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Bayesian Estimation of an Open Economy DSGE Model with Incomplete Pass-Through

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Bayesian Estimation of an Open Economy DSGE Model with Incomplete Pass-Through

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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; Bayesian Inference; Business cycle.

JEL Classification Numbers: E40; E47; E52; C11;

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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, Eichenbaum and Evans (2005) and Altig, Christiano, Eichenbaum and Lindé (2003) by incorporating open economy aspects into it. Our model combines elements of their closed economy setting with some of the features and findings of the New Open Economy Macroeconomics literature.¹

In our model, the consumers attain utility from consumption of domestically produced goods as well as imported goods, which are supplied by domestic firms and importing firms, respectively. We allow for incomplete exchange rate pass-through in both the import and export sectors by including nominal price rigidities (i.e., there is local currency price stickiness), following for example Smets and Wouters (2002).

Following Christiano, Eichenbaum and Evans (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. The relevance of these frictions will be empirically determined in the estimation procedure. In addition, we allow for stochastic fiscal policy in the model since prior research have shown the potential importance of such shocks for explaining business cycles (see, e.g., Christiano and Eichenbaum, 1992, Jonsson and Klein, 1996 and Lindé, 2003b).

Apart from bringing in 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). The working capital channel implies that an interest rate change will directly affect firms' marginal costs. Consequently, both these channels will have effects on the transmission of monetary policy. Examining the role of the working capital channel is of particular interest, since Christiano, Eichenbaum and Evans (2005) obtain a low estimated degree of price stickiness when allowing for working capital when matching the impulse responses after a monetary policy shock. In contrast, Smets and Wouters (2003a, 2003b) 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 which induces a common trend in the real variables of the model. This allows us to work with raw data when estimating the DSGE model. Compared to Smets and Wouters (2003a, 2003b) we also allow for a larger set of structural shocks, mainly due to the open economy aspects in our model. The relative importance of the various identified shocks for explaining the business cycle fluctuations will be determined in the estimation, and an interesting feature of the analysis in this paper is to examine to what extent the frictions and shocks differ between the open and closed economy setting.

We estimate the model using Bayesian estimation techniques. Smets and Wouters (2003a, 2003b) have shown that one can successfully estimate closed economy DSGE models using Bayesian methods, and that the forecasting performance of such models is quite good compared to standard, as well as Bayesian, vector autoregressive (VAR) models. We extend their work to the open economy setting, and by using data for the Euro area we offer a comparison to their closed economy framework.

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 (2003a) it is probably a less rudimentary statement than modeling the Euro area as a closed economy.² In addition, there is some empirical support for the small open economy approx-

¹Important contributions to the literature on monetary policy in open economies are Benigno and Benigno (2003), Chari, Kehoe and McGrattan (2002), Corsetti and Pesenti (2001), Galí and Monacelli (2004), Kollmann (2001), and Schmitt-Grohé and Uribe (2001) among others. In general, these models have though been calibrated and not estimated. See Lane (1999) for a survey of the New Open Economy Macroeconomics literature.

²Lindé (2003a) shows that "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.

imation. 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).³

We provide an evaluation of the open economy DSGE model's empirical properties to validate the model fit. More specifically, we compare vector autocovariance functions and unconditional second moments in the benchmark model and the data. We also provide a relative model comparison using marginal likelihoods to assess the importance of the various shocks and frictions that have been included in the model.

The interesting results related to the open economy aspects of the model are the following. The estimated model is able to capture the volatility and persistence in the real exchange rate strikingly well. Bouakez (2004) has shown that a model with time-varying markups, which are decreasing in the relative price of goods, can replicate the properties of the real exchange rate, in contrast to standard sticky price models in which the fluctuations in the real exchange rate do not generally last beyond the duration of the price contracts. However, Bouakez's model using HP-filtered data can not jointly account for the dynamics in inflation and the real exchange rate, because it underpredicts the inflation volatility. In contrast, our model is able to match the joint conditional inflation and real exchange rate dynamics using undetrended data.

Moreover, the model yields a high elasticity of substitution between domestic and imported goods. We find a value of around 11 when including this parameter in the estimation. As Obstfeld and Rogoff (2000) have shown, 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 a lot lower, in the range of 1.5 to 2, see, e.g., Collard and Dellas (2002).

Although our model embodies a number of mechanisms that have proven useful to generate persistence in inflation such as variable capital utilization, the working capital channel and a time-varying inflation target, we still find that price stickiness is an important feature for firms active in the domestic, export and import sectors. Under the traditional assumption that the households own the capital stock and assuming that the markup shocks in each sector are white noise, the implied average duration of the price contracts are rather long, of about 8 quarters which is well in line with Smets and Wouters (2003a).

However, allowing the markup shocks to be serially correlated reduces the estimated degree of price stickiness substantially. In this case, we find that the average duration is less than 2 quarters for the firms active in the consumption and investment import sectors, and about 3 quarters for the firms active in the domestic and export sectors. Since the marginal likelihoods clearly indicate that the assumption of correlated shocks in the import and export sectors is most plausible, our results suggest price stickiness around 2 – 3 quarters on average in these sectors. Given that incomplete exchange rate pass-through in the model is induced solely by nominal rigidities this amounts to about 20 – 40 percents pass-through to the import and export prices.

Because the marginal likelihood is in favor of the model with white noise markup shocks for the domestic firms, this leaves us with a rather high degree of estimated price stickiness under the conventional assumption that the households own the capital stock. However, recent research have highlighted the importance of the degree to which capital is specific to the firm for the interpretation of the price stickiness parameter, see e.g. Altig, Christiano, Eichenbaum and Lindé (2004), Sveen and Weinke (2004) and Woodford (2004). If we relax the assumption that the households own the capital stock, and instead assume that the capital is entirely specific to each firm, we can apply the

³The identifying assumption in the analysis is that that 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.

formulas in Altig et al. (2004), and reinterpret our estimates to imply an average duration of about 4.5 quarters, which appears to be in line with microeconomic evidence for Euro area countries, see e.g. Mash (2004) and the references therein.

Finally, we find that many shocks matter for the fluctuations in output and inflation in the open economy framework. That is, “open economy shocks” are important for the determination of the “domestic variables” since we find that there is a high elasticity of substitution between domestic and imported consumption goods which implies that relative prices and the exchange rate channel are very important for the dynamics of the model. For output both productivity and imported investment markup shocks are important, while for inflation imported consumption and investment markup shocks together with movements in the inflation target appear to matter the most.

The paper is organized as follows. In Section 2 the theoretical model is derived and described with particular emphasis on its open economy aspects. Section 3 contains a short description of the data used, and discusses measurement issues that arise when taking the theoretical model to the data. 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. We then report our estimation results and validate the model fit. The empirical properties of the estimated DSGE model are compared with the actual data using autocovariance functions and unconditional second moments. In Section 5 we explore the importance of nominal and real frictions in the model. Section 6 shows the impulse responses from different shocks and discusses the role of various shocks in explaining business cycles. Lastly, Section 7 provides some conclusions.

2. The open economy DSGE model

We build on the work of Christiano et al. (2005) and Altig et al. (2003) and extend their DSGE model to an open economy. As in their model the 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. Note also that consumption preferences are subject to habit formation.

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 certain capital adjustment costs. These are costs to adjusting the investment rate as well as costs of varying the utilization rate of the capital stock. 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. This gives rise to an explicit wage equation with Calvo (1983) stickiness.

Domestic firms determine the capital and labour inputs used in their production which 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. In what follows we provide the optimization problems of the different firms and the households. We also describe the behaviour of the fiscal authority, the central bank, and illustrate how the foreign economy develops.

2.1. Firms

There are three categories of firms operating in this open economy; domestic, importing and exporting firms. The intermediate domestic firms produce a differentiated good, using capital and labour inputs, which they sell to a final good producer who uses a continuum of these intermediate goods in her production. The importing firms, in turn, transform a homogenous good, bought in the world market, into a differentiated import good, which they sell to the domestic households. The exporting firms pursue a similar scheme. The exporting firms buy the domestic final good and differentiate it by brand naming. Each exporting firm is thus a monopoly supplier of its specific product in the world market.

2.1.1. Domestic firms

The domestic firms consist of three types. One hires labour from the households and transforms it into a homogeneous input good, denoted H . The other type of firm buys H , rents capital and produces an intermediate good Y_i , which it sells to a final goods producer. There is a continuum of these intermediate goods producers, each of which is a monopoly supplier of its own good and is competitive in the markets for inputs. The last type of firm transforms the intermediate product into a homogenous final good, which is used for consumption and investment by the households.

The production function of the *final good firm* takes the form

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

where $\lambda_{d,t}$ is a stochastic process determining the time-varying markup in the domestic goods market. This process is assumed to follow

$$\lambda_{d,t} = (1 - \rho_{\lambda_d}) \lambda_d + \rho_{\lambda_d} \lambda_{d,t-1} + \varepsilon_{\lambda_d,t}.$$

Note that in our benchmark model we assume that these markup shocks are white noise and set $\rho_{\lambda_d} = 0$. However, in our sensitivity analysis we will also explore the consequences of allowing the shocks to be persistent, that is $\rho_{\lambda_d} > 0$.

The final good firm takes its output price, P_t , and its input prices $P_{i,t}$ as given. Profit maximization leads to the following first order condition

$$\frac{Y_{i,t}}{Y_t} = \left(\frac{P_t}{P_{i,t}} \right)^{\frac{\lambda_{d,t}}{\lambda_{d,t}-1}}. \quad (2.2)$$

By integrating (2.2) and using (2.1), we obtain the following relation between the price of the final good and the prices of intermediate goods

$$P_t = \left[\int_0^1 P_{i,t}^{\frac{1}{1-\lambda_{d,t}}} di \right]^{(1-\lambda_{d,t})}. \quad (2.3)$$

Output of *intermediate good firm* i is given by the following production function:

$$Y_{i,t} = z_t^{1-\alpha} \epsilon_t K_{i,t}^\alpha H_{i,t}^{1-\alpha} - z_t \phi, \quad (2.4)$$

where z_t is a permanent technology shock, ϵ_t is a covariance stationary technology shock, and $H_{i,t}$ denotes homogeneous labour hired by the i^{th} firm. In (2.4), $K_{i,t}$ is the capital services stock which may differ from the physical capital stock since we allow for variable capital utilization in the model.

Also, a fixed cost is included to ensure that profits are zero in steady state. The fixed cost is assumed to grow at the same rate as consumption, investment, the real wage, and output do in steady state. If the fixed cost did not grow with z_t , the fixed cost term would eventually become irrelevant and profits would systematically become positive because of the presence of monopoly power. Moreover, we rule out entry into and exit out of the production of intermediate good i .

The process for the permanent technology level z_t is exogenously given by

$$\frac{z_t}{z_{t-1}} = \mu_{z,t}, \quad (2.5)$$

and

$$\mu_{z,t} = (1 - \rho_{\mu_z})\mu_z + \rho_{\mu_z}\mu_{z,t-1} + \varepsilon_{z,t}. \quad (2.6)$$

For the stationary shock in (2.4), we assume $E(\epsilon_t) = 1$ and that $\hat{\epsilon}_t = (\epsilon_t - 1)/1$ has the following univariate representation:

$$\hat{\epsilon}_t = \rho_\epsilon \hat{\epsilon}_{t-1} + \varepsilon_{\epsilon,t}. \quad (2.7)$$

Throughout the paper, a variable with a hat denotes log-linearized variables (i.e., $\hat{X}_t = \frac{dX_t}{X}$).

The cost minimization problem facing the intermediate firm i in period t is (assuming that $P_{i,t}$ is given, the firm is constrained to produce $Y_{i,t}$):

$$\min_{K_{i,t}, H_{i,t}} W_t R_t^f H_{i,t} + R_t^k K_{i,t} + \lambda_t P_{i,t} \left[Y_{i,t} - z_t^{1-\alpha} \epsilon_t K_{i,t}^\alpha H_{i,t}^{1-\alpha} + z_t \phi \right], \quad (2.8)$$

where R_t^k is the gross nominal rental rate per unit of capital services and W_t is the nominal wage rate per unit of aggregate, homogeneous, labour $H_{i,t}$. The inclusion of the gross effective nominal rate of interest paid by firms, R_t^f , reflects the assumption that a fraction, ν_t , of the intermediate firms' wage bill has to be financed in advance. The end of period labour costs of the firm are $W_t H_{i,t} R_t^f$ and

$$R_t^f \equiv \nu_t R_{t-1} + 1 - \nu_t, \quad (2.9)$$

where R_{t-1} is the gross nominal interest rate. By log-linearizing equation (2.9), we obtain

$$\hat{R}_t^f = \frac{\nu R}{\nu R + 1 - \nu} \hat{R}_{t-1} + \frac{\nu(R-1)}{\nu R + 1 - \nu} \hat{\nu}_t, \quad (2.10)$$

which describes the relation between the effective interest rate paid by the firms and the economy-wide nominal interest rate.⁴

The first order conditions of (2.8) with respect to $H_{i,t}$ and $K_{i,t}$ are

$$W_t R_t^f = (1 - \alpha) \lambda_t P_{i,t} z_t^{1-\alpha} \epsilon_t K_{i,t}^\alpha H_{i,t}^{-\alpha}, \quad (2.11)$$

$$R_t^k = \alpha \lambda_t P_{i,t} z_t^{1-\alpha} \epsilon_t K_{i,t}^{\alpha-1} H_{i,t}^{1-\alpha}. \quad (2.12)$$

⁴A difference compared to Christiano et al. (2005) is that the nominal interest rate that the firms pay on their loans is R_{t-1} instead of R_t , which reflects our assumption that the households purchase one-period zero-coupon bonds with certain nominal payout in period $t+1$ (see also footnote 14).

Because of the permanent technology shock and the unit-root in the price level, a number of variables are non-stationary as they contain a nominal and real stochastic trend. We follow Altig et al. (2003) and stationarize the variables in the following way

$$r_t^k \equiv \frac{R_t^k}{P_t}, \bar{w}_t \equiv \frac{W_t}{P_t z_t}, k_{t+1} \equiv \frac{K_{t+1}}{z_t} \text{ and } \bar{k}_{t+1} \equiv \frac{\bar{K}_{t+1}}{z_t}, \quad (2.13)$$

where \bar{K}_{t+1} denotes the physical capital stock. It is important to notice that the physical capital stock in period $t + 1$ is scaled with z_t since it is determined in period t , whereas capital services in period $t + 1$, K_{t+1} , is for convenience also scaled with z_t although K_{t+1} is determined in period $t + 1$. Stationarizing the variables in (2.11) and (2.12) according to (2.13) and combining the first order conditions, we obtain the following stationary solution for the scaled equilibrium rental rate of capital

$$r_t^k = \frac{\alpha}{1 - \alpha} \bar{w}_t \mu_{z,t} R_t^f k_t^{-1} H_t. \quad (2.14)$$

The Lagrangian multiplier in equation (2.8) $\lambda_t P_{i,t}$ can be interpreted as the nominal cost of producing one additional unit of the domestic good (i.e., the nominal marginal cost). The *real* marginal cost for the intermediate firms is, consequently, given by λ_t . Using the first order conditions in (2.11) and (2.12), it is possible to show that equilibrium real marginal cost ($mc_t \equiv \lambda_t$) follows

$$mc_t = \left(\frac{1}{1 - \alpha} \right)^{1 - \alpha} \left(\frac{1}{\alpha} \right)^{\alpha} \left(r_t^k \right)^{\alpha} \left(\bar{w}_t R_t^f \right)^{1 - \alpha} \frac{1}{\epsilon_t}. \quad (2.15)$$

The price setting problem of the intermediate firms is similar to the one in Smets and Wouters (2003b), following Calvo (1983). Each intermediate firm faces a random probability $(1 - \xi_d)$ that it can reoptimize its price in any period. The reoptimized price is denoted P_t^{new} . Notice that we suppress the subindex i in P_t^{new} . We do this because all firms that are allowed to reoptimize will always set the same price. With probability ξ_d the firm is not allowed to reoptimize, and its price in period $t + 1$ is then updated according to the scheme $P_{t+1} = (\pi_t)^{\kappa_d} (\bar{\pi}_{t+1}^c)^{1 - \kappa_d} P_t$, i.e. it is indexed to last period's inflation, $\pi_t = \frac{P_t}{P_{t-1}}$, and the current inflation target, $\bar{\pi}_{t+1}^c$ where κ_d is an indexation parameter.⁵ If the period t optimizing firm is not allowed to change its price during s periods ahead, the price in period $t + s$ will be $(\pi_t \pi_{t+1} \dots \pi_{t+s-1})^{\kappa_d} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1 - \kappa_d} P_t^{new}$. Thus, firm i faces the following optimization problem when setting its price:

$$\max_{P_t^{new}} E_t \sum_{s=0}^{\infty} (\beta \xi_d)^s v_{t+s} [((\pi_t \pi_{t+1} \dots \pi_{t+s-1})^{\kappa_d} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1 - \kappa_d} P_t^{new}) Y_{i,t+s} - MC_{i,t+s} (Y_{i,t+s} + z_{t+s} \phi)], \quad (2.16)$$

where the firm is using the stochastic discount factor $(\beta \xi_d)^s v_{t+s}$ to make profits conditional upon utility. β is the discount factor, v_{t+s} the marginal utility of the households' nominal income in period $t + s$, which is exogenous to the intermediate firms, and $MC_{i,t}$ is the firm's nominal marginal cost. Using equation (2.2) the first order condition of the firms' optimization problem can be written

$$E_t \sum_{s=0}^{\infty} (\beta \xi_d)^s v_{t+s} \left(\frac{\left(\frac{P_{t+s-1}}{P_{t-1}} \right)^{\kappa_d} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1 - \kappa_d}}{\left(\frac{P_{t+s}}{P_t} \right)} \right)^{-\frac{\lambda_{d,t+s}}{\lambda_{d,t+s} - 1}} Y_{t+s} P_{t+s} \times \left[\frac{\left(\frac{P_{t+s-1}}{P_{t-1}} \right)^{\kappa_d} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1 - \kappa_d}}{\left(\frac{P_{t+s}}{P_t} \right)} \frac{P_t^{new}}{P_t} - \frac{\lambda_{d,t} MC_{i,t+s}}{P_{t+s}} \right] = 0. \quad (2.17)$$

⁵The inflation target process is described in subsection 2.5.

From the aggregate price index (2.3) follows that the average price in period t is:

$$\begin{aligned}
P_t &= \left[\left(\int_0^{\xi_d} \left(P_{t-1} (\pi_{t-1})^{\kappa_d} (\bar{\pi}_t^{1-\kappa_d})^{\frac{1}{1-\lambda_{d,t}}} + \int_{\xi_d}^1 (P_t^{new})^{\frac{1}{1-\lambda_{d,t}}} di \right)^{1-\lambda_{d,t}} \right. \right. \\
&= \left. \left. \xi_d \left(P_{t-1} (\pi_{t-1})^{\kappa_d} (\bar{\pi}_t^{1-\kappa_d})^{\frac{1}{1-\lambda_{d,t}}} + (1 - \xi_d) (P_t^{new})^{\frac{1}{1-\lambda_{d,t}}} \right)^{1-\lambda_{d,t}} \right] \right. \quad (2.18)
\end{aligned}$$

where we have exploited the fact that all firms that reoptimize set the same price, P_t^{new} . Log-linearizing and combining equations (2.17) and (2.18) yields the following aggregate Phillips curve relation

$$\begin{aligned}
(\hat{\pi}_t - \hat{\pi}_t^c) &= \frac{\beta}{1 + \kappa_d \beta} (E_t \hat{\pi}_{t+1} - \rho_\pi \hat{\pi}_t^c) + \frac{\kappa_d}{1 + \kappa_d \beta} (\hat{\pi}_{t-1} - \hat{\pi}_t^c) \\
&\quad - \frac{\kappa_d \beta (1 - \rho_\pi)}{1 + \kappa_d \beta} \hat{\pi}_t^c + \frac{(1 - \xi_d)(1 - \beta \xi_d)}{\xi_d (1 + \kappa_d \beta)} (\widehat{mc}_t + \widehat{\lambda}_{d,t}). \quad (2.19)
\end{aligned}$$

Note that by letting $\kappa_d = 1$, this relation reduces to the Phillips curve in Altig et al. (2003), while setting $\kappa_d = 0$ results in the purely forward-looking Phillips curve.

2.1.2. Importing firms

The import sector consists of firms that buy a homogenous good in the world market. There are two different types of these importing firms; one that turns the imported product into a differentiated *consumption* good $C_{i,t}^m$ (through access to a "differentiating" technology, i.e. brand naming), and another that turns it into a differentiated *investment* good $I_{i,t}^m$. In each of the two categories there is a continuum of importing firms that sell their differentiated (consumption or investment) goods to the households.

The different importing firms buy the homogenous good at price P_t^* in the world market. In order to allow for incomplete exchange rate pass-through to the consumption and investment import prices we assume local currency price stickiness. The importing firms follow Calvo price setting and are allowed to change their price only when they receive a random price change signal. Each importing *consumption* firm faces a random probability $(1 - \xi_{m,c})$ that it can reoptimize its price in any period. Each importing *investment* firm faces a different probability $(1 - \xi_{m,i})$ that it can reoptimize. Let the reoptimized price for an imported consumption (investment good) be denoted $P_{new,t}^{m,c}$ ($P_{new,t}^{m,i}$). With probability $\xi_{m,c}$ ($\xi_{m,i}$) the firm does not reoptimize, and its price is then indexed to last period's inflation and the current inflation target according to the following scheme $P_{t+1}^{m,j} = \left(\pi_t^{m,j} \right)^{\kappa_{m,j}} (\bar{\pi}_{t+1}^c)^{1-\kappa_{m,j}} P_t^{m,j}$ for $j = \{c, i\}$. If a period t optimizing firm is not allowed to change its price during s periods ahead, the price in period $t + s$ is thus $\left(\pi_t^{m,j} \pi_{t+1}^{m,j} \dots \pi_{t+s-1}^{m,j} \right)^{\kappa_{m,j}} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1-\kappa_{m,j}} P_{new,t}^{m,j}$ for $j = \{c, i\}$.⁶ The consumption and investment importing firms face the following optimization problem, respectively:

$$\begin{aligned}
\max_{P_{new,t}^{m,c}} \quad & E_t \sum_{s=0}^{\infty} (\beta \xi_{m,c})^s v_{t+s} [(\pi_t^{m,c} \pi_{t+1}^{m,c} \dots \pi_{t+s-1}^{m,c})^{\kappa_{m,c}} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1-\kappa_{m,c}} P_{new,t}^{m,c} C_{i,t+s}^m \\
& - S_{t+s} P_{t+s}^* (C_{i,t+s}^m + z_{t+s} \phi^{m,c})], \quad (2.20)
\end{aligned}$$

⁶ Again, note that all importing firms that reoptimize their price will set the same price, so the subscript i can be dropped. Also, the updating scheme allows for the possibility that importing firms update to the domestic inflation target. Since the profit maximization for the importing firms involve own prices relative to the aggregate import price, as well as the firms marginal cost which is $S_t P_t^*$, it is not obvious why the domestic inflation target should be included in the updating scheme. By including the indexation parameter in the estimation, we evaluate which specification that is supported by the data.

$$\max_{P_{new,t}^{m,i}} E_t \sum_{s=0}^{\infty} (\beta \xi_{m,i})^s v_{t+s} \left[\left(\pi_t^{m,i} \pi_{t+1}^{m,i} \dots \pi_{t+s-1}^{m,i} \right)^{\kappa_{m,i}} \left(\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c \right)^{1-\kappa_{m,i}} P_{new,t}^{m,i} I_{i,t+s}^m - S_{t+s} P_{t+s}^* (I_{i,t+s}^m + z_{t+s} \phi^{m,i}) \right], \quad (2.21)$$

where profits are discounted by $(\beta \xi_{m,j})^s v_{t+s}$ for $j = \{c, i\}$. $\phi^{m,c}$ ($\phi^{m,i}$) are fixed costs, in real terms, ensuring that import profits are zero in steady state.

The final import consumption good is a composite of a continuum of i differentiated imported consumption goods, each supplied by a different firm, which follows the CES function:

$$C_t^m = \left[\int_0^1 (C_{i,t}^m)^{\frac{1}{\lambda_t^{m,c}}} di \right]^{\lambda_t^{m,c}}, \quad 1 \leq \lambda_t^{m,c} < \infty. \quad (2.22)$$

It can then be shown that each importing firm i faces the demand for imported consumption goods given by

$$C_{i,t}^m = \left(\frac{P_{i,t}^{m,c}}{P_t^{m,c}} \right)^{-\frac{\lambda_t^{m,c}}{\lambda_t^{m,c}-1}} C_t^m. \quad (2.23)$$

Equivalently, the final imported investment good is a composite of a continuum of differentiated imported investment goods as follows:

$$I_t^m = \left[\int_0^1 (I_{i,t}^m)^{\frac{1}{\lambda_t^{m,i}}} di \right]^{\lambda_t^{m,i}}, \quad 1 \leq \lambda_t^{m,i} < \infty, \quad (2.24)$$

and the demand for the differentiated imported investment goods is given by

$$I_{i,t}^m = \left(\frac{P_{i,t}^{m,i}}{P_t^{m,i}} \right)^{-\frac{\lambda_t^{m,i}}{\lambda_t^{m,i}-1}} I_t^m. \quad (2.25)$$

The processes for the time varying markups on the import consumption and investment goods are assumed to follow

$$\lambda_t^{m,c} = (1 - \rho_{\lambda^{m,c}}) \lambda^{m,c} + \rho_{\lambda^{m,c}} \lambda_{t-1}^{m,c} + \varepsilon_{\lambda^{m,c},t}, \quad (2.26)$$

$$\lambda_t^{m,i} = (1 - \rho_{\lambda^{m,i}}) \lambda^{m,i} + \rho_{\lambda^{m,i}} \lambda_{t-1}^{m,i} + \varepsilon_{\lambda^{m,i},t}. \quad (2.27)$$

Inserting the demand schedules (2.23) and (2.25) in the firms' optimization problem, the first order conditions with respect to the consumption good and the investment good are

$$E_t \sum_{s=0}^{\infty} (\beta \xi_{m,c})^s v_{t+s} \left(\frac{\left(\frac{P_{t+s-1}^{m,c}}{P_{t-1}^{m,c}} \right)^{\kappa_{m,c}} \left(\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c \right)^{1-\kappa_{m,c}}}{\left(\frac{P_{t+s}^{m,c}}{P_t^{m,c}} \right)} \right)^{-\frac{\lambda_{t+s}^{m,c}}{\lambda_{t+s}^{m,c}-1}} C_{t+s}^m P_{t+s}^{m,c} \times \\ \left[\frac{\left(\frac{P_{t+s-1}^{m,c}}{P_{t-1}^{m,c}} \right)^{\kappa_{m,c}} \left(\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c \right)^{1-\kappa_{m,c}}}{\left(\frac{P_{t+s}^{m,c}}{P_t^{m,c}} \right)} \frac{P_{new,t}^{m,c}}{P_t^{m,c}} - \frac{\lambda_{t+s}^{m,c} S_{t+s} P_{t+s}^*}{P_t^{m,c}} \right] = 0, \quad (2.28)$$

$$\begin{aligned}
& E_t \sum_{s=0}^{\infty} (\beta \xi_{m,i})^s v_{t+s} \left(\frac{\left(\frac{P_{t+s-1}^{m,i}}{P_{t-1}^{m,i}} \right)^{\kappa_{m,i}} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1-\kappa_{m,i}}}{\left(\frac{P_{t+s}^{m,i}}{P_t^{m,i}} \right)} \right)^{-\frac{\lambda_{t+s}^{m,i}}{\lambda_{t+s}^{m,i}-1}} I_{t+s}^m P_{t+s}^{m,i} \times \\
& \left[\frac{\left(\frac{P_{t+s-1}^{m,i}}{P_{t-1}^{m,i}} \right)^{\kappa_{m,i}} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1-\kappa_{m,i}}}{\left(\frac{P_{t+s}^{m,i}}{P_t^{m,i}} \right)} \frac{P_{new,t}^{m,i}}{P_t^{m,i}} - \frac{\lambda_{t+s}^{m,i} S_{t+s} P_{t+s}^*}{P_t^{m,i}} \right] = 0,
\end{aligned} \tag{2.29}$$

Stationarizing these equations and using the aggregate price indices

$$\begin{aligned}
P_t^{m,j} &= \left[\int_0^1 \left(P_{it}^{m,j} \right)^{\frac{1}{1-\lambda_t^{m,j}}} di \right]^{1-\lambda_t^{m,j}} \\
&= \left[\xi_{m,j} \left(P_{t-1}^{m,j} (\pi_{t-1}^{m,c})^{\kappa_{m,j}} (\bar{\pi}_t^c)^{1-\kappa_{m,j}} \right)^{\frac{1}{1-\lambda_t^{m,j}}} + (1 - \xi_{m,j}) \left(P_{new,t}^{m,j} \right)^{\frac{1}{1-\lambda_t^{m,j}}} \right]^{1-\lambda_t^{m,j}},
\end{aligned}$$

for $j = \{c, i\}$ implies that the log-linearized pricing equations can be written as Phillips curve relations for the imported consumption and investment good:

$$\begin{aligned}
(\hat{\pi}_t^{m,j} - \hat{\pi}_t^c) &= \frac{\beta}{1 + \kappa_{m,j}\beta} \left(E_t \hat{\pi}_{t+1}^{m,j} - \rho_{\pi} \hat{\pi}_t^c \right) + \frac{\kappa_{m,j}}{1 + \kappa_{m,j}\beta} \left(\hat{\pi}_{t-1}^{m,j} - \hat{\pi}_t^c \right) \\
&\quad - \frac{\kappa_{m,j}\beta(1 - \rho_{\pi})}{1 + \kappa_{m,j}\beta} \hat{\pi}_t^c + \frac{(1 - \xi_{m,j})(1 - \beta\xi_{m,j})}{\xi_{m,j}(1 + \kappa_{m,j}\beta)} \left(\widehat{mc}_t^{m,j} + \hat{\lambda}_t^{m,j} \right),
\end{aligned} \tag{2.30}$$

where $\widehat{mc}_t^{m,j} = \hat{p}_t^* + \hat{s}_t - \hat{p}_t^{m,j}$ for $j = \{c, i\}$. Note that the markup shocks, $\hat{\lambda}_t^{m,j}$, are observationally equivalent to shocks to the elasticity of substitution among imported consumption/investment goods, up to a scaling factor with an opposite sign (a positive substitution elasticity shock is a negative markup shock). Such shocks can thus either originate in variations of importing firms' price setting behaviour or households' willingness to substitute between different goods.⁷

2.1.3. Exporting firms

The exporting firms buy the *final* domestic good and differentiate it by brand naming. Subsequently they sell the continuum of differentiated goods to the households in the foreign market. The marginal

⁷The flexible price problem is relevant for the steady state we are linearizing around, and can be described by setting $\xi_{m,j} = 0$ for $j \in \{c, i\}$ in equations (2.28) and (2.29). In a flexible price environment the importing firms therefore must set the following price

$$P_t^{m,j} = \lambda_t^{m,j} S_t P_t^*,$$

for $j = \{c, i\}$. To see the close correspondence between substitution elasticity and markup shocks, note that we can

write $j_t^m = \left[\int_0^1 (j_{i,t}^m)^{\frac{\eta_t^{m,j}-1}{\eta_t^{m,j}}} di \right]^{\frac{\eta_t^{m,j}}{\eta_t^{m,j}-1}}$, $\eta_t^{m,j} > 1$, for $j \in \{C, I\}$. Here, the elasticity of substitution between imported

consumption/investment goods is given by $\eta_t^{m,j}$, which is related to the markup according to $\lambda_t^{m,j} = \frac{\eta_t^{m,j}}{\eta_t^{m,j}-1}$. Thus, the higher the willingness is to substitute between imported consumption/investment goods, i.e. the higher $E(\eta_t^{m,j})$ is, the lower the markup will be in steady state.

cost is thus the price of the domestic good P_t . Each exporting firm i faces the following demand $\tilde{X}_{i,t}$ for its product:

$$\tilde{X}_{i,t} = \left(\frac{P_{i,t}^x}{P_t^x} \right)^{-\frac{\lambda_{x,t}}{\lambda_{x,t}-1}} \tilde{X}_t, \quad (2.31)$$

where we assume that the export price $P_{i,t}^x$ is invoiced in the local currency of the export market. $\lambda_{x,t}$ determines the stochastic markup on the differentiated export goods.⁸ The exogenous process for the markup is assumed to be given by

$$\lambda_{x,t} = (1 - \rho_{\lambda_x}) \lambda_x + \rho_{\lambda_x} \lambda_{x,t-1} + \varepsilon_{\lambda_x,t}. \quad (2.32)$$

In order to allow for incomplete exchange rate pass-through in the export market, we assume that export prices are sticky in the foreign currency. To model this we use the Calvo setup. When setting their prices, the export firms care about the relative price between the firms' own price and the aggregate export price, as well as the price of the domestic good since this is the export firms' marginal cost. Therefore, when an export firm is not allowed to optimize its price, the firm is assumed to index the price to last period's (export price) inflation and the domestic inflation target. The price in period $t+1$ is thus $P_{t+1}^x = (\pi_t^x)^{\kappa_x} (\bar{\pi}_{t+1}^c)^{1-\kappa_x} P_t^x$. The export firms maximize profits (denoted in the local currency) taking into account that there might not be a chance to optimally change the price:

$$\begin{aligned} \max_{P_{new,i}^x} \quad & \mathbb{E}_t \sum_{s=0}^{\infty} (\beta \xi_x)^s v_{t+s} \left[\left((\pi_t^x \pi_{t+1}^x \dots \pi_{t+s-1}^x)^{\kappa_x} (\bar{\pi}_{t+1}^c \bar{\pi}_{t+2}^c \dots \bar{\pi}_{t+s}^c)^{1-\kappa_x} P_{new,t}^x \right) \tilde{X}_{i,t+s} \right. \\ & \left. - \frac{P_{t+s}}{S_{t+s}} (\tilde{X}_{i,t+s} + z_{t+s} \phi^x) \right], \end{aligned} \quad (2.33)$$

subject to equation (2.31). The log-linearized first order condition of this problem implies that the aggregate export inflation is given by

$$\begin{aligned} (\hat{\pi}_t^x - \hat{\pi}_t^c) = & \frac{\kappa_x}{1 + \beta \kappa_x} (\hat{\pi}_{t-1}^x - \hat{\pi}_t^c) + \frac{\beta}{1 + \beta \kappa_x} (\mathbb{E}_t \hat{\pi}_{t+1}^x - \rho_{\pi} \hat{\pi}_t^c) \\ & - \frac{\beta \kappa_x (1 - \rho_{\pi})}{1 + \beta \kappa_x} \hat{\pi}_t^c + \frac{(1 - \beta \xi_x)(1 - \xi_x)}{\xi_x (1 + \beta \kappa_x)} (\widehat{mc}_t^x + \hat{\lambda}_{x,t}), \end{aligned} \quad (2.34)$$

where $\widehat{mc}_t^x = \hat{p}_t - \hat{s}_t - \hat{p}_t^x$.

