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Abstract

We develop a structural model of a small open economy with gradual exchange rate pass-through and endogenous inertia in inflation and output. We then estimate the model by matching the implied impulse responses with those obtained from a VAR model estimated on Swedish data. Although our model is highly stylized it captures very well the responses of output, domestic and imported inflation, the interest rate, and the real exchange rate. However, in order to account for the observed persistence in the real exchange rate and the large deviations from UIP, we need a large and volatile premium on foreign exchange.

Keywords: Structural open-economy model, new open-economy macroeconomics, estimation, calibration.

JEL Classification: E52, F31, F41.

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1. Introduction

Small-scale structural models with optimizing agents and nominal rigidities have proved to be very useful as tools for studying monetary policy issues in both closed and open economy settings. For closed economies, a number of empirical papers have demonstrated that these models can be used to realistically describe actual economies (for example, Rotemberg and Woodford (1997), Christiano et al. (2001), Ireland (2001), and Smets and Wouters (2003)). At the same time, however, there are relatively few empirical applications for open economies.

For many practical policy issues, it is of course important to obtain quantitative predictions from a reasonably well-specified model. In practice, however, many central banks act in open economies, and therefore need to take open-economy elements seriously. Furthermore, these economies are often small and therefore do not have a significant influence on the rest of the world. The purpose of this paper is therefore to formulate a model of a small open economy with, on the one hand, close links to recent theoretical models, and on the other, rich enough dynamics to allow a good representation of actual data. The need for realistic dynamics makes us depart from much of the "New Open Economy Macroeconomics" literature that typically models price stickiness as one-period preset prices and monetary policy by a rule for money supply (for example, Obstfeld and Rogoff (1995), see Lane (2001) for a survey). Instead, our model is more closely related to the closed-economy New-Keynesian literature, modeling sticky prices through quadratic adjustment costs (following Rotemberg (1982)) and monetary policy by an interest rate rule, and is similar to those of Svensson (2000), Adolfson (2001), Benigno (2001), Galí and Monacelli (2002), and Monacelli (2003). The model allows for gradual exchange rate pass-through, following Adolfson (2001) and Monacelli (2003), as well as imperfect financial integration, following Benigno (2001). In addition, we introduce inertia in output (originating from habit formation in consumer preferences) as well as in domestic and imported inflation (by assuming that a fraction of firms follow a backward-looking rule of thumb when resetting their prices). All these extensions serve to allow for a more realistic description of actual data.

After formulating our theoretical model, we proceed by estimating the model on Swedish data. In the estimation we follow Christiano et al. (2001) and Smets and Wouters (2002) and match the impulse responses of the theoretical model with those from an empirical VAR model. As a first step, we match the responses to a monetary policy shock only. We then proceed by simultaneously matching the response of the model economy to three shocks: a monetary policy shock, an aggregate demand shock and an aggregate supply shock.

To briefly summarize our results, our model captures very well the dynamic behavior of all variables considered—the output gap, domestic inflation, the interest rate, the real exchange rate, and imported inflation—after a monetary policy shock. However, in order to explain the gradual response of the real exchange rate (due to large deviations from UIP), the model needs a very large premium on foreign bond holdings. We therefore introduce a modification to the baseline model. While in the baseline model imperfect financial integration is introduced as a premium on foreign bond holdings depending only on aggregate net foreign assets, in the modified model this premium depends also on the shocks hitting the economy. This modified model is able to generate a more persistent real exchange rate without a large average premium on foreign exchange, as the premium responds very persistently to shocks. Our overall conclusion is that although the model is a very stylized description of a small open economy, it is sufficiently rich to capture the dynamic behavior of some key Swedish macroeconomic variables.

While still small, the literature on estimated structural open-economy models has seen an increasing number of contributions in the past few years. Many of the recent papers are estimated on data from Canada relative to the U.S., for instance, Ghironi (2000), Bouakez (2002), Dib (2003), Ambler et al. (2003), and Murchison et al. (2004), while Smets and Wouters (2002) use euro area data, and Bergin (2003) uses data from Australia, Canada, and the United Kingdom. Importantly, none of these studies are able to account for the hump-shaped response of the real exchange rate, although Bouakez (2002), who focuses entirely on the behavior of the real exchange rate, is very successful in matching its unconditional persistence and volatility. Our difficulties in replicating the dynamic behavior of the real exchange rate are thus common in the literature, but our modified model nevertheless provides some clues about how to replicate this behavior in a structural open-economy model.

The paper is organized as follows. Section 2 presents the theoretical model. Section 3 estimates the VAR model and presents the methodology for estimating the theoretical model. The estimation results are presented and discussed in Section 4, while Section 5 concludes. Details on the model and the data used are given in Appendices A and B.

2. The model

We formulate a model of a small open economy with habit formation, imperfect financial integration, and gradual exchange rate pass-through. Habit formation in consumer preferences yields inertia in consumption and output. Imperfect financial integration is introduced assuming that domestic households pay a premium for taking positions in international financial markets, and leads to a premium on foreign exchange. Imperfect pass-through is introduced by assuming that prices of imported goods are sticky, rather than by assuming price differentiation. Thus, while there are persistent deviations from the law of one price in the short run, these disappear in the long run.[1] More specifically, we assume that firms face quadratic adjustment costs when reoptimizing their price. Not all firms reoptimize in every period, however. A subset of firms follow a simple rule of thumb when resetting their price, which gives rise to endogenous inertia in both domestic and imported inflation.

2.1. Imperfect pass-through, the law of one price and the real exchange rate

The imperfect pass-through of nominal exchange rate changes to the domestic currency price of imported goods complicates the notation somewhat. We therefore begin with a short account of the main prices in the model. For simplicity, we discuss these prices in their log-linearized form.

In our model domestic residents consume two categories of goods—domestically produced goods and imported goods. These goods have domestic-currency (log) prices p_t^d and p_t^m, respectively, with inflation rates $\pi_t^d \equiv p_t^d - p_{t-1}^d$ and $\pi_t^m \equiv p_t^m - p_{t-1}^m$. Imperfect pass-through means that import prices do not necessarily coincide with world market prices converted into domestic currency units, so the law of one price does not necessarily hold. Specifically, $p_t^m \neq p_t^f + s_t$, where s_t is the nominal exchange rate and p_t^f is the foreign currency price of the imported good (both in logs). This wedge between the two price levels means that we can identify two different terms of trade in the model. The first is the *domestic terms of trade*, that is, the relative

[1] This way of modelling imperfect pass-through is consistent with the empirical evidence: Campa and Goldberg (2002) reject the hypothesis of complete short-run pass-through in 22 of 25 countries during 1975–99. In the long run, however, elasticities are closer to one.

price between domestic and imported goods as perceived by the domestic resident:[2]

$$\tau_t \equiv p_t^m - p_t^d. \tag{2.1}$$

The second is the *foreign terms of trade*, that is, the relative price between the domestically produced good and the imported good on the world market:

$$\tau_t^f \equiv p_t^d - s_t - p_t^f. \tag{2.2}$$

With complete exchange rate pass-through, $p_t^m = p_t^f + s_t$, so $\tau_t = -\tau_t^f$. Under imperfect pass-through, however, there is a deviation from the law of one price given by

$$\begin{aligned} \delta_t &\equiv p_t^m - p_t^f - s_t \\ &= \tau_t + \tau_t^f. \end{aligned} \tag{2.3}$$

As shown below, consumer price (CPI) inflation is a weighted average of domestic and imported inflation:

$$\pi_t^c = (1 - \omega_m)\,\pi_t^d + \omega_m \pi_t^m, \tag{2.4}$$

where ω_m is the import share in consumption. Using equation (2.1), we can write CPI inflation as

$$\pi_t^c = \pi_t^d + \omega_m \Delta\tau_t. \tag{2.5}$$

Hence, the more open the economy, the bigger the impact of changes in the terms of trade on consumer price inflation.

Finally, the real exchange rate is defined as the ratio between the domestic and foreign aggregate price levels, measured in domestic currency:

$$\begin{aligned} q_t &\equiv s_t + p_t^f - p_t^c \qquad (2.6) \\ &= -\tau_t^f - \omega_m \tau_t, \end{aligned}$$

[2] Our way of defining the terms of trade accords well with the recent literature on open-economy models (see, for example, Galí and Monacelli (2002), Monacelli (2003), or Benigno and Thoenissen (2003)). It can however be noted that in traditional trade theory it is customary to define the terms of trade as $p_t^d - p_t^m$, so a rise in the terms of trade constitutes an "improvement" in the sense that the price of imported goods in terms of domestic (or exported) goods has fallen. In our model, a rise in τ_t means that imported goods have become more expensive.

where we have used the assumption that the domestic economy is small, so the foreign economy is (approximately) closed. In the case of perfect pass-through we obtain $q_t = (1 - \omega_m)\,\tau_t$, implying that changes in the terms of trade have smaller impact on the real exchange rate in a more open economy: as the degree of openness increases, domestic inflation becomes more correlated with world inflation, implying that the real exchange rate varies less with the terms of trade.

2.2. Households

The domestic economy is populated by infinitely-lived households, who consume Dixit-Stiglitz bundles of domestic and imported goods, denoted C_t^d and C_t^m, respectively. Domestic goods are produced by a continuum of firms acting under monopolistic competition, while imported goods are bought (at marginal cost) in the foreign market by import firms, repackaged, and sold in the domestic market, also under monopolistic competition. The bundles of domestic and imported goods are defined by

$$C_t^d \equiv \left[\int_0^1 \left(C_t^{d,i}\right)^{(\eta_d-1)/\eta_d} di\right]^{\eta_d/(\eta_d-1)}, \tag{2.7}$$

$$C_t^m \equiv \left[\int_0^1 \left(C_t^{m,i}\right)^{(\eta_m-1)/\eta_m} di\right]^{\eta_m/(\eta_m-1)}, \tag{2.8}$$

where η_d and η_m are the elasticities of substitution across goods, assumed to be greater than 1 to ensure that firms' markups are positive in steady state.[3]

Together, these bundles of domestic and imported goods form a composite consumption index defined by

$$C_t = \left[(1-\omega_m)^{1/\eta}\left(C_t^d\right)^{(\eta-1)/\eta} + \omega_m^{1/\eta}\left(C_t^m\right)^{(\eta-1)/\eta}\right]^{\eta/(\eta-1)}, \tag{2.9}$$

where ω_m is the share of imports in consumption, and η is the elasticity of substitution across the two categories of goods. This definition of the consumption index implies that the aggregate price index (the CPI) is given by

$$P_t^c = \left[(1-\omega_m)\left(P_t^d\right)^{1-\eta} + \omega_m\left(P_t^m\right)^{1-\eta}\right]^{1/(1-\eta)}. \tag{2.10}$$

Households are assumed to value consumption relative to past aggregate consumption, that is, household preferences display external habit formation of the

[3]The steady-state markups are given by $\eta_d/(\eta_d - 1)$ and $\eta_m/(\eta_m - 1)$, respectively.

"Catching up with the Joneses" type (see Abel (1990) or Smets and Wouters (2003)). Thus household j's utility depends on its own consumption C_t^j relative to lagged aggregate consumption C_{t-1} according to

$$u\left(C_t^j\right) = \Upsilon_t \frac{\left(C_t^j - hC_{t-1}\right)^{1-\sigma}}{1-\sigma}, \tag{2.11}$$

where the parameter $0 \leq h \leq 1$ determines the importance of habits, $\sigma > 0$ is related to the intertemporal elasticity of substitution, and Υ_t is a preference shock.

