the shocks $\varepsilon_{\tau^k,t}$ and $\varepsilon_{\tau^w,t}$ are set to 1%. These values are in line with the estimates for the labor income tax and the consumption tax from the exogenous fiscal VAR model.[18]

4.2. Prior distributions of the estimated parameters

The remaining 51 parameters, which mostly pertain to the nominal and real frictions in the model as well as the exogenous shock processes, are estimated. Table 2 shows the assumptions for the prior distribution of the estimated parameters. The location of the prior distribution

[17] Throughout the analysis, we maintain the assumption that the persistence coefficient in the AR(1)-process for the inflation target, $\rho_{\bar{\pi}^c}$, equals 0.975. Smets and Wouters (2003, 2005) assume that $\rho_{\bar{\pi}^c}=1$. This difference has negligible effects in the empirical analysis that follows but, at a more fundamental level, it actually implies that we assume inflation to be stationary whereas Smets and Wouters assume inflation to be non-stationary. If anything, our specification seems to be preferable for the data (see Adolfson et al., 2005).

[18] It should be noted that the fiscal shocks turn out to have rather small dynamic effects in the model, since households are Ricardian and infinitively lived. Moreover, these shocks are transitory and do not generate any permanent wealth effects. Nevertheless, we keep the fiscal shocks in the analysis for two reasons. First, this gives us more shocks than variables, which is a necessary requirement to avoid stochastic singularity in the subsequent analysis where we investigate the consequences of removing various subsets of shocks. Second, the steady state values of the fiscal variables are of importance for the dynamic effects of the other shocks in the model.

Table 2
Prior and posterior distributions

Parameter		Prior distribution			With variable capital utilization		No variable capital utilization				
					σ_a=0.049		σ_a=10^6				
					Posterior distribution		Posterior distribution				
		Type	Mean*	S.D./*df*	Mode	S.D. (Hessian)	Mode	S.D. (Hessian)	Mean	5%	95%
Calvo wages	ξ_w	Beta	0.675	0.050	0.716	0.041	0.697	0.047	0.690	0.607	0.766
Calvo domestic prices	ξ_d	Beta	0.675	0.050	0.895	0.014	0.883	0.015	0.891	0.862	0.921
Calvo import consumption prices	$\xi_{m,c}$	Beta	0.500	0.100	0.523	0.047	0.463	0.059	0.444	0.345	0.540
Calvo import investment prices	$\xi_{m,i}$	Beta	0.500	0.100	0.743	0.036	0.740	0.040	0.721	0.641	0.792
Calvo export prices	ξ_x	Beta	0.500	0.100	0.630	0.056	0.639	0.059	0.612	0.506	0.717
Calvo employment	ξ_c	Beta	0.675	0.100	0.757	0.028	0.792	0.022	0.787	0.741	0.827
Indexation wages	κ_w	Beta	0.500	0.150	0.453	0.148	0.516	0.160	0.497	0.258	0.739
Indexation domestic prices	κ_{d}	Beta	0.500	0.150	0.173	0.059	0.212	0.066	0.217	0.095	0.362
Index import consumption prices	$\kappa_{m,c}$	Beta	0.500	0.150	0.128	0.054	0.161	0.074	0.220	0.084	0.418
Index import investment prices	$\kappa_{m,i}$	Beta	0.500	0.150	0.192	0.082	0.187	0.079	0.231	0.098	0.405
Indexation export prices	κ_x	Beta	0.500	0.150	0.148	0.070	0.139	0.072	0.185	0.069	0.347
Markup domestic	λ_{d}	Inverse gamma	1.200	2	1.174	0.059	1.168	0.053	1.222	1.122	1.383
Markup imported consumption	$\lambda_{m,c}$	Inverse gamma	1.200	2	1.636	0.071	1.619	0.063	1.633	1.526	1.751
Markup imported investment	$\lambda_{m,i}$	Inverse gamma	1.200	2	1.209	0.076	1.226	0.088	1.275	1.146	1.467
Investment adjustment cost	$\tilde{S}''$	Normal	7.694	1.500	9.052	1.359	8.732	1.370	8.670	6.368	10.958
Habit formation	b	Beta	0.650	0.100	0.694	0.043	0.690	0.048	0.708	0.608	0.842
Substitution elasticity investment	η_i	Inverse gamma	1.500	4	1.585	0.220	1.669	0.273	1.696	1.393	2.142
Substitution elasticity foreign	η_f	Inverse gamma	1.500	4	1.400	0.078	1.460	0.098	1.486	1.340	1.674
Technology growth	μ_z	Truncated normal	1.006	0.0005	1.005	0.000	1.005	0.000	1.005	1.004	1.006
Capital income tax	τ_k	Beta	0.120	0.050	0.220	0.040	0.137	0.042	0.135	0.072	0.200
Labour pay-roll tax	τ_w	Beta	0.200	0.050	0.183	0.049	0.186	0.050	0.197	0.118	0.286
Risk premium	$\tilde{\phi}$	Inverse gamma	0.010	2	0.131	0.044	0.145	0.047	0.252	0.139	0.407

Unit root technology shock	ρ_{μ_z}	Beta	0.850	0.100	0.753	0.107	0.723	0.106	0.698	0.526	0.852
Stationary technology shock	ρ_{ε}	Beta	0.850	0.100	0.935	0.021	0.909	0.030	0.886	0.810	0.939
Investment-specific technology shock	ρ_{Y}	Beta	0.850	0.100	0.738	0.041	0.750	0.041	0.720	0.638	0.796
Asymmetric technology shock	$\rho_{\tilde{z}*}$	Beta	0.850	0.100	0.992	0.003	0.993	0.002	0.992	0.986	0.995
Consumption preference shock	ρ_{ζ_c}	Beta	0.850	0.100	0.935	0.021	0.935	0.029	0.892	0.722	0.964
Labour supply shock	ρ_{ζ_h}	Beta	0.850	0.100	0.646	0.057	0.675	0.062	0.676	0.565	0.774
Risk premium shock	$\rho_{\tilde{\phi}}$	Beta	0.850	0.100	0.990	0.009	0.991	0.008	0.955	0.922	0.991
Imported consumption markup shock	$\rho_{\lambda_{m,c}}$	Beta	0.850	0.100	0.984	0.008	0.978	0.016	0.970	0.943	0.991
Imported investment markup shock	$\rho_{\lambda_{m,i}}$	Beta	0.850	0.100	0.971	0.011	0.974	0.015	0.963	0.931	0.989
Export markup shock	ρ_{λ_x}	Beta	0.850	0.100	0.895	0.042	0.894	0.045	0.886	0.789	0.961
Unit root technology shock	σ_{μ_z}	Inverse gamma	0.200	2	0.122	0.023	0.130	0.025	0.137	0.099	0.185
Stationary technology shock	σ_{ε}	Inverse gamma	0.700	2	0.414	0.065	0.452	0.082	0.519	0.361	0.756
Investment-specific technology shock	σ_{Y}	Inverse gamma	0.200	2	0.397	0.046	0.424	0.046	0.469	0.389	0.561
Asymmetric technology shock	$\sigma_{\tilde{z}*}$	Inverse gamma	0.400	2	0.200	0.030	0.203	0.031	0.217	0.166	0.276
Consumption preference shock	σ_{ζ_c}	Inverse gamma	0.200	2	0.132	0.025	0.151	0.031	0.157	0.108	0.224
Labour supply shock	σ_{ζ_h}	Inverse gamma	0.200	2	0.094	0.014	0.095	0.015	0.098	0.075	0.128
Risk premium shock	$\sigma_{\tilde{\phi}}$	Inverse gamma	0.050	2	0.123	0.023	0.130	0.023	0.183	0.128	0.246
Domestic markup shock	σ_{λ}	Inverse gamma	0.300	2	0.133	0.013	0.130	0.012	0.132	0.111	0.157
Imported consumption markup shock	$\sigma_{\lambda_{m,c}}$	Inverse gamma	0.300	2	1.912	0.492	2.548	0.710	2.882	1.737	4.463
Imported investment markup shock	$\sigma_{\lambda_{m,i}}$	Inverse gamma	0.300	2	0.281	0.068	0.292	0.079	0.354	0.218	0.550
Export markup shock	σ_{λ_x}	Inverse gamma	0.300	2	1.028	0.210	0.977	0.214	1.124	0.772	1.604
Monetary policy shock	σ_{R}	Inverse gamma	0.150	2	0.126	0.013	0.133	0.013	0.135	0.113	0.160
Inflation target shock	$\sigma_{\bar{\pi}^c}$	Inverse gamma	0.050	2	0.036	0.009	0.044	0.012	0.053	0.032	0.081
Interest rate smoothing	ρ_{R}	Beta	0.800	0.050	0.885	0.020	0.874	0.021	0.881	0.844	0.915
Inflation response	r_{π}	Normal	1.700	0.100	1.615	0.103	1.710	0.067	1.730	1.577	1.876
Difference inflation response	$r_{\Delta\pi}$	Normal	0.300	0.100	0.301	0.058	0.317	0.059	0.310	0.212	0.411
Real exchange rate response	r_{x}	Normal	0.000	0.050	−0.010	0.007	−0.009	0.008	−0.009	−0.024	0.006
Output response	r_{y}	Normal	0.125	0.050	0.123	0.032	0.078	0.028	0.104	0.051	0.168
Difference output response	$r_{\Delta y}$	Normal	0.0625	0.050	0.142	0.025	0.116	0.028	0.128	0.081	0.177
Log marginal likelihood					−1917.39				−1909.34		