Further, the domestic economy is assumed to be small in relation to the foreign economy and plays a negligible part in aggregate foreign consumption. Assuming that aggregate foreign consumption follows a CES function, foreign demand for the (aggregate) domestic consumption good, C_t^x , is given by

$$C_t^x = \left[\frac{P_t^x}{P_t^*} \right]^{-\eta_f} C_t^*, \quad (2.35)$$

where C_t^* and P_t^* is the foreign consumption and price level, respectively. Notice that the specification in (2.35) allows for short run deviations from the law of one price which occur because export prices (in the local currency) are sticky.

Assuming that aggregate foreign investment also follows a CES function, foreign investment demand for the domestic good, I_t^x , is given by

$$I_t^x = \left[\frac{P_t^x}{P_t^*} \right]^{-\eta_f} I_t^*, \quad (2.36)$$

⁸The steady state markup for the exporting firms is by assumption unity, i.e. $\lambda_x = 1$.

where I_t^* is foreign investment.⁹

2.2. Households

There is a continuum of households, indexed by $j \in (0, 1)$, which attain utility from consumption, leisure and cash balances. When maximizing their intertemporal utility households decide on their current level of consumption as well as their amount of cash holdings, foreign bond holdings and their domestic deposits. They also choose the level of capital services provided to the firms, their level of investment and their capital utilization rate. 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). The j^{th} household's preferences are

$$E_0^j \sum_{t=0}^{\infty} \beta^t \left[\zeta_t^c \ln(C_{j,t} - bC_{j,t-1}) - \zeta_t^h A_L \frac{(h_{j,t})^{1+\sigma_L}}{1+\sigma_L} + A_q \frac{\left(\frac{Q_{j,t}}{z_t P_t}\right)^{1-\sigma_q}}{1-\sigma_q} \right], \quad (2.37)$$

where $C_{j,t}$ and $h_{j,t}$ denote the j^{th} household's levels of aggregate consumption and work effort, respectively. $Q_{j,t}/P_t$ are real assets the household chooses to hold in non-interest bearing form. This value is scaled with z_t in order to render real balances stationary. Finally, we allow for habit persistence in preferences by including $bC_{j,t-1}$. The time series representation for the preference shocks are

$$\begin{aligned} \hat{\zeta}_t^c &= \rho_{\zeta^c} \hat{\zeta}_{t-1}^c + \varepsilon_{\zeta^c,t}, \\ \hat{\zeta}_t^h &= \rho_{\zeta^h} \hat{\zeta}_{t-1}^h + \varepsilon_{\zeta^h,t}, \end{aligned}$$

where $E(\hat{\zeta}_t^i) = 1$ and $\hat{\zeta}_t^i = (\zeta_t^i - 1)/1$, $i \in \{c, h\}$. We will refer to ζ_t^c as consumption preference shocks and ζ_t^h as labour supply shocks.

Aggregate consumption is assumed to be given by a CES index of domestically produced and imported goods according to:

$$C_t = \left[(1 - \omega_c)^{1/\eta_c} (C_t^d)^{(\eta_c-1)/\eta_c} + \omega_c^{1/\eta_c} (C_t^m)^{(\eta_c-1)/\eta_c} \right]^{\eta_c/(\eta_c-1)}, \quad (2.38)$$

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 between domestic and foreign consumption goods. By maximizing (2.38) subject to the budget constraint $P_t C_t^d + P_t^{m,c} C_t^m = P_t^c C_t$, we obtain the following consumption demand functions

$$C_t^d = (1 - \omega_c) \left[\frac{P_t}{P_t^c} \right]^{-\eta_c} C_t, \quad (2.39)$$

$$C_t^m = \omega_c \left[\frac{P_t^{m,c}}{P_t^c} \right]^{-\eta_c} C_t, \quad (2.40)$$

where the CPI price index (defined as the minimum expenditure required to buy one unit of C_t) is given by

$$P_t^c = \left[(1 - \omega_c) (P_t)^{1-\eta_c} + \omega_c (P_t^{m,c})^{1-\eta_c} \right]^{1/(1-\eta_c)}. \quad (2.41)$$

⁹By assuming that the elasticity is the same in (2.36) as in (2.35), we can use foreign output ($Y_t^* = C_t^* + I_t^*$) as the only "demand variable", and we therefore do not need to take a stand on how much of the exporting goods are used for consumption and investment purposes respectively.

As with consumption, 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):

$$I_t = \left[(1 - \omega_i)^{1/\eta_i} (I_t^d)^{(\eta_i-1)/\eta_i} + \omega_i^{1/\eta_i} (I_t^m)^{(\eta_i-1)/\eta_i} \right]^{\eta_i/(\eta_i-1)}, \quad (2.42)$$

where ω_i is the share of imports in investment, and η_i is the elasticity of substitution between domestic and imported investment goods. Because prices of the domestically produced investment goods coincide with the prices of the domestically produced consumption goods we have the following investment demand functions:

$$I_t^d = (1 - \omega_i) \left[\frac{P_t}{P_t^i} \right]^{-\eta_i} I_t, \quad (2.43)$$

$$I_t^m = \omega_i \left[\frac{P_t^{m,i}}{P_t^i} \right]^{-\eta_i} I_t, \quad (2.44)$$

where the aggregate investment price P_t^i is given by

$$P_t^i = \left[(1 - \omega_i) (P_t)^{1-\eta_i} + \omega_i (P_t^{m,i})^{1-\eta_i} \right]^{1/(1-\eta_i)}. \quad (2.45)$$

The law of motion for the households physical capital stock is given by

$$\bar{K}_{t+1} = (1 - \delta) \bar{K}_t + \Upsilon_t F(I_t, I_{t-1}) + \Delta_t \quad (2.46)$$

and is assumed to be identical for all households.¹⁰ $F(I_t, I_{t-1})$ is a function which turns investment into physical capital. We will adopt the specification of Christiano, Eichenbaum and Evans (2005) and assume that

$$F(I_t, I_{t-1}) = \left(1 - \tilde{S}(I_t/I_{t-1}) \right) I_t \quad (2.47)$$

where $\tilde{S}(\mu_z) = \tilde{S}'(\mu_z) = 0$, and $\tilde{S}''(\mu_z) \equiv \tilde{S}'' > 0$.¹¹ Note that only the parameter \tilde{S}'' is identified and will be used in the log-linearized model. Moreover, (2.47) implies

$$\begin{aligned} F_1(I_t, I_{t-1}) &\equiv \frac{\partial F(I_t, I_{t-1})}{\partial I_t} = -\tilde{S}'(I_t/I_{t-1}) I_t/I_{t-1} + \left(1 - \tilde{S}(I_t/I_{t-1}) \right), \\ F_2(I_t, I_{t-1}) &\equiv \frac{\partial F(I_t, I_{t-1})}{\partial I_{t-1}} = \tilde{S}'(I_t/I_{t-1}) \left(\frac{I_t}{I_{t-1}} \right)^2 \end{aligned}$$

¹⁰The variable, Δ_t , reflects that households have access to a market where they can purchase new, installed capital, \bar{K}_{t+1} . Households wishing to sell \bar{K}_{t+1} are the only suppliers in this market, while households wishing to buy \bar{K}_{t+1} are the only source of demand. Since all households are identical, the only equilibrium is one in which $\Delta_t = 0$. We nevertheless introduce this variable as a convenient way to define the price of capital, $P_{k',t}$. See Christiano, Eichenbaum and Evans (2005) for further details.

¹¹One functional form for \tilde{S} that satisfies these properties is given by $\tilde{S}(x) = g_3 \{ \exp[g_1(x - \mu_z)] + \frac{g_1}{g_2} \exp[-g_2(x - \mu_z)] - (1 + \frac{g_1}{g_2}) \}$ where g_1, g_2 and g_3 are all positive constants. Recalling that real investment grows at rate μ_z in the steady state, we have that $\tilde{S}(\mu_z) = 0$, $\tilde{S}'(\mu_z) = g_1 g_3 \{ \exp[g_1(\mu_z - \mu_z)] - \exp[-g_2(\mu_z - \mu_z)] \} = 0$, and $\tilde{S}''(\mu_z) \equiv \tilde{S}'' = g_1 g_3 \{ g_1 + g_2 \} > 0$, since g_1, g_2 and g_3 are all positive.

so that the following holds in steady state:

$$\begin{aligned} F_1(I, I) &= -\tilde{S}'(\mu_z)\mu_z + \left(1 - \tilde{S}(\mu_z)\right) = 1, \\ F_2(I, I) &= \tilde{S}'(\mu_z)\mu_z^2 = 0. \end{aligned} \tag{2.48}$$

In (2.46), Υ_t is a stationary investment-specific technology shock, given by the following exogenous AR(1)-process

$$\hat{\Upsilon}_t = \rho_{\Upsilon} \hat{\Upsilon}_{t-1} + \varepsilon_{\Upsilon,t}$$

where $\hat{\Upsilon}_t = (\Upsilon_t - 1)/1$.¹²

Households face two forms of uncertainty. There is aggregate uncertainty that stems from aggregate shocks. In addition, the households face idiosyncratic uncertainty. Being a monopoly supplier of its own labour, it sets its wage rate. However, it can only adjust its wage at exogenously and randomly determined points in time. In modeling this, we follow Calvo (1983). We further restrict the analysis by making assumptions which guarantee that the frictions do not cause households to become heterogeneous. We do this by allowing households to enter into insurance markets against the outcomes of these frictions. The assumption of complete domestic financial markets in this economy - i.e., that each household can insure against any type of idiosyncratic risk through the purchase of the appropriate portfolio of securities - preserves the representative agent framework. This implies that we do not need to keep track of the entire distribution of the households' wealth, which would otherwise become a state variable. Since households are identical *ex ante* they are willing to enter such insurance contracts. As a result, all households face the same budget constraint in each period which (in nominal terms) is given by

$$\begin{aligned} &M_{j,t+1} + S_t B_{j,t+1}^* + P_t^c C_{j,t} (1 + \tau_t^c) + P_t^i I_{j,t} + P_t (a(u_{j,t}) \bar{K}_{j,t} + P_{k',t} \Delta_t) \\ = &R_{t-1} (M_{j,t} - Q_{j,t}) + Q_{j,t} + (1 - \tau_t^k) \Pi_t + (1 - \tau_t^y) \frac{W_{j,t}}{1 + \tau_t^w} h_{j,t} \\ &+ (1 - \tau_t^k) R_t^k u_{j,t} \bar{K}_{j,t} + R_{t-1}^* \Phi\left(\frac{A_{t-1}}{z_{t-1}}, \tilde{\phi}_{t-1}\right) S_t B_{j,t}^* \\ &- \tau_t^k \left[(R_{t-1} - 1) (M_{j,t} - Q_{j,t}) + \left(R_{t-1}^* \Phi\left(\frac{A_{t-1}}{z_{t-1}}, \tilde{\phi}_{t-1}\right) - 1 \right) S_t B_{j,t}^* + B_{j,t}^* (S_t - S_{t-1}) \right] \\ &+ TR_t + D_{j,t}, \end{aligned} \tag{2.49}$$

where the subscript j denotes household choice variables and upper-case variables without the subscript denote economy-wide averages. The terms on the left hand side of the equality show how the household use their resources, while the terms on the right hand side show what resources the households have at their disposal. $P_t^i I_{j,t}$ is nominal resources spent by the household on investment goods. All interest rates are expressed as gross rates, i.e. $R_t = 1 + r_t$. Households hold their financial assets in the form of cash balances, domestic bank deposits and foreign bonds. They earn interest on the amount of their nominal domestic assets that are not held as cash, i.e. $M_{j,t} - Q_{j,t}$.¹³ The interest rate they earn is R_{t-1} , since we think of the deposits paying out a nominal amount with certainty (i.e., a zero coupon

¹²In the Altig et al. (2003) model this is a trend-stationary technology shock, but for simplicity we here assume that it is stationary without a trend.

¹³Note that the end of period after-tax net interest income on funds deposited at the financial intermediary at the beginning of the period (i.e. $m_t - q_t$) is $(1 - \tau_t^k) (R_{t-1} - 1) (m_t - q_t)$ and that the resources for this type of assets that the households have at their disposal are $(1 - \tau_t^k) (R_{t-1} - 1) (m_t - q_t) + m_t$.

bond).¹⁴ They can also save in foreign bonds, which pay a risk-adjusted pre-tax gross interest rate of $R_{t-1}^* \Phi(A_{t-1}/z_{t-1}, \tilde{\phi}_{t-1})$.

Following Lundvik (1992) and Benigno (2001), the term $\Phi(\frac{A_t}{z_t}, \tilde{\phi}_t)$ is a premium on foreign bond holdings, which depends on the real aggregate net foreign asset position of the domestic economy, defined as

$$A_t \equiv \frac{S_t B_{t+1}^*}{P_t}. \quad (2.50)$$

The function $\Phi(\frac{A_t}{z_t}, \tilde{\phi}_t)$ is assumed to be strictly decreasing in A_t and to satisfy $\Phi(0, 0) = 1$. Consequently, this function captures imperfect integration in the international financial markets. If the domestic economy as a whole is a net borrower (so $B_{t+1}^* < 0$), domestic households are charged a premium on the foreign interest rate. If the domestic economy is a net lender ($B_{t+1}^* > 0$), households receive a lower remuneration on their savings. The introduction of this risk-premium is needed in order to ensure a well-defined steady-state in the model (see Schmitt-Grohé and Uribe, 2003, for further details). $\tilde{\phi}_t$, in turn, is a time varying shock to the risk premium.

Since households own the physical capital stock, the capital adjustment costs are paid by the households, which explains the presence of $a(u_t)P_t$ in the budget constraint. Here, $a(u)$ is the utilization cost function, satisfying $a(1) = 0$, $u = 1$ and $a' = (1 - \tau^k) r^k$ in steady state, and $a'' \geq 0$. u_t is the utilization rate, that is $u_t = K_t/\bar{K}_t$. $P_{k',t}\Delta_t$ is present to be able to compute the price of capital in the model. Notice that we will set ϕ so that profits, Π_t , are zero in steady state. τ_t^c is a consumption tax, τ_t^w is a pay-roll tax (assumed for simplicity to be paid by the households), τ_t^y is a labour-income tax, and τ_t^k is a capital-income tax. TR_t are lump-sum transfers from the government and $D_{j,t}$ is the household's net cash income from participating in state contingent securities at time t .

By using (2.37), (2.49) and (2.46), households solve the following Lagrangian problem:

$$\begin{aligned} & \max_{C_{j,t}, M_{j,t+1}, \Delta_t, \bar{K}_{j,t+1}, I_{j,t}, u_{j,t}, Q_{j,t}, B_{j,t+1}^*, h_{j,t}} E_0^j \sum_{t=0}^{\infty} \beta^t [\tilde{L}_t], \\ \tilde{L}_t = & \left\{ +v_t \left[\begin{aligned} & \zeta_t^c \ln(C_{j,t} - bC_{j,t-1}) - \zeta_t^h A_L \frac{(h_{j,t})^{1+\sigma_L}}{1+\sigma_L} + A_q \frac{(Q_{j,t})^{1-\sigma_q}}{1-\sigma_q} \\ & R_{t-1} (M_{j,t} - Q_{j,t}) + Q_{j,t} + (1 - \tau_t^k) \Pi_t + (1 - \tau_t^y) \frac{W_{j,t}}{1+\tau_t^w} h_{j,t} \\ & + (1 - \tau_t^k) R_{t-1}^k u_{j,t} \bar{K}_{j,t} + R_{t-1}^* \Phi(a_{t-1}, \tilde{\phi}_{t-1}) S_t B_{j,t}^* \\ & - \tau_t^k \left((R_{t-1} - 1) (M_{j,t} - Q_{j,t}) + \left(R_{t-1}^* \Phi(a_{t-1}, \tilde{\phi}_{t-1}) - 1 \right) S_t B_{j,t}^* + B_{j,t} (S_t - S_{t-1}) \right) \\ & + TR_{j,t} + D_{j,t} \\ & - \left(M_{j,t+1} + S_t B_{j,t+1}^* + P_t^c C_{j,t} (1 + \tau_t^c) + P_t^i I_{j,t} + P_t (a(u_{j,t}) \bar{K}_{j,t} + P_{k',t} \Delta_t) \right) \\ & + \omega_t [(1 - \delta) \bar{K}_{j,t} + \Upsilon_t F(i_t, i_{t-1}) + \Delta_t - \bar{K}_{j,t+1}] \end{aligned} \right] \right\}. \end{aligned}$$

We will now state the first-order conditions for the households' problem, where we make use of the fact that the households' average (aggregate) choices coincide in equilibrium. To render stationarity of all variables, we need to divide all quantities with the trend level of technology z_t (see 2.13), and multiply the Lagrangian multiplier $\psi_t \equiv v_t P_t$ with it. As explained earlier, we let small letters indicate that a variable have been stationarized (i.e., real variables are stationarized as $x_t = \frac{X_t}{z_t}$), and for the

¹⁴To see this, assume that a zero coupon bond paying out B_{t+1} in period $t+1$ can be bought at price $1/R_t$ in period t . The households pay a tax (τ_t^k) on the interest income from this bond. The following resource constraint must then hold for the bonds; $\frac{B_{t+1}}{R_t} = B_t - \tau_t^k (R_{t-1} - 1) \frac{B_t}{R_{t-1}}$. Now define $\tilde{B}_{t+1} = \frac{B_{t+1}}{R_t}$, which implies that this can be rewritten as $\tilde{B}_{t+1} = \tilde{B}_t R_{t-1} - \tau_t^k (R_{t-1} - 1) \tilde{B}_t$, so the interest earnings of period $t+1$ are known with certainty in period t (i.e., $\tau_{t+1}^k (R_t - 1) \frac{B_{t+1}}{R_t}$).

multiplier, we introduce the notation $\psi_{z,t} \equiv z_t \psi_t$. After scaling with the technology level, we obtain the following set of first-order conditions (evaluated in equilibrium)

$$\text{w.r.t. } c_t : \frac{\zeta_t^c}{c_t - bc_{t-1} \frac{1}{\mu_{z,t}}} - \beta b E_t \frac{\zeta_{t+1}^c}{c_{t+1} \mu_{z,t+1} - bc_t} - \psi_{z,t} \frac{P_t^c}{P_t} (1 + \tau_t^c) = 0, \quad (2.51)$$

$$\text{w.r.t. } m_{t+1} : -\psi_{z,t} + \beta E_t \left[\frac{\psi_{z,t+1}}{\mu_{z,t+1}} \frac{R_t}{\pi_{t+1}} - \frac{1}{\mu_{z,t+1}} \frac{\psi_{z,t+1}}{\pi_{t+1}} \tau_{t+1}^k (R_t - 1) \right] = 0, \quad (2.52)$$

$$\text{w.r.t. } \Delta_t : -\psi_t P_{k',t} + \omega_t = 0, \quad (2.53)$$

$$\text{w.r.t. } \bar{k}_{t+1} : -P_{k',t} \psi_{z,t} + \beta E_t \left[\frac{\psi_{z,t+1}}{\mu_{z,t+1}} ((1 - \delta) P_{k',t+1} + (1 - \tau_{t+1}^k) r_{t+1}^k u_{t+1} - a(u_{t+1})) \right] = 0, \quad (2.54)$$

$$\text{w.r.t. } i_t : -\psi_{z,t} \frac{P_t^i}{P_t} + P_{k',t} \psi_{z,t} \Upsilon_t F_1(i_t, i_{t-1}, \mu_{z,t}) + \beta E_t \left[P_{k',t+1} \frac{\psi_{z,t+1}}{\mu_{z,t+1}} \Upsilon_{t+1} F_2(i_{t+1}, i_t, \mu_{z,t+1}) \right] = 0, \quad (2.55)$$

$$\text{w.r.t. } u_t : \psi_{z,t} \left((1 - \tau_t^k) r_t^k - a'(u_t) \right) = 0, \quad (2.56)$$

$$\text{w.r.t. } q_t : \zeta_t^q A_q q_t^{-\sigma_q} - (1 - \tau_t^k) \psi_{z,t} (R_{t-1} - 1) = 0, \quad (2.57)$$

$$\text{w.r.t. } b_{t+1}^* : -\psi_{z,t} S_t + \beta E_t \left[\frac{\psi_{z,t+1}}{\mu_{z,t+1} \pi_{t+1}} (S_{t+1} R_t^* \Phi(a_t, \tilde{\phi}_t) - \tau_{t+1}^k S_{t+1} (R_t^* \Phi(a_t, \tilde{\phi}_t) - 1)) - \tau_{t+1}^k (S_{t+1} - S_t) \right] = 0, \quad (2.58)$$

where the investment variables in the first-order condition associated with i_t has been scaled using the expression given by (2.48).¹⁵ The log-linearized equations can be found in Appendix B.

By combining the households' first order conditions for domestic and foreign bond holdings (2.52 and 2.58, respectively) we obtain, after log-linearization, the following modified uncovered interest rate parity condition:

$$\widehat{R}_t - \widehat{R}_t^* = E_t \Delta \widehat{S}_{t+1} - \tilde{\phi}_a \widehat{a}_t + \widehat{\phi}_t, \quad (2.59)$$

where we have assumed that the premium on foreign bond holdings follows the function $\Phi(a_t, \tilde{\phi}_t) = \exp \left(-\tilde{\phi}_a (a_t - \bar{a}) + \tilde{\phi}_t \right)$. Because of imperfect integration in the international financial markets, the net foreign asset position \widehat{a}_t of the domestic economy thus enters the interest rate parity condition.

¹⁵Notice that, with the exception of b_{t+1}^* , all first order conditions above coincide with those reported in the technical appendix to Altig et al. (2003) when the tax-rates equal nil and when relative prices $\frac{P_t^c}{P_t}$, $\frac{P_t^i}{P_t}$ for consumption and investment equal unity.

2.2.1. Wage setting equation

Each household is a monopoly supplier of a differentiated labour service requested by the domestic firms. This implies that the households can determine their own wage. After having set their wages, households inelastically supply the firms' demand for labour at the going wage rate.

In modeling this wage equation we follow Erceg et al. (2000) and Christiano et al. (2005), and introduce wage stickiness à la Calvo. Each household sells its labour ($h_{j,t}$) to a firm which transforms household labour into a homogeneous input good H using the following production function:

$$H_t = \left[\int_0^1 (h_{j,t})^{\frac{1}{\lambda_w}} dj \right]^{\lambda_w}, \quad 1 \leq \lambda_w < \infty, \quad (2.60)$$

where λ_w is the wage markup. This firm takes the input price of the j^{th} differentiated labour input as given, as well as the price of the homogenous labour services. The demand for labour that an individual household faces is determined by

$$h_{j,t} = \left[\frac{W_{j,t}}{W_t} \right]^{\frac{\lambda_w}{1-\lambda_w}} H_t. \quad (2.61)$$

In every period each household faces a random probability $1 - \xi_w$ that it can change its nominal wage. The j^{th} household's reoptimized wage is set to $W_{j,t}^{new}$, taking into account the probability ξ_w that the wage will not be reoptimized in the future. The households that can not reoptimize set their wages according to

$$W_{j,t+1} = (\pi_t^c)^{\kappa_w} (\bar{\pi}_{t+1}^c)^{(1-\kappa_w)} \mu_{z,t+1} W_{j,t},$$

where

$$\mu_{z,t+1} = \frac{z_{t+1}}{z_t}.$$

Consequently, non-optimizing households index their wage rate to last period's CPI inflation rate, the current inflation target, as well as adding a technology growth factor to their wage. If a period t optimizing household is not allowed to change its wage during s periods ahead, the wage in period $t + s$ is $W_{j,t+s} = (\pi_t^c \dots \pi_{t+s-1}^c)^{\kappa_w} (\bar{\pi}_{t+1}^c \dots \bar{\pi}_{t+s}^c)^{(1-\kappa_w)} (\mu_{z,t+1} \dots \mu_{z,t+s}) W_{j,t}^{new}$. The j^{th} household that can reoptimize its wage faces the following optimization problem (where irrelevant terms have been suppressed in the household's objective function (2.51))

$$\max_{W_{j,t}^{new}} E_t \sum_{s=0}^{\infty} (\beta \xi_w)^s \left[-\zeta_{t+s}^h A_L \frac{(h_{j,t+s})^{1+\sigma_L}}{1+\sigma_L} + v_{t+s} \frac{(1-\tau_{t+s}^y)}{(1+\tau_{t+s}^w)} \times \left((\pi_t^c \dots \pi_{t+s-1}^c)^{\kappa_w} (\bar{\pi}_{t+1}^c \dots \bar{\pi}_{t+s}^c)^{(1-\kappa_w)} (\mu_{z,t+1} \dots \mu_{z,t+s}) W_{j,t}^{new} \right) h_{j,t+s} \right]. \quad (2.62)$$

Inserting the relevant expressions for $h_{j,t+s}$ in the optimization problem above yields the following first order condition

$$E_t \sum_{s=0}^{\infty} (\beta \xi_w)^s h_{j,t+s} \left[-\zeta_{t+s}^h A_L (h_{j,t+s})^{\sigma_L} + \frac{W_{j,t}^{new}}{z_t P_t} \frac{z_{t+s} v_{t+s} P_{t+s}}{\lambda_w} \frac{(1-\tau_{t+s}^y)}{(1+\tau_{t+s}^w)} \frac{\left(\frac{P_{t+s}^c}{P_{t-1}^c} \right)^{\kappa_w} (\bar{\pi}_{t+1}^c \dots \bar{\pi}_{t+s}^c)^{(1-\kappa_w)}}{\frac{P_{t+s}^d}{P_t^d}} \right] = 0, \quad (2.63)$$

which is the Euler equation for the wage rate, and where $-\zeta_{t+s}^h A_L (h_{j,t+s})^{\sigma_L}$ is the marginal disutility of labour. Log-linearizing equation (2.63) yields the log-linearized wage equation in Appendix B. When wages are fully flexible ($\xi_w = 0$), the real wage is set as a markup λ_w over the current ratio of the marginal disutility of labour and the marginal utility of additional income. In this case the households' wage decision is equivalent to the first order condition for their choice of labour input, i.e

$$-\zeta_t^h A_L H_t^{\sigma_L} + (1 - \tau_t^y) \frac{\psi_{z,t}}{\lambda_w} \frac{\bar{w}_{j,t}}{1 + \tau_t^w} = 0. \quad (2.64)$$

2.3. Government

The government budget constraint in this economy equals

$$P_t G_t + TR_t = R_{t-1} (M_{t+1} - M_t) + \tau_t^c P_t^c C_t + \frac{(\tau_t^y + \tau_t^w) W_t}{1 + \tau_t^w} H_t + \tau_t^k \left[(R_{t-1} - 1) (M_t - Q_t) + R_t^k u_t \bar{K}_t + \left(R_{t-1}^* \Phi(a_{t-1}, \tilde{\phi}_{t-1}) - 1 \right) S_t B_t^* + \Pi_t \right],$$

where TR_t has the interpretation of a budget deficit. Consequently, there is no government debt.¹⁶

We will assume that tax-rates and government expenditures are given exogenously by a simple VAR-model. Let $\tau_t = [\hat{\tau}_t^k \ \hat{\tau}_t^y \ \hat{\tau}_t^c \ \hat{\tau}_t^w \ \tilde{G}_t]'$, where \tilde{G}_t denotes detrended (HP-filtered) government expenditures. The fiscal policy VAR-model is given by

$$\Gamma_0 \tau_t = \Gamma(L) \tau_{t-1} + \varepsilon_{\tau,t}, \quad \varepsilon_{\tau,t} \sim N(0, \Sigma_\tau). \quad (2.65)$$

When estimating this process in the data, we tested whether we could reject the assumption that the off-diagonal terms in Γ_0 were zero. Since we could not reject this hypothesis, we are able to study the effects of a particular fiscal policy variable, and not just assessing their total importance for how the economy evolves.

2.4. Relative prices

We will now discuss the various stationary relative prices that enter the model. There are two different types of *domestic* relative prices. One is defined in terms of the imported consumption goods and one in terms of the investment goods. That is, the relative prices between domestic goods and imported consumption, or investment, goods perceived by the domestic agents. The two (domestic) relative prices occur since the domestic agents face different prices on the imported consumption goods and the imported investment goods:

$$\gamma_t^{mc,d} \equiv \frac{P_t^{m,c}}{P_t}, \quad (2.66)$$

$$\gamma_t^{mi,d} \equiv \frac{P_t^{m,i}}{P_t}. \quad (2.67)$$

The agents additionally make use of the following relative prices when determining their consumption and investment baskets

$$\gamma_t^{c,d} \equiv \frac{P_t^c}{P_t}, \quad (2.68)$$

$$\gamma_t^{i,d} \equiv \frac{P_t^i}{P_t}. \quad (2.69)$$

There is also the relative price between the domestically produced goods (home exports) and the foreign goods;

$$\gamma_t^{x,*} \equiv \frac{P_t^x}{P_t^*}, \quad (2.70)$$

¹⁶One way to understand that (2.65) is correct is to insert it into the households budget constraint (2.49, evaluated at the aggregate level), which implies that all the tax-terms except $P_t G_t$ and $R_{t-1} (M_{t+1} - M_t)$ will cancel as they should.

which is the relative price observed by the foreign agents (as well as the domestic exporters). Deviations from the law of one price for the export goods are given by

$$mc_t^x \equiv \frac{P_t}{S_t P_t^x}. \quad (2.71)$$

We can then make use of the above to define the following relative prices which are used by the exporting and importing firms

$$\gamma_t^f \equiv \frac{P_t}{S_t P_t^*} = mc_t^x \gamma_t^{x,*}. \quad (2.72)$$

$$mc_t^{m,c} \equiv \frac{S_t P_t^*}{P_t^{m,c}} = \frac{1}{(\gamma_t^f) (\gamma_t^{mj,d})} = \frac{1}{(mc_t^x \gamma_t^{x,*}) (\gamma_t^{mc,d})} \quad (2.73)$$

$$mc_t^{m,i} \equiv \frac{S_t P_t^*}{P_t^{m,i}} = \frac{1}{(\gamma_t^f) (\gamma_t^{mi,d})} = \frac{1}{(mc_t^x \gamma_t^{x,*}) (\gamma_t^{mi,d})} \quad (2.74)$$

2.5. The central bank

Rather than assuming that monetary policy aims at optimizing a specific loss function, we approximate the behaviour of the central bank with an instrument rule. Following Smets and Wouters (2003a), the policy maker is assumed to adjust the short run interest rate in response to deviations of CPI inflation from the inflation target ($\hat{\pi}_t^c - \hat{\pi}^c$), the output gap (\hat{y}_t) and the real exchange rate (\hat{x}_t). We also allow for interest rate smoothing. Although instrument rules are not based on optimizing behaviour, they appear to perform well from an empirical viewpoint, and it is not obvious that these rules perform substantially worse than optimal rules from a welfare perspective.¹⁷

Thus, monetary policy is approximated with the following rule (expressed in log-linear form)

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1 - \rho_R) (\hat{\pi}_t^c + r_\pi (\hat{\pi}_{t-1}^c - \hat{\pi}^c) + r_y \hat{y}_{t-1} + r_x \hat{x}_{t-1}) + r_{\Delta\pi} \Delta \hat{\pi}_t^c + r_{\Delta y} \Delta \hat{y}_t + \varepsilon_{R,t}, \quad (2.75)$$

where \hat{R}_t is the short-rate interest rate, $\hat{\pi}_t^c$ the CPI inflation rate, \hat{y}_t the output gap and \hat{x}_t denotes the log-linearized real exchange rate, which is given by

$$\hat{x}_t = \hat{S}_t + \hat{P}_t^* - \hat{P}_t^c.$$

The output gap is measured as the deviation from the trend value of output in the economy, and thus not as the deviation from the flexible price level as in Smets and Wouters (2003a). We assume that the central bank responds to the model-consistent measure of the CPI inflation rate index, $\hat{\pi}_t^c$, but omits indirect taxes $\hat{\tau}_t^c$, i.e.

$$\hat{\pi}_t^c = \left((1 - \omega_c) (\gamma^{d,c})^{1-\eta_c} \right) \hat{\pi}_t^d + \left((\omega_c) (\gamma^{mc,c})^{(1-\eta_c)} \right) \hat{\pi}_t^{m,c}. \quad (2.76)$$

$\hat{\pi}_t^c$ is a time-varying inflation target and $\varepsilon_{R,t}$ is an interest rate shock. We will refer to the first as an inflation target shock and the latter as a monetary policy shock. The deviation of the inflation target from the steady-state inflation rate is assumed to follow the process

$$\hat{\pi}_t^c = \rho_\pi \hat{\pi}_{t-1}^c + \varepsilon_{\hat{\pi}^c,t}. \quad (2.77)$$

¹⁷Onatski and Williams (2004) find that instrument rules perform relatively well compared to optimal rules in the Smets and Wouters (2003a) model, and that they are more robust to different parameter estimates.

2.6. Market clearing conditions

In equilibrium the final goods market, the loan market and the foreign bond market must clear. The final goods market clears when the demand from the households, the government and the foreign market can be met by the production of the final good firm. The loan market, in turn, clears when the demand for liquidity from the firms (financing their wage bills) equals the supplied deposits of the households plus the monetary injection by the central bank. The foreign bond market is in equilibrium when the positions of the export and importing firms equals the households' choice of foreign bond holdings.