Household j chooses a sequence of consumption, domestic bond holdings and foreign bond holdings to maximize utility:

$$\max_{C_t^j, B_t^j, B_t^{f,j}} \mathrm{E}_t \sum_{k=0}^{\infty} \beta^k u\left(C_{t+k}^j\right), \tag{2.12}$$

subject to the flow budget constraint

$$C_t^j + \frac{B_t^j}{(1+i_t)P_t^c} + \frac{S_t B_t^{f,j}}{(1+i_t^f)\Phi(A_t)P_t^c} = \frac{B_{t-1}^j}{P_t^c} + \frac{S_t B_{t-1}^{f,j}}{P_t^c} + X_t^j, \tag{2.13}$$

where B_t^j and $B_t^{f,j}$ are holdings of one-period nominal bonds denominated in the domestic and foreign currency, respectively; S_t is the nominal exchange rate (the domestic currency price of foreign currency); X_t^j is household j's share of aggregate real profits in the domestic economy (the sum of profits in the domestic sector and in the importing sector); and where domestic bonds give the gross return $(1 + i_t)$ and foreign bonds give the adjusted return $(1 + i_t^f)\Phi(A_t)$.

Following Benigno (2001), the term $\Phi(A_t)$ is a premium on foreign bond holdings, which depends on the real aggregate net foreign asset position of the domestic economy, defined as

$$A_t \equiv \frac{S_t B_t^f}{P_t^c}. \tag{2.14}$$

The function $\Phi(A_t)$ captures the costs for domestic households of undertaking positions in the international financial market, and is assumed to follow

$$\Phi(A_t) = e^{-\phi A_t}, \tag{2.15}$$

where $\phi > 0$, so $\Phi(A_t)$ is strictly decreasing in A_t and $\Phi(0) = 1$. Thus, if the domestic economy as a whole is a net borrower (so $B_t^f < 0$) domestic households are charged a premium on the foreign interest rate, while if the domestic economy is a net lender ($B_t^f > 0$) households receive a lower remuneration on their international savings.[4]

The household's maximization problem yields the consumption Euler equation

$$1 = \beta(1 + i_t)\mathrm{E}_t \left[\frac{\Upsilon_{t+1}}{\Upsilon_t} \left(\frac{C_{t+1}^j - hC_t}{C_t^j - hC_{t-1}} \right)^{-\sigma} \frac{P_t^c}{P_{t+1}^c} \right], \tag{2.16}$$

and the uncovered interest parity (UIP) condition

$$\frac{1 + i_t}{1 + i_t^f} = \mathrm{E}_t \left[\frac{S_{t+1}}{S_t} \right] \Phi(A_t), \tag{2.17}$$

where the $\Phi(A_t)$ function acts as a (risk) premium on foreign exchange. In periods when the economy is a net borrower, the domestic interest rate is higher than the foreign interest rate also when there is no expected exchange rate depreciation, while when the economy is a net lender, the domestic interest rate is lower than the foreign interest rate. Movements in the net foreign asset position thus affect the interest rate differential between the domestic and foreign economies.

Optimal intratemporal allocation across the domestic and imported goods bundles is given by

$$C_t^d = (1 - \omega_m) \left[\frac{P_t^d}{P_t^c} \right]^{-\eta} C_t, \tag{2.18}$$

$$C_t^m = \omega_m \left[\frac{P_t^m}{P_t^c} \right]^{-\eta} C_t, \tag{2.19}$$

and the demand for a differentiated good in the two categories is given by

$$C_t^{d,j} = \left[\frac{P_t^{d,j}}{P_t^d} \right]^{-\eta_d} C_t^d, \tag{2.20}$$

$$C_t^{m,j} = \left[\frac{P_t^{m,j}}{P_t^m} \right]^{-\eta_m} C_t^m. \tag{2.21}$$

Finally, the domestic economy is assumed to be small in relation to the foreign economy and thus plays a negligible part in aggregate foreign consumption. Assuming that aggregate foreign consumption also follows a CES function, aggregate

[4] Introducing a premium on foreign bond holdings also helps to ensure a well-defined steady state for consumption and asset holdings. See Schmitt-Grohé and Uribe (2003) for details.

foreign demand for the domestic good is given by

$$C_t^{df} = \left[\frac{P_t^d / S_t}{P_t^f} \right]^{-\eta} C_t^f, \tag{2.22}$$

and foreign demand for the jth domestic good is

$$C_t^{df,j} = \left[\frac{P_t^{df,j}}{P_t^{df}} \right]^{-\eta_d} C_t^{df}. \tag{2.23}$$

Here both the numerators and the denominators are in units of foreign currency and the foreign elasticities of substitution η and η_d are assumed to be the same as in the domestic economy.

Log-linearizing the consumption Euler equation, using log-linearized expressions for CPI inflation, domestic demand for domestic and imported goods, and foreign demand for domestic goods, and imposing equilibrium conditions gives the following expression for the output gap (the log deviation of aggregate output from its steady-state value, see Appendix A for details):

$$\begin{aligned} y_t &= (1 - a_y)\, y_{t-1} + a_y \mathrm{E}_t y_{t+1} + a_r \left[i_t - \mathrm{E}_t \pi_{t+1}^d \right] + a_{\tau 1} \tau_{t-1} + a_{\tau 2} \tau_t \\ &\quad + a_{\tau_3} \mathrm{E}_t \tau_{t+1} + a_{\tau f1} \tau_{t-1}^f + a_{\tau f2} \tau_t^f + a_{\tau f3} \mathrm{E}_t \tau_{t+1}^f + a_{yf1} y_{t-1}^f + a_{yf2} y_t^f \\ &\quad + a_{yf3} \mathrm{E}_t y_{t+1}^f + u_t^y, \end{aligned} \tag{2.24}$$

where lower case letters denote log deviation from steady state. The composite parameters are given by

$$\begin{aligned} a_y &= \tfrac{1}{1+h}, & a_{\tau f1} &= \tfrac{h\omega_x \eta}{1+h}, \\ a_r &= -\tfrac{(1-h)(1-\omega_x)}{(1+h)\sigma}, & a_{\tau f2} &= -\omega^x \eta, \\ a_{\tau 1} &= -\tfrac{h\eta\omega_m(1-\omega_x)}{1+h}, & a_{\tau f3} &= \tfrac{\omega_x \eta}{1+h}, \\ a_{\tau 2} &= -\tfrac{\omega_m(1-\omega_x)(1-h-\eta\sigma-h\eta\sigma)}{(1+h)\sigma}, & a_{yf1} &= -\tfrac{h\omega_x \chi_f}{1+h}, \\ a_{\tau 3} &= \tfrac{\omega_m(1-h-\eta\sigma)(1-\omega_x)}{(1+h)\sigma}, & a_{yf2} &= \omega_x \chi_f, \\ & & a_{yf3} &= -\tfrac{\omega_x \chi_f}{1+h}, \end{aligned}$$

the parameter χ_f is the income elasticity of foreign consumption, and the demand shock u_t^y is given by

$$u_t^y = \frac{(1-h)(1-\omega_x)}{(1+h)\sigma} \left[\upsilon_t - \mathrm{E}_t \upsilon_{t+1} \right], \tag{2.25}$$

where $\upsilon_t \equiv \log \Upsilon_t$.

Comparing with Adolfson (2001) and Monacelli (2003), the introduction of habits in consumer preferences ($h > 0$) implies that lags of domestic output, the domestic and foreign terms of trade, and foreign output, as well as the current terms of trade matter for the determination of domestic output. In the absence of habit formation ($h = 0$) and with complete exchange rate pass-through (so $\tau_t = -\tau_t^f$) our aggregate demand equation becomes

$$\begin{aligned} y_t \;=\; & \mathrm{E}_t y_{t+1} - \frac{1-\omega_x}{\sigma}\left[i_t - \mathrm{E}_t \pi^d_{t+1}\right] + \omega_x \chi_f \left[y_t^f - \mathrm{E}_t y^f_{t+1}\right] \\ & + \frac{\omega_m(1-\eta\sigma)(1-\omega_x) - \omega_x \eta\sigma}{\sigma} \mathrm{E}_t \Delta\tau_{t+1} + \frac{1-\omega_x}{\sigma}\left[\upsilon_t - \mathrm{E}_t \upsilon_{t+1}\right], \end{aligned} \tag{2.26}$$

while the closed-economy version of (2.24) without habit formation is given by the standard expression

$$y_t = \mathrm{E}_t y_{t+1} - \sigma^{-1}\left[i_t - \mathrm{E}_t \pi_{t+1}\right] + \sigma^{-1}\left[\upsilon_t - \mathrm{E}_t \upsilon_{t+1}\right]. \tag{2.27}$$

Log-linearizing the UIP condition (2.17) we obtain

$$i_t - i_t^f = \mathrm{E}_t \Delta s_{t+1} - \phi a_t, \tag{2.28}$$

as in Benigno (2001). As shown in Appendix A, net foreign assets will follow

$$a_t = d_a a_{t-1} + d_y y_t + d_x x_t + d_\tau \tau_t + d_{\tau f} \tau_t^f + d_{yf} y_t^f, \tag{2.29}$$

while the log-linearized real profits x_t are given by

$$x_t = e_y y_t + e_\tau \tau_t + e_{\tau f} \tau_t^f + e_{yf} y_t^f, \tag{2.30}$$

where the composite parameters d_j and e_j are functions of the structural parameters.

2.3. Firms

Our model has two sets of firms. As in, for example, Smets and Wouters (2002), we have a monopolistically competitive *imported goods sector* with sticky prices. Firms in this sector purchase a foreign good at given world prices (marginal cost) and turn it into differentiated import goods that can be used for either domestic consumption or as an input in production. Firms in the *domestic sector* produce differentiated goods using both domestic and imported inputs. Both categories of firms face a quadratic cost of price adjustment, following Rotemberg (1982). In addition, we assume that only a subset of firms reoptimize their price each period, while the remaining firms follow a simple rule of thumb when resetting their price, as in Galí and Gertler (1999), Steinsson (2003), and Amato and Laubach (2003).

With the Rotemberg pricing assumption, we must first derive the optimal flexible prices on domestically produced goods and imported goods, that is, the prices that would arise in the absence of adjustment costs. Firm i in the domestic sector produces a differentiated good Y_t^i from intermediate domestic and imported inputs ($Z_t^{d,i}$, $Z_t^{m,i}$) using the production function

$$\begin{aligned} Y_t^i &= \left(Z_t^i\right)^{1-\theta} \\ &= \left[\left(Z_t^{d,i}\right)^{1-\kappa}\left(Z_t^{m,i}\right)^{\kappa}\right]^{1-\theta}, \end{aligned} \tag{2.31}$$

where κ is the share of imports in intermediate goods, and θ is a technology parameter.

In the absence of adjustment costs, the domestic firm i would choose prices for the domestic and foreign markets (denoted $\hat{P}_t^{d,i}$ etc.) to maximize profits:

$$\max_{\hat{P}^{d,i},\hat{P}^{df,i}} \hat{P}_t^{d,i} C_t^{d,i} + S_t \hat{P}_t^{df,i} C_t^{df,i} - P_t^z Z_t^i \tag{2.32}$$

subject to the production function (2.31) and the demand functions (2.20) and (2.23). In the domestic market this yields the optimal flexible price

$$\hat{P}_t^{d,i} = \frac{\eta_d}{\eta_d - 1}\frac{1}{1-\theta} P_t^z \left(Y_t^i\right)^{\theta/(1-\theta)}, \tag{2.33}$$

where P_t^z is the aggregate price of inputs, given by

$$P_t^z = \frac{\left(P_t^d\right)^{1-\kappa}\left(P_t^m\right)^{\kappa}}{(1-\kappa)^{1-\kappa}\kappa^{\kappa}}. \tag{2.34}$$

Thus, the price set by domestic firm i in the absence of adjustment costs is a markup $\eta_d/(\eta_d - 1)$ on marginal cost.