*Note: for the inverse gamma distribution, the mode and the degrees of freedom are reported. Also, for the paramaters λ_d, η_i, η_f, $\lambda_{m,\,c}$, $\lambda_{m,\,i}$, μ_z the prior densities are translated so that the values below unity are excluded.

corresponds to a large extent to that in Smets and Wouters (2003) and the findings in Altig et al. (2003) on U.S. data. We use the beta distribution for all parameters bounded between 0 and 1. For parameters assumed to be positive, we use the inverse gamma distribution, and for the unbounded parameters, we use the normal distribution. The exact location and uncertainty of the prior can be seen in Table 2 but for a more comprehensive discussion of our choices regarding the prior distributions, we refer the reader to Adolfson et al. (2005).[19]

4.3. Posterior distributions of the estimated parameters

The joint posterior distribution of all estimated parameters is obtained in two steps. First, the posterior mode and an approximate covariance matrix, based on the inverse Hessian matrix evaluated at the mode, is obtained by numerical optimization on the log posterior density. Second, the posterior distribution is subsequently explored by generating draws using the Metropolis–Hastings algorithm. The proposal distribution is taken to be the multivariate normal density centered at the previous draw with a covariance matrix proportional to the inverse Hessian at the posterior mode; see Schorfheide (2000) and Smets and Wouters (2003) for further details. The results are reported in Table 2. It shows the posterior mode of all the parameters along with the approximate posterior standard deviation obtained from the inverse Hessian at the posterior mode. In addition, it shows the mean along with the 5th and 95th percentiles of the posterior distribution.[20]

Before turning to the results in Table 2, it should be noticed that we do not include the substitution elasticity between foreign and domestic consumption goods, η_c, (see Eq. (2.8)) in the final set of estimated parameters. When η_c is included, with the same prior as η_i and η_f, it is driven to a very high number (around 11). However, due to problems with convergence in the Metropolis–Hastings algorithm, we decided to calibrate η_c. In Table 3, we report the marginal densities for different calibrated values of η_c, using two different sets of observables to estimate the other parameters in the model. When excluding imports from the set of variables that we match, the preferred value of η_c is substantially lower (i.e., 0.5) compared to when imports are included. The reason why the model wants η_c to be high when matching imports is not surprising. According to the data, consumption goods constitute a fairly large part of imports. But aggregate consumption is a very smooth process, whereas the standard deviation of aggregate imports is considerably higher (about 3–4 times, see Fig. 1). By looking at the demand function for C_t^{m} (not shown), it is clear that one way for the model of accounting for this anomaly is by choosing η_c to be high so that C_t^{m} fluctuates a great deal whereas $C_t^{\mathrm{m}}+C_t^{\mathrm{d}}$ does not (recall that imports are measured as $C_t^{\mathrm{m}}+I_t^{\mathrm{m}}$). Thus, it is clear that η_c needs to be high in order to account for the joint

[19] We have checked the sensitivity of the results presented in Table 2 by doubling the prior standard deviation on the model's structural parameters and the persistence of the shocks. The results, which are provided in Adolfson et al. (2006), are essentially unchanged except for the domestic and imported investment sticky price parameters (ξ_d and $\xi_{m,i}$), which increase to considerably higher numbers, 0.96 and 0.98, respectively.

[20] A posterior sample of 500,000 post burn-in draws was generated. Convergence was checked using standard diagnostics such as CUSUM plots and the potential scale reduction factor on parallel simulation sequences. The results are given in Adolfson et al. (2006). In most cases, convergence was reached already after 200,000–300,000 draws, but in a few of the various model specifications, more draws were needed. The marginal likelihood was numerically computed from the posterior draws using the modified harmonic estimator in Geweke (1999).

Table 3
Marginal likelihoods for different values of η_c

Set of observables	$\eta_c=0.5$	$\eta_c=1.5$	$\eta_c=5$	$\eta_c=10$
Benchmark ($\tilde{Y}_t$)	−2215.94	−1950.81	−1909.34	−1909.24
Estimated without imports ($\tilde{M}$)	−1692.05	−1697.02	−1741.37	−1709.31

Note: All parameters are re-estimated for each set of variables and each calibrated value of η_c.

consumption and import dynamics in the data. When calibrating η_c, we decided to keep it fixed at the value of 5 throughout the analysis. This value was chosen because it produced a marginal likelihood about the same size as when keeping η_c fixed to 10, see Table 3. Furthermore, the estimated model implies that the import (export) to output ratio is around 12% in steady state. This number appears to be a reasonable estimate for the average inter-Euro import (export) to output ratio during the sample period (1980Q1–2002Q4), but it is about 4–5 percentage points lower than the current estimates of inter-Euro trade with the rest of the world (see e.g. Table 1.1 in *ECB Statistics pocket book*, January 2005).

Since we cannot include capacity utilization as an observable variable (it is not available for the Euro area), we decided to present estimation results in Table 2 for the model with and without variable capital utilization, and let the marginal likelihood indicate the most probable specification for the variables at hand.[21] From the results in Table 2, we see that the model without variable capital utilization is preferable under the assumed priors, and this specification is therefore used in the remaining part of the paper. However, this choice is not of any greater importance for the key results of the paper, since the parameter estimates are in general similar for the models with and without variable capital utilization.

An interesting result in Table 2 is that the degree of domestic price stickiness is high even though we allow for the working capital channel, and irrespective of variable capital utilization, in contrast to the findings by Christiano et al. (2005). In both specifications, we find the degree of sticky prices to be around 0.9—which is in line with the findings by Smets and Wouters (2003, 2005). Assuming that the households own the capital stock and rent it to the firms in each period, the implied average contract duration is about 8 quarters. However, under the interpretation that the domestic intermediate firms own the capital stock, we can apply the formulas derived in Altig et al. (2004), and instead compute the average contract duration to 4.5 quarters. This is a substantially lower number, and it is not in conflict with the microeconomic evidence for EU countries, see e.g. Mash (2004) and the references therein.

The estimated sticky price parameters for the other sectors ($\xi_{m,c}$, $\xi_{m,i}$ and ξ_x) are considerably lower than ξ_d, suggesting 2–3 quarters stickiness in these sectors. This implies that about 45% (25%) of an exchange rate movement is passed through to the price of import consumption (investment) goods, although the degree of pass-through differs depending on what type of shock that hits the economy. Given that only nominal rigidities determine the pass-through, it is relatively sensitive to the shape of the different impulse response functions. Moreover, as will be evident from the results in the next section, whether one allows for correlated markup shocks or not is important for the location of the posterior distribution of the ξ-parameters. A more robust finding is that the indexation parameters (i.e. the κ's) are quite low, suggesting that the estimated

[21] In the model with variable capital utilization, we fix the parameter controlling the cost of varying the utilization rate to the value estimated by Altig et al. (2003), i.e. $\sigma_a=0.049$. In the model without variable capital utilization, we use $\sigma_a=1,000,000$.

Phillips curves are mostly forward-looking, a finding consistent with the single-equation estimation results of Galí et al. (2001) on Euro area data.

The posterior mode of the persistence parameter in the unit-root technology process is estimated to be 0.72. This number compares quite well to the estimate in Altig et al. (2003). In addition, the persistence coefficient for the Kydland–Prescott type of stationary technology shock is estimated to be about 0.91. This is close to the standard value of 0.95 commonly used in the real business cycle literature. Smets and Wouters obtain a much higher number of about 0.997. We attribute our lower estimate to the inclusion of the unit-root technology shock, which accounts for a substantial amount of the lower frequency component in the aggregate quantities. In general, although some shocks are quite naturally found to be highly autocorrelated (i.e., the asymmetric technology and risk-premium shocks), the persistence coefficients for most of the shocks are substantially lower than what is found by Smets and Wouters (2003, 2005). In addition to the inclusion of the unit-root shock, part of the lower persistence is explained by the open economy aspects of the model, which is an additional source of internal propagation within the model.