2.6.1. The aggregate resource constraint

The equilibrium resource constraint from the production perspective satisfies

$$C_t^d + I_t^d + G_t + C_t^x + I_t^x \leq \epsilon_t z_t^{1-\alpha} K_t^\alpha H_t^{1-\alpha} - z_t \phi - a(u_t) \bar{K}_t. \quad (2.78)$$

By substituting (2.39), (2.35), (2.43) and (2.36) into (2.78), we obtain

$$\begin{aligned} (1 - \omega_c) \left[\frac{P_t^c}{P_t} \right]^{\eta_c} c_t + (1 - \omega_i) \left[\frac{P_t^i}{P_t} \right]^{\eta_i} i_t + g_t + \left[\frac{P_t^x}{P_t^*} \right]^{-\eta_f} y_t^* \frac{z_t^*}{z_t} \\ \leq \epsilon_t \left(\frac{1}{\mu_{z,t}} \right)^\alpha k_t^\alpha H_t^{1-\alpha} - \phi - a(u_t) \bar{k}_t \frac{1}{\mu_{z,t}}, \end{aligned} \quad (2.79)$$

where we have used the assumption that $Y_t^* = C_t^* + I_t^*$, scaled K_t and \bar{K}_t with z_{t-1} , and stationarized the other real variables with z_t . Note that Y_t^* has been scaled with z_t^* which is the reason why $\frac{z_t^*}{z_t}$ appears in the formula. z_t^* is supposed to follow a similar process as z_t . We will maintain the assumption that $\mu_z = \mu_z^*$, and treat $\tilde{z}_t^* = \frac{z_t^*}{z_t}$ as a stationary shock which measures the degree of asymmetry in the technological progress in the domestic economy versus the rest of the world. By assuming $z_0^* = z_0 = 1$ this implies that the technology levels must be the same in steady state, $\tilde{z}^* = 1$. We assume that the asymmetric technology shock follows the process (log-linearized)

$$\hat{\tilde{z}}_{t+1}^* = \rho_{\tilde{z}^*} \hat{\tilde{z}}_t^* + \varepsilon_{\tilde{z}^*,t+1}. \quad (2.80)$$

Totally differentiating equation (2.79) and evaluating in steady state, using the steady-state relationships,

$$\begin{aligned} \left(\frac{1}{\mu_z} \right)^\alpha k^\alpha H^{1-\alpha} &= y + \phi = y + (\lambda_d - 1)y = \lambda_d y, \\ \gamma^{x,*} &= 1, \\ a(u) &= 0, \\ a'(u) &= (1 - \tau^k) r^k, \\ \hat{u}_t &= du_t = \hat{k}_t - \hat{\bar{k}}_t, \\ d\epsilon_t &= \hat{\epsilon}_t, \end{aligned}$$

we derive the log-linearized resource constraint as

$$\begin{aligned}
& (1 - \omega_c) \left(\gamma^{c,d} \right)^{\eta_c} \frac{c}{y} \left(\hat{c}_t + \eta_c \hat{\gamma}_t^{c,d} \right) + (1 - \omega_i) \left(\gamma^{i,d} \right)^{\eta_i} \frac{i}{y} \left(\hat{i}_t + \eta_i \hat{\gamma}_t^{i,d} \right) \\
& + \frac{g}{y} \hat{g}_t + \frac{y^*}{y} \left(\hat{y}_t^* - \eta_f \hat{\gamma}_t^{x,*} + \hat{z}_t^* \right) \\
& = \lambda_d \left(\hat{e}_t + \alpha \left(\hat{k}_t - \hat{\mu}_{z,t} \right) \right) + (1 - \alpha) \hat{H}_t - \left(1 - \tau^k \right) r^k \frac{\bar{k}}{y} \frac{1}{\mu_z} \left(\hat{k}_t - \hat{\bar{k}}_t \right).
\end{aligned} \tag{2.81}$$

2.6.2. Evolution of net foreign assets

The evolution of net foreign assets at the aggregate level satisfies

$$S_t B_{t+1}^* = S_t P_t^x (C_t^x + I_t^x) - S_t P_t^* (C_t^m + I_t^m) + R_{t-1}^* \Phi(a_{t-1}, \tilde{\phi}_{t-1}) S_t B_t^*, \tag{2.82}$$

where we notice that $R_{t-1}^* \Phi(a_{t-1}, \tilde{\phi}_{t-1})$ is the risk-adjusted gross nominal interest rate. Note that the definition of a_t is given by

$$a_t \equiv \frac{S_t B_{t+1}^*}{P_t z_t}.$$

Multiplying through with $1/(P_t z_t)$, using $\frac{C_t^x}{z_t} + \frac{I_t^x}{z_t} = \left[\frac{P_t^x}{P_t^*} \right]^{-\eta_f} \frac{Y_t^*}{z_t^*} \frac{z_t^*}{z_t}$ and our definition of a_t , we have

$$a_t = (m c_t^x)^{-1} (\gamma_t^{x,*})^{-\eta_f} y_t^* \tilde{z}_t^* - \left(\gamma_t^f \right)^{-1} (c_t^m + i_t^m) + R_{t-1}^* \Phi(a_{t-1}, \tilde{\phi}_{t-1}) \frac{a_{t-1}}{\pi_t \mu_{z,t}} \frac{S_t}{S_{t-1}},$$

where we allow for an asymmetric technology shock $\tilde{z}_t^* = \frac{z_t^*}{z_t}$ (see the discussion in the subsection above), and where $m c_t^x = \frac{P_t}{S_t P_t^x}$. Totally differentiating this expression, and evaluating in the steady state where $a = 0$, $\Phi(0, 0) = 1$, $R^* = R$, $\frac{\bar{S}_t}{S_{t-1}} = 1$, $\gamma^f = \frac{P}{S P^*} = 1$, $m c^x = \frac{P}{S P^x} = \frac{P}{S(P/S)} = 1$, and $\gamma^{x,*} = \frac{P^x}{P^*} = \frac{P}{S P^*} = 1$, we derive the linearized equation for net foreign assets as

$$\begin{aligned}
\hat{a}_t &= -y^* \widehat{m c}_t^x - \eta_f y^* \hat{\gamma}_t^{x,*} + y^* \hat{y}_t^* + y^* \hat{z}_t^* \\
&+ (c^m + i^m) \hat{\gamma}_t^f - c^m \left(-\eta_c (1 - \omega_c) \left(\gamma^{c,d} \right)^{-(1-\eta_c)} \hat{\gamma}_t^{mc,d} + \hat{c}_t \right) \\
&+ i^m \left(-\eta_i (1 - \omega_i) \left(\gamma^{i,d} \right)^{-(1-\eta_i)} \hat{\gamma}_t^{mi,d} + \hat{i}_t \right) + \frac{R}{\pi \mu_z} \hat{a}_{t-1},
\end{aligned} \tag{2.83}$$

where we have used $\hat{a}_t = da_t$ and the expressions for \hat{c}_t^m and \hat{i}_t^m (see 2.40, 2.40, 2.66 and 2.67).

2.6.3. Loan market clearing

We also have the money market clearing condition, which reads

$$\nu W_t H_t = \mu_t M_t - Q_t, \tag{2.84}$$

or equivalently, in its stationarized form,

$$\nu \bar{w}_t H_t = \frac{\mu_t \bar{m}_t}{\pi_t \mu_{z,t}} - q_t. \tag{2.85}$$

2.7. Foreign economy

We adopt the assumption that foreign inflation, output and interest rate are exogenously given. Let $X_t^* \equiv [\pi_t^* \ \hat{y}_t^* \ R_t^*]'$ where π_t^* and R_t^* are quarterly foreign inflation and interest rates, and \hat{y}_t^* foreign HP-filtered output. The foreign economy is modeled as a VAR model,

$$F_0 X_t^* = F(L) X_{t-1}^* + \varepsilon_{x^*,t}, \quad \varepsilon_{x^*,t} \sim N(0, \Sigma_{x^*}). \quad (2.86)$$

When estimating the VAR, we assume and can not reject that F_0 in (2.86) has the following structure

$$F_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -\gamma_{\pi,0}^* & -\gamma_{y,0}^* & 1 \end{bmatrix}.$$

The above structure of F_0 is equivalent to assuming predetermined expectations in the Phillips curve and output equation. Since we cannot reject this structure of F_0 , we are able to identify the effects of a specific foreign shock.

3. Data and measurement issues

3.1. Data

To estimate the model we use quarterly Euro area data for the period 1970:1-2002:4.¹⁸ The data set we employ was first constructed by Fagan et al. (2001). We have chosen to match the following set of 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 rate. To calculate the likelihood function of the observed variables we apply the Kalman filter. 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 and derive the state space representation for the following vector of observed variables

$$\tilde{Y}_t = \begin{bmatrix} \pi_t^d & \Delta \ln(W_t/P_t) & \Delta \ln C_t & \Delta \ln I_t & \hat{x}_t & R_t & \hat{E}_t & \Delta \ln Y_t \dots \\ & \Delta \ln \tilde{X}_t & \Delta \ln \tilde{M}_t & \pi_t^{def,c} & \pi_t^{def,i} & \Delta \ln Y_t^* & \pi_t^* & R_t^* \end{bmatrix}'. \quad (3.1)$$

In comparison with the previous literature, we have chosen to work with a large number of variables, in order 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^*).¹⁹

For the Euro area there is no (official) data on aggregate hours worked, H_t . Due to these data limitations we use employment \hat{E}_t in our empirical estimations. Since employment is likely to respond

¹⁸We 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.

¹⁹We 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

$$\tilde{Y}_t = \begin{bmatrix} \pi_t^d & \ln(W_t/P_t) - \ln Y_t & \ln C_t - \ln Y_t & \ln I_t - \ln Y_t & \hat{x}_t & R_t & \hat{E}_t & \Delta \ln Y_t \dots \\ & \ln \tilde{X}_t - \ln Y_t & \ln \tilde{M}_t - \ln Y_t & \pi_t^{def,c} & \pi_t^{def,i} & \ln Y_t^* - \ln Y_t & \pi_t^* & R_t^* \end{bmatrix}'.$$

As the inflation rates, nominal interest rates, employment, and the real exchange rate are all stationary variables, this makes all of \tilde{Y}_t stationary. The estimation results for the model with this vector of observable variables are very similar to the ones using data in first differences, see Table D1.

more slowly to shocks than hours worked, we model employment using Calvo-rigidity (following Smets and Wouters, 2003a). We assume that only a fraction $(1 - \xi_e)$ of the firms can adjust the level of employment to the preferred amount of total labour input. The rest of the firms ξ_e are forced to keep the level of employment they had in the last period, $\hat{E}_{i,t+1} = \hat{E}_{i,t}^{new}$. The difference is taken up by each worker's labour input (unobserved hours per worker). That is, each worker supplies its labour inelastically after having set his or her wage. The aggregate employment equation then follows²⁰

$$\Delta \hat{E}_t = \beta E_t \Delta \hat{E}_{t+1} + \frac{(1 - \xi_e)(1 - \beta \xi_e)}{\xi_e} (\hat{H}_t - \hat{E}_t), \quad (3.2)$$

where $\hat{E}_t = d\tilde{E}_t/\tilde{E}$.

We have adjusted the raw data for three series. First, there is an upward trend in the employment series for the Euro area, presumably reflecting an increasing degree of part-time employment (apart from population growth). Since hours worked and employment per capita are stationary variables in the model, we decided to remove a linear trend in this variable prior to estimation. Second, the shares of import and export to output are increasing during the sample period, from about 0.15 to 0.36. Although these numbers are distorted by the fact that a part of this increase reflects intra-Euro trade, they also convey a clear pattern of increasing trade. In our model, import and export are assumed to grow at the same rate as output. Therefore, we decided to remove the excessive trend of import and export in the data, to render the export and import shares stationary.²¹

For all other variables in (3.1), we use the actual series (seasonally adjusted with the X12-method). It should be pointed out that the stationary variables x_t and \tilde{E}_t (the real exchange rate and employment, respectively) are measured as deviations around the mean, i.e. $\hat{x}_t = (x_t - \bar{x})/\bar{x}$ and $\hat{E}_t = (\tilde{E}_t - \bar{\tilde{E}})/\bar{\tilde{E}}$, respectively. Note also that the Fagan data set includes foreign (i.e., rest of the world) output and inflation, but not foreign interest rates. In the VAR for the exogenous foreign variables, we therefore use the Fed funds rate as a proxy for R_t^* .

In Figure 1, the solid line depict the data that we match with the model along with the “fitted” values from the model (the dashed line represent the one-sided estimates from the Kalman filter which can loosely be interpreted as the in-sample fit of the model).

3.2. Measurement issues

Here we describe how consumption, investment, export, import and output should be measured in the model in order to correspond to the data. In the data, the real GDP identity is given by

$$Y_t = \tilde{C}_t + \tilde{I}_t + G_t + \tilde{X}_t - \tilde{M}_t, \quad (3.3)$$

²⁰We assume that firm i faces the following problem

$$\min_{\tilde{E}_{i,t}^{new}} \sum_{s=0}^{\infty} (\beta \xi_e)^s \left(n_i \tilde{E}_{i,t}^{new} - H_{i,t+s} \right)^2,$$

where n_i is hours per worker in firm i . By log-linearizing the first order condition of this optimization problem and combining that with the log-linearized employment aggregator, we obtain the aggregate employment equation in the main text. Notice that \hat{H}_t and \hat{E}_t coincide if $\xi_e = 0$.

²¹In terms of our model these strong increases in import and export shares would imply that the weights of foreign consumption/investment in the consumption/investment bundles, i.e. ω_c/ω_i , are increasing over time.

where we have that

$$\begin{aligned}\tilde{C}_t &\equiv C_t^d + C_t^m, \\ \tilde{I}_t &\equiv I_t^d + I_t^m, \\ \tilde{M}_t &\equiv C_t^m + I_t^m, \\ \tilde{X}_t &\equiv C_t^x + I_t^x.\end{aligned}$$

In the theoretical model, we have the following aggregate production resource constraint

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

which can be written as

$$\left(C_t^d + C_t^m\right) + \left(I_t^d + I_t^m\right) + G_t + C_t^x + I_t^x - (C_t^m + I_t^m) \leq \epsilon_t z_t^{1-\alpha} K_t^\alpha H_t^{1-\alpha} - z_t \phi - a(u_t) \bar{K}_t. \quad (3.4)$$

Our starting point for measurement is the resource constraints in the theoretical model (3.4) and in the data (3.3). Given that we work with open economy data we must take into account that we, for example, observe $\tilde{C}_t \equiv C_t^d + C_t^m$ in the data but have C_t (which is a CES aggregate of the two sub-components, C_t^d and C_t^m) in our theoretical model. Consequently, we must adjust C_t with the appropriate relative prices. Using the demand schedules (2.39 and 2.40) from the consumption CES function we have that

$$\tilde{C}_t = C_t^d + C_t^m = \left((1 - \omega_c) \left[\frac{P_t}{P_t^c} \right]^{-\eta_c} + \omega_c \left[\frac{P_t^{m,c}}{P_t^c} \right]^{-\eta_c} \right) C_t. \quad (3.5)$$

Similarly, investment is given by

$$\tilde{I}_t = I_t^d + I_t^m = \left((1 - \omega_i) \left[\frac{P_t}{P_t^i} \right]^{-\eta_i} + \omega_i \left[\frac{P_t^{m,i}}{P_t^i} \right]^{-\eta_i} \right) I_t. \quad (3.6)$$

Total imports are given by

$$\tilde{M}_t = C_t^m + I_t^m = \omega_c \left[\frac{P_t^{m,c}}{P_t^c} \right]^{-\eta_c} C_t + \omega_i \left[\frac{P_t^{m,i}}{P_t^i} \right]^{-\eta_i} I_t, \quad (3.7)$$

while exports are defined as

$$\tilde{X}_t = C_t^x + I_t^x = \left[\frac{P_t^x}{P_t^*} \right]^{-\eta_f} Y_t^*. \quad (3.8)$$

We must also take into account that we have capital utilization costs in our theoretical model. Because of these adjustment costs, the GDP identity in the theoretical model is not directly comparable with the data, as can be seen from (3.4) and (3.3). Since the adjustment costs tend to be cyclical, we have chosen to add the adjustment costs to investment, instead of interpreting them as the residual in the real GDP identity in the data. Output is then given by

$$Y_t = \epsilon_t z_t^{1-\alpha} K_t^\alpha H_t^{1-\alpha} - z_t \phi. \quad (3.9)$$

Next, we discuss how we measure the price deflators for consumption and investment. The nominal GDP identity in the data is given by

$$P_t Y_t = (1 + \tau_t^c) \left(P_t C_t^d + P_t^{m,c} C_t^m \right) + \left(P_t I_t^d + P_t^{m,i} I_t^m \right) + P_t G_t + (P_t^x C_t^x + P_t^x I_t^x) - \left(P_t^{m,c} C_t^m + P_t^{m,i} I_t^m \right),$$

and consequently, the deflators for consumption and investment are measured as

$$P_t^{def,c} \equiv \frac{(1 + \tau_t^c) (P_t C_t^d + P_t^{m,c} C_t^m)}{C_t^d + C_t^m}, \quad (3.10)$$

$$P_t^{def,i} \equiv \frac{P_t I_t^d + P_t^{m,i} I_t^m}{I_t^d + I_t^m}. \quad (3.11)$$

Finally, the growth rate in foreign output is measured as $\ln \mu_z + \Delta \hat{y}_t^* + \Delta \hat{z}_t^*$ where \hat{z}_t^* is given by (2.80) and \hat{y}_t^* is given from (2.86).

4. Estimation

4.1. Calibrated parameters

A number of parameters are kept fixed throughout the estimation procedure. 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 the sample mean of these.²² The money growth rate μ is related to the steady state level of inflation, $\pi = \mu/\mu_z$, and is set to 1.01 (per quarter). If the steady state growth rate of output is around 0.5 percent quarterly, this number implies a steady state quarterly inflation rate of around 0.5 percent as well.²³ The discount factor β is set to 0.999, which implies a nominal interest of 5.5 percent (annually) in steady state assuming a capital-income tax of around 10 percent.²⁴ This value of β is quite high, but a lower value results in an even higher nominal interest rate, and thus an implausible high real interest rate in our view. To match the sample mean of the investment-output and labour income-output ratios, the depreciation rate δ is set to 0.013 and the share of capital in production α to 0.29. The constant in the labour disutility function A_L is set to 7.5, implying that the agents devote around 30 percent of their time to work in steady state. Following Christiano, Eichenbaum and Evans (2005), the labour supply elasticity σ_L is set to 1, and the markup power in the wage setting λ_w is set to 1.05.

The share of imports in aggregate consumption ω_c and investment ω_i are calibrated to match the sample average of the import-output ratio ($\frac{\tilde{M}}{Y}$) and the ratio of domestic consumption and investment over imported consumption and investment in the Euro area (see Andrés, Ortega and Vallés, 2003). This implies that ω_c is set to 0.31, and ω_i to 0.55, respectively. Since our measures of import and export in the data contain intra-Euro trade, these numbers probably exaggerate the degree of openness in the model to some extent. On the other hand, there is a clear upward trend in the import and export ratios over time.

Throughout the analysis, we maintain the assumption that the persistence coefficient in the AR(1)-process for the inflation target, ρ_π , equals 0.975 (see 2.77). Smets and Wouters (2003a, 2003b) assume

²²In Appendix A we show how to calculate the steady state in the model.

²³Note that since we estimate some of the parameters that affect the steady state (like μ_z), the steady state values for some variables (e.g. inflation) will change slightly during the estimation procedure.

²⁴This follows from the first order condition of the households' bond holdings, $R = \frac{\pi \mu_z - \tau^k \beta}{(1 - \tau^k) \beta}$, and the sample means of the capital-income tax τ^k and the output growth rate μ_z .

that $\rho_\pi = 1$. This difference has negligible effects in the empirical analysis that follows, but at a more fundamental level it actually implies that we assume that inflation is stationary whereas Smets and Wouters assume that inflation is non-stationary. If anything, the data appear to prefer our specification.²⁵

The (steady state) government expenditure-output ratio (g_r), the labour-income tax, the consumption tax, and the cash to money ratio (measured as M_1/M_3) are all set equal to their sample means. This implies $g_r = 0.2037$, $\tau^y = 0.1771$, $\tau^c = 0.1249$, and $A_q = 0.3776$, respectively. Since we lack data on capital-income taxes as well as pay-roll taxes we approximate these with the following AR(1) processes,

$$\hat{\tau}_t^k = \rho_{\tau^k} \hat{\tau}_{t-1}^k + \varepsilon_t^{\tau^k}, \quad (4.1)$$

$$\hat{\tau}_t^w = \rho_{\tau^w} \hat{\tau}_{t-1}^w + \varepsilon_t^{\tau^w}, \quad (4.2)$$

and set the persistence parameters ρ_{τ^k} and ρ_{τ^w} to 0.9. The standard deviations for the shocks $\varepsilon_t^{\tau^k}$ and $\varepsilon_t^{\tau^w}$ are set to 1 percent. These values are in line with the estimates for the other fiscal policy variables, where we used two lags in (2.65) based on various information criteria and a simple likelihood ratio test. Although both the persistence coefficients and standard deviations for the fiscal policy variables are quite high, we still find that these variables have small dynamic effects in the model. Presumably due to the assumption of Ricardian households and that the fiscal shocks are transitory and do not generate any wealth effects for the infinitely lived households. There are two reasons for keeping the fiscal policy shocks in the model nevertheless. First, they reduce the degree of stochastic singularity in the model. As is clear from the previous section, we match the model to more variables than estimated shocks, which would not be possible if we did not include the fiscal policy shocks. Second, although the dynamic effects are small, the steady state values of the fiscal policy variables matter for the dynamic effects of the other shocks in the model.

Given our choice of working with an interest rate rule (rather than a money growth rule), and not including money growth as an observable variable, the money demand shocks are badly identified since they have very small real effects (the household money demand shock, $\hat{\zeta}_t^q$ have zero effects, but the firm money demand shock $\hat{\nu}_t$ have some real effects due to its influence on the effective interest rate, see 2.10). We therefore decided not to include these shocks in the analysis. The interest rate rule choice also implies that the curvature parameter related to money demand σ_q is not identified when money growth is not included as an observable variable. We therefore keep σ_q fixed at 10.62, following the findings in Christiano, Eichenbaum and Evans (2005).

Finally, based in various information criteria and a likelihood ratio test, we choose to include 4 lags in the foreign VAR (2.86).

4.2. Prior distributions of the estimated parameters

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

²⁵We investigated this by comparing the log marginal likelihood of the benchmark model (−1909.34, see Table 1) with the log marginal likelihood for a specification of the model where $\rho_\pi = 1$ were imposed. As the latter estimation produced a log marginal likelihood of −1912.10, the data slightly prefers our specification. However, it should be emphasized that the posterior mode for the estimated parameters was very little affected.

The Bayesian estimation technique allows us to use the prior information from earlier studies at both the macro and micro level in a formal way. Table 1 shows the assumptions for the prior distribution of the estimated parameters. The location of the prior distribution of the 51 parameters we estimate corresponds to a large extent to those in Smets and Wouters (2003a) and the findings in Altig et al. (2003) on U.S. data. For all the parameters bounded between 0 and 1 we use the beta distribution. This consequently applies to the nominal stickiness parameters ξ , the indexation parameters κ , the habit persistence b , the tax rates τ , and the persistence parameters of the shock processes ρ . The domestic price and wage stickiness parameters are set so that the average length between price, or wage, adjustments is 3 quarters. In contrast, the stickiness parameters pertaining to import and export prices are set lower so as to get a reasonable degree of exchange rate pass-through. The prior standard deviation of these parameters are twice as large as their domestic counterparts, reflecting a greater prior uncertainty. For all the shocks which we allow to be serially correlated, we set the prior mean of the autoregressive coefficient to 0.85.

For parameters assumed to be positive, such as the standard deviations of the shocks, σ , and the substitution elasticities between and within goods, η and λ (where λ can be interpreted as the markup), we use the inverse gamma distribution. The prior mode of the substitution elasticity between foreign and domestic investment goods is set to 1.5, which is a standard value used in the macro literature, see ,e.g., Chari et al. (2002). Likewise, the prior mode of the substitution elasticity among goods in the foreign economy is set to 1.5 with 4 degrees of freedom.²⁶ The prior mean of the gross markup in the domestic and import sectors are all set to 1.20, implying substitution elasticities across domestic goods as well as across imported consumption/investment goods of 6. We let the data quite freely determine the size of the average markup by setting the degree of freedom to 2 for these parameters. Following Cooley and Hansen (1995), we set the standard deviation of the stationary technology shock to 0.7 percent. The size of the unit root technology shock, in turn, is set to 0.2 a priori based on the findings of Altig et al. (2003) on US data. From Altig et al. we also take the standard deviation of the monetary policy shock $\varepsilon_{R,t}$, which is set to 0.15. The size of the risk premium shock, $\sigma_{\tilde{\phi}}$, and the prior on the risk premium parameter related to net foreign assets, $\tilde{\phi}$, are set to 0.05 and 0.01, respectively, based on an estimated UIP-equation on Swedish data, see Lindé, Nessén and Söderström (2003). For some of the shocks, the earlier literature give less guidance and we rely on simple regressions to pin down the prior distribution of their processes. For example, the inflation target shock $\varepsilon_{\hat{\pi}^c,t}$ is set to 0.05, which is the standard error of regressing the HP-trend in domestic inflation on its first lag. At the same time, we impose a persistence parameter for this shock to be 0.975. Smets and Wouters (2003b) impose a persistence coefficient of unity for this shock (see the discussion in Section 4.1). The size of the asymmetric technology shock \hat{z}_t^* is set to 0.40. This number is estimated from the residuals of a first-order autoregression of the series obtained when subtracting the HP-trend in domestic output from the HP-trend in foreign output.

Before discussing the remaining priors on the shocks, it is important to note that we found it convenient to rescale the parameter multiplying the markup shocks in the Phillips curves for the domestic, import and export goods with the inverse of $\frac{(1-\xi_j)(1-\beta\xi_j)}{\xi_j(1+\kappa_j\beta)}$ for $j = \{d, mc, mi, x\}$ so that the shocks in these equations enter in an additive way, in order to decrease the degree of non-linearity when estimating the model. Similarly, we rescaled the investment specific technology shock, the labour supply shock and the consumption preference shock so that these shocks enter in an additive fashion as well. Although this was not of any major importance for the baseline estimation of the model, we found it important when carrying out the sensitivity analysis because the effective prior standard

²⁶Notice that we do not include the substitution elasticity between foreign and domestic consumption goods, η_c , (see equation (2.38)) in the final set of estimated parameters in Table 1. The reasons are discussed in the beginning of Section 4.3.

deviation of the shocks changes with the value of the nominal/real friction parameters. Smets and Wouters (2003b) adopt the same strategy. Therefore, to obtain the size of the four truly fundamental markup shocks, the estimated standard deviations reported in Tables 1 and 2 should be multiplied by their respective scaling parameter (e.g., $\frac{\xi_d(1+\kappa_d\beta)}{(1-\xi_d)(1-\beta\xi_d)}$ in the case of the domestic markup shock).

We now return to discussing the priors affected by this procedure. The standard error for the domestic markup shock, $\sigma_{\lambda_d,t}$, is set to 0.3. This is the resulting standard error of the residuals when computing a first-order autoregression of the high frequency component of domestic inflation (measured as the HP-filtered inflation rate). Following Smets and Wouters (2003a, 2003b), we initially assume that this shock is not serially correlated, i.e. we impose that $\rho_{\lambda_d} = 0$. We will, however, do some sensitivity analysis of the effects when this shock is allowed to be serially correlated (see Section 5). The standard deviations of the markup shocks in the import and export sectors, i.e. $\sigma_{\lambda^{m,c},t}$, $\sigma_{\lambda^{m,i},t}$ and $\sigma_{\lambda_x,t}$ are all set to 0.3. For some of the disturbances that we have even less information about, it is difficult to carry out similar exercises. We therefore set their standard deviations to 0.2. This pertains to the two preference shocks $\varepsilon_{\zeta^c,t}$, $\varepsilon_{\zeta^h,t}$ and the investment specific technology shock $\varepsilon_{\Upsilon,t}$. In order to let the data determine the importance of the disturbances, the degree of freedom is set to 2. This gives a rather uninformative prior.

For the steady state quarterly gross growth rate, μ_z , we use the normal distribution. We center the prior around 1.006, implying an annual growth rate of about 2.4 percent. Note that as we work with GDP data, this number is a mixture of productivity growth and population growth. For most of the parameters in the monetary policy rule we also use the normal distribution. The prior mean is set to standard values, following Smets and Wouters (2003a), which mitigates the problems with indeterminacy when solving the model and computing the likelihood. The prior mean on the inflation coefficient is set to 1.7, and the lagged interest rate coefficient to 0.8. The output reaction of 0.125 per quarter corresponds to a standard Taylor response of 0.5 for the annualized interest rate. Finally, we also allow for an interest rate response to the real exchange rate, but the prior mean of this parameter is set to zero.

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 Hessian matrix evaluated at the mode is computed by standard numerical optimization routines (Matlab's `fmincon` and a slightly modified version of Christopher Sims' optimizer `csmnwel`). The likelihood is computed by first solving the model and then using the Kalman filter (see Appendix C). Second, draws from the joint posterior are generated 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 (2003a) for details. The results are reported in Table 1. 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.²⁷ Figures 2a-2c summarizes this information visually by plotting the prior and the posterior distributions for the estimated parameters.

Before turning to the results in Table 1, it should be noticed that we do not include the substitution elasticity between foreign and domestic consumption goods, η_c , (see equation 2.38) 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

²⁷A posterior sample of 500,000 post burn-in draws was generated. Convergence was checked using standard diagnostics such as CUSUM plots and ANOVA on parallel simulation sequences. In most cases, we had convergence after around 200,000 – 300,000 draws, but in a few cases more draws were needed. To obtain convergence, we found it to be of critical importance to obtain a good estimate of the Hessian matrix, and typically the modified version of Sims optimizer `csmnwel` produced more accurate Hessian matrices than Matlab's `fmincon`.

high number (around 11). The reason why the model wants η_c to be high is not surprising. According to the data, consumption goods constitute a 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 Figure 1). From equation (2.40), it is clear that one way for the model to account for this anomaly is by choosing η_c to be high so that C_t^m fluctuates a lot whereas $C_t^m + C_t^d$ does not (remember that the import equals $C_t^m + I_t^m$). It is thus clear that η_c needs to be high in order to account for the joint consumption and import dynamics. However, due to problems with convergence in the Metropolis-Hastings algorithm, we decided to calibrate η_c because this parameter is negatively correlated with the standard deviation of the markup shock on imported consumption goods, $\sigma_{\lambda_{m,c}}$ in the generated Markov chains. 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 11. Lower values of η_c (e.g., 3), produced drastically lower marginal likelihoods.

We report two estimation results in Table 1, one where we keep the capital utilization rate fixed at the value estimated by Altig et al. (2003), i.e. $\sigma_a = 0.049$, and another where we do not allow for variable capital utilization, i.e. $\sigma_a = 10^6$. Initially, we included this parameter in the estimations, but encountered problems with convergence in the Metropolis-Hastings algorithm due to the high correlation with some other parameters. Presumably, the reason for this problem was that we could not include capacity utilization as an observable variable (it is not available on Euro area data). We therefore decided to present estimation results for the model with and without variable capital utilization, and let the marginal likelihood indicate the most probable specification for the variables at hand.²⁸

From the results in Table 1, we see that the model without variable capital utilization is preferable under the assumed priors. The Bayes factor is 3134 in favor of the model without variable capital utilization and this specification is therefore used in the remaining part of the paper. This choice is, however, 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.

A particularly interesting result in Table 1 is that the degree of domestic price stickiness is not affected by whether we allow for variable capital utilization or not, in contrast to the findings by Christiano, Eichenbaum and Evans (2005). For both specifications of the models, we find the degree of sticky prices to be around 0.9 - which is in line with the findings by Smets and Wouters (2003a, 2003b) - whereas Christiano, Eichenbaum and Evans (2005) obtain an estimate of the price stickiness of 0.60 in the model with variable capital utilization and 0.92 in the model without. An addition, our model do not yield a lower degree of domestic price stickiness when including the working capital channel. Again, this is in contrast with the results in Christiano, Eichenbaum and Evans (2005) who obtain an estimate of the price stickiness of 0.60 in the model with working capital and 0.89 in the model without. There are several possible reasons why the results differ. One obvious candidate is that the data sets are different. However, Smets and Wouters (2003b) report high price stickiness also for U.S. data. Another candidate is that the estimation techniques differ. Our paper and Smets and Wouters' paper use Bayesian estimation techniques whereas Christiano, Eichenbaum and Evans (2005) match the impulse responses to a monetary policy shock only. In contrast, when matching the impulse response functions for three identified shocks, Altig et al. (2004) obtain about the same

²⁸The marginal likelihood of a model i is defined as $m_i = \int L_i(\theta_i; x) p_i(\theta_i) d\theta_i$, where $L_i(\theta_i; x)$ is the usual likelihood function of the model's parameter vector conditional on the observed data x . $p_i(\theta_i)$ is the prior distribution of the model's parameters. m_i is the unconditional probability of the observed data, under the assumed prior distribution, and is therefore a measure of model fit. The marginal likelihood is a relative measure and should be compared across competing models. The Bayes factor comparing two models i and j is defined as $B_{ij} = m_i/m_j$. The marginal likelihood is computed numerically from the posterior draws using the modified harmonic estimator in Geweke (1999).

amount of price stickiness as we do. The estimation technique does consequently not seem to matter for the obtained results to any greater extent. Instead, the main reason behind the different results appears to be that the working capital channel is able to produce a lot of inflation inertia (without price stickiness) to a monetary policy shock, but not so much for other shocks. Since monetary policy shocks are not the main shocks behind the business cycles, we obtain different results in the model when we match all the variability in the data and not just the impulse response functions to a monetary policy shock as Christiano, Eichenbaum and Evans (2005) do. Moreover, allowing for a time-varying inflation target, which in principle should be able to lower the intrinsic inflation persistence and/or correlation in the shocks, does not seem to produce lower persistence in this multivariate setting.

The implied average contract duration, assuming that the households own the capital stock and rent it to the firms each period, is around 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), to compute the average contract duration to about 4.7 quarters instead. This is a substantially lower number, and 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 (e.g. $\xi_{m,c}$, $\xi_{m,i}$ and ξ_x) are substantially lower than ξ_d , suggesting 2-3 quarters stickiness in these sectors. However, 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 distributions 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 Phillips curves are mostly forward-looking, a finding consistent with the single-equation estimation results of Galí, Gertler and Lopez-Salido (2001) on Euro area data. At first glance, this result may appear to support the results by Levin and Piger (2004), who provide univariate evidence that intrinsic inflation persistence is substantially moderated when allowing for a level-shift in the (central bank target) inflation rate. However, although the domestic Phillips curve is mostly forward-looking, we still find domestic inflation persistence to be intrinsic in the following sense. If we generate artificial time series from the estimated model with and without the time-varying inflation target and estimate simple AR(1) models on the generated inflation series, we find the autocorrelation coefficient to be about 0.81 and 0.77 on average, respectively.²⁹ So in this sense, accounting for a time-varying inflation target do not generate substantially lower inflation persistence in our multivariate setting, in contrast to the univariate results by Levin and Piger (2004).