In the import sector, firm i maximizes

$$\max_{\hat{P}^{m,i}} \left(\hat{P}_t^{m,i} - S_t P_t^{zf}\right) C_t^{m,i}, \tag{2.35}$$

where P_t^{zf} is marginal cost in the foreign economy, subject to the demand function (2.21), yielding the optimal flexible price

$$\hat{P}_t^{m,i} = \frac{\eta_m}{\eta_m - 1} S_t P_t^{zf} = S_t P_t^f, \tag{2.36}$$

where the optimal foreign price is a markup on marginal cost:

$$P_t^f = \frac{\eta_m}{\eta_m - 1} P_t^{zf}, \tag{2.37}$$

assuming that foreign firms face the same demand elasticity as the import firm.

Turning now to price-setting behavior in the face of quadratic adjustment costs, those firms in sector j that reoptimize in each period minimize the expected log deviation of the price from the optimal flexible price, given the adjustment cost γ_j:

$$\min_{p_t^{opt,j}} \mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \left\{ \left(p_{t+s}^{opt,j} - \hat{p}_{t+s}^j\right)^2 + \gamma_j \left(p_{t+s}^{opt,j} - p_{t+s-1}^{opt,j}\right)^2 \right\}, \tag{2.38}$$

for $j = d, m$. The first-order condition implies that the rate of change of these reoptimized prices will follow

$$\pi_t^{opt,j} = \beta \mathrm{E}_t \pi_{t+1}^{opt,j} + \frac{1}{\gamma_j} \left(\hat{p}_t^j - p_t^{opt,j}\right), \tag{2.39}$$

where the optimal flexible price in the domestic sector is, log-linearizing equations (2.33) and (2.34),

$$\hat{p}_t^d = (1-\kappa) p_t^d + \kappa p_t^m + \frac{\theta}{1-\theta} y_t, \tag{2.40}$$

and the optimal flexible price in the import sector is, from (2.36),

$$\hat{p}_t^m = p_t^f + s_t. \tag{2.41}$$

As already mentioned, in each sector j a fraction α_j of firms does not reoptimize their price, but instead use a mechanical rule of thumb whereby prices are set to equal the observed aggregate price in the previous period adjusted for the previous period's inflation rate in that sector:

$$p_t^{rule,j} = p_{t-1}^j + \pi_{t-1}^j. \tag{2.42}$$

The price level in sector j is then given by

$$p_t^j = (1 - \alpha_j) p_t^{opt,j} + \alpha_j p_t^{rule,j}, \tag{2.43}$$

and the inflation rate is

$$\pi_t^j = (1 - \alpha_j) \pi_t^{opt,j} + \alpha_j \pi_t^{rule,j}. \tag{2.44}$$

Combining the above and solving for the inflation rate in the domestic and imported sectors (see Appendix A), we obtain, after adding a domestic aggregate supply (or "cost-push") shock,[5] u_t^d,

$$\begin{aligned} \pi_t^d &= b_{\pi 1} \mathrm{E}_t \pi_{t+1}^d + b_{\pi 2} \pi_{t-1}^d + b_{\pi 3} \pi_{t-2}^d + b_y y_t + b_\tau \tau_t + u_t^d, & (2.45) \\ \pi_t^m &= c_{\pi 1} \mathrm{E}_t \pi_{t+1}^m + c_{\pi 2} \pi_{t-1}^m + c_{\pi 3} \pi_{t-2}^m + c_\tau \left[\tau_t + \tau_t^f \right], & (2.46) \end{aligned}$$

where the composite parameters are given by

$$\begin{array}{ll} b_{\pi 1} = \beta \gamma_d \Psi_d, & c_{\pi 1} = \beta \gamma_m \Psi_m, \\ b_{\pi 2} = \alpha_d \left(1 + 2\gamma_d + \beta \gamma_d\right) \Psi_d, & c_{\pi 2} = \alpha_m \left(1 + 2\gamma_m + \beta \gamma_m\right) \Psi_m, \\ b_{\pi 3} = -\alpha_d \gamma_d \Psi_d, & c_{\pi 3} = -\alpha_m \gamma_m \Psi_m, \\ b_y = \frac{\theta(1-\alpha_d)}{1-\theta} \Psi_d, & c_\tau = -\left(1 - \alpha_m\right) \Psi_m, \\ b_\tau = \kappa \left(1 - \alpha_d\right) \Psi_d, & \end{array}$$

and where

$$\Psi_j = \left[\alpha_j + \gamma_j \left(1 + 2\beta \alpha_j\right)\right]^{-1}, \qquad j = d, m.$$

Thus, with rule-of-thumb price setters, two lags of inflation enter the expressions for domestic and imported inflation, and inflation becomes less sensitive to both inflation expectations and marginal cost. Expressions (2.45) and (2.46) encompass expressions from the earlier literature. For example, without rule-of-thumb price setters (setting $\alpha_d = \alpha_m = 0$), we obtain the same expressions as Adolfson (2001). Under perfect exchange rate pass-through, (2.45) becomes

$$\pi_t^d = \beta \mathrm{E}_t \pi_{t+1}^d + \frac{1}{\gamma_d} \left[\frac{\theta}{1-\theta} y_t + \kappa \left(p_t^f + s_t - p_t^d \right) \right], \tag{2.47}$$

and neglecting open-economy aspects, we obtain the more traditional New-Keynesian

[5] This supply shock could be interpreted as a shock to the adjustment cost γ_d. A similar shock could of course be introduced for the importing sector. However, in this paper we will only consider domestic supply shocks, and so we refrain from introducing shocks that have no role in the analysis.

Phillips curve

$$\pi_t^d = \beta \mathrm{E}_t \pi_{t+1}^d + \frac{\theta}{\gamma_d(1-\theta)} y_t, \tag{2.48}$$

see, for example, Roberts (1995).

2.4. The foreign economy, monetary policy and exogenous shocks

We are primarily interested in the workings of the small open economy, and therefore use a highly stylized model of the rest of the world. We let the foreign inflation rate, output gap and interest rate follow the VAR model

$$\begin{aligned} y_t^f &= a_y^f(L) y_{t-1}^f + b_y^f(L)\pi_{t-1}^f + c_y^f(L) i_{t-1}^f + \varepsilon_t^{yf}, && (2.49) \\ \pi_t^f &= a_\pi^f(L) y_{t-1}^f + b_\pi^f(L)\pi_{t-1}^f + c_\pi^f(L) i_{t-1}^f + \varepsilon_t^{\pi f}, && (2.50) \\ i_t^f &= a_i^f(L) y_t^f + b_i^f(L)\pi_t^f + c_i^f(L) i_{t-1}^f + \varepsilon_t^{if}, && (2.51) \end{aligned}$$

where the lag lengths will be determined by the estimated VAR. Note that we let foreign inflation and output be predetermined with respect to the interest rate, as in the estimated VAR (see below).

We close the model by assuming a linear interest rate rule for domestic monetary policy. In particular, we will use the same specification as in the estimated VAR model, meaning that the interest rate i_t is set according to

$$\begin{aligned} i_t &= \left(1 - \sum_{j=1}^{2} f_j^i\right) \left[\sum_{j=0}^{2} f_j^y y_{t-j} + \sum_{j=0}^{2} f_j^d \bar{\pi}_{t-j}^d + \sum_{j=1}^{2} f_j^q q_{t-j} + \sum_{j=1}^{2} f_j^m \bar{\pi}_{t-j}^m\right] \\ &+ \sum_{j=1}^{2} f_j^i i_{t-j} + \varepsilon_t^i, && (2.52) \end{aligned}$$

where $\bar{\pi}_t^d, \bar{\pi}_t^m$ are four-quarter rates of domestic and imported inflation, respectively. Thus, monetary policy responds to the current output gap and domestic inflation and two lags of output, domestic and imported inflation, and the real exchange rate q_t. Furthermore, the policy rule also includes two lags of the interest rate, capturing interest rate smoothing behavior. Note that policy is assumed not to respond to current values of imported inflation and the real exchange rate, in order to be consistent with the identifying assumptions in the VAR (see below). Finally, ε_t^i is a domestic monetary policy shock, assumed to be i.i.d. with mean zero and standard deviation σ_i.

Apart from the policy shock, there are two domestic shocks in the model: an aggregate demand shock (u_t^y) and an aggregate supply shock (u_t^d). We allow for first-order serial correlation in both of these:

$$u_{t+1}^j = \rho_j u_t^j + \varepsilon_{t+1}^j, \qquad j = y, d, \tag{2.53}$$

where the disturbances ε_t^j are i.i.d. with mean zero and standard deviation σ_j.

In sum, our model consists of the output gap in equation (2.24), the UIP condition in equation (2.28), net foreign assets and profits in equation (2.29) and (2.30), domestic and imported inflation in equations (2.45) and (2.46), the domestic and foreign terms of trade in equations (2.1) and (2.2), the real exchange rate in equation (2.6), the three equations (2.49)–(2.51) describing the foreign sector, the monetary policy rule in equation (2.52) and the shocks in (2.53). To solve the model, we use the "AIM" algorithm developed by Anderson and Moore (1985).

3. Estimation methodology

To parameterize the model, we first estimate a VAR model for the Swedish economy, and identify three shocks: to monetary policy, aggregate demand and aggregate supply, corresponding to the shocks in the theoretical model. Using the interest rate equation from this VAR as the monetary policy rule, we calculate impulse responses to the three shocks in the theoretical model. We then choose parameters in the theoretical model in order to minimize the distance between the impulse responses in the theoretical model and in the estimated VAR, following the methodology of Christiano et al. (2001). In this section we first describe the VAR model and the identifying assumptions that we impose in order to identify the three shocks. We then discuss in more detail our estimation methodology.

3.1. The VAR

The VAR model we use is adopted from Lindé (2003), and is estimated on quarterly Swedish data from 1986:1 to 2002:4.[6] The reduced-form VAR model is specified according to

$$X_t = \delta_0 + \delta_1 D_{1,t} + \delta_2 D_{2,t} + \delta_3 T_t + \sum_{i=0}^{2} C_i Z_{t-i} + \sum_{i=1}^{2} B_i X_{t-i} + e_t, \tag{3.1}$$

[6] Swedish financial markets were highly regulated in the 1970s and early 1980s. Therefore we begin our sample in 1986.

where $D_{1,t}$ is a dummy variable equal to 1 in 1992:3 and 0 otherwise, $D_{2,t}$ is a dummy variable equal to 1 in 1993:1 and thereafter, T_t is a linear time trend, and Z_t is a vector of exogenous variables. The dummy variable for 1992:3 is included to capture the exceptionally high interest rates enforced in order to defend the fixed exchange rate during the European exchange rate crisis. Despite these efforts, Sweden entered into a floating exchange rate regime in late November 1992, and the dummy variable $D_{2,t}$ is included in order to capture possible effects of the new exchange rate regime.