4.4. Model fit

In Fig. 1, we report the data and the benchmark model's Kalman filtered one-sided estimates of the observed variables, computed at the posterior mode of the estimated parameters. The in-sample fit of the model appears to be satisfactory, with the exception of the real wage which is predicted to grow too fast in the model compared to the data. To further assess the conformity between the data and the model, we conduct a posterior predictive analysis in the spirit of Gelman et al. (2004) where the actual data are compared to artificial time series generated from the estimated benchmark DSGE model. More specifically, we compare vector autocovariance functions in the model and the data (see, e.g., Fuhrer and Moore, 1995).[22]

The vector autocovariance functions are computed by estimating an unrestricted 3-lag VAR model with an uninformative prior on i) Euro area data for the period 1970Q2–2002Q4 and ii) sampled data from the DSGE model.[23] We include the following 13 variables in the VAR: π_t, $\Delta\ln(W_t/P_t)$, $\Delta\ln C_t$, $\Delta\ln I_t$, $\hat{x}_t$, R_t, $\hat{E}_t$, $\Delta\ln Y_t$, $\Delta\ln\tilde{X}_t$, $\Delta\ln\tilde{M}_t$, $\Delta\ln Y_t^*$, π_t^* and R_t^*. In Fig. 2, we report the median vector autocovariance function in percentage terms in the DSGE model (thin line) along with the 2.5 and 97.5 percentiles (dotted lines) for a subset of the variables included in the VAR. The thick line refers to the actual data, and the variables are measured as in Eq. (3.1).

The posterior predictive intervals for the vector autocovariance functions turn out to be relatively wide in the model, but it can nevertheless be of interest to use them to assess the model fitness. From the figure, we see that the realized volatility and autocorrelation in most variables

[22] Fuhrer and Moore (1995) compare vector autocorrelation functions, whereas we report autocovariance functions in order to also examine the ability to explain the absolute variances. We believe that autocovariance functions are more informative than standard deviations and autocorrelations since the former provide a more extensive summary of the second moment information in compact form. However, in Adolfson et al. (2005) we also report univariate moments, which give a very similar overall picture.

[23] To compute the vector autocovariance functions in the DSGE model, we draw n parameter combinations from the posterior distribution and for each parameter draw, we simulate an artificial data set of the same length as the actual data series. Then, we use the n data sets to estimate vector autocovariance functions (see Hamilton, 1994), using exactly the same VAR specification as was applied on the actual data.

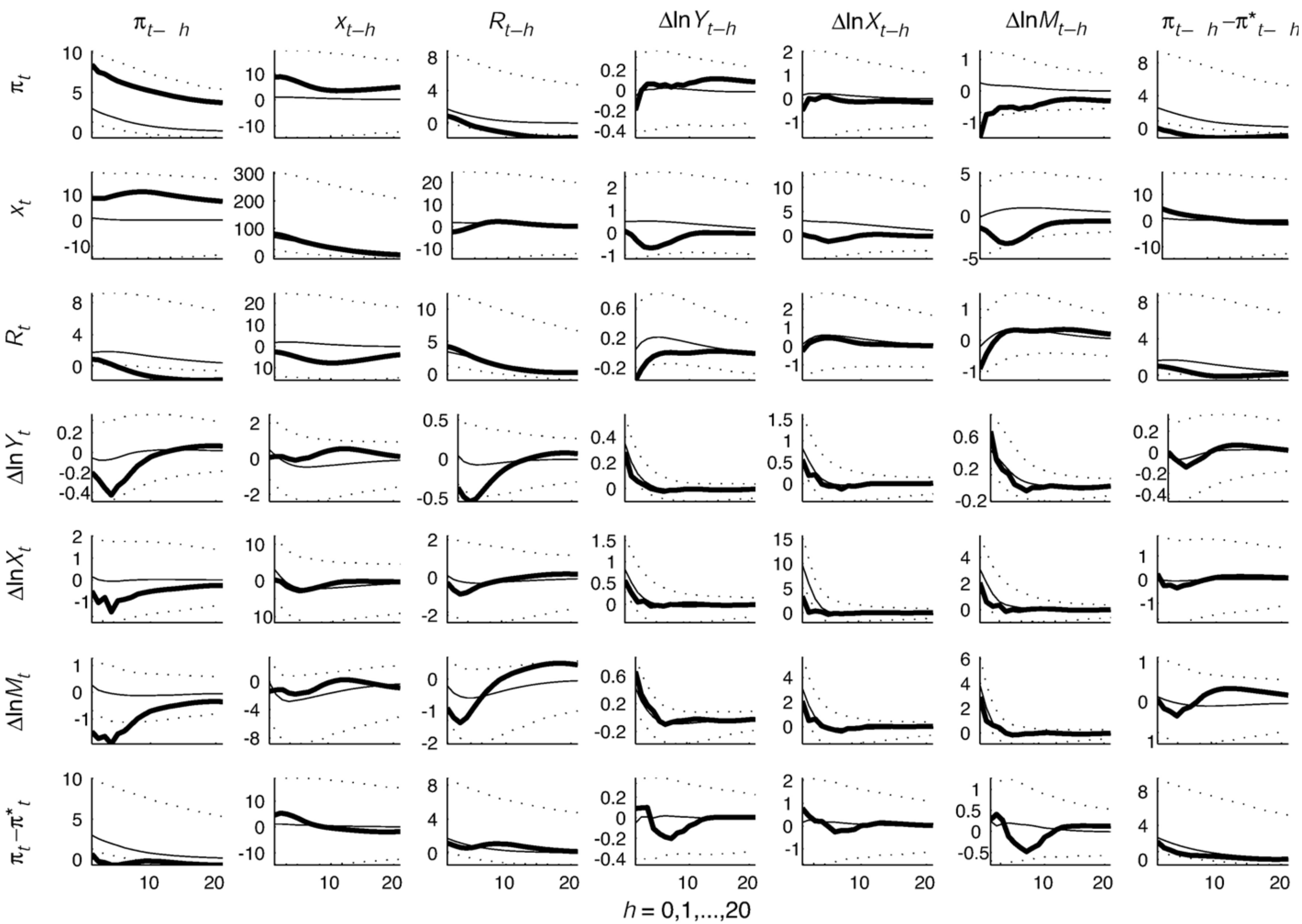

Fig. 2. Autocovariance functions in the data (thick) and the DSGE model (posterior predictive median; thin, and 95% posterior probability intervals; dotted).

are very well captured by the model. The DSGE model's probability intervals cover the variance in the data for all variables except exports, which turn out to be too high and persistent in the model relative to the data.[24] In particular, the model is able to replicate the inflation and real exchange rate dynamics, although we are using unfiltered data. The variance of domestic inflation in the data is higher than the posterior predictive median from the model. The reason is that the model typically cannot generate as persistent sequences of inflation as in the data during the sample (see Fig. 1).[25] However, the model's posterior predictive intervals for the autocovariance of inflation do encapsulate the actual values in the data, since the posterior predictive distribution for the autocovariance function of inflation is skewed upwards. Moreover, the posterior predictive median volatility of the inflation differential between the domestic and foreign economy is very close to the data estimate, which is the inflation variable studied by Bouakez (2005), for example. Bouakez finds that his model with time-varying markups can replicate the properties of the real exchange rate, but not jointly with the inflation differential. Besides, it should be noted that Bouakez reduces the volatility and persistence in the real exchange rate by using HP-filtered data, which makes his empirical exercise substantially less challenging. In contrast, our model is able to match the variance and persistence in both the real exchange rate and the inflation differential without detrending the data.[26] Further, looking at the off-diagonals, we see from Fig. 2 that the model has a hard time replicating the joint behavior of domestic inflation and imports. Higher domestic inflation (π_{t-h}) is a signal of higher future imports ($\Delta \ln \tilde{M}_t$) in the model, since this will make it more profitable to consume and invest in imported goods, but this covariance is (surprisingly) strongly negative in the data.

Although there seems to be room for improvements in some respects, we think our model does a good job in replicating conventional statistics for measuring the fit of a model.

5. The role of frictions and shocks

After validating a good fit of the open economy DSGE model, we can proceed with establishing the importance of the various frictions and shocks included in the model. Table 4 shows the posterior mode estimates of the parameters and the marginal likelihood when some of the nominal and real frictions in the model are essentially turned off. The columns report the estimated parameters when there is; i) low wage stickiness, ii) low domestic price stickiness, iii) low habit formation, iv) low investment adjustment cost, v) low import price stickiness, vi) low export price stickiness, vii) no working capital, viii) persistent domestic markup shocks, and ix)

[24] From Fig. 1, it is apparent that the model's one-sided Kalman filtered estimates of the observed variables follow the actual values rather well, so the reason why exports are overly volatile in the model relative to the data is that the estimated shock processes come out slightly correlated in the Kalman filter. Presumably, this could have improved if we had been able to include some price variable related to exports in the estimation of the model.