Further, we see that the unconditional variances of the markup shocks in the import and export sectors are considerably higher than in the domestic sector. Moreover, the posterior mode for the average markup is about the same in the domestic sector as in the importing investment sector (the net markups are around 20 percent in these sectors), whereas the markups are considerably higher for the firms that import consumption goods (around 60 percent). Thus, the data suggests that the domestic households' willingness to substitute among the importing consumption goods is rather limited in comparison with the importing investment goods.

The estimated model implies the import/export to output ratio to be around 12 percent in the 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 percent 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). Due to the increasing import/export-output share, the model is most likely underestimating the “true” steady state value. But as mentioned in Section 3.1, the model is not designed to capture the increasing import/export to output ratios. Despite this

²⁹This is also the reason why the vector autocovariance function for inflation display a high degree of persistence (see Section 4.4). Inflation persistence in the DSGE model is mostly generated by (unobserved) correlated shocks that are not included in standard VARs.

limitation, the intention is nonetheless that the model should be able to capture the dynamics of the open economy variables.

The posterior mode of the persistence parameter in the unit-root technology process is estimated to be 0.72. This number compares quite favorably 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 (see e.g. Cooley and Hansen, 1995). Smets and Wouters obtain a much higher number of about 0.997.³⁰ 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 real variables. In general, although some shocks quite naturally are 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 found by Smets and Wouters (2003a, 2003b). 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 extra source of internal propagation. Further, the posterior mode for the gross quarterly steady state growth rate (μ_z) is centered around 1.005, implying an annual steady state growth rate of about 2 percent for the Euro area.

4.4. Model fit

In Figure 1 we report the Kalman filtered one-sided estimates of the observed variables, computed for the posterior mode of the estimated parameters in the benchmark model along with the actual variables. Roughly speaking, the one-sided estimates correspond to fitted values in a regression. As is evident from the figure, the in-sample fit of the model is satisfactory. In Figure 3, we report the two-sided estimates (basing inference on the full sample) of the unobserved (quarterly) shocks in the benchmark model. It is important to note that we plot the shock series, for example $\hat{\epsilon}_t$ and not the innovations $\varepsilon_{\epsilon,t}$. From the figure, we see that the annualized time-varying inflation target drops from about $0.8 \times 4 + 2 = 5.2$ percent in the beginning of the 1980's to about 2 percent (which is the posterior mode of the long-run inflation target) in the beginning of 2000 with the introduction of the Euro. The asymmetric technology shock series (remember $\tilde{z}_t^* = \frac{z_t^*}{z_t}$) is very persistent and has an upward trend due to the fact that growth in the Euro area was on average lower than the growth rate in the world economy during this period (i.e., $\Delta \ln z_t^*$ is higher than $\Delta \ln z_t$, implying that \tilde{z}_t^* must start out below the steady state with $\tilde{z}^* = 1$, due to our assumption that $\mu_{z^*} = \mu_z$). The two-sided series for the risk-premium shock is also in line with our a priori expectations. It gradually builds up during the 1980s and reaches its maximum around 1990 when we know there was a lot of turmoil in the exchange rate market. It then gradually returns to zero during the latter part of the 1990s and the beginning of 2000. For the other shocks, we have less strong a priori beliefs to evaluate the outcome of these shocks against. We are therefore reluctant to say that the two-sided estimates of these shocks can be considered as evidence against the plausibility of the model. This is one important reason for why we carry out an independent assessment of the models' fit using two standard fitness criterion below.

To further assess the conformity of the data and the model we conduct a posterior predictive analysis where the actual data are compared to artificial time series generated from the estimated benchmark DSGE model. The comparison will be made in two dimensions. First, we compare vector autocovariance functions in the model and the data (see, e.g., Fuhrer and Moore, 1995), and second, we compare unconditional second-order moments as is standard in the RBC literature (see, e.g., Cooley and Hansen, 1995).

The vector autocovariance functions are computed by estimating an unrestricted VAR model on

³⁰Note that the difference between a persistence coefficient of 0.91 and 0.995 is huge in terms of the persistence of a shock. The former number implies that 0.02 of a unit increase are in effect after 40 quarters while the latter implies 0.82.

Euro area data for the period 1970Q2–2002Q4. We include the following 10 variables in the estimated VAR; annualized domestic inflation π_t , the real wage $\Delta \ln(W_t/P_t)$, consumption $\Delta \ln C_t$, investment $\Delta \ln I_t$, the real exchange rate x_t , the annualized nominal short-term interest rate R_t , employment \tilde{E}_t , output $\Delta \ln Y_t$, exports $\Delta \ln \tilde{X}_t$ and imports $\Delta \ln \tilde{M}_t$. All real variables are included in growth rates (first differences in logs, $\Delta \ln$).³¹ To compute the vector autocovariance functions in the model, we draw n_s parameter combinations from the posterior distribution and simulate n_s artificial data sets of the same length as for the Euro area. We then use the n_s data sets to estimate vector autocovariance functions (see Hamilton, 1994), using exactly the same VAR specification as was applied on the actual data. In Figure 4, we report the obtained median vector autocovariance function in the DSGE model (thin line) along with the 2.5 and 97.5 percentiles (dotted lines) in the generated distribution. The thick line refers to the actual data. In order to be able to convey the results in one figure, we report the results for a subset of variables included in the VARs; π_t , x_t , R_t , $\Delta \ln Y_t$, $\Delta \ln \tilde{X}_t$ and $\Delta \ln \tilde{M}_t$.

By and large, we see that the vector autocovariance functions in the model and the data compare very well, giving additional credibility to the estimated DSGE model. Indeed, most of the autocovariances in the model look a lot like those computed in the data. However, there are some exceptions. First, we see that the inflation persistence is a little bit too low in the model relative to the data. This reflects the fact that in the data, the inflation series is very persistent (see Figure 1) and that one very important source of inflation persistence in the benchmark model is the inflation target shock (see Figure 6). When generating artificial samples in the DSGE model, the typical sequence drawn for this shock will not be as persistent as in the data because of the large decrease in the inflation target shock (see Figure 3). Consequently we will tend to underestimate the inflation persistence in the model relative to the data. Also, in the data, contemporaneously higher inflation seems to be associated with lower import growth today to a greater extent than can be replicated by the model. Moreover, in the model higher interest rates in previous periods (R_{t-h}) are associated with too high output growth today ($\Delta \ln Y_t$) relative to the data. We also notice that the autocovariance function for exports are too high and persistent in the model relative to the data. This implies that the unconditional persistence and standard deviation for exports are too high in the model. From Figure 1, it is apparent that the one-sided estimates from the Kalman filter 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. Finally, higher domestic inflation (π_{t-h}) in the model is a signal of higher future imports ($\Delta \ln \tilde{M}_t$), because it will be more profitable to consume and invest imported goods in this case, but in the data this covariance is (surprisingly) strongly negative.

The conclusions from the autocovariance functions in Figure 4 are in line with the unconditional moments reported in Table 4. We see that the high unconditional variances in domestic inflation and the nominal interest rate are hard to replicate in the model, although the model is quite successful in replicating the first-order autocorrelation coefficients for the series. The standard deviations for the other series are fairly well captured by the model, with the exception for exports, which are too volatile in the model compared to the data. Given the autocovariance functions, this was to be expected. The problem appears to be that exports are too persistent in the model. Also consumption and investment are too persistent. The DSGE model, however, captures the persistence and volatility in the real exchange rate strikingly well, so the highly persistent and volatile real exchange rate is not a puzzle according to the model.³² Turning to the cross-correlations, we see that the model does very

³¹We use 3 lags in the estimated VARs because 4 lags produce characteristic roots outside the unit circle in the VAR estimated on Euro area data. We have also done the calculations with the foreign variables $\Delta \ln Y_t^*$, π_t^* and R_t^* included in the estimated VARs (not imposing block exogeneity), but the results were found to be very similar.

³²It should be noted that this conclusion is robust to if we assume that the markup shocks for the importing and exporting firms are white noise. The reason is that when these shocks are assumed to be iid, the higher degree of sticky

well in most respects, given the uncertainty about the exact numbers. There are a couple of misses, however. First, the cross-correlation between import growth/consumption growth and output growth are too weak in the model relative to the data. Second, the model has difficulties in accounting for the strong positive correlation between inflation and the nominal interest rate. However, the autocovariance functions for these variables were found to be satisfactory (see Figure 4), which is an indication that the unconditional cross-correlation between these variables are atypical, and due to the strong downward trend in these variables (see Figure 1). The failure of the model in this respect is therefore understandable. Turning to the cross-correlations between the real exchange rate and the rest of the variables, we notice that the correlation between domestic inflation and the real exchange rate is strongly positive in the data. The model suggests that this cross-correlation should be around zero, but the probability interval is very broad and cover the estimate in the data.³³ Finally, it is noticeable how weak the correlation is between the real exchange rate and the export and import growth in both the model and the data. This explains why price stickiness in the price setting for the exporting and importing firms are found to be of crucial importance for the model's behaviour. If those frictions were not included, these cross-correlations would be substantially higher.

To sum up, although there seems to be room for improvements in some aspects, we think our model does a very good job in replicating conventional statistics for measuring the fit of a model. In particular, the model is able to generate highly volatile and persistent real exchange rates, and to explain the joint behaviour of a large set of key macroeconomic variables very well. For exports, the model does less well. Presumably, the results would have been improved if we had been able to include some price variable related to exports in the estimation of the 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 role of the various frictions and shocks that are included in the model. This relative model comparison is carried out using the marginal likelihood. Table 2 shows the posterior mode and marginal likelihood when some of the nominal and real frictions in the model are turned off as well as some other modifications of the model. This is done in an attempt to assess the importance of the different frictions in the model. The columns report the estimated parameter vector (posterior mode) when; *i*) there is no wage stickiness, *ii*) there is no (domestic) price stickiness, *iii*) there is no habit formation, *iv*) there is no investment adjustment cost, *v*) the LOP holds in imports, *vi*) the LOP holds in exports, *vii*) there is no working capital channel, *viii*) we allow for persistent domestic markup shocks, and *ix*) the markup shocks are i.i.d. (uncorrelated) in all sectors. For ease of comparison the benchmark results are also reproduced.

The results in Table 2 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 models' empirical performance. Table 2 also indicates that a version

prices that occurs produces a persistent and volatile real exchange rate. However, under this assumption, the role of markup shocks in explaining exchange rate fluctuations are reduced from about 55 to 20 percent in the medium term.

³³The reason why the probability interval is so wide is that both these variables are highly persistent, and that different shocks induce both positive and negative correlation between the variables. For example, in a given simulated sample, markup shocks for the importing consumption firms, which induce a strong positive correlation between inflation and the real exchange rate can be very important, whereas in another sample, shocks that induce a weaker/negative correlation can have a stronger impact.

of the model without the working capital channel is preferable, the Bayes factor is 65 in favor of the model without working capital.

The next to the last column in Table 2 contains results when allowing the markup shocks in the domestic Phillips curve to be serially correlated. We assume the same prior for the persistence parameter, ρ_{λ_d} , as for the other shocks. A striking result is that the serially correlated domestic markup shocks produce a much lower domestic price stickiness parameter, ξ_d shrinks from 0.88 to 0.66. This implies a fall in the average price contract duration from 8 to 3 quarters. Under the interpretation that the domestic intermediate firms own the capital stock, the resulting price contract duration is slightly less than 2 quarters. However, the fall in ξ_d is accompanied with a posterior mode for ρ_{λ_d} of 0.995, which is a very high number. Also, the Bayes factor is 487 in favor of the model with white noise domestic markup shocks, so the data appear to be supportive of the benchmark specification of the model. However, the analysis of marginal likelihoods should not be over-emphasized, given its sensitivity to the choice of prior distribution, and we can not rule out the model with correlated shocks with certainty. Our interpretation is that the data offer two explanations behind the high inflation inertia that we see; either a rather high degree of price stickiness or highly correlated shocks.

The last column in Table 2 displays the results when all markup shocks are assumed to be white noise. This restriction is associated with a large drop in log marginal likelihood. Thus, the specification with correlated markup shocks in the import and export sectors are clearly preferable. In particular, the correlated markup shocks play an important role in accounting for the behaviour of the real exchange rate. Moreover, it is interesting to note that the posterior estimates of the stickiness parameters (the ξ 's) are very similar in this case, ranging from 0.85 – 0.91. With uncorrelated markup shocks, we also find a larger role for indexation to past inflation, in particular in the domestic and export sectors. This is not surprising, when less of the persistence is generated by correlated shocks there must be a larger role for intrinsic persistence (i.e. lagged inflation) to account for the inflation dynamics.

In Table 3, we examine the role of various shocks in the model. We shut down some of the shocks, and study the impact on the estimated parameters (posterior mode) and the marginal likelihood. What we learn from this exercise is that when considering the relatively large set of observable variables that we match, all shocks appear to matter, but in particular we find that technology shocks and the markup shocks in the Phillips curves for imported consumption/investment goods and export goods are the most important.

Regarding the role of the time-varying inflation target, the marginal likelihoods are not very informative. The Bayes factor is only 2 in favor of the model without the time-varying inflation target. Given our choice of priors, the data are hence not very instructive about the model choice in this case. We also learn from Table 3 that the fiscal policy shocks are not very important for the empirical performance of the model, suggesting that more work is needed to incorporate fiscal policy shocks in a more realistic way than what was done in this paper.³⁴ For instance, amending the model with “rule-of-thumb” consumers and production in the government sector along with the introduction of government debt/endogenous tax/government spending rules might be an interesting avenue for future research.

³⁴When we shut down the fiscal policy shocks, we set all the steady state tax rates and the tax-rate shocks to nil. We also set shocks to government expenditures to nil, but keep steady state government expenditures as share of output to 0.2 in the model.

6. Impulse response functions and variance decompositions

6.1. Impulse response functions

Figures 5a-5m report the impulse response functions (median and 5th, 95th percentiles) for each estimated shock in the baseline model. To understand how the nominal frictions shape the impulse response functions, we also include the responses when all nominal frictions are taken out of the model, so prices and wages are flexible (we set $\xi_d = \xi_{m,c} = \xi_{m,i} = \xi_x = \xi_w = 0.01$). The results for the benchmark model are graded on the left y-axis, and the flexible price-wage version of the model (dashed line) is graded 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 deviations from steady state (i.e., percentage deviations).³⁵

There are many interesting features with the estimated impulse response functions worth noting. First, we note in Figure 5a that employment rises after a positive permanent shock to technology, supporting the results reported by Altig et al. (2003, 2004) for the U.S. economy. The effect on real variables are permanent since the shock leads to a permanent increase in z_t . As in Altig et al. (2003), it is the case that the response of monetary policy is very important for shaping the dynamics to the shock, so the rise in employment is mostly attributed to monetary policy.³⁶ In contrast, we see from Figure 5b that employment falls after a positive stationary technology shock. This is also true even if prices and wages are flexible. In order to obtain the standard increase for employment along with a much stronger response of output, we need to moderate the investment adjustment cost (\tilde{S}'') substantially in the flexible price-wage calibration of the model. Evidently, our estimation results suggest a more modest role for stationary technology shocks than what is standard in the RBC literature. Turning to the dynamic effects of an investment-specific technology shock in Figure 5c, we see that this shock has strong cyclical effects on both “closed economy” quantities such as output, investment and consumption and “open economy” variables such as import, export and the real exchange rate. The role of the investment adjustment cost (\tilde{S}'') is of course crucial for shaping the dynamics of this shock. From Figure 5d, we see that a positive realization of the asymmetric technology shock \tilde{z}_t^* (remember $\tilde{z}_t^* = z_t^*/z_t$) appreciates the real exchange rate. Although we maintain the assumption that the domestic and international steady state growth rates are equal (i.e., $\mu_z = \mu_z^*$), our model has the property that the real exchange rate appreciates in steady state if the growth rate in foreign technology exceeds the domestic technology growth rate.³⁷ As is clear from Figure 5d, this shock has the potential of explaining some of the lower frequency movements in the real exchange rate along with differences in the growth rates of the rest of the world and the Euro area.

The consumption preference shock accounts for a substantial amount of the cyclical behaviour of consumption as can be seen from Figure 5e. Quite naturally, investment drops while households increase their labour effort in order to finance the desired increase in consumption. The habit persistence coefficient b generates the hump-shaped consumption response. We also see that without price and wage stickiness, this shock has rather large effects on the inflation dynamics. The dynamics to this shock are very sensitive to the substitution elasticity between domestic and foreign consumption goods

³⁵That is, annualized inflation is measured as $4\pi\hat{\pi}_t$ where π is the steady-state gross quarterly inflation rate and $\hat{\pi}_t$ is the quarterly inflation rate. Similarly, the annualized nominal interest rate is measured as $4R\hat{R}_t$.

³⁶That the response of policy is important for shaping the dynamic effects of a shock is of course also generally the case for the other shocks as well.

³⁷Abstracting from capital income taxes in the analysis, i.e. $\tau^k = 0$, we have that $\bar{x}_{t+1}/\bar{x}_t = \mu_z/\mu_z^*$. That is, if $\mu_z^* > \mu_z$ then $\bar{x}_{t+1} < \bar{x}_t$ which is equivalent to an appreciating real exchange rate \bar{x} in steady state. The intuition is that if the domestic country grows at a faster rate than the foreign country, the domestic agents want to import (export) more goods from (to) the world market. But in equilibrium, the real value of exports in the foreign economy (i.e., exports times the inverse of the real exchange rate) can not grow at a faster rate than the foreign economy. This implies that the real exchange rate must depreciate.

(η_c) as well as the markup/substitution elasticity among the imported consumption goods ($\frac{\lambda_{m,c}}{\lambda_{m,c}-1}$). The effects of a negative labour supply shock (i.e., an increase in the disutility of working, ζ_t^h , see 2.37) is depicted in Figure 5f. As expected, employment, consumption and investment falls, which also induce a fall in output. The effects on import and export quantities are rather limited. Set aside the effect on the real wage, this shock has qualitatively very similar dynamics as a (negative) stationary technology shock. This is why some authors classify this shock as a (negative) supply shock, see for example the discussion in Smets and Wouters (2003a). When prices and wages are flexible, this shock has rather limited effects on the economy, so the nominal frictions are very important for shaping the dynamics of the labour supply shock.

A (positive) risk premium shock depreciates both the nominal and the real exchange rate as can be seen in Figure 5g. This makes imported consumption and investment goods more expensive which forces total imports to decrease. There is also an initial dip in the consumption deflator inflation. The reason for this somewhat counterintuitive result is that the relative price between the imported consumption good and the domestic good increases due to the exchange rate depreciation and thereby affects the different consumption baskets that enter the definition of the consumption deflator.³⁸ The large effect on the consumption deflator inflation is due to the high substitution elasticity between imported and domestic consumption goods ($\eta_c = 5$). If this parameter was lowered, the substitution effect would be lower, implying that the relative price effect is smaller and we would instead see an increase in the consumption deflator inflation. The exchange rate pass-through can be calculated from the impulse response functions of inflation and the nominal exchange rate following any shock to the exchange rate. We choose to examine the pass-through following a shock to the risk premium since this shock can be interpreted as an autonomous change in the expectations about the future exchange rate. The contemporaneous response in the price on imported consumption goods is about 45 percent of the change in the exchange rate. For the imported investment goods we obtain 18 percent pass-through. This is entirely driven by the larger estimated price stickiness in the imported investment sector, since the incomplete pass-through in the model originates only from nominal price rigidities (see Table 1).

The impulse responses to the markup shocks are depicted in Figures 4h-4k. Note that the markup shock in the domestic sector $\hat{\lambda}_{d,t}$ (Figure 5h) is uncorrelated, whereas the other markup shocks ($\hat{\lambda}_t^{m,c}$, $\hat{\lambda}_t^{m,i}$, $\hat{\lambda}_{x,t}$) are rather persistent (see Table 1). The impulse response of the domestic markup shock leads to a rather short-lived increase in domestic inflation, which in turn produces a somewhat more persistent real exchange rate appreciation. The shock also induces a slight fall in aggregate quantities. Turning to the imported consumption and investment markup shocks, we see that they have strong and rather persistent effects on imports, exports and the real exchange rate. Note that a positive markup shock in the importing consumption(investment) goods sector leads to a drop(rise) in the consumption deflator for the same reasons as for the risk premium shock. With a lower value of η_c , we instead obtain a rise(drop) of the consumption deflator. Following an import consumption markup shock, the resulting relative price effects induce investment to rise whereas consumption drops and

³⁸From the definition of the consumption and investment deflators (see equations (3.10) and (3.11)), the log-linearized consumption deflator inflation can be written using the relative price between imported consumption goods and domestic goods according to the following:

$$\begin{aligned}\hat{\pi}_t^{def,c} &= \frac{c^d}{(c^d + \lambda^{m,c}c^m)}\hat{\pi}_t^d + \frac{\lambda^{m,c}c^m}{(c^d + \lambda^{m,c}c^m)}\hat{\pi}_t^{m,c} + \left(\left(\frac{c^d}{(c^d + \lambda^{m,c}c^m)} - \frac{C^d}{C^d + C^m}\right)\eta_c\omega_c(\gamma^{c,mc})^{-(1-\eta_c)}\right. \\ &\quad \left.- \left(\frac{\lambda^{m,c}c^m}{(c^d + \lambda^{m,c}c^m)} - \frac{C^m}{C^d + C^m}\right)\eta_c(1-\omega_c)\left(\gamma^{c,d}\right)^{-(1-\eta_c)}\right)\Delta\hat{\gamma}_t^{mc,d} + \frac{\tau^c}{1+\tau^c}\Delta\hat{\tau}_t^c,\end{aligned}$$

where we have used the equations (2.39), (2.40) and (2.66).

vice versa for the import investment shock. The net effect on output is therefore rather small for the $\hat{\lambda}_t^{m,c}$ shock, whereas for the $\hat{\lambda}_t^{m,i}$ shock we see a substantial and persistent drop in output. The latter result is not surprising, given that the price stickiness $\xi_{m,i}$ is larger for the imported investment goods than for the imported consumption goods. It is also the case that the investment adjustment costs (\tilde{S}'') creates some persistence in investment. Since the persistence parameter in the process for $\hat{\lambda}_t^{m,i}$ is quite high, this explains why the exchange rate appreciates very persistently after a positive realization of $\varepsilon_t^{m,i}$. In Figure 5k, we learn that an unexpected positive export markup shock is associated with a very large drop in exports, and a depreciation in the real exchange rate along with a drop in imports. Without sticky prices and wages, we see that none of the markup shocks have any noteworthy effects on aggregate quantities and prices. This is quite natural, since these shocks have essentially zero distortionary effects as they appear additive in the pricing equations in the model. Another more general feature of the impulse response functions is that the real wage generally responds relatively little, so there is a substantial amount of real wage inertia due to the high degree of price and wage stickiness.

Finally, we turn to the dynamic effects of the two monetary policy shocks in the model. The first one is a white noise shock to the nominal interest rate, $\varepsilon_{R,t}$, whose dynamic effects are depicted in Figure 5l. 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 identify the effects of monetary policy shocks, but the latter results indicate that inflation in the model is somewhat less inertial than the typical estimates in the VAR literature.³⁹ 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 ($\sigma_a = 10^6$). However, as pointed out by Christiano, Eichenbaum and Evans (2005), it is the combination of real and nominal frictions that enables their model to reproduce the impulse response functions in the VAR. Here, we use Bayesian methods and fit the model to all the variation in the data, and not just the dynamic effects of a policy shock. 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 similar to the ones generated in identified VARs. In our view, this gives a lot of credibility to the analysis and further support to the view that the “conventional wisdom” about the effects of monetary policy applies even in the open economy framework. There is, however, one exception and that is the real exchange rate. Although the nominal frictions in the model provides 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 persuasive feature of estimated VARs, see, e.g., Eichenbaum and Evans (1995), Faust and Rogers (2003), and Lindé, Nessén and Söderström (2003). Lindé, Nessén and Söderström show that if the sensitivity of the risk-premium related to net foreign assets is large enough (i.e. $\tilde{\phi}_a$ is above 1.5), it is possible to obtain a hump-shaped response of the real exchange rate, but they argue that this number is implausibly high. With flexible prices and wages, monetary policy has very small effects on aggregate quantities, and a strong immediate effect on inflation. The behaviour of the real exchange rate in this case is the classic response implied by the UIP condition. An initial appreciation is followed by a strong and persistent depreciation (over-shooting).

The second policy shock is a stationary inflation target shock, for which the impulse response

³⁹See, for example, Christiano, Eichenbaum and Evans (2005), and Altig et al (2003, 2004) for US evidence, and Angeloni et al. (2003) for Euro area evidence.

functions are shown in Figure 5m.⁴⁰ The figure shows that a temporary increase in the inflation target of about 0.05 percent is associated with a persistent increase in the inflation rate of about 0.20 percent and a modest rise in output of about 0.05 percent. As expected, the real exchange rate depreciates and the nominal interest rate increases. With flexible prices and wages, essentially only inflation and nominal interest rates are affected by this shock.

6.2. Variance decompositions

We report the variance decompositions of the 5th, 50th and 95th percentiles of the posterior distribution for some selected variables in Table 5.⁴¹ The purpose is to make a formal assessment of the contribution of each structural shock to fluctuations in the endogenous variables at different horizons. We focus here on the 1, 4, 8 and 20 quarters horizon.⁴² We define short run as being 1-4 quarters, medium run as 8 quarters, and the long run to be 20 quarters.

The technology shocks (the stationary, unit-root, investment-specific and asymmetric technology shocks) account for about 30 percent of the output fluctuations in the short run, and then gradually increase to about 45 percent in the long run. The three “supply shocks” in the model, the two productivity shocks ($\mu_{z,t}$ and ϵ_t) and the labour supply shock account for about 40 percent of the fluctuations in output in the long-run, results well in line with Smets and Wouters (2003a). Evidently, the data do not support the idea of a predominant part of business cycles being due to technology shocks. In order to account for the observed joint fluctuations in the large set of variables that we study, the model needs other shocks than the technology (“closed economy”) shocks to account for the movements in output. For instance, we find that the markup shocks account for about 15 percent in the short to medium run and as much as 33 percent in the long run of the output fluctuations. In particular, the export markup shock is important in the short run and the importing investment markup shock is important in the long run.⁴³ However, the result that other shocks than technology are important for macroeconomic fluctuations are supported by identified VARs, see e.g. Galí (2000) and Altig et al. (2003, 2004). By and large, the relative importance of technology and non-technology shocks in our model are in line with their results. Monetary policy shocks account for about 15 percent of output fluctuations in the short run and less than 5 percent in the long run.

Turning to inflation, the domestic markup shocks account for most of the fluctuations in the short run, which is not surprising given the small coefficient on marginal cost in (2.19) implied by our estimates ξ_d and κ_d . Despite the small coefficient on marginal cost, the labour supply shock is one of the most important sources of inflation volatility in the short and medium run because this shock is the predominant source of variation in the real wage (see Figures 5a-5m). In the long run, since the labour supply shock is less persistent, the inflation target shock appears to be the single most important source of inflation volatility. But also the import consumption markup and the investment-specific technology shock are central sources of inflation volatility in the long run.

Import and export markup shocks account for most of the fluctuations in the real exchange rate and exports. In the short and medium run, they account for about 50–60 percent, and in the long run they account for as much as 65 percent. The nominal rigidities in the model imply that the return of the

⁴⁰As already discussed in greater detail in Section 4.1, the persistence coefficient in the AR(1)-process for the exogenous inflation target shock is calibrated to be less than unity (0.975).

⁴¹Note that as we report the 5th, 50th and 95th percentiles of the posterior distribution for each shock in Table 5, the fractions reported do not exactly sum up to unity at each horizon.

⁴²The longer the horizon, the more of the fluctuations is due to the unit-root technology shock. In the limit, this shock accounts for 100 percent of the fluctuations in aggregate quantities in this model, since this is the only permanent shock.

⁴³Even if the variance in the imported consumption markup shock process is much higher than in the process for the imported investment markup shock, it is still the case that the imported investment markup shock is much more important for the output fluctuations in the long run. This emphasizes the role of the supply side of the imported investment goods.

real exchange rate to the steady state is slow for the markup shocks, in particular they also enable the imported investment and consumption markup shocks and the investment specific technology shocks to produce hump-shaped impulse responses of the real exchange rate. Consequently, these shocks are also the most important source of fluctuations in the real exchange rate in the medium to long run. Given our relatively simplistic modelling of the import and export sectors, these shocks most likely capture a whole range of mechanisms and shocks that do not feature in the model (e.g., oil prices, intermediate import inputs in production etc.). It is also notable that the risk-premium shocks do not appear to be an important source of variation in the real exchange rate. However, as can be seen from Table 2, if we assume that all markup shocks are white noise, then the role of risk premium shocks are enhanced considerably. Nevertheless, the model appears to have the right propagation regarding the real exchange rate since the typical autocovariance function from an estimated VAR implied by the DSGE model are well in line with the one generated from the data (see Figure 4). For imports, the export and import markup shocks play a prominent role as well. However, quite naturally also investment-specific markup shocks are an important source of variation, as imported investment goods are a substantial part in the investment CES basket, and investment itself is a highly volatile process.

Monetary policy shocks are a prominent source of interest volatility in short run, whereas in the medium to long run, investment-specific and inflation target shocks are predominantly important. Since investment specific shocks have rather large real effects in the short and medium run, this is not surprising.

At a more general level, we find a small role for the exogenous fiscal and foreign shocks. In the short run, the foreign shocks account for around 10 percent of the fluctuations in output, export, import and the real exchange rate, but in the long run fiscal and foreign shocks together most likely account for less than 5 percent.

Another distinct feature of Table 5 is that many shocks have dynamic effects on many of the variables. That is, “open economy” shocks have important dynamic effects on “closed economy” variables and vice versa, suggesting a substantial amount of internal propagation within the model due to the open economy aspects of it. The key parameter behind this propagation mechanism is the high value of the substitution elasticity between domestic and imported consumption goods, η_c , that the data strongly prefer. Given the results in Table 3, which conveyed that most shocks matter for the empirical fit of the model, this result is perhaps not surprising. Our interpretation is that the open economy frictions and shocks appear to add interesting dynamics to the closed economy setting in Smets and Wouters (2003a).

Finally, in Figure 6 we plot the historical decompositions for four subsets of shocks along with the actual time series that we fit our model to. From the figure, we can learn the role of various shocks during the sample period. Notice that the figure depicts the raw data, and not the steady state deviations. In general, we see that the “domestic shocks” - in particular the technology shocks - account for most of the variation in the domestic variables (inflation, interest rate and output), and that “open economy shocks” account for most of the variation in the real exchange rate. During the sample period, the strong positive trend for the asymmetric technology shock explains the appreciating real exchange rate, which is why the “closed economy shocks” explain little of the variation in the real exchange rate during the sample, but technology shocks - where the asymmetric technology shock is included - explain the downward trend in the real exchange rate. The monetary policy shocks, and in particular 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 percent.

7. Conclusions

In this paper, we have modified the benchmark closed economy monetary business cycle model of Christiano, Eichenbaum and Evans (2005) into an open economy model. The key features of the open economy part of the model is incomplete pass-through of exchange rate movements to prices of import goods used in private consumption and as investment in the physical capital stock, as well as incomplete pass-through of exchange rate movements to prices of export goods sold to the foreign economy. Another open economy feature of the model is the domestic households' ability to borrow and lend at a risk-adjusted nominal interest rate in the world financial market. Following Smets and Wouters (2003a, 2003b), we introduce a large number of shocks in the economy, and estimate the model using Bayesian techniques on Euro area data.

We do an extensive test for the role of various frictions, and find strong support for the nominal and real frictions we embed into the model; sticky prices in the domestic, import and export sectors, sticky wages, investment adjustment costs and habit persistence in consumption. We do not find evidence that variable capital utilization is important for the empirical success of the model, nor have any greater impact on the estimated parameters. However, this result is most likely contingent upon that we do not include capacity utilization as an observable variable when estimating the model (since this is not available for the Euro area). Moreover, the working capital channel is not an effective channel to generate inflation persistence when subjecting the model to fit all the variation in the data and not just the dynamic effects of a monetary policy shock as in Christiano, Eichenbaum and Evans (2005).

We also conduct an extensive test for the role of various shocks included in the model. According to our estimated model, many shocks matter for the fluctuations in the 15 endogenous variables that we study. There is a substantial amount of internal propagation via the high substitution between foreign and domestic consumption goods which the data strongly prefer. Supply or technology shocks are about as important for output fluctuations as demand or non-technology shocks. For inflation, we find that markup shocks and inflation target shocks are most prominent, but there is a clear role for technology shocks as well. The real exchange rate in the model is mostly driven by import and export markup shocks.

The estimated model - although fitted to explain all the variation in the data and not only the dynamics of a monetary policy shock - have 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. For the real exchange rate, the estimated model implies a quick appreciation following an unexpected increase in the nominal interest rate. This finding is not in line with the results in the identified VAR literature which typically report a gradual appreciation, see, e.g., Eichenbaum and Evans (1995), and Faust and Rogers (2003). The fast response in our model is driven by the UIP condition in the model, and although the nominal frictions generate persistence in the real exchange rate, they cannot produce a hump-shaped response of the real exchange rate in the model. However, it should be kept in mind that the identification of the effects of policy shocks in VARs typically rest on a recursive ordering of variables, a requirement that is not fulfilled by the DSGE model used here. Therefore, strictly speaking, there is some uncertainty about what to make out of the comparison of the model impulse responses versus those in VARs.

When we subject the estimated model to independent empirical validation methods, we find that the empirical performance is very good. In particular, the model can reproduce the joint inflation and real exchange rate dynamics, a task that has turned out to be difficult (see Bouakez (2004) for further discussion). However, one shortcoming of the model is that it overpredicts the persistence and volatility of exports relative to the data.

By and large, we think 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 open economy business cycles. We are also currently working on examining the forecasting properties of the estimated model with alternative best-practice models such as Bayesian VARs, random walks and various moving average type of models (ARIMA). Of particular interest is, of course, the forecasting properties of the model related to real exchange rates, export and import. However, there are a number of dimensions in which the model can be improved.

First, we assume that all agents in the economy have perfect information about all shocks hitting the economy. As recent work have shown, relaxing this assumption can generate interesting dynamics in the economy, see e.g. Collard and Dellas (2004) and Lippi and Neri (2003).