Using the notation from the theoretical model, the variables in X_t and Z_t are

$$X_t = \left[\begin{array}{ccccc} y_t & \pi_t^d & i_t & q_t & \pi_t^m \end{array} \right]' \tag{3.2}$$

and

$$Z_t = \left[\begin{array}{ccc} y_t^f & \pi_t^f & i_t^f \end{array} \right]', \tag{3.3}$$

where y_t is real Swedish GDP (seasonally adjusted in logs); π_t^d is the inflation rate on domestic goods (measured by the GDP deflator); i_t is the quarterly average nominal repo interest rate (or its equivalent prior to June 1994); q_t is the average real trade-weighted exchange rate; π_t^m is the inflation rate for imported goods (measured at producer prices); and y_t^f, π_t^f and i_t^f denote the foreign trade-weighted GDP at market prices (seasonally adjusted), inflation, and nominal interest rate, respectively. (See Appendix B for details.) All variables except interest rates are measured in logs. Rather than measuring the inflation rates as quarterly rates (that is, first differences), we use annual changes (fourth differences) because of what seems to be time-varying seasonal variation in the price indices that can neither be explained with other macroeconomic time series nor changes in indirect taxes.[7]

To identify the monetary policy shock we impose the "recursiveness assumption" that has become standard in the closed economy literature (see, for example, Sims (1992), Christiano et al. (1999), Christiano et al. (2001) and Angeloni et al. (2003)). Thus we assume that a shock to monetary policy has no contemporaneous effects on aggregate demand and domestic inflation, while the nominal exchange rate (and

[7]Lindé (2003) performs sensitivity analysis of the VAR model in (3.1) along several dimensions: the number of lags, the identification scheme for the policy shock, the inclusion of monetary aggregates, the length of the sample period, and the choice of modeling the foreign variables as endogenous or exogenous. The impulse responses reported here, including that for the real exchange rate, are robust to these alternative specifications. This is due to the circumstance that the off-diagonal elements in the estimated covariance-matrix are fairly small. Furthermore, the policy shocks that we identify are very similar to the ones reported by Berg et al. (2002), who estimate traditional and forward-looking Taylor rules on Swedish data, using the actual forecasts used by Sveriges Riksbank.

thus the real exchange rate and possibly imported inflation) is allowed to respond contemporaneously. This amounts to the assumption that financial markets clear after the central bank has determined the nominal interest rate. Implicitly we have in mind a policy rule on the form

$$i_t = f_1(L) X_{1,t} + f_2(L) X_{2,t-1} + f_3(L) i_{t-1} + f_4(L) Z_t + \varepsilon_t^i, \tag{3.4}$$

where $X_{1,t}$ consists of y_t and π_t^d, $X_{2,t}$ consists of q_t and π_t^m, Z_t is defined in (3.3), and ε_t^i is the monetary policy shock which is orthogonal to the information set in (3.4). To identify the aggregate demand and aggregate supply shocks, we assume that aggregate demand shocks have no contemporaneous effects on π_t^d, and aggregate supply shocks have no contemporaneous effects on y_t. These identifying assumptions are consistent with the theoretical model, see further below.

With these assumptions, the reduced-form VAR model in (3.1) can be written as (neglecting the constant, the time trend, the dummy variables and the exogenous variables)

$$A_0 X_t = \sum_{i=1}^{2} A_i X_{t-i} + u_t, \tag{3.5}$$

where

$$A_i = A_0 B_i, \tag{3.6}$$

$$u_t = A_0 e_t, \quad u_t \sim N(0, D), \tag{3.7}$$

where D is a diagonal matrix, and A_0 has the structure

$$A_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ a_{31} & a_{32} & 1 & 0 & 0 \\ a_{41} & a_{42} & a_{43} & 1 & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix}. \tag{3.8}$$

The third column in A_0 implies that the interest rate contemporaneously affects only the real exchange rate and inflation on imported goods. The first and second columns imply that aggregate demand shocks affect all variables contemporaneously except inflation on domestic goods and aggregate supply shocks affect all variables contemporaneously except output. When we estimate the structural VAR, we impose the normalization $a_{45} = 0$, otherwise the last two shocks are not identified. This assumption has no effect on our results, as we are using only the first three shocks in the analysis. Note that when $a_{45} = 0$, A_0 is over-identified with one degree of freedom. According to the estimation results we cannot reject this restriction, the p-value being 0.25.

Figure 1 shows the resulting impulse response functions to a monetary policy, aggregate demand, and aggregate supply shock, with bootstrapped 95 percent confidence intervals. The impulse response functions for output and inflation to the monetary policy shock are similar to those reported on U.S. data, see, for example, Christiano et al. (1999): output and inflation display a "hump-shaped" pattern with peak effects after six to eight quarters, although the interest rate reverts back to steady state very rapidly. The real exchange rate appreciates gradually with a peak effect after four quarters and then depreciates back to its steady state value.[8] The effects on imported inflation are similar to those on the real exchange rate. An aggregate demand shock is followed by a long period of high output and domestic inflation, with a peak effect on inflation after six to eight quarters, while there are no strong effects on the interest rate, the real exchange rate or imported inflation. An aggregate supply shock is followed by a period of higher domestic inflation lasting about four quarters, and lower output with peak effect after about two years. Monetary policy responds in a contractionary manner, the real exchange rate appreciates and imported inflation falls. We note that the impulse response functions are often not significantly different from zero, although the confidence intervals are not symmetric around zero.

Given that we have only identified three domestic shocks in the VAR model, it is of interest to see how much of the variation in the economy that can be accounted for by these shocks in relation to the other two domestic shocks. Table 1 reports variance decompositions for the three shocks, conditional on the exogenous variables, at four-, eight- and 20-quarter horizons.[9] The three identified shocks account for roughly 85 percent of the variation in output, domestic inflation and the interest rate at all three horizons considered. For the real exchange rate and imported inflation, the three shocks account for 60–70 percent of the variation. Among the identified shocks, the aggregate supply shock seems to be most important. As in other studies

[8] This gradual real exchange rate response is consistent with the ample evidence of "delayed overshooting" and large deviations from UIP, reported by, for example, Clarida and Galí (1994), Eichenbaum and Evans (1995), Grilli and Roubini (1996), and Faust and Rogers (2003).

[9] The variance decompositions have roughly converged after 20 quarters, so those numbers can also be interpreted as the long-run fraction of variability due to different shocks.

(for example, Altig et al. (2002)), shocks to monetary policy contribute to only a small fraction of the fluctuations in other variables.[10]

3.2. The methodology

When estimating the structural parameters in the theoretical model we begin by matching the theoretical impulse responses after a single monetary policy shock to the ones obtained from the VAR model, following Christiano et al. (2001) and Smets and Wouters (2002). We then extend the work of these authors by simultaneously matching the response of the model to all three identified shocks in the VAR: the monetary policy shock, the aggregate demand shock and the aggregate supply shock. Throughout we will use the interest rate equation from the VAR as the policy rule in the theoretical model, although the coefficients will be allowed to deviate slightly from the VAR estimates (see below).

When matching the theoretical and empirical impulse responses, it is imperative that the identifying restrictions we use in the VAR are consistent with those in the theoretical model. We therefore make the same assumptions in the theoretical model that were used to identify the shocks in the VAR. Specifically, we assume that domestic firms and households make their price-setting and consumption decisions without knowledge about the other part's decision, and before observing the current monetary policy shock. Thus, domestic inflation and the output gap are not affected contemporaneously by shocks to the other variable, nor by monetary policy shocks. Furthermore, as the VAR model is formulated in terms of four-quarter inflation, all model responses for domestic and imported inflation are converted into four-quarter rates.

Before estimating the parameters in the model, a few parameters can be calibrated directly from Swedish data: the share of imports in inputs, κ; the share of imports in consumption, ω_m; and the share of exports in domestic production, ω_x. These parameters are set to the average shares in Sweden over the sample period, yielding $\kappa = 0.32$, $\omega_m = 0.33$, and $\omega_x = 0.36$. We also set the discount factor to $\beta = 0.99$, implying a 4% steady-state real interest rate in a quarterly model. These parameters are shown in Table 2.

The remaining parameters are estimated by minimizing a measure of the distance between the impulse responses given by the VAR (in Figure 1) and the theoretical

[10] Note that we have decomposed only the variance emanating from the five domestic shocks. As shown by Lindé (2003), foreign shocks account for around 50 percent of all variation in the VAR model.

model. Let the set of these parameters be defined by

$$\xi \equiv \left\{h, \sigma, \eta, \eta_d, \eta_m, \theta, \gamma_d, \gamma_m, \alpha_d, \alpha_m, \sigma_i^2, \rho_y, \sigma_y^2, \rho_d, \sigma_d^2, f\right\}, \tag{3.9}$$

where the vector f contains the relevant parameters in the monetary policy rule (2.52). Next, let $\Gamma(\xi)$ denote the mapping from the parameter vector ξ to the vector of model impulse responses, and $\hat{\Gamma}$ the vector of impulse responses from the VAR. The estimator for ξ is then given by

$$\hat{\xi} = \arg\min_{\xi} \left[\hat{\Gamma} - \Gamma(\xi)\right]' V^{-1} \left[\hat{\Gamma} - \Gamma(\xi)\right], \tag{3.10}$$

where V is a diagonal matrix with the sample variances of $\hat{\Gamma}$ on the diagonal.[11] This means that in minimizing the distance, we are giving higher priority to those point estimates that have smaller standard deviations. We use 20 quarters of impulse responses when estimating the model.

In the estimation we *a priori* define ranges within which the parameters are allowed to vary. For the structural parameters, these ranges are taken from the theoretical restrictions, while for the parameters in the policy rule, the ranges are determined by bootstrapping 95 percent confidence intervals for the coefficients estimated in the VAR.[12]

To calculate standard errors of the estimated parameters, let

$$g\left(\hat{\xi}, \hat{\Gamma}\right) = 0 \tag{3.11}$$

denote the first-order condition from minimizing the loss-function (3.10) when the estimation has converged. A first-order Taylor approximation of (3.11) evaluated around the true values ξ and Γ then gives

$$g_\xi\left(\hat{\xi} - \xi\right) + g_\Gamma\left(\hat{\Gamma} - \Gamma\right) = 0, \tag{3.12}$$

[11] The shaded areas in the figures reflect the standard errors of each impulse response, which are the diagonal elements in the $\hat{V}$ matrix. The $\hat{V}$ matrix is computed by bootstrapping the estimated VAR model with $2,000$ replications.

[12] We reestimate the coefficients in the policy rule rather than directly using the estimated coefficients in the VAR interest rate equation in order to take estimation uncertainty in the VAR into account.

which can be re-arranged as

$$\left(\hat{\xi} - \xi\right) = -\left(g_{\xi}\right)^{-1} g_{\Gamma} \left(\hat{\Gamma} - \Gamma\right), \tag{3.13}$$

where g_{ξ} and g_{Γ} are the partial derivatives of g. If we define $D \equiv \left(g_{\xi}\right)^{-1} g_{\Gamma}$, equation (3.13) implies that the standard errors can be computed as

$$\hat{\sigma}\left(\xi\right) = \sqrt{DWD'}, \tag{3.14}$$

where all derivates are evaluated at the point estimates $\hat{\xi}$ and $\hat{\Gamma}$.[13]

4. Results

4.1. The baseline model

The results from estimating the model to match the impulse responses to a policy shock are displayed in Figure 2 and the first column of Table 3. In Figure 2, each panel shows the impulse response in the theoretical model (the grey solid line) along with those from the VAR (the dark crossed line) and the 95% confidence interval. Note that in all figures, domestic and imported inflation are measured as four-quarter rates.

As seen in Figure 2, the theoretical model manages very well in capturing the dynamic response of all variables to the monetary policy shock: the model responses are everywhere well inside the 95% confidence intervals, and are often very close to the VAR point estimates. Thus, in the theoretical model, a contractionary monetary policy shock is followed by gradual and hump-shaped declines in output, domestic inflation and imported inflation, a quick real appreciation with a gradual return of the real exchange rate to its steady state, and a fairly rapid return of the nominal interest rate to its initial level. This behavior is very similar to that of the estimated VAR.