[25] We note that Smets and Wouters (2003) report similar results in a closed economy model with a non-stationary inflation target.

[26] Bouakez underpredicts inflation volatility since the firm's markup in his model is dependent on its relative price, which is the reason why the large markup variations required to capture the exchange rate cause too much endogenous rigidity. In our model, the time-varying markups (i.e., import consumption and investment shocks) that are needed to capture the fluctuations in the real exchange rate turns out to be less important for explaining the behavior of the inflation rate (see Section 6.2), which is the reason why the connection between the exchange rate and inflation is weaker and that we obtain a more plausible estimated degree of price rigidity.

uncorrelated (i.i.d.) markup shocks in all sectors. For ease of comparison, the benchmark estimates are also reproduced.

The results in Table 4 show that all the nominal and real frictions play an important role in the model. In particular, price stickiness in the domestic and import sectors, and investment adjustment costs are important. Since most of the parameters governing the role of nominal and real frictions are far from zero, these findings are not surprising. It is, however, somewhat surprising that although the price stickiness parameters related to the import goods are not particularly high, they still appear to be of crucial importance for the model's empirical performance. This is especially the case when all markup shocks are assumed to be white noise. Table 4 also indicates that a version of the model without the working capital channel is preferable; the Bayes factor is 65 in favor of the model without working capital.

In Table 5, we examine the role of various shocks in the model. We practically shut down sets of shocks, and study the impact on the estimated parameters and the marginal likelihood. What we learn from this exercise is that when considering the relatively large set of observables we match, all shocks appear to be of importance, but in particular the most important are the technology shocks as well as the markup shocks in the Phillips curves for import and export goods. From Table 5, we also see that the fiscal policy shocks are not critical for the empirical performance of the model, suggesting that more work is needed to incorporate fiscal policy in a more realistic way than what was done in this paper.

6. Impulse response functions and historical decompositions

6.1. Impulse response functions to a monetary policy shock

Fig. 3 reports the impulse response functions (median and 5th, 95th percentiles) to a monetary policy shock (one-standard deviation increase in $\varepsilon_{R,t}$). To understand how the nominal frictions shape the impulse response functions, we also include the responses when all nominal frictions are removed from the model, so that prices and wages are flexible (i.e., $\xi_d=\xi_{m,c}=\xi_{m,i}=\xi_x=\xi_w=0.01$). The responses for the benchmark model (solid lines) are graded on the left y-axis, and the flexible price-wage version of the model (dashed line) on the right y-axis. Notice that the inflation and nominal interest rates are reported as annualized quarterly rates, while the quantities are reported as log-level deviations from steady state (i.e., percentage deviations).

In the figure, we see that following an unanticipated temporary increase in the nominal interest rate, the responses are hump-shaped with the exception of the real exchange rate which jumps down (i.e., appreciates) and then returns to zero from below. The effect on aggregate quantities – output, investment, consumption, export and import – peaks after about one to two years, whereas the effect on inflation reaches its maximum after one year. The responses of the real variables are well in line with the literature that have used identified VARs to study the effects of monetary policy shocks, but inflation in the model is somewhat less inertial than the typical VAR estimates.[27] The single most important reason why the effect on inflation occurs somewhat faster in the model is that the capital utilization cost is set to a very high number (σ_a=1,000,000).

We use Bayesian methods and fit the model to all the variation in the data, not just the dynamic effects of a policy shock like Christiano et al. (2005). Still, we find the empirical relevance of the nominal and real frictions to be such that the impulse response functions to a policy shock are very

[27] See, for example, Angeloni et al. (2003) for Euro area evidence, and Christiano et al. (2005) and Altig et al. (2003, 2004) for US evidence.

Table 4
Sensitivity analysis with respect to frictions, posterior mode estimates

Parameter		Benchmark	Low wage stickiness	Low price stickiness	Low habit persistence	Low invest. adjustment cost	Low import price stickiness	Low export price stickiness	No working capital channel	Persistent domestic markup shock	IID markup shocks
			$\xi_w=0.1$	$\xi_d=0.1$	$b=0.1$	$\tilde{S}''=0.1$	$\xi_{m,c}=\xi_{m,i}=0.2$	$\xi_x=0.1$	$\nu=0.01$	$\rho_{\lambda_d}>0$	$\rho_{\lambda_d}=\rho_{\lambda_{mc}}=\rho_{\lambda_{mi}}=\rho_{\lambda_x}=0$
Calvo wages	ξ_w	0.697		0.669	0.687	0.733	0.706	0.710	0.702	0.626	0.687
Calvo domestic prices	ξ_d	0.883	0.866		0.878	0.898	0.885	0.899	0.863	0.661	0.882
Calvo import consumption prices	$\xi_{m,c}$	0.463	0.463	0.464	0.405	0.468		0.466	0.454	0.523	0.899 [a]
Calvo import invment prices	$\xi_{m,i}$	0.740	0.706	0.733	0.696	0.458		0.762	0.742	0.714	0.912 [a]
Calvo export prices	ξ_x	0.639	0.657	0.637	0.668	0.646	0.711		0.640	0.669	0.853 [a]
Calvo employment	ξ_e	0.792	0.774	0.782	0.763	0.765	0.787	0.776	0.786	0.795	0.784
Indexation wages	κ_w	0.516	0.409	0.696	0.442	0.489	0.424	0.466	0.523	0.291	0.480
Indexation domestic prices	κ_d	0.212	0.197	0.617	0.195	0.192	0.223	0.196	0.228	0.171	0.188
Index import consumption prices	$\kappa_{m,c}$	0.161	0.161	0.141	0.173	0.152	0.834	0.144	0.165	0.148	0.256
Index import invment prices	$\kappa_{m,i}$	0.187	0.190	0.203	0.181	0.130	0.594	0.170	0.184	0.200	0.830
Indexation export prices	κ_x	0.139	0.134	0.140	0.128	0.142	0.126	0.724	0.137	0.125	0.262
Markup domestic	λ_d	1.168	1.149	1.123	1.162	1.203	1.151	1.164	1.164	1.155	1.160
Markup imported consumption	$\lambda_{m,c}$	1.619	1.677	1.652	1.721	1.545	1.203	1.636	1.629	1.642	1.515
Markup imported investment	$\lambda_{m,i}$	1.226	1.280	1.268	1.250	1.218	1.850	1.178	1.227	1.255	1.160
Investment adjustment cost	$\tilde{S}''$	8.732	8.920	8.691	9.091		6.737	8.249	8.784	7.143	9.499
Habit formation	b	0.690	0.669	0.611		0.660	0.916	0.752	0.688	0.614	0.647
Substitution elasticity investment	η_i	1.669	1.678	1.601	1.751	2.823	3.394	1.494	1.660	1.616	1.405
Substitution elasticity foreign	η_f	1.460	1.470	1.481	1.462	1.460	1.443	1.375	1.460	1.577	1.356
Technology growth	μ_z	1.005	1.005	1.005	1.005	1.005	1.006	1.005	1.005	1.006	1.005
Capital income tax	τ_k	0.137	0.182	0.165	0.228	0.132	0.213	0.143	0.150	0.265	0.172
Labour pay-roll tax	τ_w	0.186	0.184	0.186	0.186	0.185	0.185	0.186	0.186	0.185	0.186
Risk premium	$\tilde{\phi}$	0.145	0.146	0.086	0.176	0.485	0.300	0.140	0.147	0.095	0.035
Unit root technology shock	ρ_{μ_z}	0.723	0.610	0.611	0.609	0.748	0.809	0.636	0.716	0.792	0.741
Stationary technology shock	ρ_ε	0.909	0.995	0.999	0.917	0.921	0.848	0.991	0.913	0.997	0.904
Investment-specific technology shock	ρ_Υ	0.750	0.749	0.769	0.694	0.922	0.469	0.741	0.748	0.562	0.785