Second, the treatment of fiscal policy in the model is very simplistic. It would be of great interest to empirically test for the relevance of non-Ricardian households, and examine to what extent the introduction of government debt (i.e., adding fiscal policy rules) and government production would affect the empirical performance of the model. In addition, that would enable a study of the interaction of monetary and fiscal policy in an empirically reasonable model.

Third, there is no well-developed banking sector in the model as in for example Christiano, Motto and Rostagno (2003). An interesting extension would therefore be to test for the empirical relevance of the financial accelerator channel of monetary policy.

Finally, we have not analyzed optimal monetary policy in the context of the model. A full-blown welfare analysis of optimal policy is beyond the current scope of the paper and is something we leave for future work.

Appendix A. Steady state

In this subsection, we will compute the steady state in the model. Note that the stationary first-order condition for m_{t+1} (2.52) in steady state reduce to

$$-1 + \beta \left[\frac{1}{\mu_z} \frac{1}{\pi} \left(R - \tau^k (R - 1) \right) \right] = 0, \quad (\text{A.1})$$

or equivalently

$$\begin{aligned} R - \tau^k (R - 1) &= \frac{\pi \mu_z}{\beta} \\ \Leftrightarrow \\ R &= \frac{\pi \mu_z - \tau^k \beta}{(1 - \tau^k) \beta}. \end{aligned} \quad (\text{A.2})$$

From the definitional equation for money growth, we have

$$\pi = \frac{\mu}{\mu_z}. \quad (\text{A.3})$$

The stationarized version of the first-order condition for b_{t+1}^* in (2.58) is simplified to

$$-S_t + \beta \left[\frac{1}{\mu_z \pi} \left(S_{t+1} R^* \Phi\left(\frac{A}{z}, \tilde{\phi}\right) - \tau^k S_{t+1} \left(R^* \Phi\left(\frac{A}{z}, \tilde{\phi}\right) - 1 \right) - \tau^k (S_{t+1} - S_t) \right) \right] = 0 \quad (\text{A.4})$$

and if we assume that

$$R^* = R, \quad (\text{A.5})$$

then we see by comparison of (A.1) and (A.4) that one possible steady state is characterized by

$$\begin{aligned} S_t &= S_{t+1} = 1, \\ \Phi\left(\frac{A_t}{z_t}, \tilde{\phi}_t\right) &= \Phi\left(\frac{A}{z}, \tilde{\phi}\right) = 1, \end{aligned}$$

which with our assumption that $\Phi\left(\frac{A}{z}, \tilde{\phi}\right) = \exp\left(-\tilde{\phi}_a A/z + \tilde{\phi}\right)$ implies that $B^* = A = 0$, and $\tilde{\phi} = 0$. Thus, in steady state, the net foreign asset position is zero.⁴⁴

The first order-condition for i_t in (2.55) simplifies to (using 2.48, i.e. $F_1 = 1, F_2 = 0, \Upsilon = 1$)

$$P_{k'} = \frac{P^i}{P}. \quad (\text{A.6})$$

⁴⁴In contrast, letting $\pi = \pi^*$ but assuming that domestic and foreign capital income taxes are not the same; τ^k and zero, respectively), we know from the foc of m_{t+1} that $R = \frac{\pi \mu_z - \tau^k \beta}{(1 - \tau^k) \beta}$. The foreign counterpart (without taxes) implies that $R^* = \frac{\pi \mu_z}{\beta}$ (given the same money growth and discounting). We consequently allow for different domestic and foreign interest rates in this example. The foc for b_{t+1}^* in equation (A.4) then implies the following in steady state; $\frac{S_t}{E_t S_{t+1}} = \beta \left[\frac{1}{\mu_z} \frac{1}{\pi} (R^* - \tau^k (R^* - 1)) \right]$. Inverting this and using $R^* = \frac{\pi \mu_z}{\beta}$; $\frac{E_t S_{t+1}}{S_t} = \frac{1}{[1 - \tau^k \beta (R^* - 1)]} \begin{cases} > 1 & \text{iff } \tau^k > 0 \\ = 1 & \text{iff } \tau^k = 0 \end{cases}$. Hence, the exchange rate is depreciating in steady state if we allow for larger capital income taxes at home than abroad.

Thus, we need to pin down the relative price in steady state. We will here assume, in addition to $R = R^*$ that $\pi = \pi^*$ and that $P_0 = P_0^*$, i.e. that the steady-state price levels in the beginning of time were the same. Notice that (2.41) can be used to define the following relative prices

$$\gamma_t^{c,d} \equiv \left(\frac{P_t^c}{P_t} \right) = \left[(1 - \omega_c) + \omega_c \left(\frac{P_t^{m,c}}{P_t} \right)^{1-\eta_c} \right]^{1/(1-\eta_c)}, \quad (\text{A.7})$$

$$\gamma_t^{c,mc} \equiv \left(\frac{P_t^c}{P_t^{m,c}} \right) = \left[(1 - \omega_c) \left(\frac{P_t}{P_t^{m,c}} \right)^{1-\eta_c} + \omega_c \right]^{1/(1-\eta_c)}, \quad (\text{A.8})$$

Combining (A.7) and (A.8) evaluated in steady state, and using the results in footnote 7, we derive

$$\gamma^{c,d} = \left[(1 - \omega_c) + \omega_c \left(\frac{\eta^{m,c}}{\eta^{m,c} - 1} \frac{SP_t^*}{P_t} \right)^{1-\eta_i} \right]^{1/(1-\eta_i)},$$

and

$$\gamma^{c,mc} = \left[(1 - \omega_c) \left(\frac{\eta^{m,c} - 1}{\eta^{m,c}} \frac{P_t}{SP_t^*} \right)^{1-\eta_i} + \omega_c \right]^{1/(1-\eta_i)},$$

where we have used the notation $\frac{\eta^{m,c}}{\eta^{m,c} - 1} = \lambda^{m,c}$, i.e. $\eta^{m,c}$ is the substitution elasticity among the imported consumption goods. Under the above assumption, we have that $\frac{SP_t^*}{P_t} = 1$ and consequently,

$$\gamma^{c,d} = \left[(1 - \omega_c) + \omega_c \left(\frac{\eta^{m,c}}{\eta^{m,c} - 1} \right)^{1-\eta_c} \right]^{1/(1-\eta_c)}, \quad (\text{A.9})$$

and also

$$\gamma^{c,mc} = \left[(1 - \omega_c) \left(\frac{\eta^{m,c} - 1}{\eta^{m,c}} \right)^{1-\eta_c} + \omega_c \right]^{1/(1-\eta_c)}. \quad (\text{A.10})$$

Similarly, we have that

$$\gamma^{i,d} \equiv \frac{P^i}{P} = \left[(1 - \omega_i) + \omega_i \left(\frac{\eta^{m,i}}{\eta^{m,i} - 1} \right)^{1-\eta_i} \right]^{1/(1-\eta_i)}, \quad (\text{A.11})$$

and

$$\gamma^{i,mi} \equiv \frac{P^i}{P^{m,i}} = \left[(1 - \omega_i) \left(\frac{\eta^{m,i} - 1}{\eta^{m,i}} \right)^{1-\eta_i} + \omega_i \right]^{1/(1-\eta_i)}, \quad (\text{A.12})$$

again using the notation $\frac{\eta^{m,i}}{\eta^{m,i} - 1} = \lambda^{m,i}$ where $\eta^{m,c}$ is the substitution elasticity among the imported investment goods.. Here it is important to note the following. If $0 < \eta_j < \infty$ and $1 < \eta^{m,j} < \infty$, then P^j/P will be greater than unity as long as $\omega_j > 0$ because then the households will substitute between the foreign and domestic goods and the mark-up on the foreign good is higher than unity $\left(\frac{\eta^{m,j}}{\eta^{m,j} - 1} \right)$ when $\eta^{m,j} < \infty$. Also, $P^j/P^{m,j}$ will be less than unity as long as $\omega_c < 1$ and $\eta^{m,j} < \infty$ because the

price of the domestic good will always be lower than the charged price of the foreign good given our assumption that $\frac{SP_t^*}{P_t} = 1$. Combining equations (A.9) and (A.10) we have that:

$$\frac{P^{m,c}}{P} = \left[\frac{(1 - \omega_c) + \omega_c \left(\frac{\eta^{m,c}}{\eta^{m,c} - 1} \right)^{1-\eta_c}}{(1 - \omega_c) \left(\frac{\eta^{m,c} - 1}{\eta^{m,c}} \right)^{1-\eta_c} + \omega_c} \right]^{1/(1-\eta_c)} = \frac{\eta^{m,c}}{\eta^{m,c} - 1}, \quad (\text{A.13})$$

and equations (A.11) and (A.12)

$$\frac{P^{m,i}}{P} = \left[\frac{(1 - \omega_i) + \omega_i \left(\frac{\eta^{m,i}}{\eta^{m,i} - 1} \right)^{1-\eta_i}}{(1 - \omega_i) \left(\frac{\eta^{m,i} - 1}{\eta^{m,i}} \right)^{1-\eta_i} + \omega_i} \right]^{1/(1-\eta_i)} = \frac{\eta^{m,i}}{\eta^{m,i} - 1}. \quad (\text{A.14})$$

Finally, it is useful to note that all relative prices equal unity when $\eta^{m,j} = \infty$ irrespective of ω_j and η_j .

Furthermore, note that the export price equals the foreign price level in steady state $P^x = P^*$, implying that the steady state markup in the export market must be one;

$$P^x = \frac{P}{S}. \quad (\text{A.15})$$

There are thus only *short run* deviations from the law of one price.

Using (A.6) in the first-order condition for \bar{k}_{t+1} in (2.54), we obtain (using our assumption that $u_t = \frac{k_t}{k_t} = u = 1 \Rightarrow a(u) = a(1) = 0$ in steady state)

$$\begin{aligned} \beta \left[\frac{1}{\mu_z} \left((1 - \delta)P_{k'} + (1 - \tau^k)r^k \right) \right] &= P_{k'} \\ &\Leftrightarrow \\ r^k &= \frac{\mu_z P_{k'} - \beta(1 - \delta)P_{k'}}{(1 - \tau^k)\beta}. \end{aligned}$$

From (2.14), we also have that

$$r^k = \frac{\alpha}{1 - \alpha} \mu_z \bar{w} R^f \frac{H}{k}, \quad (\text{A.16})$$

where from (2.9)

$$R^f \equiv \nu R + 1 - \nu. \quad (\text{A.17})$$

Using that

$$P = \lambda_d MC,$$

in steady state, or equivalently,

$$\frac{MC}{P} = \frac{1}{\lambda_d}, \quad (\text{A.18})$$

we have from (2.15) that

$$\frac{1}{\lambda_d} = \left(\frac{1}{1 - \alpha} \right)^{(1-\alpha)} \left(\frac{1}{\alpha} \right)^\alpha (r^k)^\alpha (\bar{w} R^f)^{1-\alpha}. \quad (\text{A.19})$$

We now want to solve for c , y , g , H , K , m , and q . In the end, we also want to check that all steady-state relationships are correct.

Real profits, Π^R , are given by

$$\Pi^R \equiv \left(\frac{P}{MC}\right)y - r^k \frac{k}{\mu_z} - \bar{w}R^f H - \phi,$$

where y is scaled output (i.e., $\frac{Y}{z}$) given by (2.4). The first term is the (real) income from sales, the next two terms represent the (real) cost of producing y , and ϕ denotes the fixed cost (or equivalently, the firm's profit from working under monopolistic competition). Because of its monopoly power the firm is paid a markup, λ_d , over its marginal cost (see (A.18)). In contrast, under perfect competition we know that there is no markup (profits are zero), and y must equal $y = r^k \frac{k}{\mu_z} - \bar{w}R^f H$. We now want to impose $\Pi^R = 0$ in steady state also in our monopolistic case, and determine the size of the fixed cost, ϕ , such that this zero profit condition is fulfilled. From the cost side, and perfect competition, we have that the real production cost must equal y (from (2.8)). Combining the two equations above, and using (A.18), the zero profit condition reduces to:

$$\Pi^R \equiv \lambda_d y - y - \phi = 0,$$

or equivalently,

$$\phi = (\lambda_d - 1)y. \quad (\text{A.20})$$

This has a simple interpretation. $(\lambda_d - 1)y$ is the excess over what is paid to factors of production, when steady-state output is y . This is completely absorbed by the fixed costs if (A.20) is satisfied. However, ϕ is included in y , so another way to write (A.20) is to use the steady-state version of (2.4).⁴⁵ We then have

$$\phi = (\lambda_d - 1) (\mu_z^{-\alpha} k^\alpha H^{1-\alpha} - \phi),$$

or equivalently

$$\phi = \frac{\lambda_d - 1}{\lambda_d} \mu_z^{-\alpha} \left(\frac{k}{H}\right)^\alpha H \quad (\text{A.21})$$

From the law-of-motion for capital (2.46), we have in steady state (using the steady state properties of 2.47, and stationarizing \bar{K}_{t+1} with z_t)

$$k = \frac{1 - \delta}{\mu_z} k + i,$$

or equivalently

$$i = \left(1 - \frac{1 - \delta}{\mu_z}\right) k. \quad (\text{A.22})$$

The consumption Euler equation (2.51) is in steady state given by

$$\frac{1}{c - bc \frac{1}{\mu_z}} - \beta b \frac{1}{c \mu_z - bc} - \psi_z \frac{P^c}{P} (1 + \tau^c) = 0,$$

⁴⁵Note that the scaled version of (2.4) reads at the aggregate level $y_t = \mu_{z,t}^{-\alpha} \epsilon_t k_t^\alpha H_t^{1-\alpha} - \phi$ and in steady state we thus have $y = \mu_z^{-\alpha} k^\alpha H^{1-\alpha} - \phi$.

or equivalently

$$\psi_z = \frac{1}{c} \frac{\mu_z - \beta b}{(1 + \tau^c)(\mu_z - b)} \left(\frac{P^c}{P} \right)^{-1} \quad (\text{A.23})$$

Since the effective steady-state wage is divided by the markup λ_w , the first-order condition for the households labour decision in (2.64) reduces to in steady state

$$-A_L H^{\sigma_L} + (1 - \tau^y) \frac{\psi_z}{\lambda_w} \frac{\bar{w}}{1 + \tau^w} = 0,$$

or equivalently

$$H = \left[\frac{(1 - \tau^y) \frac{\psi_z}{\lambda_w} \frac{\bar{w}}{1 + \tau^w}}{A_L} \right]^{1/\sigma_L}. \quad (\text{A.24})$$

The resource constraint (2.78) in steady state is given by

$$c^d + i^d + c^x + i^x = (1 - g_r) \left(\mu_z^{-\alpha} \left(\frac{k}{H} \right)^\alpha H - \phi \right).$$

Using (2.39), (2.35), (2.43) and (2.36), (A.21), we have

$$(1 - \omega_c) \left[\frac{P^c}{P} \right]^{\eta_c} c + (1 - \omega_i) \left[\frac{P^i}{P} \right]^{\eta_i} i + c^x + i^x = \frac{(1 - g_r)}{\lambda_d} \mu_z^{-\alpha} \left(\frac{k}{H} \right)^\alpha H. \quad (\text{A.25})$$

Thus, in order to proceed, we must assume something regarding c^x and i^x in steady state. Here we will adopt the assumption that export equals import in steady state, an assumption consistent with a zero foreign debt and unchanged nominal exchange rate in steady-state. From (2.82), this implies that (dividing through with z_t)

$$c^m + i^m = c^x + i^x,$$

and using (2.40) and (2.44) evaluated in steady state;

$$\begin{aligned} c^m &= \omega_c \left[\frac{P^{m,c}}{P^c} \right]^{-\eta_c} c = \omega_c \left[\frac{P^c}{P^{m,c}} \right]^{\eta_c} c, \\ i^m &= \omega_i \left[\frac{P^{m,i}}{P^i} \right]^{-\eta_i} i = \omega_i \left[\frac{P^i}{P^{m,i}} \right]^{\eta_i} i, \end{aligned}$$

this can be rewritten as

$$\begin{aligned} \omega_c \left[\frac{P^c}{P^{m,c}} \right]^{\eta_c} c + \omega_i \left[\frac{P^i}{P^{m,i}} \right]^{\eta_i} i &= (c^x + i^x), \\ \omega_c \left[\frac{P^c}{P^{m,c}} \right]^{\eta_c} c + \omega_i \left[\frac{P^i}{P^{m,i}} \right]^{\eta_i} i &= \tilde{x}, \end{aligned} \quad (\text{A.26})$$

which thus determines the aggregate export (of consumption and investment goods), and where the relative prices are determined in equations (A.13, A.10, A.14, and A.12).

Using this and (A.22) in (A.25), we obtain

$$\begin{aligned} &\left((1 - \omega_c) \left[\frac{P^c}{P} \right]^{\eta_c} + \omega_c \left[\frac{P^c}{P^{m,c}} \right]^{\eta_c} \right) c + \left((1 - \omega_i) \left[\frac{P^i}{P} \right]^{\eta_i} + \omega_i \left[\frac{P^i}{P^{m,i}} \right]^{\eta_i} \right) \left(1 - \frac{1 - \delta}{\mu_z} \right) \left(\frac{k}{H} \right) H \\ &= \frac{(1 - g_r)}{\lambda_d} \mu_z^{-\alpha} \left(\frac{k}{H} \right)^\alpha H, \end{aligned}$$

or equivalently,

$$\begin{aligned} & \left((1 - \omega_c) \left[\frac{P^c}{P} \right]^{\eta_c} + \omega_c \left[\frac{P^c}{P^{m,c}} \right]^{\eta_c} \right) c \\ &= \left[\frac{(1 - g_r)}{\lambda_d} \mu_z^{-\alpha} \left(\frac{k}{H} \right)^\alpha - \left((1 - \omega_i) \left[\frac{P^i}{P} \right]^{\eta_i} + \omega_i \left[\frac{P^i}{P^{m,i}} \right]^{\eta_i} \right) \left(1 - \frac{1 - \delta}{\mu_z} \right) \left(\frac{k}{H} \right) \right] H. \end{aligned}$$

We now substitute out for H in this expression using (A.23) and (A.24). For convenience, we introduce the definitions

$$\begin{aligned} D_1 &\equiv (1 - \omega_c) \left[\frac{P^c}{P} \right]^{\eta_c} + \omega_c \left[\frac{P^c}{P^{m,c}} \right]^{\eta_c}, \\ D_2 &\equiv \left[\frac{(1 - g_r)}{\lambda_d} \mu_z^{-\alpha} \left(\frac{k}{H} \right)^\alpha - \left((1 - \omega_i) \left[\frac{P^i}{P} \right]^{\eta_i} + \omega_i \left[\frac{P^i}{P^{m,i}} \right]^{\eta_i} \right) \left(1 - \frac{1 - \delta}{\mu_z} \right) \left(\frac{k}{H} \right) \right], \\ D_3 &\equiv \left[\frac{(1 - \tau^y) \frac{1}{\lambda_w} \frac{\bar{w}}{1 + \tau^w}}{A_L} \right]^{1/\sigma_L}, \\ D_4 &\equiv \frac{\mu_z - \beta b}{(1 + \tau^c)(\mu_z - b)} \left(\frac{P^c}{P} \right)^{-1}, \end{aligned} \tag{A.27}$$

since we can compute these constants using previous results. We then have the following system of equations

$$\begin{aligned} D_1 c &= D_2 H, \\ H &= D_3 (\psi_z)^{1/\sigma_L}, \\ \psi_z &= \frac{1}{c} D_4, \end{aligned}$$

and the solution for H , c and ψ_z are given by

$$\begin{aligned} H &= \left[D_3 D_4^{1/\sigma_L} \left(\frac{D_2}{D_1} \right)^{-1/\sigma_L} \right]^{\frac{\sigma_L}{1 + \sigma_L}}, \\ c &= \frac{D_2}{D_1} H, \\ \psi_z &= \frac{1}{c} D_4. \end{aligned} \tag{A.28}$$

Once equipped with the solution for H , we can compute y as

$$y = \frac{1}{\lambda_d} \mu_z^{-\alpha} \left(\frac{k}{H} \right)^\alpha H \tag{A.29}$$

using our solution for $\frac{k}{H}$ from (A.16). ϕ is computed using (A.21) and steady state government expenditures g as

$$g = g_r y, \tag{A.30}$$

The first-order condition for the capital utilization rate in (2.56) evaluated in steady state equals

$$a'(1) = (1 - \tau^k) r^k. \tag{A.31}$$

The first-order condition for the households cash decision in (2.57) evaluated in steady-state is given by

$$\begin{aligned} A_q q^{-\sigma_q} &= (1 - \tau^k) \psi_z (R - 1) \\ \Leftrightarrow \\ q &= \left(\frac{A_q}{(1 - \tau^k) \psi_z (R - 1)} \right)^{\frac{1}{\sigma_q}}, \end{aligned}$$

which can be used to compute q in steady state.

Finally, we can compute m using the loan market clearing condition (2.84) evaluated in steady state,

$$\begin{aligned} \nu \bar{w} H &= \frac{\mu m}{\pi \mu_z} - q \\ \Leftrightarrow \\ m &= \nu \bar{w} H + q \end{aligned} \tag{A.32}$$

in steady state.

Using the steady-state relationships above, we can compute $P_{k'}$, r^k , \bar{w} , R , R^f and $\frac{H}{k}$ in the following way. First, compute R from (A.2), second, compute R^f from (A.17), third, use (A.6) and (A.16) to compute r^k , fourth use (A.19) to compute $\bar{w} R^f$ and when divide the result with R^f to obtain \bar{w} , and fifth, use the solutions for r^k , \bar{w} , and R^f in (A.16) to compute $\frac{H}{k}$.

Using these results, we can compute c , i , y , g , ϕ , ψ_z , H , K , m , \tilde{x} and q in the following way. First, define the composite coefficients D_1 , D_2 , D_3 and D_4 defined in (A.27). Second, use (A.28) to compute c , H and ψ_z . Third, use A.21 to compute ϕ . Fourth, compute k by multiplying $\frac{k}{H}$ with H . Fifth, compute y using (A.29). Sixth, compute g from (A.30). Seventh, use (A.32) to compute q . Eighth, use (A.22) to compute i . Ninth, compute \tilde{x} using (A.26). Finally, use (A.32) to compute m .

Appendix B. The log-linearized model

In this appendix, we will present all the log-linearized equations in the model.

First, we have the domestic Phillips curve, see (2.19)

$$\begin{aligned} (\hat{\pi}_t - \hat{\pi}_t^c) &= \frac{\beta}{1 + \kappa_d \beta} (\mathbb{E}_t \hat{\pi}_{t+1} - \rho_\pi \hat{\pi}_t^c) + \frac{\kappa_d}{1 + \kappa_d \beta} (\hat{\pi}_{t-1} - \hat{\pi}_t^c) \\ &\quad - \frac{\kappa_d \beta (1 - \rho_\pi)}{1 + \kappa_d \beta} \hat{\pi}_t^c + \frac{(1 - \xi_d)(1 - \beta \xi_d)}{\xi_d (1 + \kappa_d \beta)} (\widehat{mc}_t + \widehat{\lambda}_{d,t}), \end{aligned} \quad (\text{B.1})$$

where log-linearized marginal costs are given by (see 2.15)

$$\begin{aligned} \widehat{mc}_t &= \alpha \hat{r}_t^k + (1 - \alpha) [\widehat{w}_t + \hat{R}_t^f] - \hat{\epsilon}_t \\ &= \alpha (\hat{\mu}_{z,t} + \hat{H}_t - \hat{k}_t) + \widehat{w}_t + \hat{R}_t^f - \hat{\epsilon}_t, \end{aligned}$$

where we have used that the log-linearized real rental rate of capital, \hat{r}_t^k , is given by (see 2.14)

$$\hat{r}_t^k = \hat{\mu}_{z,t} + \widehat{w}_t + \hat{R}_t^f + \hat{H}_t - \hat{k}_t.$$

Also, \hat{R}_t^f is given by (2.10).

The Phillips curves for the imported consumption and investment goods (see 2.30) are given by

$$\begin{aligned} (\hat{\pi}_t^{m,c} - \hat{\pi}_t^c) &= \frac{\beta}{1 + \kappa_{m,c} \beta} (\mathbb{E}_t \hat{\pi}_{t+1}^{m,c} - \rho_\pi \hat{\pi}_t^c) + \frac{\kappa_{m,c}}{1 + \kappa_{m,c} \beta} (\hat{\pi}_{t-1}^{m,c} - \hat{\pi}_t^c) - \\ &\quad \frac{\kappa_{m,c} \beta (1 - \rho_\pi)}{1 + \kappa_{m,c} \beta} \hat{\pi}_t^c + \frac{(1 - \xi_{m,c})(1 - \beta \xi_{m,c})}{\xi_{m,c} (1 + \kappa_{m,c} \beta)} (\widehat{mc}_t^{m,c} + \widehat{\lambda}_t^{m,c}), \end{aligned} \quad (\text{B.2})$$

$$\begin{aligned} (\hat{\pi}_t^{m,i} - \hat{\pi}_t^c) &= \frac{\beta}{1 + \kappa_{m,i} \beta} (\mathbb{E}_t \hat{\pi}_{t+1}^{m,i} - \rho_\pi \hat{\pi}_t^c) + \frac{\kappa_{m,i}}{1 + \kappa_{m,i} \beta} (\hat{\pi}_{t-1}^{m,i} - \hat{\pi}_t^c) - \\ &\quad \frac{\kappa_{m,i} \beta (1 - \rho_\pi)}{1 + \kappa_{m,i} \beta} \hat{\pi}_t^c + \frac{(1 - \xi_{m,i})(1 - \beta \xi_{m,i})}{\xi_{m,i} (1 + \kappa_{m,i} \beta)} (\widehat{mc}_t^{m,i} + \widehat{\lambda}_t^{m,i}), \end{aligned} \quad (\text{B.3})$$

where (see 2.73 and 2.74)

$$\begin{aligned} \widehat{mc}_t^{m,c} &= -\widehat{mc}_t^x - \hat{\gamma}_t^{x,*} - \hat{\gamma}_t^{mc,d}, \\ \widehat{mc}_t^{m,i} &= -\widehat{mc}_t^x - \hat{\gamma}_t^{x,*} - \hat{\gamma}_t^{mi,d}. \end{aligned}$$

The Phillips curve for the exporting firms is given by (see 2.34)

$$\begin{aligned} (\hat{\pi}_t^x - \hat{\pi}_t^c) &= \frac{\kappa_x}{1 + \beta \kappa_x} (\hat{\pi}_{t-1}^x - \hat{\pi}_t^c) + \frac{\beta}{1 + \beta \kappa_x} (\mathbb{E}_t \hat{\pi}_{t+1}^x - \rho_\pi \hat{\pi}_t^c) \\ &\quad + \frac{(1 - \beta \xi_x)(1 - \xi_x)}{\xi_x (1 + \beta \kappa_x)} (\widehat{mc}_t^x + \widehat{\lambda}_t^x) - \frac{\beta \kappa_x (1 - \rho_\pi)}{1 + \beta \kappa_x} \hat{\pi}_t^c. \end{aligned} \quad (\text{B.4})$$

The log-linearized real wage equation, which is derived from (2.63), can be written

$$\mathbb{E}_t \left[\begin{array}{l} \eta_0 \widehat{w}_{t-1} + \eta_1 \widehat{w}_t + \eta_2 \widehat{w}_{t+1} + \eta_3 (\widehat{\pi}_t^d - \widehat{\pi}_t^c) + \eta_4 (\widehat{\pi}_{t+1}^d - \rho_{\widehat{\pi}^c} \widehat{\pi}_t^c) \\ + \eta_5 (\widehat{\pi}_{t-1}^c - \widehat{\pi}_t^c) + \eta_6 (\widehat{\pi}_t^c - \rho_{\widehat{\pi}^c} \widehat{\pi}_t^c) \\ + \eta_7 \widehat{\psi}_{z,t}^\tau + \eta_8 \widehat{H}_t + \eta_9 \widehat{\tau}_t^y + \eta_{10} \widehat{\tau}_t^w + \eta_{11} \widehat{\zeta}_t^h \end{array} \right] = 0, \quad (\text{B.5})$$

where $b_w = \frac{[\lambda_w \sigma_L - (1 - \lambda_w)]}{[(1 - \beta \xi_w)(1 - \xi_w)]}$ and

$$\begin{pmatrix} \eta_0 \\ \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \\ \eta_6 \\ \eta_7 \\ \eta_8 \\ \eta_9 \\ \eta_{10} \\ \eta_{11} \end{pmatrix} = \begin{pmatrix} b_w \xi_w \\ (\sigma_L \lambda_w - b_w (1 + \beta \xi_w^2)) \\ b_w \beta \xi_w \\ -b_w \xi_w \\ b_w \beta \xi_w \\ b_w \xi_w \kappa_w \\ -b_w \beta \xi_w \kappa_w \\ (1 - \lambda_w) \\ -(1 - \lambda_w) \sigma_L \\ -(1 - \lambda_w) \frac{\tau^y}{(1 - \tau^y)} \\ -(1 - \lambda_w) \frac{\tau^w}{(1 + \tau^w)} \\ -(1 - \lambda_w) \end{pmatrix}.$$

Log-linearizing (2.51), we derive

$$\mathbb{E}_t \left[\begin{array}{l} -b\beta\mu_z \widehat{c}_{t+1} + (\mu_z^2 + b^2\beta) \widehat{c}_t - b\mu_z \widehat{c}_{t-1} + b\mu_z (\widehat{\mu}_{z,t} - \beta \widehat{\mu}_{z,t+1}) + \\ + (\mu_z - b\beta) (\mu_z - b) \widehat{\psi}_{z,t} + \frac{\tau^c}{1 + \tau^c} (\mu_z - b\beta) (\mu_z - b) \widehat{\tau}_t^c + (\mu_z - b\beta) (\mu_z - b) \widehat{\gamma}_t^{c,d} \\ - (\mu_z - b) (\mu_z \widehat{\zeta}_t^c - b\beta \widehat{\zeta}_{t+1}^c) \end{array} \right] = 0. \quad (\text{B.6})$$

Log-linearizing (2.55), using the properties of (2.47), we obtain

$$\mathbb{E}_t \left\{ \widehat{P}_{k',t} + \widehat{Y}_t - \widehat{\gamma}_t^{i,d} - \mu_z^2 \widetilde{S}'' [(\widehat{i}_t - \widehat{i}_{t-1}) - \beta (\widehat{i}_{t+1} - \widehat{i}_t) + \widehat{\mu}_{z,t} - \beta \widehat{\mu}_{z,t+1}] \right\} = 0. \quad (\text{B.7})$$

The log-linearized version of (2.52) is given by

$$\mathbb{E}_t \left[-\mu \widehat{\psi}_{z,t} + \mu \widehat{\psi}_{z,t+1} - \mu \widehat{\mu}_{z,t+1} + (\mu - \beta \tau^k) \widehat{R}_t - \mu \widehat{\pi}_{t+1} + \frac{\tau^k}{1 - \tau^k} (\beta - \mu) \widehat{\tau}_{t+1}^k \right] = 0, \quad (\text{B.8})$$

and log-linearizing (2.54), we derive

$$\mathbb{E}_t \left[\begin{array}{l} \widehat{\psi}_{z,t} + \widehat{\mu}_{z,t+1} - \widehat{\psi}_{z,t+1} - \frac{\beta(1-\delta)}{\mu_z} \widehat{P}_{k',t+1} + \widehat{P}_{k',t} - \frac{\mu_z - \beta(1-\delta)}{\mu_z} \widehat{r}_{t+1}^k \\ + \frac{\tau^k}{(1 - \tau^k)} \frac{\mu_z - \beta(1-\delta)}{\mu_z} \widehat{\tau}_{t+1}^k \end{array} \right] = 0, \quad (\text{B.9})$$

where the log-linearized expression for the real rental rate of capital is defined after (B.1).