The main difference between the model and the VAR relate to the peak effects of output and domestic inflation: in the model, the peak effect on output comes slightly before that in the VAR (after four quarters rather than six quarters), while for domestic inflation the peak effect in the model comes slightly after that in the VAR (after nine quarters rather than seven quarters). Nevertheless, the overall

[13] In case a parameter estimate reaches its permitted boundary, we calculate its standard error by perturbing the parameter.

pattern in the theoretical model and the VAR is very similar.

The parameter estimates are shown in the first column of Table 3, with standard errors in parentheses. We first note that habit formation in consumption seems moderate ($h = 0.23$), and is not statistically significant. However, a sensitivity analysis (reported below) shows that a non-zero habit parameter is indeed crucial in order to obtain the inertial response of the output gap shown in Figure 2. Domestic prices are very sticky ($\gamma_d = 63.10$), while import prices are less sticky ($\gamma_m = 13.66$), although these parameters are not very precisely estimated. In both the domestic and import sectors, there are significant fractions of backward-looking price setters ($\alpha_d = 0.92$, $\alpha_m = 0.77$, and both are precisely estimated), giving rise to substantial inertia in domestic and imported inflation (again see Figure 2). The estimated demand elasticities in the domestic and imported sectors reach their lower and upper limits ($\eta_d = 6.00, \eta_m = 21.00$), respectively, but these are not very well identified in the model; any values between 6 and 21 result in very similar impulse responses.

We can obtain a sense of what our estimated Rotemberg parameter for domestic inflation (γ_d) implies for the behavior of price-setting firms by comparing with the Calvo (1983) model of price-setting. In the closed-economy version of our model with rule-of-thumb price setters, the relationship between domestic inflation and real marginal cost is measured by the coefficient $(1 - \alpha_d)[\alpha_d + \gamma_d(1 + 2\alpha_d\beta)]$, where γ_d is the adjustment cost parameter and α_d is the fraction of rule-of-thumbers. This can be compared with the closed-economy Phillips curve in Galí and Gertler (1999), who also allow for rule-of-thumb price setters. In their Phillips curve, the coefficient on marginal cost is $(1 - \omega)(1 - q)(1 - \beta q)/[q + \omega(1 - q(1 - \beta))]$, where q is the Calvo parameter (the probability that a given firm will keep its price fixed in a given period), ω is the fraction of rule-of-thumb firms, and β is the discount factor. Setting the discount factor to $\beta = 0.99$ and the fraction of rule-of-thumb firms to $\alpha_d = \omega = 0.90$ (as estimated in the baseline model), our estimate of $\gamma_d = 63.10$ is equivalent to a Calvo parameter around $q = 0.90$, which is similar to the estimates in Galí and Gertler (1999) and Smets and Wouters (2002). Of course, this relationship between the Rotemberg and Calvo parameters will be slightly different in the open-economy model. Nevertheless, the closed-economy comparison provides some perspective on the degree of domestic price stickiness in our estimated model; in fact, our estimate seems to be in the range of those found in the previous literature.

We can also investigate the implications of our estimates of the parameters for import prices (γ_m and α_m) for the degree of pass-through from changes in the nominal exchange rate to imported and CPI inflation, conditional on a monetary policy shock. In the baseline model, the contemporaneous impact of a policy shock on the nominal exchange rate is -0.56, while the impact on (quarterly) imported inflation is -0.03 and that on (quarterly) CPI inflation is -0.01. Thus, the rather large impact on the exchange rate is consistent with very small effects on both imported and CPI inflation. Considering the dynamic response to the policy shock, the correlation of nominal exchange rate changes with imported inflation is 0.56, while the correlation with CPI inflation is 0.39. Thus, our parameter estimates imply a farily limited degree of exchange rate pass-through in the short run, although pass-through is complete in the long run. If import prices were perfectly flexible, so $\gamma_m = \alpha_m = 0$, the law of one price would hold also in the short run, and the correlation between nominal exchange rate changes and imported inflation would be one.

Finally, we note that the parameter determining the premium on foreign exchange is very large and significant ($\phi = 7.12$ with a standard error of 2.53). To judge how large our estimate of ϕ is, we can solve the model for a given ϕ and calculate the effects of a change in the net foreign asset position on the interest rate differential. If we set $\phi = 2$, which is at the lower boundary of a 95% confidence interval, a ten percentage point reduction in the ratio of NFA to steady-state output leads to a 4.5 percentage point increase in the nominal interest rate differential. Lane and Milesi-Ferretti (2001) estimate the sensitivity of the real interest rate differential to the ratio of net foreign assets to annual exports in a panel of industrialized countries. Their results can not be applied directly to our model, but their typical estimate implies that a ten percentage point reduction in the quarterly NFA/GDP-ratio leads to a 4.33 basis point increase in the quarterly real interest rate differential. Thus, our lower boundary estimate of ϕ leads to an effect of NFA on the interest rate spread that is more than 100 times larger than that estimated by Lane and Milesi-Ferretti (2001).[14] Similarly, if we estimate the log-linearized UIP condition (2.28) using data on the interest rate differential, the nominal exchange rate and real net foreign assets, we obtain a point estimate of $\phi = 0.0077$ with a standard error of 0.05, implying that a reasonable range of ϕ would be from 0 to

[14] According to the estimates of Lane and Milesi-Ferretti (2001), a ten percentage point reduction in the NFA/export ratio leads to a 25 basis points increase in the annualized real interest rate differential, so a ten percentage point reduction in the ratio of NFA to quarterly exports leads to a $25/16 = 1.56$ basis point increase in the quarterly real interest rate differential. In our sample, the average export to GDP ratio in Sweden is 36%, so a ten percentage point reduction in the quarterly NFA/GDP-ratio leads to a 4.33 basis point increase in the quarterly real interest rate differential. Benigno (2001) and Kollman (2002) use calibrations of ϕ that are similar to those estimated by Lane and Milesi-Ferretti (2001).

0.115.

The very large estimate for ϕ obtained in our model is needed to capture the gradual response of the real exchange rate and the large deviations from UIP implied by this response. As these large deviations must be explained only by movements in net foreign assets, which do not respond much to the monetary policy shock, the premium must be very sensitive to these movements, thus yielding a large ϕ. But this large ϕ also implies a very large average premium on foreign exchange. Below, we therefore report impulse responses where ϕ is restricted to be smaller. We then move on to estimate a slightly modified model, where the premium on foreign exchange is allowed to vary directly in response to the shocks in the model. In this model, the average premium will be smaller, as shocks are zero on average.

For completeness, Table 4 shows the reestimated coefficients in the monetary policy rule (2.52). As mentioned above, the structure of this rule is the same as the estimated interest rate equation in the VAR, but the coefficients have been reestimated, in order to take estimation uncertainty in the VAR into account. In this estimation, the coefficients are allowed to vary within bootstrapped 95% confidence intervals around the VAR estimates.

4.2. Sensitivity analysis

Four parameters seem particularly important for capturing the dynamic behavior of the estimated VAR: the habit formation parameter, h, the fractions of backward-looking price setters in the two sectors, α_d and α_m, and the parameter determining the premium on foreign bond holdings, ϕ. To gain further intuition about the importance of these parameters, we reestimate the model, each time restricting one parameter to some given level or range. Thus, we estimate the model (*i*) allowing only for a small premium on foreign bond holdings, restricting ϕ to be between 0 and 0.115, where the upper boundary is taken from our single-equation estimation of the log-linearized UIP condition; (*ii*) with no habits in consumption, so $h = 0$; (*iii*) with only forward-looking firms in the domestic sector, so $\alpha_d = 0$; and (*iv*) with only forward-looking firms in the import sector, so $\alpha_m = 0$. Also in the latter three models we will restrict ϕ to be "reasonable", that is, somewhere between 0 and 0.115. The obtained impulse responses in these special cases are shown in Figures 3–6.

First, Figure 3 shows the impulse responses when we restrict the premium on foreign exchange to be fairly small, so $\phi \in (0, 0.115]$. The estimated value for ϕ is now 0.001 with standard error of 0.03, which is close to the single-equation estimate, but is not statistically significant. The responses of output, the interest rate, and domestic and imported inflation are very similar to those in the baseline model and the VAR. However, with such a small premium, the model is not able to match the gradual behavior of the real exchange rate: after an initial real appreciation, the exchange rate immediately starts depreciating back towards its steady-state level. This response is similar to models with perfect capital mobility, without premia on foreign exchange, so in restricting ϕ to be small we essentially eliminate the deviations from UIP.

In the model without habit formation, shown in Figure 4, there is less persistence in output, as expected. Instead of a hump-shaped response to the policy shock, the maximum effect on output is immediate, after which output slowly returns to its initial level. Although the estimate of the habit parameter h was not very large, nor significantly different from zero, it is clear that we need some habit formation in order to match the hump-shaped response of output.

In the model without backward-looking behavior in the domestic sector, shown in Figure 5, domestic inflation is persistent, but not very smooth. The hump-shaped response is now due to the behavior of output and the interest rate, rather than to intrinsic inflation persistence. The model without backward-looking behavior in the import sector is shown in Figure 6. Again, there is still some persistence in imported inflation, due to the behavior of the other variables, but the response is further away from the VAR response. Figures 5 and 6 show that in order to replicate the smooth hump-shaped responses of domestic and imported inflation that we find in the VAR, we need a large fraction of backward-looking behavior among firms.[15]

4.3. Additional dynamics in the foreign exchange premium

In the baseline model used so far the dynamics of the foreign exchange premium comes only from movements in net foreign assets, and in order to explain the large deviations from UIP the premium must be very sensitive to these movements. In the following, we modify the model somewhat in order to introduce direct effects of shocks on the premium. Although this version of the model will create similar foreign exchange premia in response to shocks as the baseline model, it may lead to a smaller average premium if the estimated ϕ is smaller than in the baseline model, as the shocks will be zero on average.

[15] If we eliminate backward-looking behavior in both sectors, all responses would be similar to that in Figure 5, except for imported inflation, which would follow Figure 6. We also estimated models without sticky prices in one or both sectors. If there are no sticky prices in the domestic sector, we obtain very small real effects of monetary policy.

Specifically, the log-linearized UIP condition is now assumed to be given by

$$i_t - i_t^f = \mathrm{E}_t \Delta s_{t+1} - \phi a_t - \phi_t^i - \phi_t^y - \phi_t^d, \tag{4.1}$$

where

$$\phi_t^j = \rho_\phi^j \phi_{t-1}^j + \phi_1^j \varepsilon_t^j + \phi_2^j \varepsilon_{t-1}^j, \tag{4.2}$$

for $j = i, y, d$, and where ε_t^i is the policy shock, ε_t^y is the aggregate demand shock, and ε_t^d is the domestic aggregate supply shock. Thus, the premium on foreign exchange now depends not only on real net foreign assets but also on the shocks to monetary policy, aggregate demand and aggregate supply, with these direct effects assumed to follow ARMA(1,1) processes.

The results from estimating the modified model to match the monetary policy shock are shown in Figure 7, and the estimated parameters are shown in the second column of Table 3. In the modified model the response of output is closer to the VAR responses than in the baseline model in Figure 2, while for domestic and imported inflation, the responses are very similar. The real exchange rate shows less persistence than in the baseline model, and is not as close to the VAR response, but is everywhere inside the confidence interval.