Asymmetric technology shock	$\rho_{\tilde{z}^*}$	0.993	0.993	0.994	0.994	0.995	0.907	0.994	0.993	0.953	0.990
Consumption preference shock	ρ_{ζ_c}	0.935	0.894	0.987	0.959	0.944	0.496	0.791	0.938	0.992	0.911
Labour supply shock	ρ_{ζ_h}	0.675	0.933	0.471	0.637	0.686	0.689	0.718	0.657	0.536	0.656
Risk premium shock	$\rho_{\tilde{\phi}}$	0.991	0.991	0.987	0.993	0.957	0.955	0.992	0.991	0.991	0.920
Domestic markup shock	ρ_{λ_d}									0.995	
Imported consumption markup shock	$\rho_{\lambda_{m,c}}$	0.978	0.979	0.986	0.989	0.959	0.978	0.938	0.982	0.975	
Imported investment markup shock	$\rho_{\lambda_{m,i}}$	0.974	0.976	0.969	0.969	0.980	0.989	0.982	0.973	0.990	
Export markup shock	ρ_{λ_x}	0.894	0.877	0.923	0.881	0.857	0.864	0.986	0.894	0.928	
Unit root technology shock	σ_{μ_z}	0.130	0.120	0.127	0.118	0.134	0.128	0.119	0.130	0.132	0.128
Stationary technology shock	σ_{ε}	0.452	0.371	0.292	0.429	0.423	0.478	0.337	0.431	0.422	0.450
Investment-specific technology shock	σ_{Y}	0.424	0.425	0.385	0.442	5.796	0.666	0.436	0.424	0.444	0.376
Asymmetric technology shock	$\sigma_{\tilde{z}^*}$	0.203	0.211	0.217	0.218	0.201	0.185	0.212	0.204	0.186	0.204
Consumption preference shock	σ_{ζ_c}	0.151	0.150	0.207	0.730	0.150	0.121	0.137	0.151	0.155	0.163
Labour supply shock	σ_{ζ_h}	0.095	0.195	0.097	0.095	0.091	0.095	0.089	0.096	0.098	0.096
Risk premium shock	$\sigma_{\tilde{\phi}}$	0.130	0.129	0.121	0.137	0.229	0.171	0.122	0.128	0.122	0.344
Domestic markup shock	σ_{λ}	0.130	0.134	0.261	0.132	0.136	0.130	0.130	0.129	0.125	0.129
Imported consumption markup shock	$\sigma_{\lambda_{m,c}}$	2.548	2.622	2.548	3.505	2.468	4.798	2.654	2.657	1.810	1.147
Imported investment markup shock	$\sigma_{\lambda_{m,i}}$	0.292	0.368	0.316	0.391	1.640	13.247	0.243	0.289	0.341	0.414
Export markup shock	σ_{λ_x}	0.977	0.922	0.938	0.885	0.988	0.783	13.836	0.973	0.789	1.272
Monetary policy shock	σ_R	0.133	0.134	0.144	0.142	0.150	0.115	0.126	0.133	0.144	0.130
Inflation target shock	$\sigma_{\bar{\pi}^c}$	0.044	0.048	0.041	0.037	0.036	0.039	0.047	0.043	0.041	0.049
Interest rate smoothing	ρ_R	0.874	0.834	0.805	0.813	0.865	0.877	0.889	0.869	0.824	0.851
Inflation response	r_π	1.710	1.704	1.746	1.657	1.753	1.703	1.722	1.700	1.660	1.697
Difference inflation response	$r_{\Delta\pi}$	0.317	0.368	0.365	0.403	0.349	0.345	0.282	0.327	0.384	0.304
Real exchange rate response	r_x	−0.009	−0.007	−0.007	−0.003	−0.018	−0.008	−0.008	−0.008	−0.008	0.003
Output response	r_y	0.078	0.058	−0.001	0.042	0.064	0.043	0.109	0.080	−0.030	0.056
Difference output response	$r_{\Delta y}$	0.116	0.087	0.088	0.145	0.244	0.123	0.142	0.115	0.130	0.104
Log marginal likelihood		−1909.34	−1918.38	−1967.99	−1936.70	−1994.00	−1986.50	−1937.89	−1905.16	−1915.53	−1975.5

[a] The same prior is used as for the domestic price stickiness parameter.

Table 5
Sensitivity with respect to shocks, posterior mode estimates

Parameter		Bench mark	No time-varying inflation target	No technology shocks	No preference shocks	No domestic markup shock	Smaller import/export markup shocks	No risk premium or asymmetric technology shocks	No fiscal shocks
			$\sigma_{\bar{\pi}^c}=0.0001$	$\sigma_z=\sigma_\varepsilon=\sigma_Y=0$	$\sigma_{\zeta_c}=\sigma_{\zeta_h}=0.01$	$\sigma_\lambda=0$	$\sigma_{\lambda_{m,c}}=\sigma_{\lambda_{m,i}}=\sigma_{\lambda_x}=0.3$	$\sigma_{\tilde{\phi}}=\sigma_{\tilde{z}^*}=0$	
Calvo wages	ξ_w	0.697	0.711	0.684	0.810	0.698	0.709	0.695	0.708
Calvo domestic prices	ξ_d	0.883	0.882	0.926	0.930	0.843	0.893	0.867	0.887
Calvo import consumption prices	$\xi_{m,c}$	0.463	0.495	0.566	0.489	0.485	0.944	0.498	0.495
Calvo import investment prices	$\xi_{m,i}$	0.740	0.721	0.682	0.604	0.742	0.980	0.755	0.735
Calvo export prices	ξ_x	0.639	0.638	0.690	0.675	0.643	0.942	0.607	0.619
Calvo employment	ξ_e	0.792	0.786	0.793	0.806	0.800	0.782	0.795	0.801
Indexation wages	κ_w	0.516	0.482	0.587	0.153	0.741	0.461	0.639	0.494
Indexation domestic prices	κ_{d}	0.212	0.246	0.956	0.952	0.092	0.167	0.329	0.207
Index import consumption prices	$\kappa_{m,c}$	0.161	0.148	0.171	0.180	0.160	0.535	0.144	0.153
Index import investment prices	$\kappa_{m,i}$	0.187	0.202	0.274	0.262	0.200	0.711	0.182	0.192
Indexation export prices	κ_x	0.139	0.143	0.128	0.124	0.136	0.421	0.144	0.145
Markup domestic	λ_{d}	1.168	1.182	1.122	1.141	1.172	1.165	1.151	1.181
Markup imported consumption	$\lambda_{m,c}$	1.619	1.604	1.628	1.806	1.633	1.228	1.655	1.557
Markup imported investment	$\lambda_{m,i}$	1.226	1.240	1.198	1.646	1.237	1.309	1.195	1.272
Investment adjustment cost	$\tilde{S}''$	8.732	8.763	1.985	7.850	9.346	9.197	9.014	8.679
Habit formation	b	0.690	0.680	0.674	0.673	0.717	0.619	0.747	0.731
Substitution elasticity investment	η_i	1.669	1.708	2.525	1.610	1.665	1.380	1.622	1.587
Substitution elasticity foreign	η_f	1.460	1.459	1.415	1.557	1.448	4.593	1.505	1.440

Technology growth	μ_z	1.005	1.005	1.005	1.005	1.005	1.005	1.006	1.006
Capital income tax	τ_k	0.137	0.120	0.253	0.248	0.158	0.259	0.196	
Labour pay-roll tax	τ_w	0.186	0.185	0.186	0.186	0.186	0.188	0.187	
Risk premium	$\tilde{\phi}$	0.145	0.137	0.046	0.331	0.161	0.027	0.216	0.112
Unit root technology shock	ρ_{μ_z}	0.723	0.793		0.829	0.680	0.729	0.830	0.829
Stationary technology shock	ρ_{ε}	0.909	0.906		0.984	0.918	0.898	0.872	0.904
Investment specific technology shock	ρ_{Υ}	0.750	0.748		0.695	0.751	0.652	0.729	0.763
Asymmetric technology shock	$\rho_{\tilde{z}*}$	0.993	0.994	0.994	0.930	0.993	0.995		0.993
Consumption preference shock	ρ_{ζ_c}	0.935	0.937	0.989		0.972	0.944	0.979	0.924
Labour supply shock	ρ_{ζ_h}	0.675	0.696	0.624		0.632	0.607	0.708	0.697
Risk premium shock	$\rho_{\tilde{\phi}}$	0.991	0.991	0.927	0.941	0.991	0.927		0.991
Imported consumption markup shock	$\rho_{\lambda_{m,c}}$	0.978	0.965	0.984	0.968	0.977		0.967	0.962
Imported investment markup shock	$\rho_{\lambda_{m,i}}$	0.974	0.983	0.974	0.985	0.966		0.991	0.981
Export markup shock	ρ_{λ_x}	0.894	0.894	0.833	0.881	0.893		0.920	0.905
Unit root technology shock	σ_{μ_z}	0.130	0.137		0.155	0.131	0.133	0.155	0.137
Stationary technology shock	σ_{ε}	0.452	0.449		0.464	0.544	0.466	0.482	0.467
Investment specific technology shock	σ_{Υ}	0.424	0.419		0.425	0.420	0.465	0.476	0.426
Asymmetric technology shock	$\sigma_{\tilde{z}*}$	0.203	0.197	0.249	0.185	0.209	0.203		0.195
Consumption preference shock	σ_{ζ_c}	0.151	0.149	0.223		0.155	0.170	0.158	0.136
Labour supply shock	σ_{ζ_h}	0.095	0.092	0.095		0.104	0.096	0.092	0.092
Risk premium shock	$\sigma_{\tilde{\phi}}$	0.130	0.133	0.156	0.213	0.131	0.346		0.129
Domestic markup shock	σ_{λ}	0.130	0.132	0.158	0.135		0.128	0.127	0.130
Imported consumption markup shock	$\sigma_{\lambda_{m,c}}$	2.548	2.200	1.542	2.384	2.317		2.300	2.204