The log-linearized UIP condition is given by (see 2.59),

$$\mathbb{E}_t \Delta \widehat{S}_{t+1} - (\widehat{R}_t - \widehat{R}_t^*) - \widetilde{\phi}_a \widehat{a}_t + \widehat{\phi}_t = 0, \quad (\text{B.10})$$

and the aggregate resource constraint is given by (see 2.81)

$$\begin{aligned}
& (1 - \omega_c) \left(\gamma^{c,d} \right)^{\eta_c} \frac{c}{y} \left(\hat{c}_t + \eta_c \hat{\gamma}_t^{c,d} \right) + (1 - \omega_i) \left(\gamma^{i,d} \right)^{\eta_i} \frac{i}{y} \left(\hat{i}_t + \eta_i \hat{\gamma}_t^{i,d} \right) \\
& + \frac{g}{y} \hat{g}_t + \frac{y^*}{y} \left(\hat{y}_t^* - \eta_f \hat{\gamma}_t^{x,*} + \hat{z}_t^* \right) \\
& = \\
& \lambda_d \left(\hat{c}_t + \alpha \left(\hat{k}_t - \hat{\mu}_{z,t} \right) + (1 - \alpha) \hat{H}_t \right) - \left(1 - \tau^k \right) r^k \frac{\bar{k}}{y \mu_z} \frac{1}{\mu_z} \left(\hat{k}_t - \hat{\bar{k}}_t \right).
\end{aligned} \tag{B.11}$$

The log-linearized law of motion for capital is given by (see 2.46, note that $\Delta_t = 0$ for all t in equilibrium)

$$\hat{\bar{k}}_{t+1} = (1 - \delta) \frac{1}{\mu_z} \hat{\bar{k}}_t - (1 - \delta) \frac{1}{\mu_z} \hat{\mu}_{z,t} + \left(1 - (1 - \delta) \frac{1}{\mu_z} \right) \hat{\Upsilon}_t + \left(1 - (1 - \delta) \frac{1}{\mu_z} \right) \hat{i}_t, \tag{B.12}$$

and the expression for the capacity utilization rate is (see 2.56)

$$\begin{aligned}
\hat{u}_t &= \hat{k}_t - \hat{\bar{k}}_t \\
&= \frac{1}{\sigma_a} \hat{r}_t^k - \frac{1}{\sigma_a} \frac{\tau^k}{(1 - \tau^k)} \hat{\tau}_t^k,
\end{aligned} \tag{B.13}$$

The log-linearized version of the first-order conditions for cash holdings is (see 2.57)

$$\hat{q}_t = \frac{1}{\sigma_q} \left[\hat{\zeta}_t^q + \frac{\tau^k}{1 - \tau^k} \hat{\tau}_t^k - \hat{\psi}_{z,t} - \frac{R}{R - 1} \hat{R}_{t-1} \right]. \tag{B.14}$$

We also need to relate money growth to real balances, domestic inflation and real growth, i.e.

$$\mu_t = \frac{M_{t+1}}{M_t} = \frac{\bar{m}_{t+1} z_t P_t}{\bar{m}_t z_{t-1} P_{t-1}} = \frac{\bar{m}_{t+1} \mu_{z,t} \pi_t}{\bar{m}_t},$$

and log-linearizing, we have

$$\hat{\mu}_t - \hat{\bar{m}}_{t+1} - \hat{\mu}_{z,t} - \hat{\pi}_t + \hat{\bar{m}}_t = 0. \tag{B.15}$$

Log-linearizing the loan market clearing condition (2.85), we get

$$\nu \bar{w} H \left(\hat{\nu}_t + \hat{w}_t + \hat{H}_t \right) = \frac{\mu \bar{m}}{\pi \mu_z} \left(\hat{\mu}_t + \hat{\bar{m}}_t - \hat{\pi}_t - \hat{\mu}_{z,t} \right) - q \hat{q}_t. \tag{B.16}$$

The log-linearized equilibrium law of motion for net foreign assets are given by (see 2.83)

$$\begin{aligned}
\hat{a}_t &= -y^* \hat{m} \hat{c}_t^x - \eta_f y^* \hat{\gamma}_t^{x,*} + y^* \hat{y}_t^* + y^* \hat{z}_t^* \\
&+ (c^m + i^m) \hat{\gamma}_t^f \\
&- \left(\begin{aligned} & c^m \left(-\eta_c (1 - \omega_c) \left(\gamma^{c,d} \right)^{-(1-\eta_c)} \hat{\gamma}_t^{mc,d} + \hat{c}_t \right) + \\ & i^m \left(-\eta_i (1 - \omega_i) \left(\gamma^{i,d} \right)^{-(1-\eta_i)} \hat{\gamma}_t^{mi,d} + \hat{i}_t \right) \end{aligned} \right) + \frac{R}{\pi \mu_z} \hat{a}_{t-1}.
\end{aligned} \tag{B.17}$$

We also have the following log-linearized relative prices (see subsection 2.4)

$$\hat{\gamma}_t^{mc,d} = \hat{\gamma}_{t-1}^{mc,d} + \hat{\pi}_t^{m,c} - \hat{\pi}_t^d, \tag{B.18}$$

$$\widehat{\gamma}_t^{mi,d} = \widehat{\gamma}_{t-1}^{mi,d} + \widehat{\pi}_t^{m,i} - \widehat{\pi}_t^d, \quad (\text{B.19})$$

$$\widehat{\gamma}_t^{x,*} \equiv \widehat{\gamma}_{t-1}^{x,*} + \widehat{\pi}_t^x - \widehat{\pi}_t^*, \quad (\text{B.20})$$

$$\widehat{mc}_t^x = \widehat{mc}_{t-1}^x + \widehat{\pi}_t - \widehat{\pi}_t^x - \Delta \widehat{S}_t, \quad (\text{B.21})$$

The log-linearized policy rule are given by (see 2.75)

$$\widehat{R}_t = \rho_R \widehat{R}_{t-1} + (1 - \rho_R) \left(\widehat{\pi}_t^c + r_\pi (\widehat{\pi}_{t-1}^c - \widehat{\pi}_t^c) + r_y \widehat{y}_{t-1} + r_x \widehat{x}_{t-1} \right) + r_{\Delta\pi} (\widehat{\pi}_t^c - \widehat{\pi}_{t-1}^c) + r_{\Delta y} \Delta \widehat{y}_t + \varepsilon_{R,t}, \quad (\text{B.22})$$

where

$$\begin{aligned} \widehat{\pi}_t^c &= \left((1 - \omega_c) (\gamma^{d,c})^{1-\eta_c} \right) \widehat{\pi}_t^d + \left((\omega_c) (\gamma^{mc,c})^{(1-\eta_c)} \right) \widehat{\pi}_t^{m,c}, \\ \widehat{y}_t &= \lambda_d \left(\widehat{\epsilon}_t + \alpha \left(\widehat{k}_t - \widehat{\mu}_{z,t} \right) + (1 - \alpha) \widehat{H}_t \right), \\ \widehat{x}_t &= -\omega_c (\gamma^{c,mc})^{-(1-\eta_c)} \widehat{\gamma}_t^{mc,d} - \widehat{\gamma}_t^{x,*} - \widehat{mc}_t^x. \end{aligned}$$

Finally, we have the employment equation (see 3.2), which can be written

$$\widehat{E}_t = \frac{\beta}{1 + \beta} \mathbf{E}_t \widehat{E}_{t+1} + \frac{1}{1 + \beta} \widehat{E}_{t-1} + \frac{(1 - \xi_e)(1 - \beta \xi_e)}{(1 + \beta) \xi_e} \left(\widehat{H}_t - \widehat{E}_t \right). \quad (\text{B.23})$$

To write the equations above plus the exogenous process on the form given by equations (C.1) and (C.2) in the main text, we define \tilde{z}_t and θ_t as follows

$$\tilde{z}_t = \begin{bmatrix} \widehat{\pi}_t & \widehat{\pi}_t^{m,c} & \widehat{\pi}_t^{m,i} & \widehat{\pi}_t^x & \widehat{w}_t & \widehat{c}_t & \widehat{i}_t & \widehat{\psi}_{z,t} & \widehat{P}_{k',t} & \Delta \widehat{S}_t & \widehat{H}_t & \dots \\ \widehat{k}_{t+1} & \widehat{k}_t & \widehat{q}_t & \widehat{m}_{t+1} & \widehat{\mu}_t & \widehat{a}_t & \widehat{\gamma}_t^{mc,d} & \widehat{\gamma}_t^{mi,d} & \widehat{\gamma}_t^{x,*} & \widehat{mc}_t^x & \widehat{R}_t & \widehat{E}_t \end{bmatrix}'$$

$$\theta_t = \begin{bmatrix} \theta_t^s & \theta_t^\tau & \theta_t^* \end{bmatrix}',$$

where

$$\begin{aligned} \theta_t^s &= \begin{bmatrix} \widehat{\epsilon}_t & \widehat{\epsilon}_{t-1} & \widehat{\mu}_{z,t} & \widehat{\mu}_{z,t-1} & \widehat{\nu}_t & \widehat{\zeta}_t^c & \widehat{\zeta}_t^h & \widehat{\zeta}_t^q & \widehat{\lambda}_{d,t} & \widehat{\lambda}_t^{m,c} & \widehat{\lambda}_t^{m,i} & \widetilde{\phi}_t & \widehat{\Upsilon}_t & \widehat{z}_t^* & \widehat{\lambda}_{x,t} & \epsilon_{R,t} & \widehat{\pi}_t^c \end{bmatrix}, \\ \theta_t^\tau &= \begin{bmatrix} \widehat{\tau}_t^k & \widehat{\tau}_t^y & \widehat{\tau}_t^c & \widehat{\tau}_t^w & \widehat{g}_t & \widehat{\tau}_{t-1}^k & \widehat{\tau}_{t-1}^y & \widehat{\tau}_{t-1}^c & \widehat{\tau}_{t-1}^w & \widehat{g}_{t-1} \end{bmatrix}, \\ \theta_t^* &= \begin{bmatrix} \widehat{\pi}_t^* & \widehat{y}_t^* & \widehat{R}_t^* & \widehat{\pi}_{t-1}^* & \widehat{y}_{t-1}^* & \widehat{R}_{t-1}^* & \widehat{\pi}_{t-2}^* & \widehat{y}_{t-2}^* & \widehat{R}_{t-2}^* & \widehat{\pi}_{t-3}^* & \widehat{y}_{t-3}^* & \widehat{R}_{t-3}^* \end{bmatrix}, \end{aligned}$$

and where the parameter matrices α_0 , α_1 , α_2 , β_0 and β_1 corresponds to the equations (B.1 – B.23).

Appendix C. Model solution and likelihood formation

First, we compute the non-stochastic steady state of the model. This is described in Appendix A, where details about the determination of the steady state can be found. Second, we log-linearize the relevant first order conditions and the market clearing conditions around this steady state. Appendix B presents all the equations of the log-linearized model. To solve the log-linearized model we use the AIM algorithm developed by Anderson and Moore (1985). The fundamental difference equation solved by the Anderson and Moore algorithm for this model can be written as

$$E_t \{ \alpha_0 \tilde{z}_{t+1} + \alpha_1 \tilde{z}_t + \alpha_2 \tilde{z}_{t-1} + \beta_0 \theta_{t+1} + \beta_1 \theta_t \} = 0, \quad (C.1)$$

where \tilde{z}_t is a $n_{\tilde{z}} \times 1$ vector with endogenous variables and θ_t is a $n_{\theta} \times 1$ vector with exogenous variables which follows

$$\theta_t = \rho \theta_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim N(0, \Sigma). \quad (C.2)$$

Note that if the processes for the exogenous variables are given by more than one lag, we expand θ_t with lags of the relevant exogenous variable.

The solution of the fundamental difference equation can then be written as

$$\tilde{z}_t = A \tilde{z}_{t-1} + B \theta_t \quad (C.3)$$

where A is the “feedback” matrix and B is the “feedforward” matrix.

The solution of the model given by (C.3) and (C.2) can be transformed to the following state-space representation for the unobserved state variables ξ_t in the model

$$\xi_{t+1} = F_{\xi} \xi_t + v_{t+1}, \quad E(v_{t+1} v'_{t+1}) = Q,$$

and the observation equation can be written

$$\tilde{Y}_t = A'_X X_t + H' \xi_t + \zeta_t,$$

where \tilde{Y}_t is a vector of observed variables, X_t a vector with exogenous or predetermined variables (e.g., a constant) and where the measurement errors ζ_t are normally distributed with zero mean and $E(\zeta_t \zeta'_t) = R$. Following Hamilton (1994), the Kalman updating equations are given by

$$\begin{aligned} \hat{\xi}_{t+1|t} &= F_{\xi} \hat{\xi}_{t|t-1} + K_t \left(\tilde{Y}_t - A'_X X_t - H' \hat{\xi}_{t|t-1} \right), \\ P_{t+1|t} &= F_{\xi} P_{t|t-1} F'_{\xi} - K_t H' P_{t|t-1} F'_{\xi} + Q, \end{aligned}$$

where $K_t \equiv F_{\xi} P_{t|t-1} H (H' P_{t|t-1} H + R)^{-1}$, $P_{t|t-1} \equiv E[(\xi_t - \hat{\xi}_{t|t-1})(\xi_t - \hat{\xi}_{t|t-1})']$ and $\hat{\xi}_{t|t-1}$ is the linear projection of ξ_t on the data observed up to period $t-1$. The log-likelihood is computed as

$$\ln L = -\frac{Tn}{2} \log 2\pi - \frac{1}{2} \sum_{t=1}^T \log |\Sigma_t| - \frac{1}{2} \sum_{t=1}^T \left(\tilde{Y}_t - A'_X X_t - H' \hat{\xi}_{t|t-1} \right)' \Sigma_t^{-1} \left(\tilde{Y}_t - A'_X X_t - H' \hat{\xi}_{t|t-1} \right)$$

where $\Sigma_t = H' P_{t|t-1} H + R$. We set $R = 0.10$ for all “domestic” variables and $R = 0$ for the foreign variables. We allow R to be non-zero for the domestic variables because we know that the data series at hand are only at best good approximations of the true series. This is in particular true for the “open-economy” variables included in \tilde{Y}_t , because the data do not distinguish between intra- and inter-trade. However, it should be emphasized that our chosen value of 0.10 is very small, so the fluctuations driven by the measurement errors are tiny.

Appendix D. Results based on data in levels with cointegration restrictions

Table D1: Posterior distributions based on data in first differences, and levels with cointegration restrictions

Parameter		First differences					Levels with cointegration				
		Posterior distribution					Posterior distribution				
		mode	std. dev. (Hess- ian)	mean	5%	95%	mode	std. dev. (Hess- ian)	mean	5%	95%
Calvo wages	ξ_w	0.697	0.047	0.690	0.607	0.766	0.693	0.076	0.684	0.603	0.761
Calvo domestic prices	ξ_d	0.883	0.015	0.891	0.862	0.921	0.930	0.008	0.935	0.920	0.948
Calvo import cons. prices	$\xi_{m,c}$	0.463	0.059	0.444	0.345	0.540	0.619	0.086	0.598	0.512	0.684
Calvo import inv. prices	$\xi_{m,i}$	0.740	0.040	0.721	0.641	0.792	0.774	0.025	0.751	0.690	0.805
Calvo export prices	ξ_x	0.639	0.059	0.612	0.506	0.717	0.649	0.070	0.642	0.548	0.736
Calvo employment	ξ_e	0.792	0.022	0.787	0.741	0.827	0.833	0.019	0.827	0.787	0.862
Indexation wages	κ_w	0.516	0.160	0.497	0.258	0.739	0.592	0.153	0.564	0.309	0.797
Indexation domestic prices	κ_d	0.212	0.066	0.217	0.095	0.362	0.200	0.142	0.217	0.093	0.367
Index. import cons. prices	$\kappa_{m,c}$	0.161	0.074	0.220	0.084	0.418	0.145	0.076	0.190	0.077	0.337
Index. import inv. prices	$\kappa_{m,i}$	0.187	0.079	0.231	0.098	0.405	0.202	0.092	0.240	0.102	0.418
Indexation export prices	κ_x	0.139	0.072	0.185	0.069	0.347	0.148	0.079	0.192	0.074	0.359
Markup domestic	λ_d	1.168	0.053	1.222	1.122	1.383	1.169	0.054	1.202	1.116	1.337
Markup imported cons.	$\lambda_{m,c}$	1.619	0.063	1.633	1.526	1.751	1.535	0.073	1.595	1.408	1.800
Markup imported invest.	$\lambda_{m,i}$	1.226	0.088	1.275	1.146	1.467	1.164	0.052	1.193	1.116	1.308
Investment adj. cost	\tilde{S}^n	8.732	1.370	8.670	6.368	10.958	8.227	1.849	8.342	6.036	10.710
Habit formation	b	0.690	0.048	0.708	0.608	0.842	0.761	0.030	0.741	0.677	0.795
Subst. elasticity invest.	η_i	1.669	0.273	1.696	1.393	2.142	1.526	0.133	1.611	1.355	2.017
Subst. elasticity foreign	η_f	1.460	0.098	1.486	1.340	1.674	1.416	0.129	1.449	1.315	1.629
Technology growth	μ_z	1.005	0.000	1.005	1.004	1.006	1.006	0.000	1.006	1.005	1.006
Capital income tax	τ_k	0.137	0.042	0.135	0.072	0.200	0.241	0.030	0.237	0.196	0.282
Labour pay-roll tax	τ_w	0.186	0.050	0.197	0.118	0.286	0.185	0.100	0.197	0.118	0.287
Risk premium	$\tilde{\phi}$	0.145	0.047	0.252	0.139	0.407	0.095	0.033	0.130	0.069	0.214
Unit root tech. shock	ρ_{μ_z}	0.723	0.106	0.698	0.526	0.852	0.810	0.075	0.764	0.589	0.904
Stationary tech. shock	ρ_{ε}	0.909	0.030	0.886	0.810	0.939	0.980	0.004	0.981	0.972	0.989
Invest. spec. tech. shock	ρ_Y	0.750	0.041	0.720	0.638	0.796	0.799	0.042	0.788	0.706	0.867
Asymmetric tech. shock	ρ_{z^*}	0.993	0.002	0.992	0.986	0.995	0.993	0.007	0.988	0.972	0.998
Consumption pref. shock	ρ_{ζ_c}	0.935	0.029	0.892	0.722	0.964	0.990	0.003	0.988	0.979	0.994
Labour supply shock	ρ_{ζ_h}	0.675	0.062	0.676	0.565	0.774	0.824	0.044	0.816	0.758	0.868
Risk premium shock	$\rho_{\tilde{\phi}}$	0.991	0.008	0.955	0.922	0.991	0.995	0.010	0.985	0.960	0.998
Imp. cons. markup shock	$\rho_{\lambda_{m,c}}$	0.978	0.016	0.970	0.943	0.991	0.960	0.022	0.956	0.927	0.979
Imp. invest. markup shock	$\rho_{\lambda_{m,i}}$	0.974	0.015	0.963	0.931	0.989	0.983	0.007	0.979	0.961	0.992
Export markup shock	ρ_{λ_x}	0.894	0.045	0.886	0.789	0.961	0.906	0.046	0.879	0.792	0.943
Unit root tech. shock	σ_z	0.130	0.025	0.137	0.099	0.185	0.120	0.026	0.132	0.092	0.183
Stationary tech. shock	σ_{ε}	0.452	0.082	0.519	0.361	0.756	0.467	0.076	0.486	0.366	0.634
Invest. spec. tech. shock	σ_Y	0.424	0.046	0.469	0.389	0.561	0.328	0.051	0.347	0.279	0.427
Asymmetric tech. shock	σ_{z^*}	0.203	0.031	0.217	0.166	0.276	0.343	0.043	0.360	0.291	0.437
Consumption pref. shock	σ_{ζ_c}	0.151	0.031	0.157	0.108	0.224	0.113	0.027	0.126	0.088	0.179
Labour supply shock	σ_{ζ_h}	0.095	0.015	0.098	0.075	0.128	0.085	0.017	0.091	0.071	0.115
Risk premium shock	$\sigma_{\tilde{\phi}}$	0.130	0.023	0.183	0.128	0.246	0.119	0.030	0.150	0.105	0.210
Domestic markup shock	σ_{λ}	0.130	0.012	0.132	0.111	0.157	0.122	0.012	0.126	0.105	0.149
Imp. cons. markup shock	$\sigma_{\lambda_{m,c}}$	2.548	0.710	2.882	1.737	4.463	0.943	0.305	1.198	0.630	1.917
Imp. invest. markup shock	$\sigma_{\lambda_{m,i}}$	0.292	0.079	0.354	0.218	0.550	0.219	0.038	0.266	0.183	0.381
Export markup shock	σ_{λ_x}	0.977	0.214	1.124	0.772	1.604	0.893	0.220	0.959	0.677	1.326
Monetary policy shock	σ_R	0.133	0.013	0.135	0.113	0.160	0.125	0.012	0.132	0.111	0.156
Inflation target shock	σ_{π^c}	0.044	0.012	0.053	0.032	0.081	0.056	0.013	0.060	0.040	0.083
Interest rate smoothing	ρ_R	0.874	0.021	0.881	0.844	0.915	0.834	0.020	0.833	0.795	0.867
Inflation response	r_{π}	1.710	0.067	1.730	1.577	1.876	1.687	0.069	1.719	1.588	1.857
Diff. infl response	$r_{\Delta\pi}$	0.317	0.059	0.310	0.212	0.411	0.388	0.231	0.380	0.275	0.486
Real exch. rate response	r_x	-0.009	0.008	-0.009	-0.024	0.006	-0.012	0.006	-0.011	-0.018	-0.004
Output response	r_y	0.078	0.028	0.104	0.051	0.168	0.059	0.016	0.062	0.042	0.084
Diff. output response	$r_{\Delta\pi}$	0.116	0.028	0.128	0.081	0.177	0.129	0.008	0.129	0.090	0.172

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Table 1: Prior and posterior distributions

Parameter		Prior distribution			With variable capital utilization $\sigma_a = 0.049$		No variable capital utilization $\sigma_a = 10^6$				
		type	mean*	std.dev./df	mode	std. dev. (Hessian)	mode	std. dev. (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 cons. 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 inv. 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_e	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 cons. 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 inv. 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	inv. gamma	1.200	2	1.174	0.059	1.168	0.053	1.222	1.122	1.383
Markup imported cons.	$\lambda_{m,c}$	inv. gamma	1.200	2	1.636	0.071	1.619	0.063	1.633	1.526	1.751
Markup imported invest.	$\lambda_{m,i}$	inv. gamma	1.200	2	1.209	0.076	1.226	0.088	1.275	1.146	1.467
Investment adj. cost	\tilde{S}^c	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
Subst. elasticity invest.	η_i	inv. gamma	1.500	4	1.585	0.220	1.669	0.273	1.696	1.393	2.142
Subst. elasticity foreign	η_f	inv. gamma	1.500	4	1.400	0.078	1.460	0.098	1.486	1.340	1.674
Technology growth	μ_z	trunc. 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	$\tilde{\phi}$	inv. gamma	0.010	2	0.131	0.044	0.145	0.047	0.252	0.139	0.407
Unit root tech. shock	ρ_{μ_z}	beta	0.850	0.100	0.753	0.107	0.723	0.106	0.698	0.526	0.852
Stationary tech. shock	ρ_ε	beta	0.850	0.100	0.935	0.021	0.909	0.030	0.886	0.810	0.939
Invest. spec. tech shock	ρ_Y	beta	0.850	0.100	0.738	0.041	0.750	0.041	0.720	0.638	0.796
Asymmetric tech. shock	ρ_{z^*}	beta	0.850	0.100	0.992	0.003	0.993	0.002	0.992	0.986	0.995
Consumption pref. shock	ρ_{ξ_c}	beta	0.850	0.100	0.935	0.021	0.935	0.029	0.892	0.722	0.964
Labour supply shock	ρ_{ξ_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
Imp. cons. 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
Imp. invest. 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 tech. shock	σ_z	inv. gamma	0.200	2	0.122	0.023	0.130	0.025	0.137	0.099	0.185
Stationary tech. shock	σ_ε	inv. gamma	0.700	2	0.414	0.065	0.452	0.082	0.519	0.361	0.756
Invest. spec. tech. shock	σ_Y	inv. gamma	0.200	2	0.397	0.046	0.424	0.046	0.469	0.389	0.561
Asymmetric tech. shock	σ_{z^*}	inv. gamma	0.400	2	0.200	0.030	0.203	0.031	0.217	0.166	0.276
Consumption pref. shock	σ_{ξ_c}	inv. gamma	0.200	2	0.132	0.025	0.151	0.031	0.157	0.108	0.224
Labour supply shock	σ_{ξ_h}	inv. gamma	0.200	2	0.094	0.014	0.095	0.015	0.098	0.075	0.128
Risk premium shock	$\sigma_{\tilde{\phi}}$	inv. gamma	0.050	2	0.123	0.023	0.130	0.023	0.183	0.128	0.246
Domestic markup shock	σ_{λ}	inv. gamma	0.300	2	0.133	0.013	0.130	0.012	0.132	0.111	0.157
Imp. cons. markup shock	$\sigma_{\lambda_{m,c}}$	inv. gamma	0.300	2	1.912	0.492	2.548	0.710	2.882	1.737	4.463
Imp. invest. markup shock	$\sigma_{\lambda_{m,i}}$	inv. gamma	0.300	2	0.281	0.068	0.292	0.079	0.354	0.218	0.550
Export markup shock	σ_{λ_x}	inv. gamma	0.300	2	1.028	0.210	0.977	0.214	1.124	0.772	1.604
Monetary policy shock	σ_R	inv. gamma	0.150	2	0.126	0.013	0.133	0.013	0.135	0.113	0.160
Inflation target shock	σ_{π^c}	inv. 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
Diff. infl response	$r_{\Delta\pi}$	normal	0.300	0.100	0.301	0.058	0.317	0.059	0.310	0.212	0.411
Real exch. 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
Diff. output response	$r_{\Delta\pi}$	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 parameters $\lambda_d, \eta_i, \eta_f, \lambda_{m,c}, \lambda_{m,i}$ and μ_z the prior distributions are truncated at 1.

Table 2: Sensitivity analysis with respect to frictions

Parameter		Posterior mode									
		Bench- mark	No wage sticki- ness	No price sticki- ness	No habit persist- ence	No invest. adj. cost	LOP imports	LOP exports	No working capital channel	Persis- tent dom. markup shock	IID markup shocks
		$\xi_w = 0.1$	$\xi_d = 0.1$	$b = 0.1$	$\tilde{S} = 0.1$	$\xi_{m,c} = \xi_{m,i} = 0.2$	$\xi_x = 0.1$	$\nu = 0.01$	$\rho_{\lambda_d} > 0$	$\rho_{\lambda_d} = \rho_{\lambda_w} = \rho_{\lambda_x} = 0$	
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 cons. prices	$\xi_{m,c}$	0.463	0.463	0.464	0.405	0.468		0.466	0.454	0.523	0.899 [*]
Calvo import inv. prices	$\xi_{m,i}$	0.740	0.706	0.733	0.696	0.458		0.762	0.742	0.714	0.912 [*]
Calvo export prices	ξ_x	0.639	0.657	0.637	0.668	0.646	0.711		0.640	0.669	0.853 [*]
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 cons. 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 inv. 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 cons.	$\lambda_{m,c}$	1.619	1.677	1.652	1.721	1.545	1.203	1.636	1.629	1.642	1.515
Markup imported invest.	$\lambda_{m,i}$	1.226	1.280	1.268	1.250	1.218	1.850	1.178	1.227	1.255	1.160
Investment adj. 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
Subst. elasticity invest.	η_i	1.669	1.678	1.601	1.751	2.823	3.394	1.494	1.660	1.616	1.405
Subst. 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	ϕ	0.145	0.146	0.086	0.176	0.485	0.300	0.140	0.147	0.095	0.035
Unit root tech. 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 tech. shock	ρ_ε	0.909	0.995	0.999	0.917	0.921	0.848	0.991	0.913	0.997	0.904
Invest. spec. tech shock	ρ_γ	0.750	0.749	0.769	0.694	0.922	0.469	0.741	0.748	0.562	0.785
Asymmetric tech. shock	ρ_{z^*}	0.993	0.993	0.994	0.994	0.995	0.907	0.994	0.993	0.953	0.990
Consumption pref. shock	σ_{ε_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_{ε_h}	0.675	0.933	0.471	0.637	0.686	0.689	0.718	0.657	0.536	0.656
Risk premium shock	ρ_{ϕ}	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	
Imp. cons. markup shock	$\rho_{\lambda_{m,c}}$	0.978	0.979	0.986	0.989	0.959	0.978	0.938	0.982	0.975	
Imp. invest. 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 tech. shock	σ_z	0.130	0.120	0.127	0.118	0.134	0.128	0.119	0.130	0.132	0.128
Stationary tech. shock	σ_ε	0.452	0.371	0.292	0.429	0.423	0.478	0.337	0.431	0.422	0.450
Invest. spec. tech. shock	σ_γ	0.424	0.425	0.385	0.442	5.796	0.666	0.436	0.424	0.444	0.376
Asymmetric tech. shock	σ_{z^*}	0.203	0.211	0.217	0.218	0.201	0.185	0.212	0.204	0.186	0.204
Consumption pref. shock	σ_{ε_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_{ε_h}	0.095	0.195	0.097	0.095	0.091	0.095	0.089	0.096	0.098	0.096
Risk premium shock	σ_{ϕ}	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
Imp. cons. 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
Imp. invest. 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	$\sigma_{\bar{\pi}}$	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
Diff. infl 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 exch. 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
Diff. output response	$r_{\Delta\pi}$	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

*Note: The same prior is used as for the domestic price stickiness parameter.

Table 3: Sensitivity with respect to shocks

Parameter		Bench- mark	Posterior mode						No fiscal shocks
			No varying inflation target	No technology shocks	No preference shocks	No domestic markup shock	No imported/ exported shocks	No risk premium + asymm. tech. shocks	
			$\sigma_{\tilde{\pi}} = 0.0001$	$\sigma_z = \sigma_\varepsilon = \sigma_Y = 0$	$\sigma_{\zeta_c} = \sigma_{\zeta_h} = 0.01$	$\sigma_\lambda = 0$	$\sigma_{\lambda_{m,c}} = \sigma_{\lambda_{m,i}} = \sigma_{\lambda_x} = 0.3$	$\sigma_{\tilde{\theta}} = \sigma_{z^*} = 0$	
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 cons. prices	$\xi_{m,c}$	0.463	0.495	0.566	0.489	0.485	0.944	0.498	0.495
Calvo import inv. 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 cons. prices	$\kappa_{m,c}$	0.161	0.148	0.171	0.180	0.160	0.535	0.144	0.153
Index. import inv. 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 cons.	$\lambda_{m,c}$	1.619	1.604	1.628	1.806	1.633	1.228	1.655	1.557
Markup imported invest.	$\lambda_{m,i}$	1.226	1.240	1.198	1.646	1.237	1.309	1.195	1.272
Investment adj. cost	\tilde{S}^v	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
Subst. elasticity invest.	η_i	1.669	1.708	2.525	1.610	1.665	1.380	1.622	1.587
Subst. 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 tech. shock	ρ_{μ_z}	0.723	0.793		0.829	0.680	0.729	0.830	0.829
Stationary tech. shock	ρ_ε	0.909	0.906		0.984	0.918	0.898	0.872	0.904
Invest. spec. tech shock	ρ_Y	0.750	0.748		0.695	0.751	0.652	0.729	0.763
Asymmetric tech. shock	ρ_{z^*}	0.993	0.994	0.994	0.930	0.993	0.995		0.993
Consumption pref. 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	$\rho_{\tilde{\theta}}$	0.991	0.991	0.927	0.941	0.991	0.927		0.991
Imp. cons. markup shock	$\rho_{\lambda_{m,c}}$	0.978	0.965	0.984	0.968	0.977		0.967	0.962
Imp. invest. 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 tech. shock	σ_z	0.130	0.137		0.155	0.131	0.133	0.155	0.137
Stationary tech. shock	σ_ε	0.452	0.449		0.464	0.544	0.466	0.482	0.467
Invest. spec. tech. shock	σ_Y	0.424	0.419		0.425	0.420	0.465	0.476	0.426
Asymmetric tech. shock	σ_{z^*}	0.203	0.197	0.249	0.185	0.209	0.203		0.195
Consumption pref. 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	$\sigma_{\tilde{\theta}}$	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
Imp. cons. markup shock	$\sigma_{\lambda_{m,c}}$	2.548	2.200	1.542	2.384	2.317		2.300	2.204
Imp. invest. 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	$\sigma_{\tilde{\pi}}$	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
Diff. infl response	$r_{\Delta\pi}$	0.317	0.327	0.258	0.310	0.360	0.347	0.275	0.294
Real exch. 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
Diff. output response	$r_{\Delta\pi}$	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

Table 4: Unconditional second moments in the Euro area and in the estimated DSGE model

Variable	Standard Deviation	Autocorrelation	Corr with $\Delta \ln Y_t$	Corr with π_t^d	Corr with x_t
Data: 1980Q1 – 2002Q4					
π_t^d	2.83	0.93	-0.24	1.00	0.56
$\Delta \ln(W_t/P_t)$	0.43	0.18	0.31	0.03	0.01
$\Delta \ln C_t$	0.50	0.12	0.70	-0.20	-0.03
$\Delta \ln I_t$	1.90	0.28	0.75	-0.23	0.00
x_t	10.53	0.96	0.06	0.56	1.00
R_t	3.49	0.99	-0.22	0.89	0.38
\tilde{E}_t	2.17	0.99	-0.10	-0.22	-0.18
$\Delta \ln Y_t$	0.48	0.27	1.00	-0.23	0.05
$\Delta \ln \tilde{X}_t$	1.80	0.13	0.54	-0.21	0.01
$\Delta \ln \tilde{M}_t$	1.56	0.34	0.71	-0.37	-0.07
Model					
π_t^d	1.63 (1.07–2.73)	0.82 (0.59–0.94)	-0.07 (-0.40 to 0.28)	1.00	0.08 (-0.60 to 0.68)
$\Delta \ln(W_t/P_t)$	0.55 (0.41–0.75)	0.53 (0.29–0.72)	0.05 (-0.26 to 0.36)	0.14 (-0.19 to 0.44)	0.09 (-0.24 to 0.40)
$\Delta \ln C_t$	0.67 (0.50–0.88)	0.61 (0.41–0.77)	0.41 (0.08 to 0.65)	-0.11 (-0.45 to 0.25)	0.05 (-0.32 to 0.40)
$\Delta \ln I_t$	2.50 (1.91–3.32)	0.62 (0.42–0.77)	0.61 (0.36 to 0.78)	0.02 (-0.31 to 0.34)	-0.01 (-0.32 to 0.31)
x_t	7.51 (4.34–13.90)	0.93 (0.80–0.98)	0.11 (-0.23 to 0.44)	0.08 (-0.60 to 0.68)	1.00
R_t	1.71 (1.00–2.99)	0.94 (0.83–0.98)	0.02 (-0.34 to 0.38)	0.53 (0.01 to 0.84)	0.11 (-0.64 to 0.74)
\tilde{E}_t	1.84 (0.90–3.47)	0.99 (0.96–1.00)	0.01 (-0.25 to 0.27)	0.00 (-0.66 to 0.66)	0.31 (-0.56 to 0.84)
$\Delta \ln Y_t$	0.59 (0.46–0.76)	0.57 (0.38–0.73)	1.00	-0.07 (-0.40 to 0.28)	0.12 (-0.23 to 0.44)
$\Delta \ln \tilde{X}_t$	3.13 (2.41–4.01)	0.60 (0.41–0.74)	0.45 (0.16 to 0.66)	0.03 (-0.29 to 0.34)	0.13 (-0.17 to 0.42)
$\Delta \ln \tilde{M}_t$	2.11 (1.66–2.68)	0.53 (0.33–0.69)	0.34 (0.04 to 0.58)	0.08 (-0.20 to 0.35)	-0.02 (-0.27 to 0.24)

Note: For the model, we report the median from the simulated distribution of moments, computed from the 12,204 samples of length 92 periods each, which were generated by simulating the DSGE model using parameters bootstrapped off the posterior distribution. The numbers in parenthesis are the 2.5th and the 97.5th percentiles of the simulated distribution of moments. No filtering procedures were used. $\Delta \ln$ implies that a variable is expressed in growth rates. Both domestic inflation and the nominal interest rate are reported in annualized units.