As expected, the main difference in the parameter estimates is that the modified model obtains a much smaller estimate of ϕ, which is now 0.08 rather than 7.12 in the baseline model, and is not statistically significant. On the other hand, there is substantial inertia in the premium on foreign exchange coming from the direct effect to the policy shock, as $\rho_\phi^i = 0.99$. For the other parameters, the modified model implies significantly more habit persistence ($h = 0.88$) and a larger elasticity of substitution across domestic and foreign goods ($\eta = 2.04$). We also note that the two demand elasticities η_d and η_m have reached the opposite boundaries compared with the baseline model, reflecting the fact that they are not very precisely estimated.

4.4. Estimation using all shocks

Finally, we use the modified model to match the impulse responses to all three identified shocks in the VAR: the policy shock, the aggregate demand shock and the aggregate supply shock. This is mainly intended as a robustness exercise, indicating to what extent the estimated parameters depend on the monetary policy shock. The results should be interpreted with care, however, as the identification of the aggregate demand and aggregate supply shocks in the VAR is more controversial than the identification of the monetary policy shock. Note also that the aggregate supply shock in the VAR is a shock to the four-quarter inflation rate, while in the theoretical model it is a shock to the quarterly rate of inflation. The resulting impulse responses are shown in three rows of graphs in Figure 8, and the parameter values are presented in the last column of Table 3.

A comparison of the responses following a policy shock in Figure 7 and the top row of Figure 8 reveals that output and domestic inflation are less responsive in the three-shock estimation. Nevertheless, the model responses are still inside the VAR confidence intervals, and in the case of imported inflation, the real exchange rate and the interest rate the responses are very similar. After the aggregate demand shock (second row of graphs in Figure 8) the model does well in tracking output and the interest rate, but less so for domestic and imported inflation and the real exchange rate, although again the responses are inside the confidence intervals. Finally, after the aggregate supply shock (last row of graphs) the model responses occasionally fall outside the confidence intervals, and the general impression is less favorable.

The parameter estimates in Table 3 reveal that the three-shock estimation yields a substantial reduction in the fraction of backward-looking firms in the domestic sector (α_d), which is now essentially zero. The reason is that the VAR response of domestic inflation to the aggregate supply shock is not very persistent. There is also a reduction in the price stickiness of the import sector (γ_m, which falls from 4.39 to 0.18) and a further reduction in the parameter determining the premium on foreign exchange (ϕ, which now is 0.001). Finally, we note that there is substantial inertia in the foreign exchange premium after all shocks: $\rho_\phi^i = 0.91, \rho_\phi^y = 0.99, \rho_\phi^d = 0.91$, again in order to account for the large deviations from UIP.

5. Concluding remarks

In this paper we formulate a small open-economy model with gradual exchange rate pass-through, imperfect financial integration, and endogenous inertia in domestic and imported inflation and consumption, combining and extending the models of Adolfson (2001) and Benigno (2001). We then estimate the key parameters in the model on Swedish data by matching the impulse response functions to a policy shock in the model with those obtained from a VAR model using standard identifying assumptions.

The theoretical model is very successful in capturing the observed dynamic behavior of output, the interest rate, domestic and imported inflation, and the real exchange rate after a policy shock. However, in order to match the observed persistence in the real exchange rate, a large and fairly volatile premium on foreign exchange is needed. This difficulty in accounting for real exchange rate persistence and the large deviations from UIP seems to be a common feature of estimated open-economy models and no apparent micro-founded solutions exist today. We explore one possible modification of the baseline model, which may be interpreted as a reduced-form formulation of an endogenous risk premium, and this model is indeed more successful in matching the response of the real exchange rate without the need for a very large average foreign exchange premium. The modified model provides some clues about how to replicate the behavior of the exchange rate in a structural open-economy model; the underlying mechanisms for such an endogenous risk premium are left for future research.

The approach of choosing parameters in a theoretical model to replicate the empirical impulse response functions to a policy shock has recently been criticized by Leeper and Roush (2003), among others. We nevertheless pursue this approach because we believe it offers important insights about the properties of the model. If the identifying assumptions of the policy shock are not too inaccurate, the cost associated with our approach is small. In the end, the adopted approach gives us useful insights about the crucial role of the UIP condition and the modification needed in order for the model to provide a realistic description of the data. Natural extensions of our work would be to introduce foreign shocks in the model and estimate the model by maximum likelihood using the Kalman filter, possibly with Bayesian methods as Smets and Wouters (2003). We strongly believe, however, that the insights gained from our approach are very likely to be relevant also when applying other empirical methods.

A. Model appendix

This appendix provides some details concerning the steady state of the model and the log-linearization of aggregate demand.

A.1. Steady state

We log-linearize the model around a steady state with zero inflation and where the domestic terms of trade (P^m/P^d) is normalized to unity. Letting variables without time subscripts denote steady-state values, this implies that $P^m = P^d = P^c = SP^f$.

First, using the consumption Euler equation (2.16), we get

$$1 = \beta(1+i), \tag{A.1}$$

so

$$\beta = \frac{1}{1+i}. \tag{A.2}$$

Since a similar relationship will hold for the foreign economy, and assuming that the discount factor is the same in the domestic and foreign economies, we get

$$1+i = 1+i^f = \frac{1}{\beta}. \tag{A.3}$$

Using this in the first-order condition for foreign bond holdings yields

$$\beta \frac{\lambda S}{\Phi(A) P^c} = \beta \frac{\lambda S}{P^c}, \tag{A.4}$$

implying that $\Phi(A) = 1$ or $B^f = A = 0$. Thus, in steady state, the net foreign asset position is zero. Assuming that domestic bonds are in zero net supply, aggregating the budget constraint (2.13) and evaluating it in steady state then gives $C = X$, so in steady state, consumption equals real profits.

Aggregating over all domestic firms, real profits in the domestic sector are given by

$$X_t^d = \frac{1}{P_t^c} \left[P_t^d C_t^d + S_t P_t^{df} C_t^{df} - P_t^z Z_t \right], \tag{A.5}$$

and, similarly, in the import sector real profits are

$$X_t^m = \frac{1}{P_t^c} \left[P_t^m - S_t P_t^{zf} \right] C_t^m. \tag{A.6}$$

In steady state, since $P^d = P^m = P^c = SP^f$ and $P^{df} = P^d/S = P^f$, demand is

$$\begin{aligned} C^d &= (1-\omega_m)C, && \text{(A.7)} \\ C^m &= \omega_m C, && \text{(A.8)} \\ C^{df} &= C^f, && \text{(A.9)} \end{aligned}$$

using (2.18), (2.19), and (2.22). Using (2.33), (2.41), and (2.31), we get

$$\begin{aligned} P^z &= \frac{(\eta_d-1)(1-\theta)}{\eta_d} P^d Y^{-\theta/(1-\theta)}, && \text{(A.10)} \\ P^{zf} &= \frac{\eta_m-1}{\eta_m}\frac{P^m}{S}, && \text{(A.11)} \\ Z &= Y^{1/(1-\theta)}. && \text{(A.12)} \end{aligned}$$

Thus, steady state real profits generated in the domestic sector are

$$X^d = (1-\omega_m)C + C^f - \frac{(\eta_d-1)(1-\theta)}{\eta_d} Y, \tag{A.13}$$

and using the identity

$$\begin{aligned} Y &= C^d + C^{df} \\ &= (1-\omega_m)C + C^f, && \text{(A.14)} \end{aligned}$$

we get

$$\begin{aligned} X^d &= (1-\omega_m)C + C^f - \frac{(\eta_d-1)(1-\theta)}{\eta_d}\left[(1-\omega_m)C + C^f\right] \\ &= \frac{\eta_d-(\eta_d-1)(1-\theta)}{\eta_d}\left[(1-\omega_m)C + C^f\right] \\ &= \frac{1-\theta+\eta_d\theta}{\eta_d}\left[(1-\omega_m)C + C^f\right]. && \text{(A.15)} \end{aligned}$$

Likewise, using (A.11), real steady-state profits created in the import sector are given by

$$\begin{aligned} X^m &= \frac{1}{P^c}\left[P^m - \frac{\eta_m-1}{\eta_m}P^m\right]\omega_m C, \\ &= \frac{\omega_m}{\eta_m} C. && \text{(A.16)} \end{aligned}$$

Total real profits are then given by

$$X = \left[\frac{(1-\theta+\eta_d\theta)(1-\omega_m)}{\eta_d} + \frac{\omega_m}{\eta_m}\right] C + \frac{1-\theta+\eta_d\theta}{\eta_d} C^f, \tag{A.17}$$

and using $C = X$ yields

$$X = \frac{\eta_m (1-\theta+\eta_d\theta)}{\eta^d\eta_m - \eta_m (1-\theta+\eta_d\theta)(1-\omega_m) - \omega_m\eta_d} C^f \equiv \Gamma_1 C^f \tag{A.18}$$

Thus, steady-state profits are proportional to foreign steady-state consumption.

Combining (A.14) and (A.18) gives

$$\begin{aligned} C^f &= Y - (1-\omega_m)C \\ &= Y - (1-\omega_m)\Gamma_1 C^f, \end{aligned} \tag{A.19}$$

since $C = X$. In steady state, equation (2.34) implies that

$$\begin{aligned} P^z &= \frac{\left(P^d\right)^{1-\kappa}(P^m)^\kappa}{(1-\kappa)^{1-\kappa}\kappa^\kappa} \\ &= \frac{P}{(1-\kappa)^{1-\kappa}\kappa^\kappa}, \end{aligned} \tag{A.20}$$

and combining with (A.10) gives

$$\begin{aligned} Y &= \left[\frac{\eta_d}{(\eta_d-1)(1-\theta)}\frac{1}{(1-\kappa)^{1-\kappa}\kappa^\kappa}\right]^{(\theta-1)/\theta} \\ &\equiv \Gamma_2^{(\theta-1)/\theta}. \end{aligned} \tag{A.21}$$

Combining (A.19) and (A.21) we obtain

$$\begin{aligned} C^f &= \Gamma_2^{(\theta-1)/\theta} - (1-\omega_m)\Gamma_1 C^f \\ &= \frac{1}{1+(1-\omega_m)\Gamma_1}\Gamma_2^{(\theta-1)/\theta}. \end{aligned} \tag{A.22}$$

Thus, steady-state profits are given by

$$X = \frac{\Gamma_1}{1+(1-\omega_m)\Gamma_1}\Gamma_2^{(\theta-1)/\theta}. \tag{A.23}$$

A.2. The log-linearized model

For any variable X_t, let x_t denote the log-deviation from steady state, that is,

$$x_t \equiv \log X_t - \log X. \tag{A.24}$$

A.2.1. Aggregate demand

Log-linearizing the Euler equation (2.16) gives

$$\begin{aligned} c_t &= \frac{h}{1+h}c_{t-1} + \frac{1}{1+h}\mathrm{E}_t c_{t+1} - \frac{1-h}{(1+h)\sigma}\left[i_t - \mathrm{E}_t \pi^c_{t+1}\right] \\ &\quad - \frac{1-h}{(1+h)\sigma}\mathrm{E}_t \Delta \upsilon_{t+1}, \end{aligned} \tag{A.25}$$

where π^c_t is the CPI inflation rate, given by

$$\begin{aligned} \pi^c_t &= (1-\omega_m)\pi^d_t + \omega_m \pi^m_t \\ &= \pi^d_t + \omega_m \Delta \tau_t, \end{aligned} \tag{A.26}$$

which is the first difference of the log-linearized CPI from (2.10):

$$\begin{aligned} p^c_t &= (1-\omega_m)p^d_t + \omega_m p^m_t \\ &= p^d_t + \omega_m \tau_t, \end{aligned} \tag{A.27}$$

using (2.1). Similarly, linearizing the input price index (2.34) yields

$$\begin{aligned} p^z_t &= (1-\kappa)p^d_t + \kappa p^m_t \\ &= p^d_t + \kappa \tau_t. \end{aligned} \tag{A.28}$$

Linearizing domestic demand for domestic and imported goods in (2.18) and (2.19) and foreign demand for domestic goods in (2.22) yields, using (A.27), (2.1) and (2.2),

$$
\begin{aligned}
c_t^d &= c_t - \eta\left[p_t^d - p_t^c\right] \\
&= c_t + \eta\omega_m\tau_t, && \text{(A.29)} \\
c_t^m &= c_t - \eta\left[p_t^m - p_t^c\right] \\
&= c_t - \eta(1-\omega_m)\tau_t, \\
&= c_t^d - \eta\tau_t, && \text{(A.30)} \\
c_t^{df} &= c_t^f - \eta\left[p_t^d - s_t - p_t^f\right] \\
&= \chi_f y_t^f - \eta\left[p_t^d - s_t - p_t^f\right] \\
&= \chi_f y_t^f - \eta\tau_t^f, && \text{(A.31)}
\end{aligned}
$$

where by assumption $c_t^f = \chi_f y_t^f$, so χ_f is the income elasticity of foreign consumption.