(continued on next page)

Table 5 (*continued*)

Parameter		Bench mark	No time-varying inflation target	No technology shocks	No preference shocks	No domestic markup shock	Smaller import/export markup shocks	No risk premium or asymmetric technology shocks	No fiscal shocks
			$\sigma_{\bar{\pi}^c}=0.0001$	$\sigma_z=\sigma_\varepsilon=\sigma_Y=0$	$\sigma_{\zeta_c}=\sigma_{\zeta_h}=0.01$	$\sigma_\lambda=0$	$\sigma_{\lambda_{m,c}}=\sigma_{\lambda_{m,i}}=\sigma_{\lambda_x}=0.3$	$\sigma_{\tilde{\phi}}=\sigma_{\tilde{z}^*}=0$	
Imported investment markup shock	$\sigma_{\lambda_{m,i}}$	0.292	0.327	0.412	0.721	0.296		0.253	0.303
Export markup shock	σ_{λ_x}	0.977	0.979	0.849	0.807	0.965		1.066	1.055
Monetary policy shock	σ_R	0.133	0.136	0.135	0.130	0.134	0.120	0.129	0.137
Inflation target shock	$\sigma_{\bar{\pi}^c}$	0.044		0.207	0.150	0.043	0.047	0.070	0.042
Interest rate smoothing	ρ_R	0.874	0.867	0.890	0.871	0.863	0.860	0.884	0.883
Inflation response	r_π	1.710	1.745	1.725	1.592	1.671	1.664	1.619	1.712
Difference inflation response	$r_{\Delta\pi}$	0.317	0.327	0.258	0.310	0.360	0.347	0.275	0.294
Real exchange rate response	r_x	−0.009	−0.015	0.013	−0.004	−0.008	0.010	−0.018	−0.018
Output response	r_y	0.078	0.048	0.131	0.145	0.082	0.068	0.088	0.081
Difference output response	$r_{\Delta y}$	0.116	0.143	0.168	0.143	0.075	0.134	0.132	0.127
Log marginal likelihood		−1909.34	−1908.58	−1992.90	−1949.38	−1910.94	−2038.19	−1931.29	−1914.81

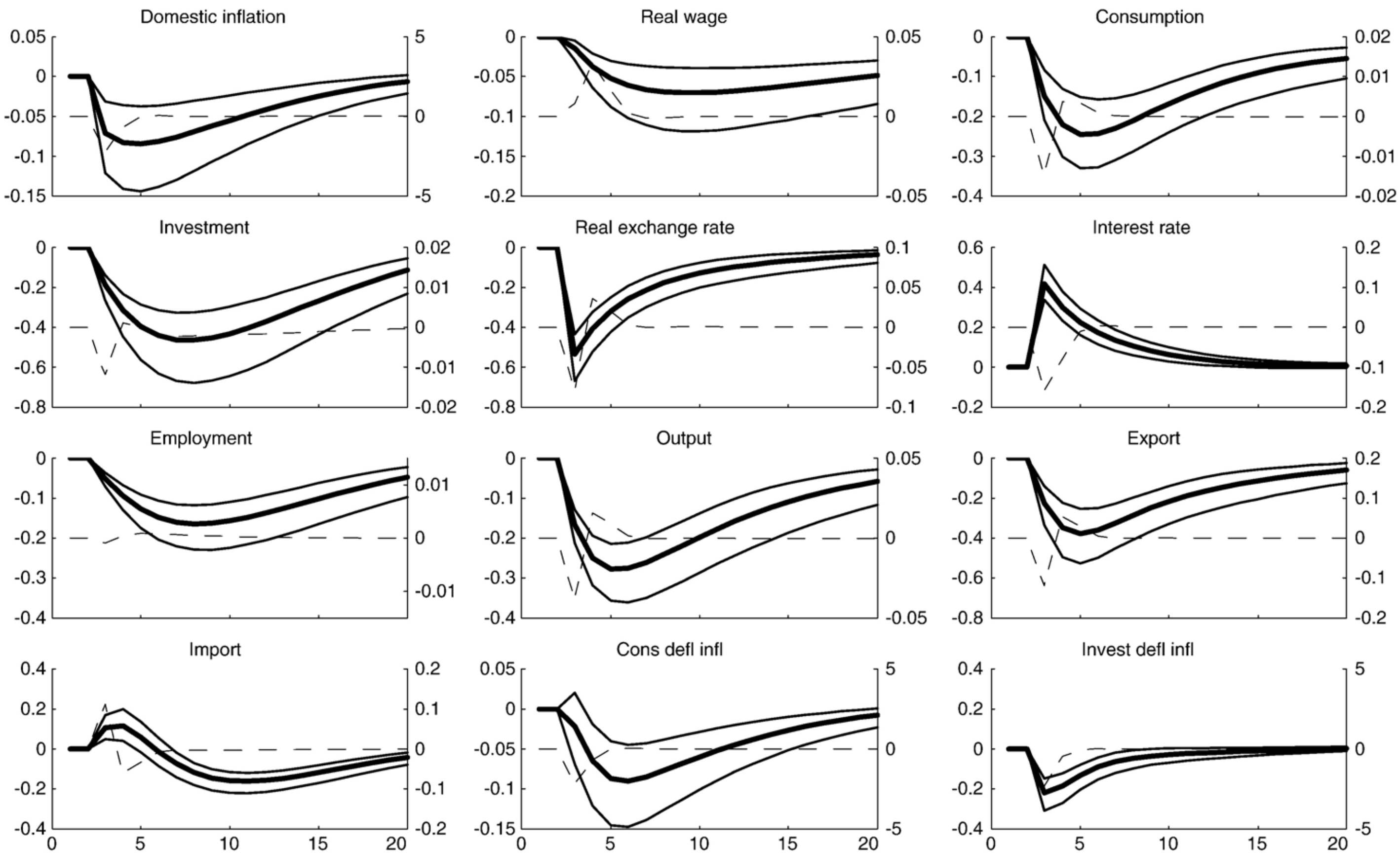

Fig. 3. Impulse responses (posterior median and 95% uncertainty intervals) to a one standard deviation monetary policy shock. Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

similar to those generated in identified VARs. In our view, this gives credibility to the analysis and further support to the view that the "conventional wisdom" about the effects of monetary policy applies also in the open economy framework. There is one exception, however, and that is the real exchange rate. Although the nominal frictions in the model provide some persistence in the real exchange rate following a policy shock, it is evident that the model does not provide us with a hump-shaped response of the real exchange rate which is a pervasive feature of estimated VARs, see, e.g., Eichenbaum and Evans (1995), Faust and Rogers (2003), and Lindé et al. (2003). However, it should be kept in mind that the identification of the effects of policy shocks in VARs typically rests on a recursive ordering of the variables, a requirement that is not fulfilled by the DSGE model used here. With flexible prices and wages, monetary policy has very small effects on aggregate quantities, and a strong immediate effect on inflation.

6.2. Historical decompositions

In Fig. 4, we plot the historical decompositions (generated at the posterior mode) for four subsets of shocks along with the actual time series. Notice that the figure depicts the actual data, and not the steady state deviations, and that output is graphed in yearly growth rates. From the figure, we can learn the role of various shocks during the sample period. In general, we see that the "domestic" shocks (i.e., the unit-root, stationary and investment specific technology shocks, the consumption preference shock, the labor supply shock, the domestic markup shock, the monetary policy shock and the inflation target shock) – and in particular the technology shocks – account for most of the variation in the domestic variables (inflation, interest rate and output), and

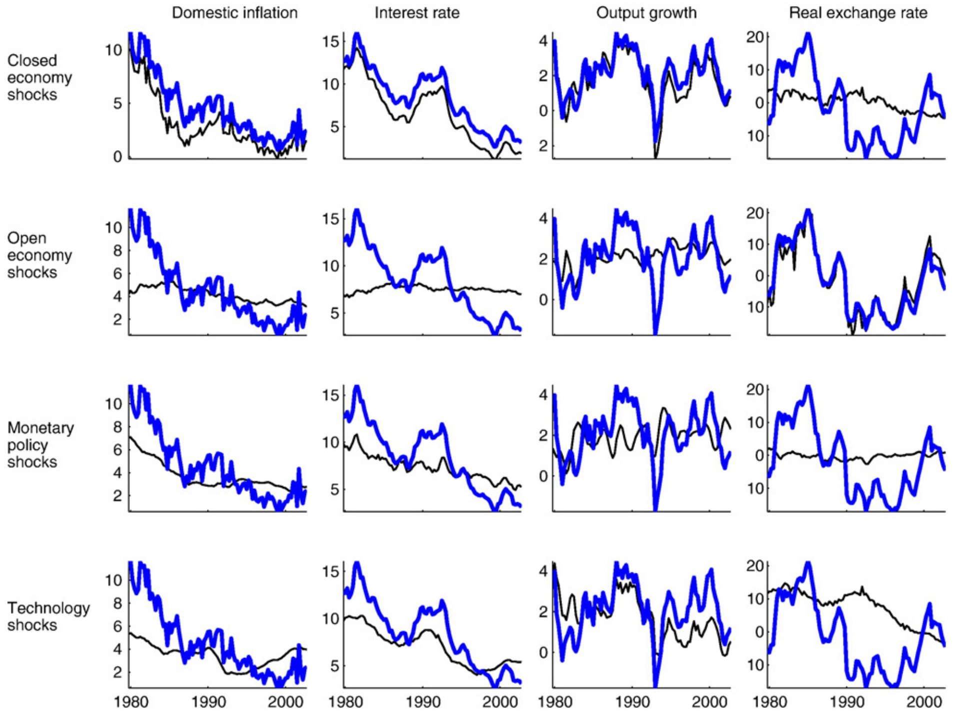

Fig. 4. Historical decompositions, data (thick) and model (thin).