Table 5: Variance decompositions. 5th median (bold) and 95th percentiles

1 quarter	Domestic inflation			Real exchange rate			Interest rate			Output			Exports			Imports		
Stationary technology	0.075	0.114	0.160	0.000	0.004	0.011	0.021	0.038	0.061	0.002	0.014	0.033	0.000	0.003	0.007	0.000	0.003	0.007
Unit root technology	0.026	0.046	0.090	0.004	0.010	0.020	0.002	0.016	0.051	0.057	0.087	0.135	0.020	0.028	0.039	0.014	0.022	0.036
Investment specific technology	0.002	0.024	0.059	0.071	0.097	0.123	0.074	0.113	0.150	0.169	0.202	0.239	0.051	0.070	0.091	0.201	0.244	0.290
Asymmetric technology	0.002	0.004	0.008	0.011	0.014	0.018	0.000	0.001	0.004	0.004	0.006	0.009	0.019	0.027	0.038	0.013	0.018	0.024
Consumption preference	0.012	0.037	0.059	0.024	0.038	0.058	0.035	0.066	0.094	0.090	0.124	0.161	0.015	0.025	0.040	0.023	0.033	0.046
Labour supply	0.152	0.201	0.254	0.001	0.010	0.028	0.039	0.070	0.107	0.002	0.023	0.053	0.001	0.005	0.014	0.000	0.003	0.010
Risk premium	0.006	0.013	0.024	0.077	0.098	0.122	0.038	0.052	0.069	0.049	0.063	0.081	0.037	0.051	0.068	0.086	0.112	0.140
Domestic markup	0.238	0.302	0.381	0.007	0.012	0.017	0.061	0.095	0.131	0.030	0.041	0.053	0.004	0.007	0.010	0.030	0.037	0.047
Import consumption markup	0.008	0.044	0.085	0.229	0.265	0.304	0.029	0.061	0.091	0.002	0.016	0.044	0.128	0.162	0.195	0.212	0.247	0.285
Import investment markup	0.002	0.022	0.062	0.112	0.146	0.182	0.008	0.038	0.068	0.004	0.027	0.054	0.083	0.105	0.129	0.001	0.014	0.040
Export markup	0.001	0.010	0.028	0.072	0.097	0.127	0.003	0.023	0.046	0.053	0.080	0.106	0.284	0.336	0.405	0.083	0.113	0.146
Monetary policy	0.017	0.037	0.059	0.059	0.071	0.087	0.211	0.274	0.357	0.091	0.118	0.151	0.027	0.038	0.051	0.013	0.027	0.042
Inflation target	0.061	0.100	0.155	0.013	0.021	0.033	0.028	0.048	0.078	0.021	0.036	0.060	0.006	0.010	0.018	0.001	0.004	0.011
Fiscal variables	0.006	0.012	0.021	0.003	0.005	0.008	0.019	0.031	0.044	0.050	0.057	0.067	0.001	0.003	0.005	0.001	0.002	0.004
Foreign variables	0.005	0.012	0.021	0.086	0.103	0.123	0.044	0.062	0.084	0.074	0.092	0.113	0.095	0.123	0.153	0.083	0.112	0.142
4 quarters	Domestic inflation			Real exchange rate			Interest rate			Output			Exports			Imports		
Stationary technology	0.067	0.115	0.175	0.002	0.011	0.022	0.034	0.062	0.103	0.013	0.035	0.063	0.002	0.007	0.015	0.002	0.006	0.010
Unit root technology	0.040	0.070	0.137	0.000	0.004	0.014	0.008	0.032	0.096	0.072	0.115	0.184	0.022	0.034	0.051	0.033	0.052	0.081
Investment specific technology	0.004	0.046	0.101	0.104	0.132	0.162	0.110	0.175	0.241	0.202	0.237	0.281	0.071	0.094	0.120	0.197	0.239	0.285
Asymmetric technology	0.003	0.007	0.014	0.011	0.015	0.019	0.004	0.007	0.012	0.000	0.002	0.004	0.005	0.008	0.012	0.018	0.025	0.035
Consumption preference	0.018	0.053	0.090	0.025	0.041	0.064	0.084	0.129	0.169	0.098	0.129	0.164	0.017	0.029	0.047	0.006	0.019	0.033
Labour supply	0.200	0.269	0.345	0.003	0.020	0.038	0.087	0.134	0.191	0.025	0.068	0.109	0.002	0.014	0.027	0.003	0.010	0.018
Risk premium	0.005	0.015	0.030	0.041	0.055	0.074	0.029	0.043	0.061	0.030	0.040	0.054	0.029	0.039	0.053	0.072	0.100	0.135
Domestic markup	0.012	0.025	0.039	0.004	0.007	0.011	0.012	0.026	0.044	0.017	0.025	0.037	0.003	0.005	0.008	0.000	0.002	0.005
Import consumption markup	0.017	0.076	0.139	0.259	0.304	0.353	0.002	0.025	0.070	0.002	0.021	0.049	0.156	0.189	0.227	0.148	0.185	0.224
Import investment markup	0.004	0.037	0.099	0.152	0.189	0.228	0.004	0.038	0.088	0.010	0.035	0.062	0.114	0.141	0.170	0.060	0.097	0.132
Export markup	0.001	0.012	0.041	0.075	0.106	0.141	0.019	0.058	0.088	0.057	0.082	0.108	0.283	0.333	0.394	0.108	0.150	0.196
Monetary policy	0.024	0.055	0.090	0.032	0.042	0.057	0.065	0.103	0.151	0.083	0.108	0.142	0.023	0.032	0.043	0.000	0.005	0.014
Inflation target	0.096	0.156	0.235	0.006	0.011	0.019	0.056	0.092	0.143	0.018	0.031	0.054	0.004	0.008	0.014	0.002	0.006	0.012
Fiscal variables	0.010	0.019	0.031	0.002	0.003	0.006	0.008	0.015	0.026	0.010	0.015	0.021	0.001	0.003	0.005	0.000	0.001	0.002
Foreign variables	0.005	0.013	0.024	0.037	0.053	0.072	0.025	0.039	0.057	0.031	0.043	0.057	0.044	0.057	0.072	0.067	0.098	0.130

Table 5 (cont.): Variance decompositions. 5th median (bold) and 95th percentiles

8 quarters	Domestic inflation			Real exchange rate			Interest rate			Output			Exports			Imports		
Stationary technology	0.021	0.071	0.136	0.007	0.017	0.031	0.032	0.069	0.126	0.027	0.054	0.093	0.005	0.013	0.024	0.000	0.004	0.010
Unit root technology	0.043	0.075	0.152	0.000	0.003	0.014	0.025	0.054	0.133	0.092	0.150	0.244	0.028	0.047	0.078	0.062	0.101	0.163
Investment specific technology	0.016	0.089	0.146	0.119	0.148	0.185	0.059	0.137	0.227	0.190	0.240	0.295	0.086	0.113	0.145	0.061	0.120	0.192
Asymmetric technology	0.003	0.009	0.017	0.012	0.015	0.020	0.004	0.008	0.015	0.000	0.001	0.002	0.006	0.008	0.012	0.025	0.037	0.054
Consumption preference	0.017	0.050	0.099	0.016	0.037	0.065	0.098	0.147	0.198	0.079	0.111	0.153	0.014	0.030	0.052	0.004	0.017	0.035
Labour supply	0.137	0.205	0.285	0.019	0.040	0.060	0.108	0.168	0.240	0.074	0.122	0.169	0.014	0.030	0.046	0.001	0.006	0.019
Risk premium	0.000	0.006	0.022	0.003	0.014	0.034	0.001	0.010	0.027	0.002	0.010	0.020	0.007	0.015	0.029	0.026	0.057	0.110
Domestic markup	0.013	0.025	0.042	0.000	0.002	0.005	0.001	0.007	0.015	0.009	0.015	0.024	0.001	0.002	0.005	0.008	0.012	0.016
Import consumption markup	0.033	0.106	0.181	0.256	0.308	0.366	0.004	0.041	0.114	0.001	0.013	0.040	0.167	0.208	0.255	0.083	0.121	0.166
Import investment markup	0.005	0.051	0.127	0.200	0.247	0.294	0.005	0.053	0.129	0.050	0.076	0.107	0.152	0.194	0.239	0.162	0.201	0.241
Export markup	0.001	0.011	0.048	0.059	0.093	0.137	0.019	0.052	0.079	0.037	0.058	0.081	0.201	0.283	0.364	0.128	0.185	0.252
Monetary policy	0.020	0.052	0.095	0.015	0.026	0.040	0.021	0.047	0.078	0.057	0.083	0.121	0.014	0.022	0.034	0.024	0.033	0.045
Inflation target	0.113	0.184	0.281	0.002	0.006	0.012	0.082	0.132	0.203	0.010	0.020	0.040	0.001	0.004	0.010	0.008	0.014	0.025
Fiscal variables	0.013	0.024	0.037	0.001	0.003	0.006	0.006	0.016	0.029	0.007	0.013	0.020	0.001	0.002	0.005	0.001	0.003	0.005
Foreign variables	0.003	0.009	0.017	0.020	0.030	0.041	0.012	0.024	0.037	0.007	0.014	0.024	0.009	0.018	0.030	0.041	0.068	0.105
20 quarters	Domestic inflation			Real exchange rate			Interest rate			Output			Exports			Imports		
Stationary technology	0.001	0.016	0.073	0.006	0.017	0.036	0.005	0.036	0.101	0.018	0.047	0.091	0.005	0.014	0.030	0.009	0.018	0.031
Unit root technology	0.041	0.072	0.153	0.005	0.012	0.029	0.054	0.092	0.183	0.155	0.244	0.390	0.056	0.097	0.174	0.102	0.171	0.285
Investment specific technology	0.108	0.174	0.247	0.005	0.039	0.092	0.094	0.154	0.213	0.070	0.129	0.198	0.006	0.037	0.081	0.076	0.133	0.206
Asymmetric technology	0.008	0.017	0.030	0.014	0.020	0.029	0.004	0.012	0.024	0.003	0.005	0.009	0.011	0.017	0.025	0.036	0.054	0.080
Consumption preference	0.016	0.046	0.108	0.007	0.031	0.072	0.043	0.111	0.183	0.002	0.029	0.108	0.006	0.026	0.061	0.018	0.038	0.061
Labour supply	0.004	0.040	0.103	0.025	0.044	0.071	0.053	0.104	0.174	0.079	0.121	0.179	0.020	0.036	0.060	0.030	0.045	0.065
Risk premium	0.001	0.005	0.014	0.011	0.019	0.029	0.002	0.009	0.018	0.002	0.006	0.015	0.008	0.015	0.023	0.012	0.053	0.083
Domestic markup	0.000	0.003	0.009	0.000	0.001	0.002	0.001	0.003	0.006	0.000	0.002	0.006	0.000	0.001	0.002	0.000	0.001	0.004
Import consumption markup	0.080	0.180	0.291	0.209	0.328	0.458	0.009	0.080	0.202	0.052	0.099	0.152	0.130	0.224	0.331	0.018	0.090	0.182
Import investment markup	0.013	0.099	0.204	0.267	0.387	0.501	0.006	0.067	0.228	0.128	0.192	0.261	0.201	0.319	0.434	0.081	0.186	0.288
Export markup	0.007	0.022	0.071	0.008	0.041	0.123	0.004	0.022	0.059	0.006	0.029	0.079	0.027	0.138	0.360	0.040	0.106	0.246
Monetary policy	0.001	0.005	0.032	0.003	0.009	0.022	0.001	0.009	0.021	0.012	0.027	0.057	0.003	0.008	0.019	0.001	0.007	0.016
Inflation target	0.139	0.234	0.368	0.000	0.001	0.004	0.128	0.201	0.305	0.000	0.003	0.009	0.000	0.001	0.004	0.001	0.003	0.007
Fiscal variables	0.016	0.027	0.038	0.003	0.006	0.009	0.014	0.027	0.041	0.010	0.017	0.025	0.002	0.005	0.008	0.002	0.004	0.006
Foreign variables	0.002	0.006	0.013	0.013	0.020	0.029	0.006	0.014	0.027	0.005	0.009	0.015	0.016	0.023	0.033	0.038	0.059	0.085

Figure 1: Data (bold) and one-sided predicted values (thin)

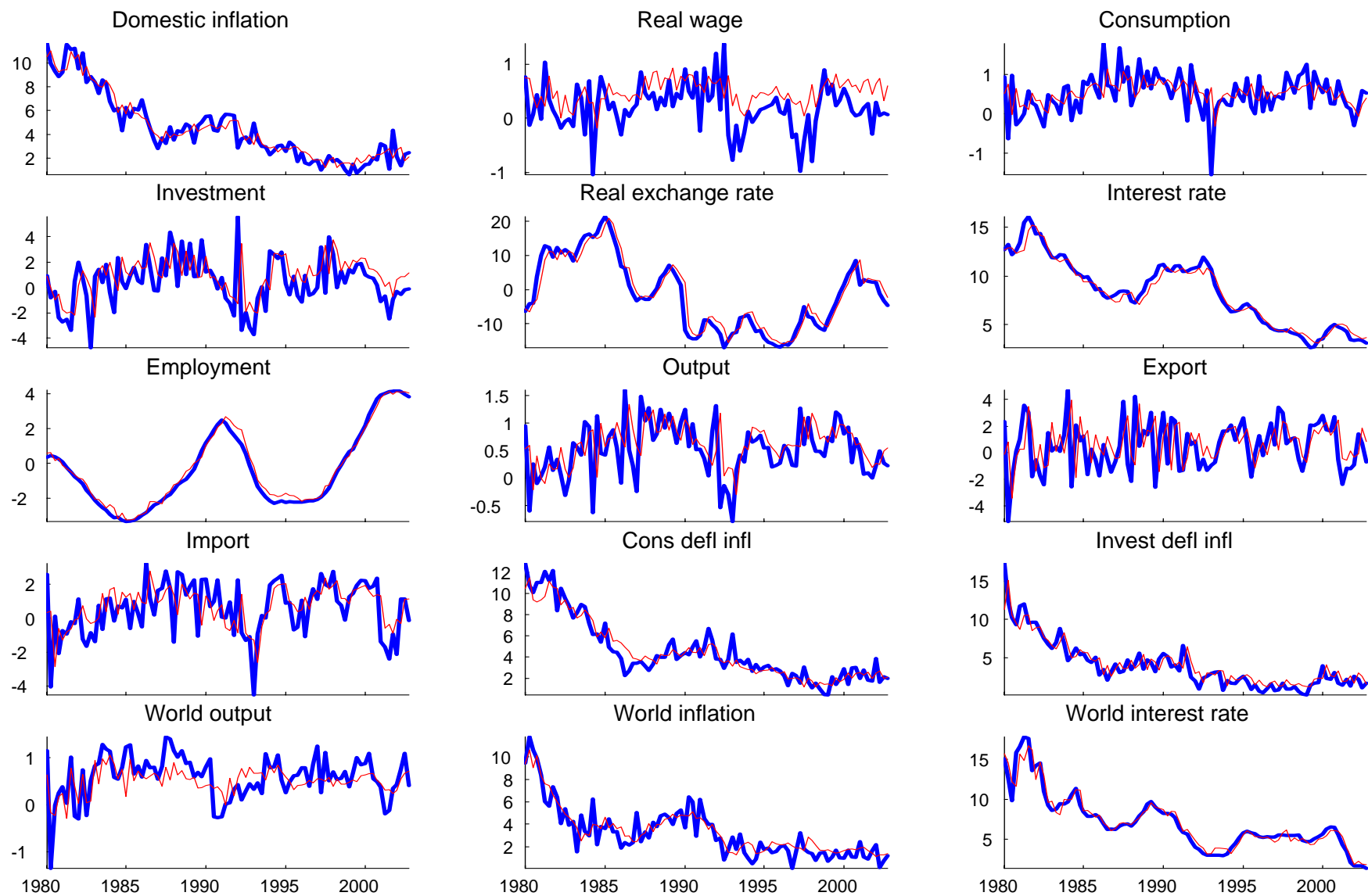


Figure 2a: Prior and posterior distributions, friction parameters

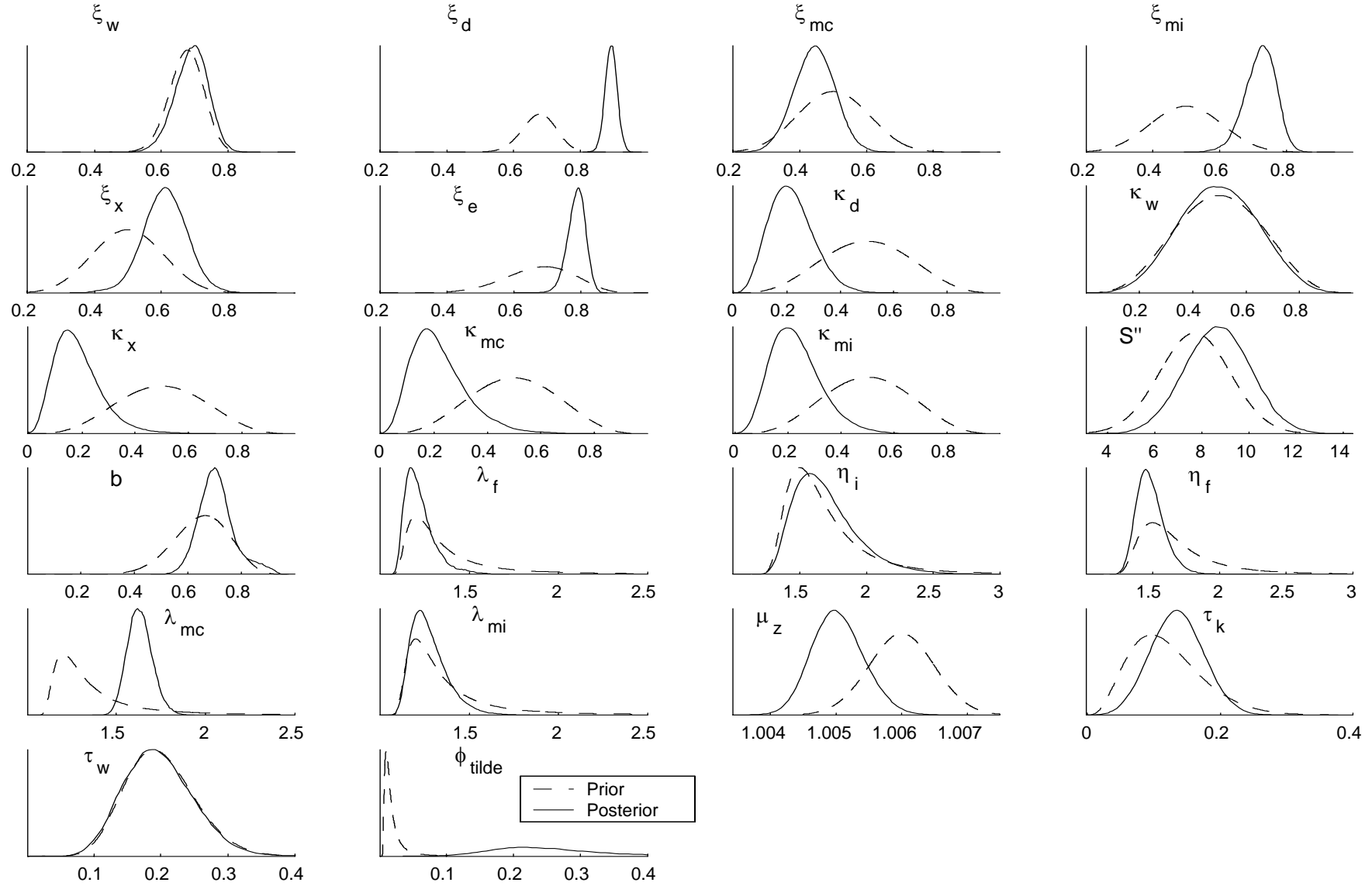


Figure 2b: Prior and posterior distributions, shock processes parameters

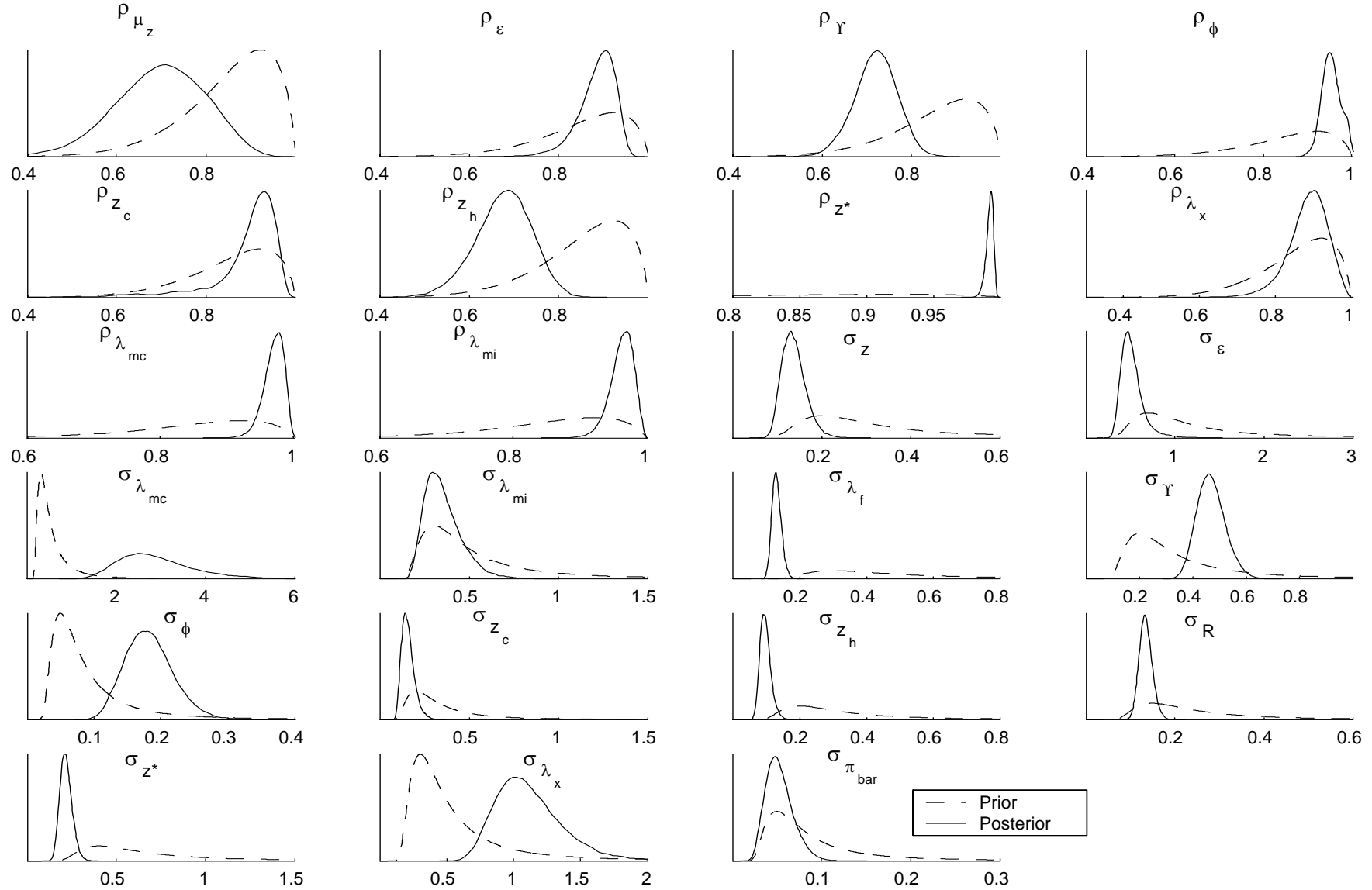


Figure 2c: Prior and posterior distributions, policy parameters

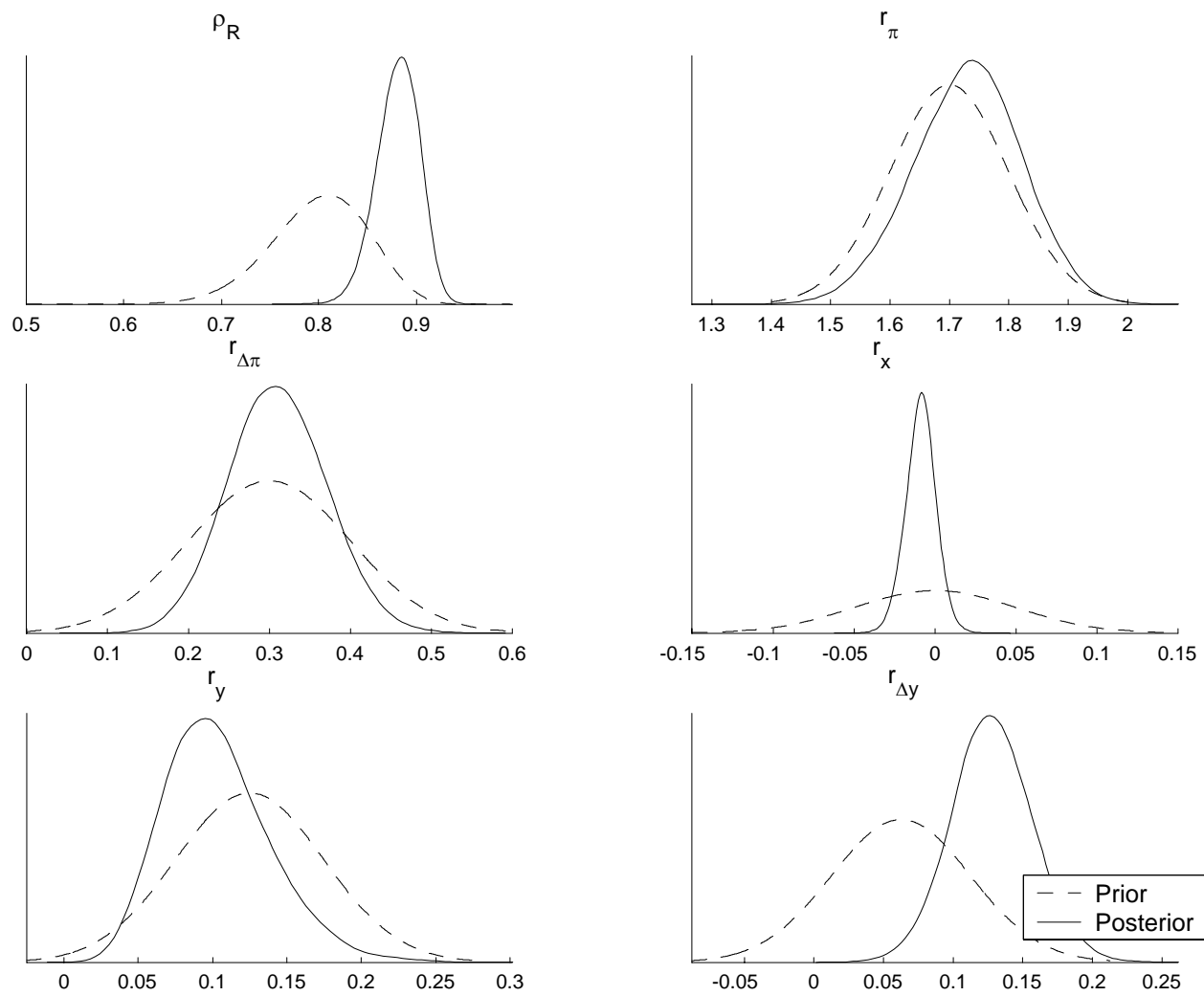


Figure 3: Smoothed (two-sided) estimates of the unobserved shocks

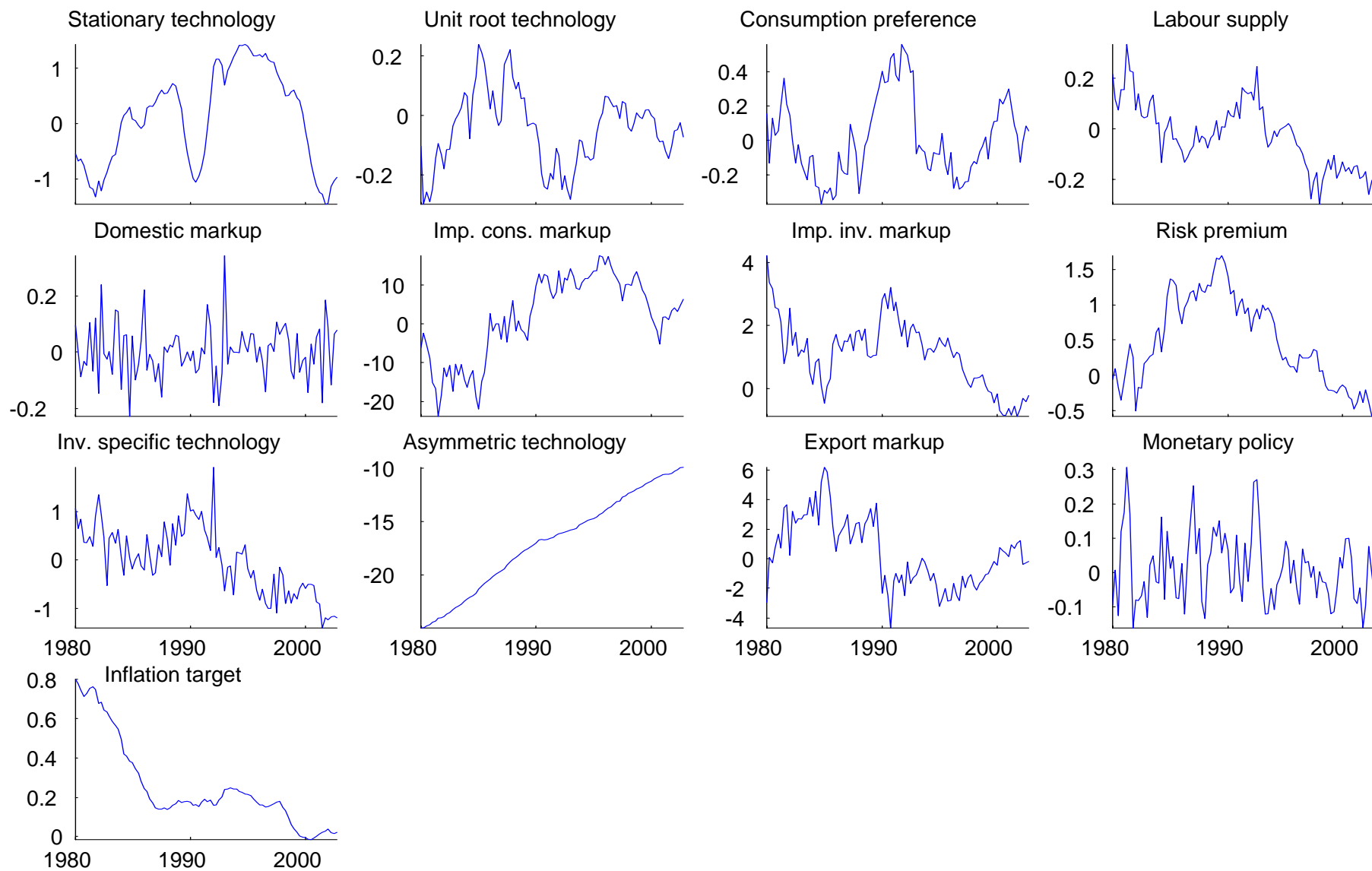
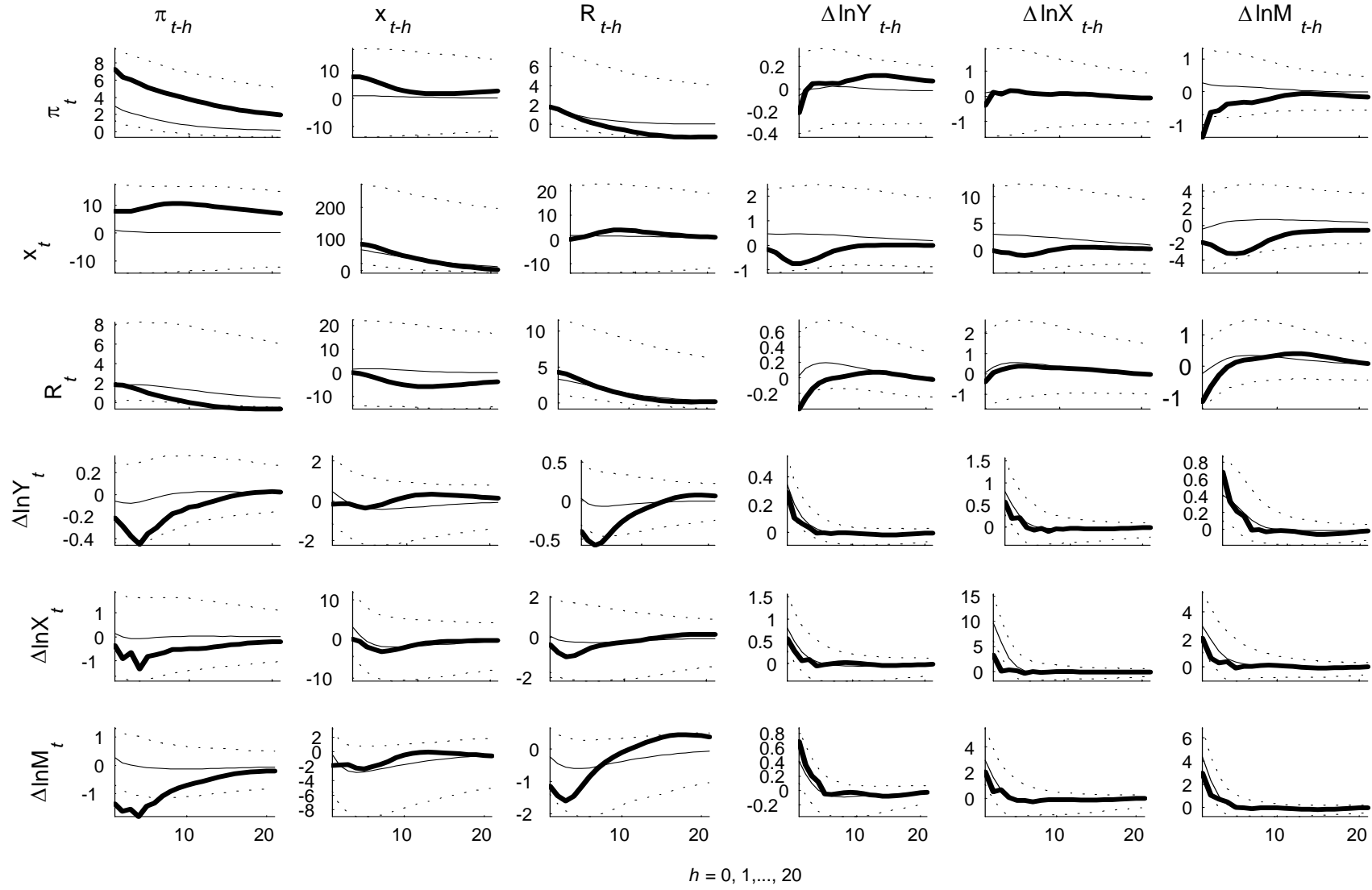
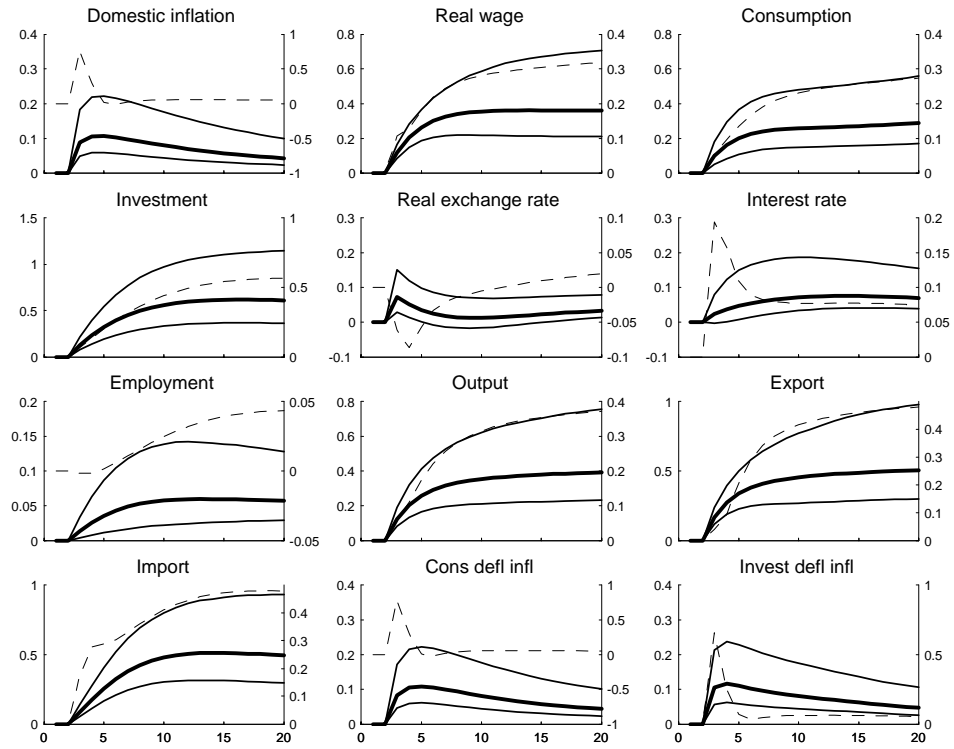


Figure 4: Autocovariance functions



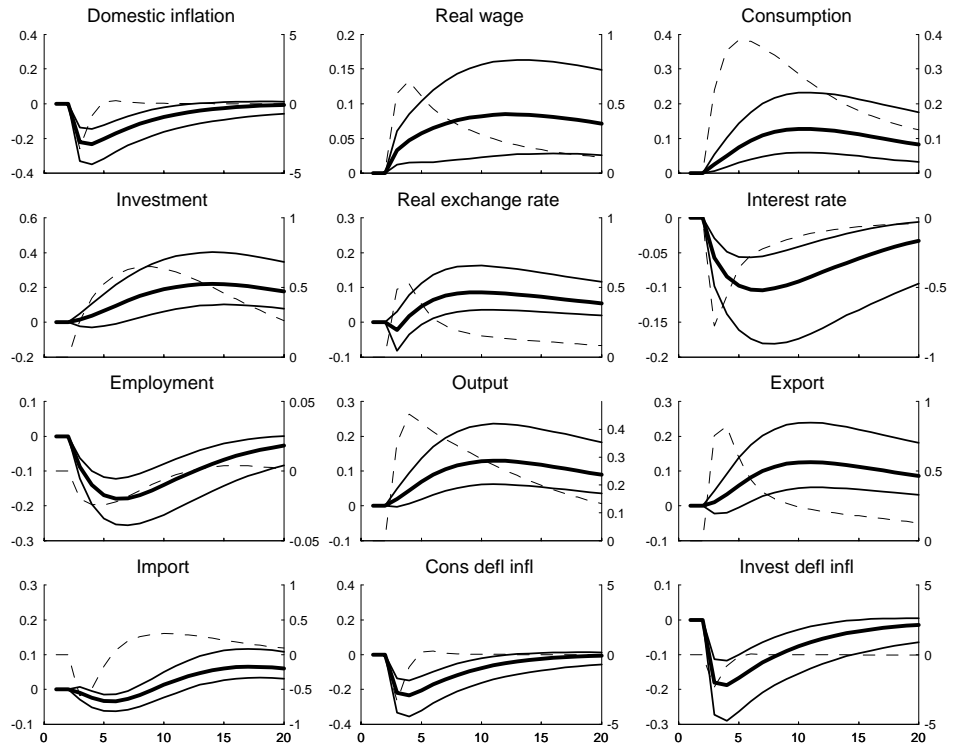
Note: VAR (thick), DSGE posterior median (thin) and DSGE 95% posterior probability density (dashed).