Aggregate demand for domestic goods is then given by

$$
\begin{aligned}
y_t &= (1-\omega_x)c_t^d + \omega_x c_t^{df} \\
&= (1-\omega_x)\left[c_t + \eta\omega_m\tau_t\right] + \omega_x\left[\chi_f y_t^f - \eta\tau_t^f\right], && \text{(A.32)}
\end{aligned}
$$

where ω_x is the export share of domestic production. Solving for c_t we obtain

$$
c_t = \frac{1}{1-\omega_x}y_t - \eta\omega_m\tau_t - \frac{\omega_x}{1-\omega_x}\left[\chi_f y_t^f - \eta\tau_t^f\right], \tag{A.33}
$$

and using this and (A.26) in the linearized Euler equation (A.25) we get

$$
\begin{aligned}
&\frac{1}{1-\omega_x}y_t - \eta\omega_m\tau_t - \frac{\omega_x}{1-\omega_x}\left[\chi_f y_t^f - \eta\tau_t^f\right] \\
&= \frac{h}{1+h}\left\{\frac{1}{1-\omega_x}y_{t-1} - \eta\omega_m\tau_{t-1} - \frac{\omega_x}{1-\omega_x}\left[\chi_f y_{t-1}^f - \eta\tau_{t-1}^f\right]\right\} \\
&\quad + \frac{1}{1+h}\left\{\frac{1}{1-\omega_x}\mathrm{E}_t y_{t+1} - \eta\omega_m\mathrm{E}_t\tau_{t+1} - \frac{\omega_x}{1-\omega_x}\left[\chi_f\mathrm{E}_t y_{t+1}^f - \eta\mathrm{E}_t\tau_{t+1}^f\right]\right\} \\
&\quad - \frac{1-h}{(1+h)\sigma}\left[i_t - \mathrm{E}_t\pi_{t+1}^d - \omega_m\mathrm{E}_t\Delta\tau_{t+1}\right] - \frac{1-h}{(1+h)\sigma}\mathrm{E}_t\Delta\upsilon_{t+1}. && \text{(A.34)}
\end{aligned}
$$

Solving for y_t and collecting terms then gives

$$\begin{aligned} y_t &= (1-a_y)\, y_{t-1} + a_y \mathrm{E}_t y_{t+1} + a_r \left[i_t - \mathrm{E}_t \pi^d_{t+1}\right] + a_{\tau 1}\tau_{t-1} \\ &\quad + a_{\tau 2}\tau_t + a_{\tau_3}\mathrm{E}_t\tau_{t+1} + a_{\tau f1}\tau^f_{t-1} + a_{\tau f2}\tau^f_t + a_{\tau f3}\mathrm{E}_t\tau^f_{t+1} \\ &\quad + a_{yf1}y^f_{t-1} + a_{yf2}y^f_t + a_{yf3}\mathrm{E}_t y^f_{t+1} + u^y_t, \end{aligned} \tag{A.35}$$

which is equation (2.24).

A.2.2. Net foreign assets

Since domestic bonds are in zero net supply, aggregating the budget constraint (2.13) yields

$$C_t + \frac{A_t}{(1+i^f_t)\Phi(A_t)} = A_{t-1}\frac{P^c_{t-1}}{P^c_t}\frac{S_t}{S_{t-1}} + X_t. \tag{A.36}$$

Log-linearizing and using $A = 0, 1 + i^f = 1/\beta$, and $C = X$ then gives

$$Xc_t + \beta a_t = a_{t-1} + Xx_t, \tag{A.37}$$

or

$$a_t = \frac{1}{\beta}\left[a_{t-1} - Xc_t + Xx_t\right]. \tag{A.38}$$

Using (A.32) we then obtain equation (2.29):

$$a_t = d_a a_{t-1} + d_y y_t + d_x x_t + d_\tau \tau_t + d_{\tau f}\tau^f_t + d_{yf} y^f_t, \tag{A.39}$$

where

$$\begin{aligned} d_a &= \frac{1}{\beta}, \\ d_y &= -\frac{\Gamma_1}{\beta(1-\omega_x)[1+(1-\omega_m)\Gamma_1]}\Gamma_2^{(\theta-1)/\theta}, \\ d_x &= \frac{\Gamma_1}{\beta[1+(1-\omega_m)\Gamma_1]}\Gamma_2^{(\theta-1)/\theta}, \\ d_\tau &= \frac{\eta\omega_m\Gamma_1}{\beta[1+(1-\omega_m)\Gamma_1]}\Gamma_2^{(\theta-1)/\theta}, \\ d_{\tau f} &= -\frac{\eta\omega_x\Gamma_1}{\beta(1-\omega_x)[1+(1-\omega_m)\Gamma_1]}\Gamma_2^{(\theta-1)/\theta}, \\ d_{yf} &= \frac{\chi_f\omega_x\Gamma_1}{\beta(1-\omega_x)[1+(1-\omega_m)\Gamma_1]}\Gamma_2^{(\theta-1)/\theta}, \end{aligned}$$

and

$$\Gamma_1 \equiv \frac{\eta_m (1-\theta+\eta_d\theta)}{\eta_d\eta_m - \eta_m (1-\theta+\eta_d\theta)(1-\omega_m) - \omega_m\eta_d},$$
$$\Gamma_2 \equiv \frac{\eta_d}{(\eta_d-1)(1-\theta)(1-\kappa)^{1-\kappa}\kappa^\kappa}.$$

Total real profits are given by

$$X_t = \frac{1}{P_t^c}\left[P_t^d C_t^d + S_t P_t^{df} C_t^{df} - P_t^z Z_t + P_t^m C_t^m - S_t P_t^{zf} C_t^m\right], \tag{A.40}$$

and log-linearization yields

$$\begin{aligned} X x_t &= -\frac{1}{(P^c)^2}\left\{P^d C^d + S P^{df} C^{df} - P^z Z + \left(P^m - S P^{zf}\right) C^m\right\} P^c p_t^c \\ &+ \frac{1}{P^c}\left\{P^d C^d \left[p_t^d + c_t^d\right] + S P^{df} C^{df}\left[s_t + p_t^{df} + c_t^{df}\right] - P^z Z\left[p_t^z + z_t\right]\right\} \\ &+ \frac{1}{P^c}\left\{P^m C^m \left[p_t^m + c_t^m\right] - S P^{zf} C^m \left[s_t + p_t^{zf} + c_t^m\right]\right\} \end{aligned} \tag{A.41}$$

Again using $P^d = P^m = P^c = SP^f$, $P^{df} = P^d/S$, $C = X$, $Y = (1-\omega_m)C + C^f$, and equations (A.7)–(A.12), we get

$$\begin{aligned} x_t &= -p_t^c + (1-\omega_m)\left[p_t^d + c_t^d\right] + \frac{1}{\Gamma_1}\left[s_t + p_t^{df} + c_t^{df}\right] \\ &- \frac{(\eta_d-1)(1-\theta)}{\eta_d}\left[(1-\omega_m) + \frac{1}{\Gamma_1}\right]\left[p_t^z + z_t\right] + \omega_m\left[p_t^m + c_t^m\right] \\ &- \frac{(\eta_m-1)\omega_m}{\eta_m}\left[s_t + p_t^{zf} + c_t^m\right]. \end{aligned} \tag{A.42}$$

To write x_t in terms of the real variables y_t, τ_t, y_t^f, and τ_t^f, first use (A.27), (A.28), (A.30), log-linearized versions of (2.31) and (2.37):

$$z_t = \frac{1}{1-\theta} y_t, \tag{A.43}$$
$$p_t^{zf} = p_t^f, \tag{A.44}$$

the fact that $p_t^{df} = p_t^d - s_t$, and the definitions of τ_t and τ_t^f in (2.1) and (2.2) to get

$$\begin{aligned}
x_t &= \left\{\frac{1-\theta+\eta_d\theta}{\eta_d}\frac{1}{\Gamma_1} - \frac{(\eta_d-1)(1-\theta)(1-\omega_m)}{\eta^d} - \frac{(\eta_m-1)\,\omega_m}{\eta_m}\right\} p_t^d \\
&+ \frac{\eta_m-(\eta_m-1)\omega_m}{\eta_m(1-\omega_x)}\left[y_t - \omega_x c_t^{df}\right] - \frac{\eta_d-1}{\eta_d}\left[1-\omega_m+\frac{1}{\Gamma_1}\right] y_t \\
&- \left\{\eta\omega_m - \frac{(\eta_m-1)\,\eta\omega_m}{\eta_m} + \frac{\kappa(\eta_d-1)(1-\theta)}{\eta_d}\left[1-\omega_m+\frac{1}{\Gamma_1}\right]\right\}\tau_t \\
&+ \frac{1}{\Gamma_1}c_t^{df} + \frac{(\eta_m-1)\omega_m}{\eta_m}\tau_t^f. \qquad (A.45)
\end{aligned}$$

Collecting terms and using

$$c_t^d = \frac{1}{1-\omega_x}y_t - \frac{\omega_x}{1-\omega_x}c_t^{df} \qquad (A.46)$$

from (A.32) then gives us the final expression

$$x_t = e_y y_t + e_\tau \tau_t + e_{\tau f}\tau_t^f + e_{yf} y_t^f, \qquad (A.47)$$

where

$$\begin{aligned}
e_y &= \frac{\eta_m-(\eta_m-1)\,\omega_m}{\eta_m\,(1-\omega_x)} - \frac{\eta_d-1}{\eta_d}\left[1-\omega_m+\frac{1}{\Gamma_1}\right], \\
e_\tau &= -\frac{\eta\omega_m}{\eta_m} - \frac{\kappa\,(\eta_d-1)\,(1-\theta)}{\eta_d}\left[1-\omega_m+\frac{1}{\Gamma_1}\right], \\
e_{\tau f} &= \frac{(\eta_m-1)\,\omega_m}{\eta_m} + \frac{\eta\omega_x\left[\eta_m-(\eta_m-1)\,\omega_m\right]}{\eta_m\,(1-\omega_x)} - \frac{\eta}{\Gamma_1}, \\
e_{yf} &= -\frac{\chi_f\omega_x\left[\eta_m-(\eta_m-1)\,\omega_m\right]}{\eta_m\,(1-\omega_x)} + \frac{\chi_f}{\Gamma_1}.
\end{aligned}$$