Table 6
Unconditional second moments for the real exchange rate

	Data	Model — benchmark	Model — i.i.d. markup shocks
Standard deviation	10.53	7.85 (4.52–14.43)	5.99 (4.03–8.90)
Autocorrelation	0.96	0.93 (0.81–0.98)	0.86 (0.70–0.94)

Note: The table reports the median and the 95th percent uncertainty intervals (in parenthesis) of the simulated distribution of second moments computed by simulating the two different model specifications 10,000 times at the posterior mode with 92 periods every time.

that "open economy" shocks (i.e., the import and export markup shocks, the risk premium shock, the asymmetric technology shock and the foreign VAR innovations) account for most of the variation in the real exchange rate. These results support the notion that the real exchange rate is disconnected from the rest of the economy in the sense that the shocks that account for most of the variation in the real exchange rate explain proportionally less of the fluctuations in output. However, as the "open economy" shocks account for about a third of the fluctuations in output at the five-year horizon (variance decompositions not shown), there is a certain amount of internal propagation within the model due to its open economy aspects. Out of the "open economy" shocks, the variance decompositions also demonstrate that the two import markup shocks are more important than the risk premium shock for understanding the real exchange rate volatility, both in the short and the long run.

To assess the role of the correlated markup shocks, we show in Table 6 the unconditional second moments for the real exchange rate in the data and in the model with autocorrelated and i.i.d. markup shocks, respectively. The table demonstrates that persistent markup shocks are needed to explain both the volatility and the autocorrelation of the exchange rate. To elaborate on this, Fig. 5 shows the impulse response functions of some key variables after an autocorrelated as well as an i.i.d. shock to the markups in the four different goods sectors. The solid lines depict the benchmark parameterization (first column in Table 4), and the dashed lines depict the specification with uncorrelated markup shocks (last column in Table 4). The figure shows that the autocorrelated markup shocks in the import and export sectors all have strong effects on the real exchange rate, but that it is especially the markup shocks in the import sectors that generate a persistent adjustment in the exchange rate. In particular, the import investment markup shock generates a very persistent adjustment in the exchange rate which is due to the higher degree of price stickiness and lower substitution elasticity in this sector as compared to the consumption sector. The autocorrelated import investment markup shock also creates a persistent drop in output due to the implied higher capital cost and the appreciating currency. However, given that a smaller proportion of the output fluctuations in our sample is explained by this shock compared to the real exchange rate fluctuations, the model is less dependent on autocorrelated (rather than i.i.d.) markup shocks to account for the dynamics of output.[28]

[28] Notice also that consumption deflator inflation responds negatively to a positive import consumption markup shock because of the high substitution elasticity between domestic and imported goods, η_c. Households substitute away from the imported good and the deflator falls due to the large drop in imported consumption. Domestic inflation also declines because of the expenditure switching effect from domestic to imported investment goods and the fall in export demand which induces a decline in aggregate demand for domestically produced goods.

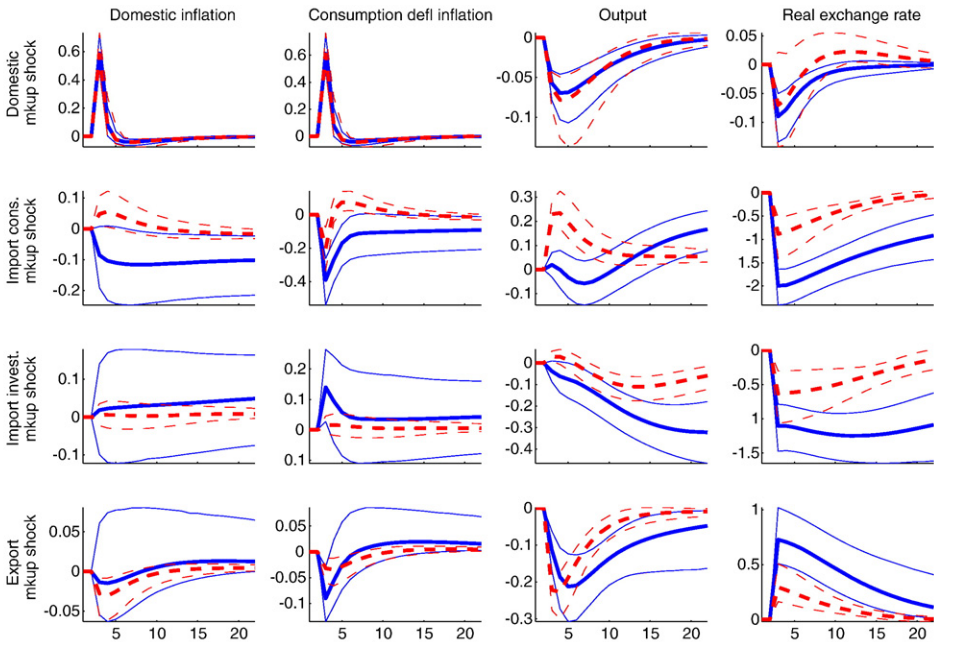

Fig. 5. Impulse responses (posterior median and 95% uncertainty intervals) to a one standard deviation markup shock in each of the four sectors. Benchmark model (solid) and i.i.d. markup shocks (dashed). Note: The domestic markup shocks are i.i.d also in the benchmark model. The discrepancy between the solid and dashed lines reflect differences in parameterizations (see Table 4).

Returning to the historical decompositions in Fig. 4, we see that out of the "closed economy" shocks, the technology shocks are most important for understanding variations in output during the sample, whereas they are less important for explaining the decline in domestic inflation. In addition to technology shocks, preference shocks and in particular shocks to labor supply constitute an important source of output fluctuations during this period. From Fig. 4, we see that monetary policy shocks and especially variations in the inflation target explain about 400 basis points of the downturn in inflation during the sample, where the estimated steady state level is around 2%. Both policy shocks have also induced some variation in output growth during the period, but to a lesser extent than the technology and labor supply shocks. The inflation dynamics in the very short run (i.e., one quarter ahead) is predominantly explained by domestic markup shocks, but since this shock is white noise, the inflation volatility at a one- to two-year horizon is accounted for by the labor supply shock which is an important source of variation in the real wage (not shown).[29]

7. Conclusions

In this paper, we have modified the closed economy monetary business cycle model of Christiano et al. (2005) to an open economy model. We find there to be strong support for the nominal and real frictions that are embedded in the model; sticky prices in the domestic, import

[29] We refer to Adolfson et al. (2005) for the variance decompositions.

and export sectors, sticky wages, investment adjustment costs and habit persistence in consumption. We do not find any evidence that variable capital utilization is important for the empirical success of the model, nor that it has any greater impact on the estimated parameters.[30] Moreover, the working capital channel is not an effective way of generating inflation persistence when subjecting the model to fit all variation in the data and not just the dynamic effects of a monetary policy shock as in Christiano et al. (2005).

According to our estimated model, many shocks are of importance for the fluctuations in the 15 variables we study. There is a substantial amount of internal propagation via the high substitution elasticity between foreign and domestic consumption goods which is strongly preferable by the data. The estimated model – although fitted to explain all the variation in the data and not only the dynamics of a monetary policy shock – has a monetary transmission mechanism well in line with those reported in identified VARs (see, e.g., Angeloni et al. (2003) for Euro area evidence) for standard variables like inflation, output, consumption and investment.

When the estimated model is subjected to independent empirical validation tests, we find that the empirical performance appears to be fairly good. In particular, the model can reproduce the inflation and real exchange rate dynamics, a task that has turned out to be difficult (see e.g. Bouakez (2005) for further discussion). However, it should be recognized that the model's performance in this regard is contingent upon the inclusion of some exogenous shocks. Another shortcoming of the model is that it overpredicts the persistence and volatility of exports relative to the data.