Figure 5a: Impulse responses to a unit root technology shock



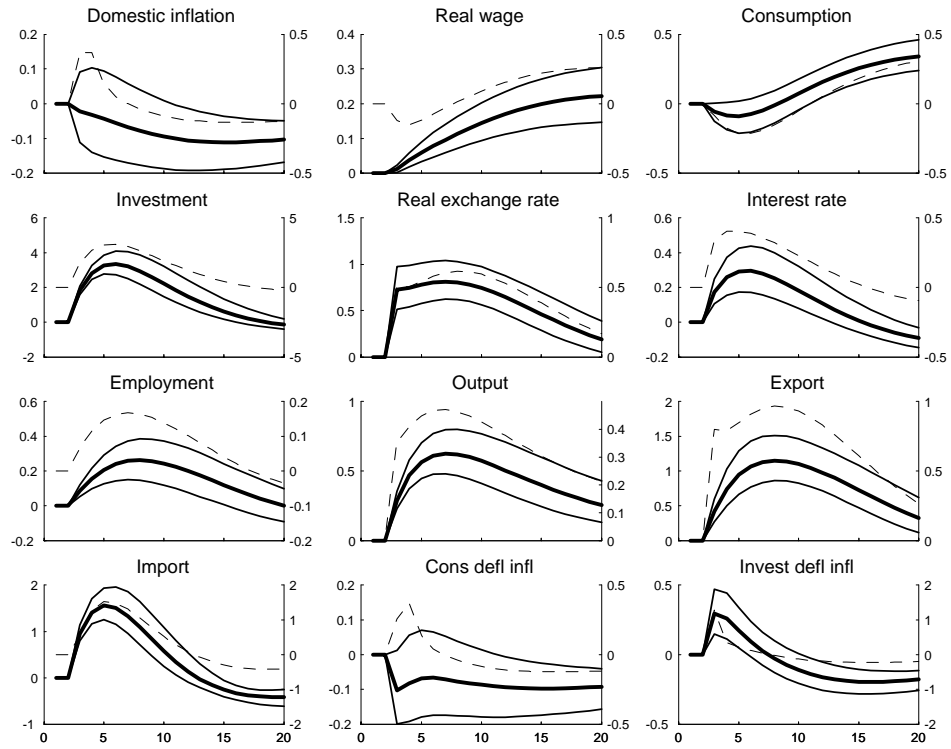
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5b: Impulse responses to a stationary technology shock



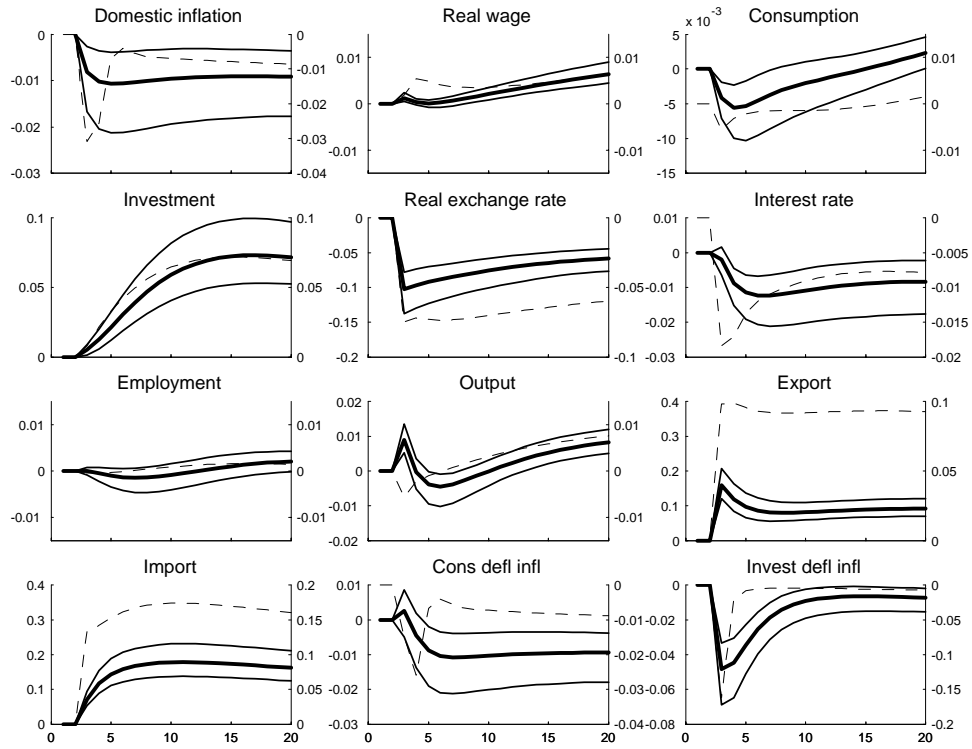
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5c: Impulse responses to a investment specific technology shock



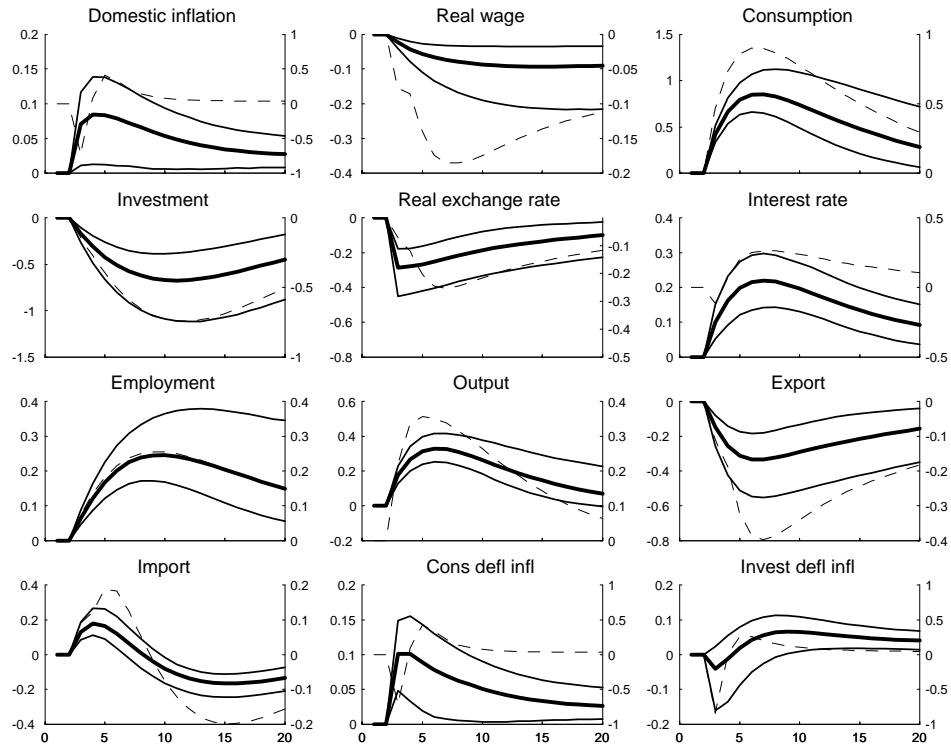
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5d: Impulse responses to an asymmetric technology shock



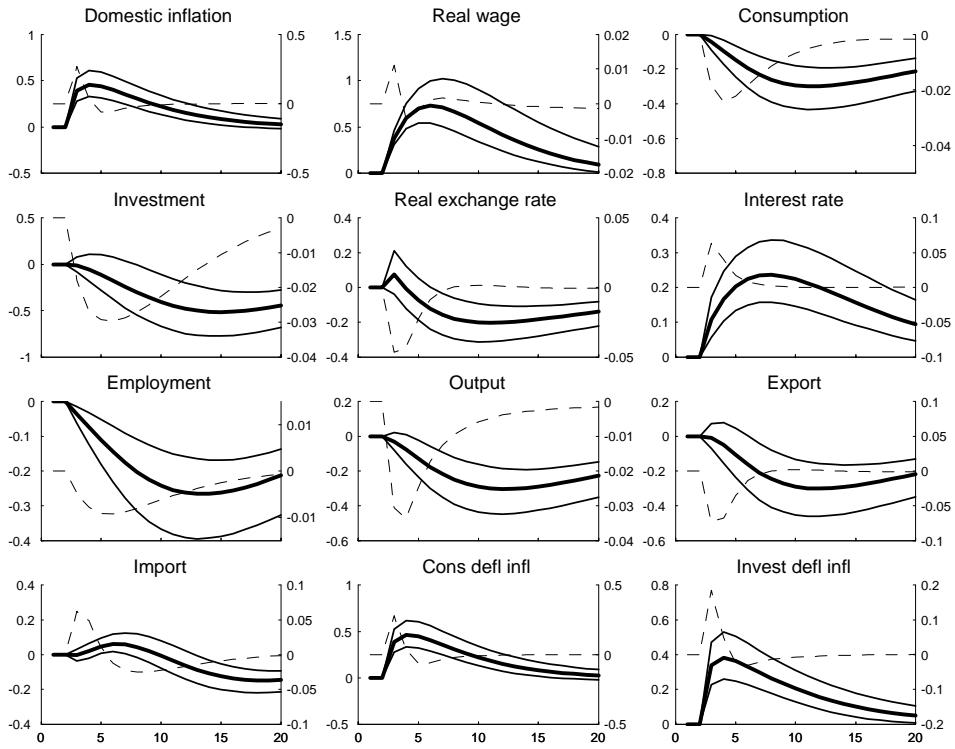
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5e: Impulse responses to a consumption preference shock



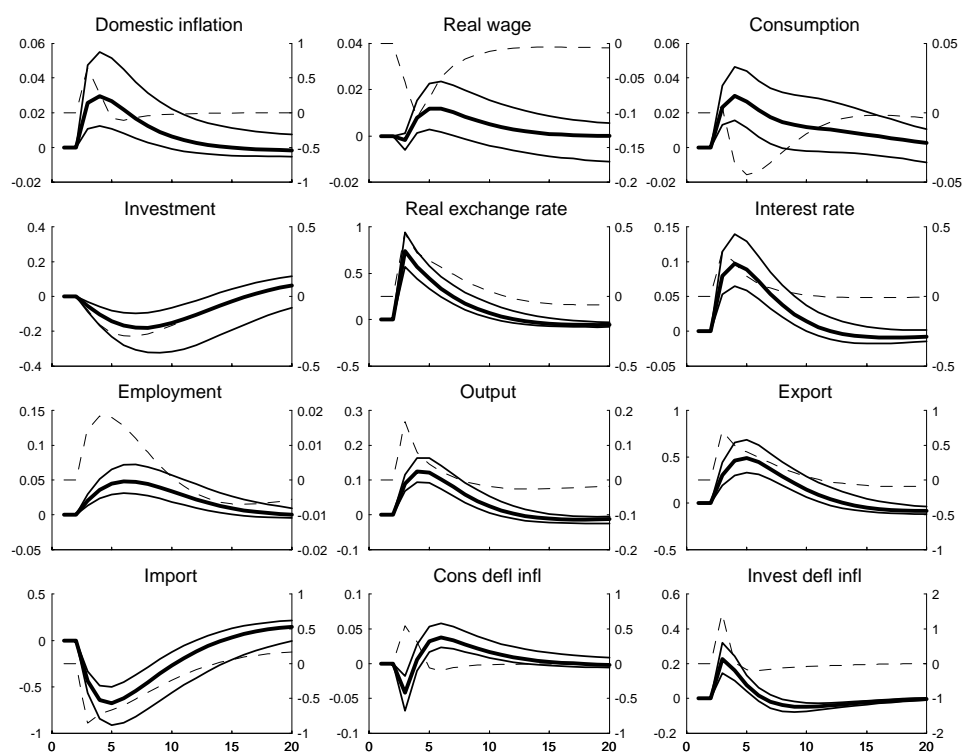
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5f: Impulse responses to a labour supply shock



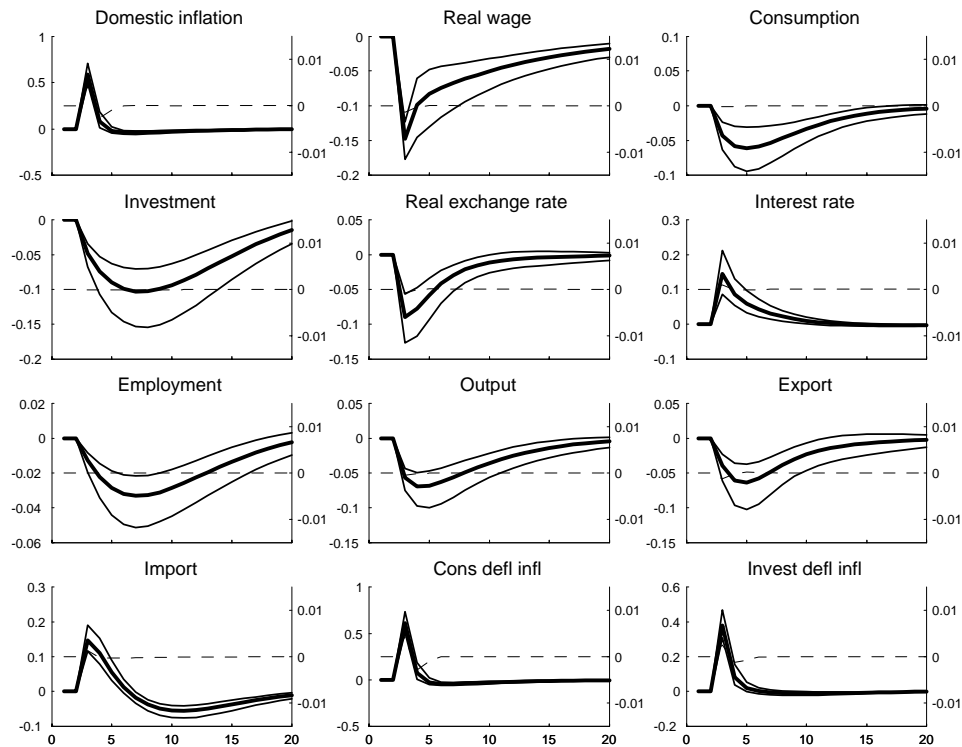
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5g: Impulse responses to a risk premium shock



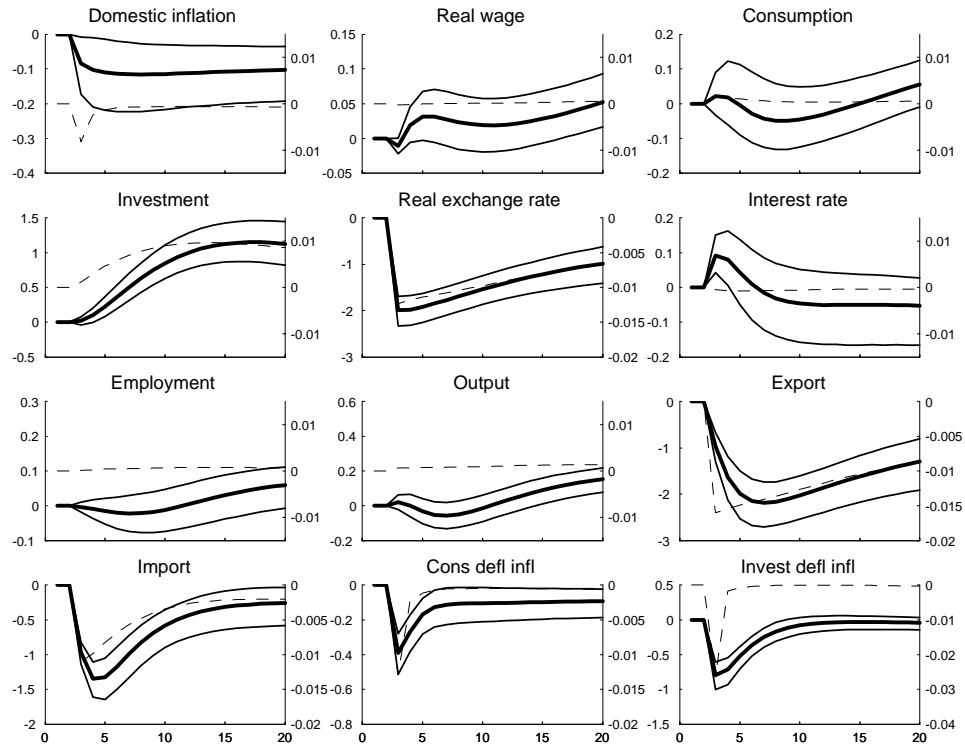
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5h: Impulse responses to a domestic markup shock



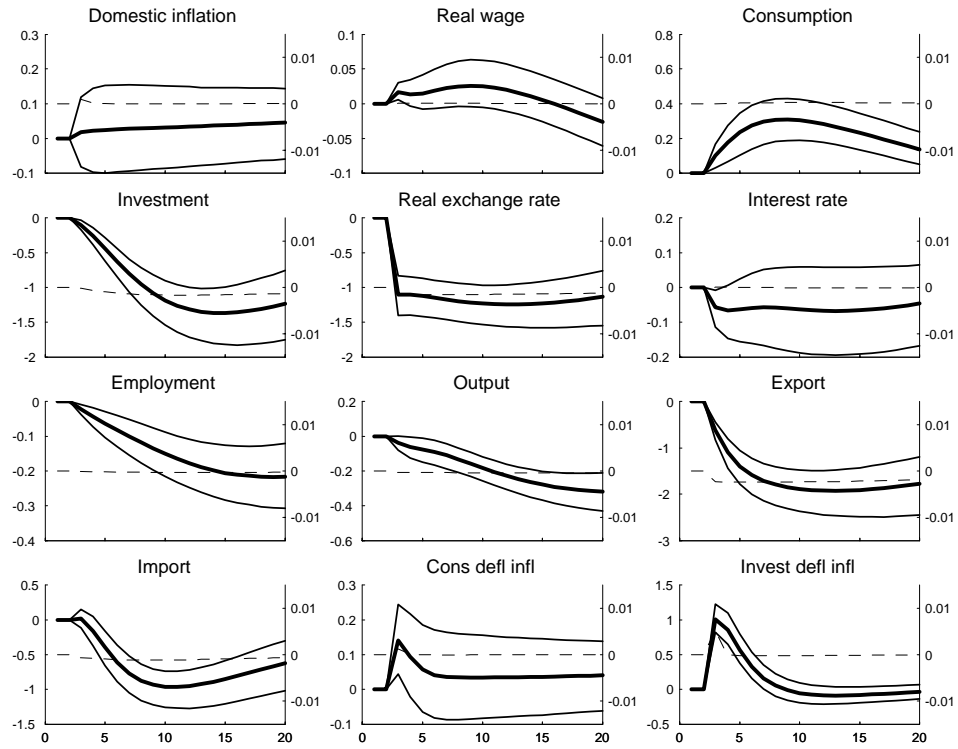
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5i: Impulse responses to an imported consumption markup shock



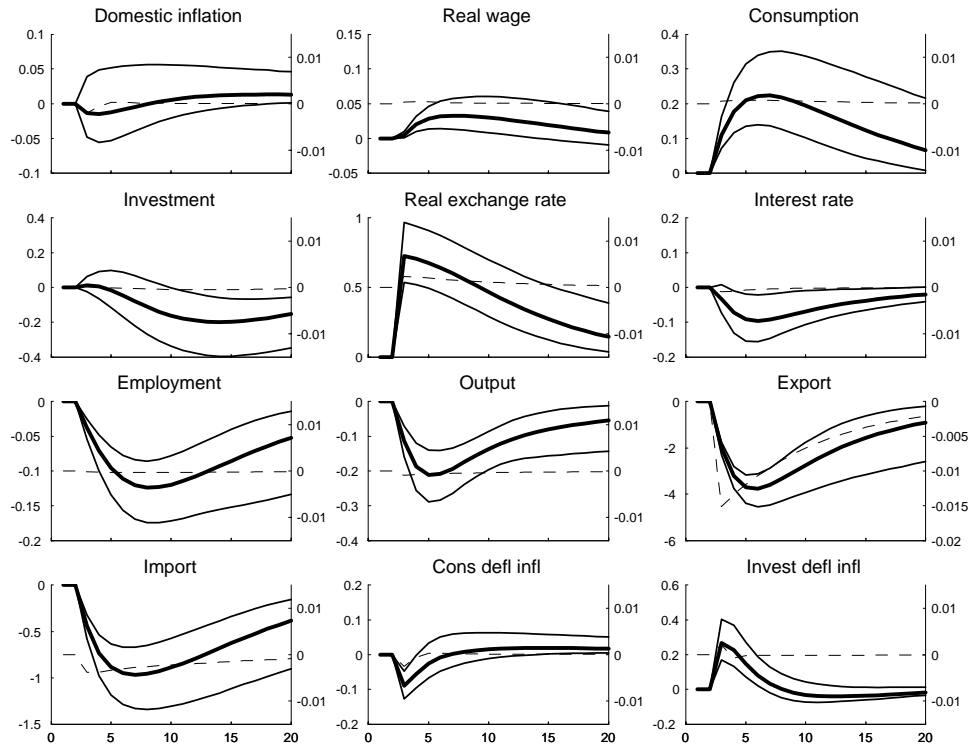
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5j: Impulse responses to an imported investment markup shock



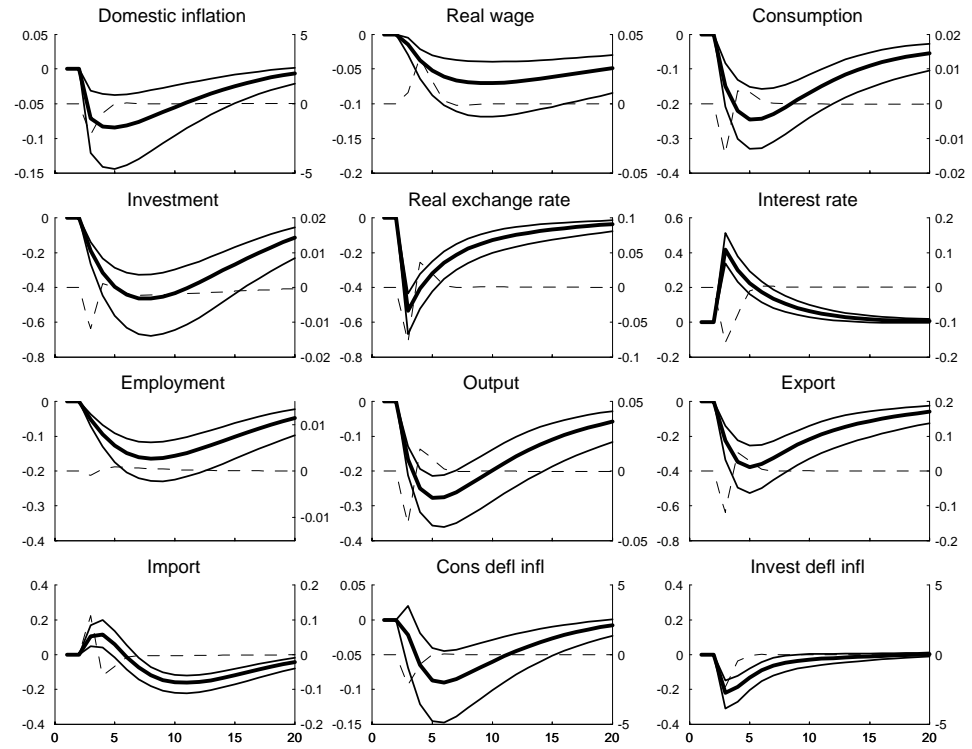
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5k: Impulse responses to an export markup shock



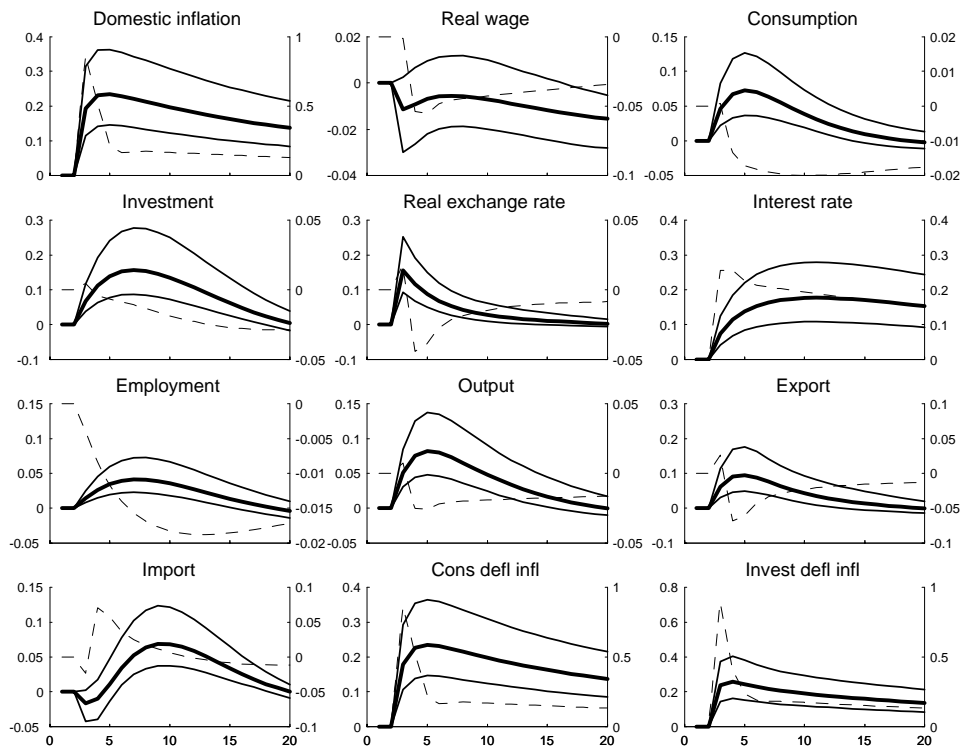
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5l: Impulse responses to a monetary policy shock



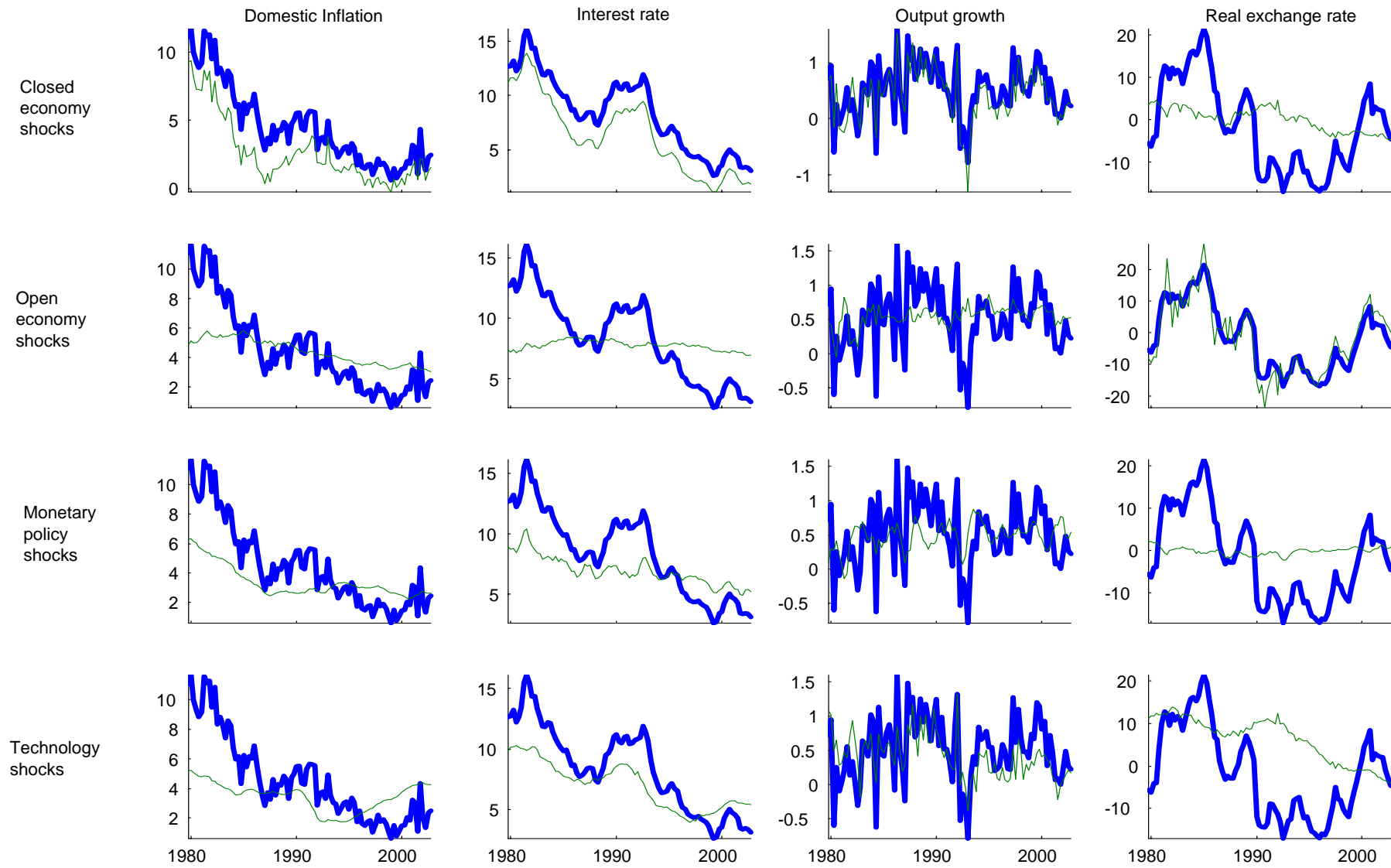
Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 5m: Impulse responses to an inflation target shock



Note: Benchmark (solid, left axis) and flexible prices and wages (dashed, right axis).

Figure 6: Historical decompositions, data (thick) and model (thin)



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