By and large, our paper has shown that it is possible to extend the benchmark closed economy model into an open economy setup and obtain an empirically plausible model to analyze business cycles in the open economy.

Acknowledgements

We would like to thank two anonymous referees, the editor Charles Engel, as well as Fabio Canova, Gabriel Fagan, Dale Henderson, Eric Leeper, James Nason, Øistein Røisland, and Frank Smets for useful comments and helpful discussions. We also thank participants in seminars at Federal Reserve Bank of Cleveland, Institute for International Economic Studies (IIES), Norges Bank, Sveriges Riksbank, and participants in the following workshops and conferences: "Dynamic Macroeconomic Theory", Copenhagen; "2nd ECB/IMOP Workshop on Dynamic Macroeconomics", Hydra; "19th Annual Congress of the European Economic Association", Madrid; "Small Monetary Models", Banque de France; and "Recent Developments in Macroeconomic Modelling—Exploring the Consequences of the Zero Nominal Interest Rate Floor", Bank of Japan. The working paper version of this paper was written while Lindé was a visiting scholar at the Institute for International Economic Studies (Stockholm University), and their hospitality is gratefully acknowledged. Villani was partly financially supported by a grant from the Swedish Research Council (Vetenskapsrådet, grant no. 412-2002-1007). 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.

[30] This result might be contingent upon the fact that capacity utilization is not used as an observable variable when estimating the model (since this variable is not available for the Euro area).

References

Adolfson, M., Laséen, S., Lindé, J., Villani, M., 2005. Bayesian estimation of an open economy DSGE model with incomplete pass-through. Working Paper, vol. 179. Sveriges Riksbank.

Adolfson, M., Laséen, S., Lindé, J., Villani, M., 2006. Appendix to: Bayesian Estimation of an Open Economy DSGE Model with Incomplete Pass-Through. Manuscript. Sveriges Riksbank.

Adolfson, M., Lindé, J., Villani, M., in press. Forecasting performance of an open economy DSGE model, Econometric Reviews. Working Paper, vol. 190. Sveriges Riksbank.

Altig, D., Christiano, L.J., Eichenbaum, M., Lindé, J., 2003. The Role of Monetary Policy in the Propagation of Technology Shocks. Manuscript. Northwestern University.

Altig, D., Christiano, L.J., Eichenbaum, M., Lindé, J., 2004. Firm-specific capital, nominal rigidities and the business cycle. Working Paper, vol. 176. Sveriges Riksbank.

Ambler, S., Rebei, N., Dib, A., 2004. Optimal taylor rules in an estimated model of a small open economy. Working Paper, vol. 2004-36. Bank of Canada.

Angeloni, I., Kasyap, A.K., Mojon, B., Terlizzese, D., 2003. The output composition puzzle: a difference in the monetary transmission mechanism in the Euro area and U.S. Journal of Money, Credit and Banking 35 (6), 1265–1306.

Bouakez, H., 2005. Nominal rigidity, desired markup variations, and real exchange rate persistence. Journal of International Economics 66 (1), 49–74.

Calvo, G., 1983. Staggered prices in a utility maximizing framework. Journal of Monetary Economics 12, 383–398.

Christiano, L.J., Eichenbaum, M., Evans, C., 2005. Nominal rigidities and the dynamic effects of a shock to monetary policy. Journal of Political Economy 113 (1), 1–45.

Collard, F., Dellas, H., 2002. Exchange rate systems and macroeconomic stability. Journal of Monetary Economics 49 (3), 571–599.

Corsetti, G., Pesenti, P., 2001. Welfare and macroeconomic interdependence. Quarterly Journal of Economics 116 (2), 421–445.

de Walque, G., Wouters, R., Smets, F., 2005. An Open Economy DSGE Model Linking the Euro Area and the US Economy. Manuscript. National Bank of Belgium.

Del Negro, M., F. Schorfheide, F. Smets and R. Wouters, in press. On the fit and forecasting performance of new Keynesian models, Journal of Business and Economic Statistics. Working Paper, No 2004-37. Federal Reserve Bank of Atlanta.

Devereux, M.B., Engel, C., 2002. Exchange rate pass-through, exchange rate volatility and exchange rate disconnect. Journal of Monetary Economics 49 (4), 913–940.

Duarte, M., Stockman, A.C., 2005. Rational speculation and exchange rates. Journal of Monetary Economics 52, 3–29.

Eichenbaum, M., Evans, C., 1995. Some empirical evidence on the effects of shocks to monetary policy on exchange rates. Quarterly Journal of Economics 110, 975–1010.

Erceg, C., Henderson, D., Levin, A., 2000. Optimal monetary policy with staggered wage and price contracts. Journal of Monetary Economics 46 (2), 281–313.

Fagan, G., Henry, J., Mestre, R., 2005. An area-wide model for the Euro area. Economic Modelling 22 (1), 39–59.

Faust, J., Rogers, J.H., 2003. Monetary policy's role in exchange rate behavior. Journal of Monetary Economics 50, 1403–1424.

Fuhrer, J., Moore, G., 1995. Inflation persistence. Quarterly Journal of Economics CX, 127–160.

Galí, J., Monacelli, T., 2005. Monetary policy and exchange rate volatility in a small open economy. Review of Economic Studies 72 (3), 707–734 (July).

Galí, J., Gertler, M., Lopez-Salido, D., 2001. European inflation dynamics. European Economic Review 45 (7), 1237–1270.

Gelman, A., Carlin, J., Stern, H., Rubin, D., 2004. Bayesian Data Analysis, 2nd edition. Chapman and Hall, New York.

Geweke, J., 1999. Using simulation methods for Bayesian econometrics models: inference, development and communication. Econometric Reviews 18 (1), 1–73.

Hamilton, J., 1994. Times Series Analysis. Princeton University Press.

Justiniano, A., Preston, B., 2004. Small Open Economy DSGE Models: Specification, Estimation and Model Fit. manuscript. Columbia University.

Kollmann, R., 2001. The exchange rate in a dynamic-optimizing business cycle model with nominal rigidities: a quantitative investigation. Journal of International Economics 55, 243–262.

Lindé, J., 2003. Comment on the output composition puzzle: a difference in the monetary transmission mechanism in the Euro area and U.S. by Angeloni, I., Kasyap, A.K., Mojon, B. and D. Terlizzese. Journal of Money, Credit and Banking 35 (6), 1309–1318.

Lindé, J., Nessén, M., Söderström, U., 2003. Monetary Policy in an Estimated Open-Economy Model with Imperfect Pass-Through. Working Paper, vol. 167. Sveriges Riksbank.
Lubik, T., Schorfheide, F., 2005. A Bayesian look at new open economy macroeconomics. In: Gertler, M., Rogoff, K. (Eds.), NBER Macroeconomics Annual. MIT Press.
Lundvik, P., 1992. Foreign demand and domestic business cycles: Sweden 1891–1987, chapter 3 in business cycles and growth. Monograph Series, vol. 22. Institute for International Economic Studies, Stockholm University.
Mash, R., 2004. Optimising microfoundations for inflation persistence. Working Paper, vol. 183. University of Oxford.
Obstfeld, M., Rogoff, K., 2000. The six major puzzles in international macroeconomics: is there a common cause? In: Bernanke, B., Rogoff, K. (Eds.), NBER Macroeconomics Annual. MIT Press.
Onatski, A., Williams, N., 2004. Empirical and Policy Performance of a Forward-Looking Monetary Model. Manuscript. Princeton University.
Rabanal, P., Tuesta, V., 2006. Euro–Dollar real exchange rare dynamics in an estimated two-country model: what is important and what is not? Working Paper, vol. 06/177. International Monetary Fund.
Schmitt-Grohé, S., Uribe, M., 2001. Stabilization policy and the cost of dollarization. Journal of Money, Credit and Banking 33 (2), 482–509.
Schorfheide, F., 2000. Loss function-based evaluation of DSGE models. Journal of Applied Econometrics 15 (6), 645–670.
Smets, F., Wouters, R., 2002. Openness, imperfect exchange rate pass-through and monetary policy. Journal of Monetary Economics 49 (5), 913–940.
Smets, F., Wouters, R., 2003. An estimated dynamic stochastic general equilibrium model of the Euro area. Journal of the European Economic Association 1 (5), 1123–1175.
Smets, F., Wouters, R., 2005. Comparing shocks and frictions in US and Euro area Business cycles: a Bayesian DSGE approach. Journal of Applied Econometrics 20 (2), 161–183.
Woodford, M., 2003. Interest and Prices: Foundations of a Theory of Monetary Policy. Princeton University Press, Princeton.