A.2.3. Aggregate supply

To derive the aggregate supply equations (2.45)–(2.46), note that equations (2.42)–(2.44) imply that

$$\begin{aligned}
p_t^{opt,j} &= \frac{1}{1-\alpha_j}p_t^j - \frac{\alpha_j}{1-\alpha_j}p_t^{rule,j} \\
&= p_t^j + \frac{\alpha_j}{1-\alpha_j}\left[\pi_t^j - \pi_{t-1}^j\right], \qquad (A.48) \\
\pi_t^{opt,j} &= \frac{1}{1-\alpha_j}\pi_t^j - \frac{\alpha_j}{1-\alpha_j}\left[2\pi_{t-1}^j - \pi_{t-2}^j\right]. \qquad (A.49)
\end{aligned}$$

Aggregate inflation is then given by

$$
\begin{aligned}
\pi_t^j &= (1-\alpha_j)\pi_t^{opt,j} + \alpha_j \pi_t^{rule,j} \\
&= (1-\alpha_j)\left\{\beta \mathrm{E}_t \pi_{t+1}^{opt,j} + \frac{1}{\gamma_j}\left[\hat{p}_t^j - p_t^{opt,j}\right]\right\} + \alpha_j\left\{2\pi_{t-1}^j - \pi_{t-2}^j\right\} \\
&= (1-\alpha_j)\left\{\frac{\beta}{1-\alpha_j}\mathrm{E}_t \pi_{t+1}^j - \frac{\alpha_j\beta}{1-\alpha_j}\left[2\pi_t^j - \pi_{t-1}^j\right]\right\} \\
&\quad + \frac{1-\alpha_j}{\gamma_j}\left\{\hat{p}_t^j - p_t^j - \frac{\alpha_j}{1-\alpha_j}\left[\pi_t^j - \pi_{t-1}^j\right]\right\} \\
&\quad + \alpha_j\left\{2\pi_{t-1}^j - \pi_{t-2}^j\right\},
\end{aligned}
\tag{A.50}
$$

and collecting terms yields

$$
\begin{aligned}
\pi_t^j &= \beta \mathrm{E}_t \pi_{t+1}^j - \frac{\alpha_j\left(1+2\beta\gamma_j\right)}{\gamma_j}\pi_t^j + \frac{\alpha_j\left(1+2\gamma_j+\beta\gamma_j\right)}{\gamma_j}\pi_{t-1}^j - \alpha_j\pi_{t-2}^j \\
&\quad + \frac{1-\alpha_j}{\gamma_j}\left[\hat{p}_t^j - p_t^j\right] \\
&= \beta\gamma_j\Psi_j \mathrm{E}_t \pi_{t+1}^j + \alpha_j\left(1+2\gamma_j+\beta\gamma_j\right)\Psi_j\pi_{t-1}^j - \alpha_j\gamma_j\Psi_j\pi_{t-2}^j \\
&\quad + (1-\alpha_j)\Psi_j\left[\hat{p}_t^j - p_t^j\right],
\end{aligned}
\tag{A.51}
$$

where

$$
\Psi_j = \left[\alpha_j + \gamma_j\left(1+2\alpha_j\beta\right)\right]^{-1}. \tag{A.52}
$$

Using the expression for the optimal flexible domestic price in (2.40) gives an expression for domestic inflation as

$$
\begin{aligned}
\pi_t^d &= \beta\gamma_d\Psi_d \mathrm{E}_t \pi_{t+1}^d + \alpha_d\left(1+2\gamma_d+\beta\gamma_d\right)\Psi_d\pi_{t-1}^d - \alpha_d\gamma_d\Psi_d\pi_{t-2}^d \\
&\quad + (1-\alpha_d)\Psi_d\left\{\frac{\theta}{1-\theta}y_t + \kappa\left[p_t^m - p_t^d\right]\right\},
\end{aligned}
\tag{A.53}
$$

and using (2.41) yields the expression for imported inflation

$$
\begin{aligned}
\pi_t^m &= \beta\gamma_m\Psi_m \mathrm{E}_t \pi_{t+1}^m + \alpha_m\left(1+2\gamma_m+\beta\gamma_m\right)\Psi_m\pi_{t-1}^m \\
&\quad - \alpha_m\gamma_m\Psi_m\pi_{t-2}^m + (1-\alpha_m)\Psi_m\left[p_t^f + s_t - p_t^m\right].
\end{aligned}
\tag{A.54}
$$

Finally, using (2.1)–(2.2) and adding a domestic cost-push shock u_t^d, we can write domestic and imported inflation as

$$\pi_t^d = b_{\pi 1}\mathrm{E}_t\pi_{t+1}^d + b_{\pi 2}\pi_{t-1}^d + b_{\pi 3}\pi_{t-2}^d + b_y y_t + b_\tau \tau_t + u_t^d, \tag{A.55}$$

$$\pi_t^m = c_{\pi 1}\mathrm{E}_t\pi_{t+1}^m + c_{\pi 2}\pi_{t-1}^m + c_{\pi 3}\pi_{t-2}^m + c_\tau \left[\tau_t + \tau_t^f\right], \tag{A.56}$$

which are equations (2.45) and (2.46).

B. Data appendix

B.1. Parameters

The calibrated parameters of the model are

$\kappa = 0.32$: share of imports in inputs. Imported inputs as percentage of total inputs in the producer and import stages, 2002. Source: Statistics Sweden, PR 10 SM 0203, Table 8.

$\omega_m = 0.33$: share of imports in consumption. Average share of imported inflation (UNDIMPX) in core inflation (UND1X) over 1986–2002. Source: Sveriges Riksbank.

$\omega_x = 0.36$: share of exports in domestic production. Average export share of GDP over 1986–2001, current prices. Source: Statistics Sweden.

B.2. Time series

Time series for Swedish GDP, GDP deflator and import prices at the producer level were obtained from Statistics Sweden. Nominal and real exchange rates were obtained from Sveriges Riksbank.

Foreign variables are weighted according to trade weights, given in Table B.1 (source: Sveriges Riksbank). Foreign CPI is a weighted combination (geometric mean) of national CPI:

$$p_t^f \equiv \exp\left[\sum_{i=1}^{19} w_i \ln\left(p_t^{fi}\right)\right], \qquad \text{(B.1)}$$

where p_t^{fi} is the consumer price index for country i, taken from the OECD Main Economic Indicators (1995=100). Similarly, foreign GDP is constructed as

$$y_t^f \equiv \exp\left[\sum_{i=1}^{19} w_i \ln\left(y_t^{fi}\right)\right], \qquad \text{(B.2)}$$

where y_t^{fi} is real GDP for country i, taken from the OECD Main Economic Indicators (1995=100).

Table B.1: Trade weights (%)

Country	Weight	Country	Weight
Australia	0.27	Italy	6.05
Austria	1.71	Japan	5.20
Belgium	3.55	Netherlands	4.24
Canada	1.16	New Zealand	0.14
Denmark	5.60	Norway	5.58
Finland	6.69	Portugal	0.93
France	7.15	Spain	2.48
Germany	22.28	Switzerland	2.74
Greece	0.27	U.K.	11.56
Ireland	0.77	U.S.	11.63

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Table 1: Fraction of variance attributed to various domestic shocks at different horizons (%)

	4 quarters				8 quarters				20 quarters			
	AD	AS	MP	Other	AD	AS	MP	Other	AD	AS	MP	Other
y_t	74.9	10.4	1.6	13.1	44.6	36.7	3.9	14.8	39.0	41.9	4.4	14.7
π_t^d	1.9	88.7	0.5	8.9	9.1	71.4	2.1	17.4	12.6	68.1	3.6	15.7
i_t	5.7	19.0	66.5	8.8	5.8	22.2	58.5	13.5	7.0	29.3	50.2	13.5
q_t	9.2	47.9	5.4	37.5	10.1	60.1	5.9	23.9	10.5	59.2	5.9	24.4
π_t^m	1.0	35.3	0.9	62.8	0.7	55.6	2.0	41.7	8.0	54.0	3.5	34.5

Note: AD is the aggregate demand shock; AS is the aggregate supply shock; MP is the monetary policy shock; and Other are the remaining domestic shocks in the VAR.

Table 2: Fixed parameters

Parameter	Value
κ	0.32
ω_m	0.33
ω_x	0.36
β	0.99

Note: The table shows the values for those parameters which are directly calibrated using Swedish data. See Appendix B for details.

Table 3: Parameter estimates

	Baseline model		Modified model			
	Policy shock		Policy shock		All shocks	
			(a) Structural parameters			
h	0.23	(0.25)	0.88	(0.09)	0.82	(0.05)
σ	2.56	(0.87)	1.93	(0.66)	5.00	$(1.77)^*$
η	0.56	(0.082)	2.04	(0.59)	0.54	(0.02)
η_d	6.00	$(28.75)^*$	21.00	$(39.09)^*$	15.26	(138.75)
η_m	21.00	$(> 100.00)^*$	6.00	$(12.69)^*$	6.00	$(37.43)^*$
θ	0.47	(0.047)	0.43	(0.09)	0.49	(0.002)
γ_d	63.10	(29.84)	120.76	(27.08)	167.75	(9.73)
α_d	0.92	(0.011)	0.84	(0.09)	0.001	$(0.11)^*$
γ_m	13.66	(4.82)	4.93	(5.37)	0.18	(1.38)
α_m	0.77	(0.11)	0.87	(0.04)	0.88	(0.02)
ϕ	7.12	(2.53)	0.08	(0.09)	0.001	(0.001)
			(b) FX premium parameters			
ρ_ϕ^i			0.99	(0.00)	0.91	(0.03)
ϕ_1^i			−0.85	(0.85)	−2.96	(1.60)
ϕ_2^i			1.43	(0.51)	2.94	(1.55)
ρ_ϕ^y					0.99	$(0.02)^*$
ϕ_1^y					−0.46	(0.01)
ϕ_2^y					0.46	(0.01)
ρ_ϕ^d					0.91	(0.02)
ϕ_1^d					−5.38	(1.39)
ϕ_2^d					5.38	(1.34)
			(c) Shock parameters			
σ_i	0.86		0.87		0.87	
ρ_y					0.00	$(0.10)^*$
σ_y					0.67	
ρ_d					0.00	$(0.19)^*$
σ_d					0.97	

Note: The table shows the model parameters estimated to match the VAR impulse responses to a policy shock only or to all three identified shocks: a monetary policy shock, an aggregate demand shock and an aggregate supply shock, in the baseline theoretical model or in the modified model which includes additional dynamics in the premium on foreign exchange. Standard errors are in parentheses, * denotes that the parameter estimate is a corner solution, so the standard error is computed using perturbations of the parameter.

Table 4: Estimated policy rule parameters

	Baseline model	Modified model	
	Policy shock	Policy shock	All shocks
f_0^y	0.17	0.17	−0.12
f_1^y	−0.37	−0.20	−0.04
f_2^y	−0.47	−0.22	−0.00
f_0^d	−0.48	0.18	−0.01
f_1^d	0.48	0.19	0.00
f_2^d	0.93	0.54	0.95
f_1^q	0.30	0.25	−0.04
f_2^q	−0.16	−0.15	0.02
f_1^m	−0.02	0.04	−0.05
f_2^m	0.26	0.11	0.14
f_1^i	0.35	0.36	0.19
f_2^i	0.10	0.10	0.07

Note: The table shows the parameters in the policy rule (2.52) estimated to match the VAR impulse responses to a policy shock only or to three shocks ("All shocks"): a monetary policy shock, an aggregate demand shock and an aggregate supply shock, in the baseline theoretical model, or the modified model which includes additional dynamics in the premium on foreign exchange.

Figure 1: Impulse responses in estimated VAR model

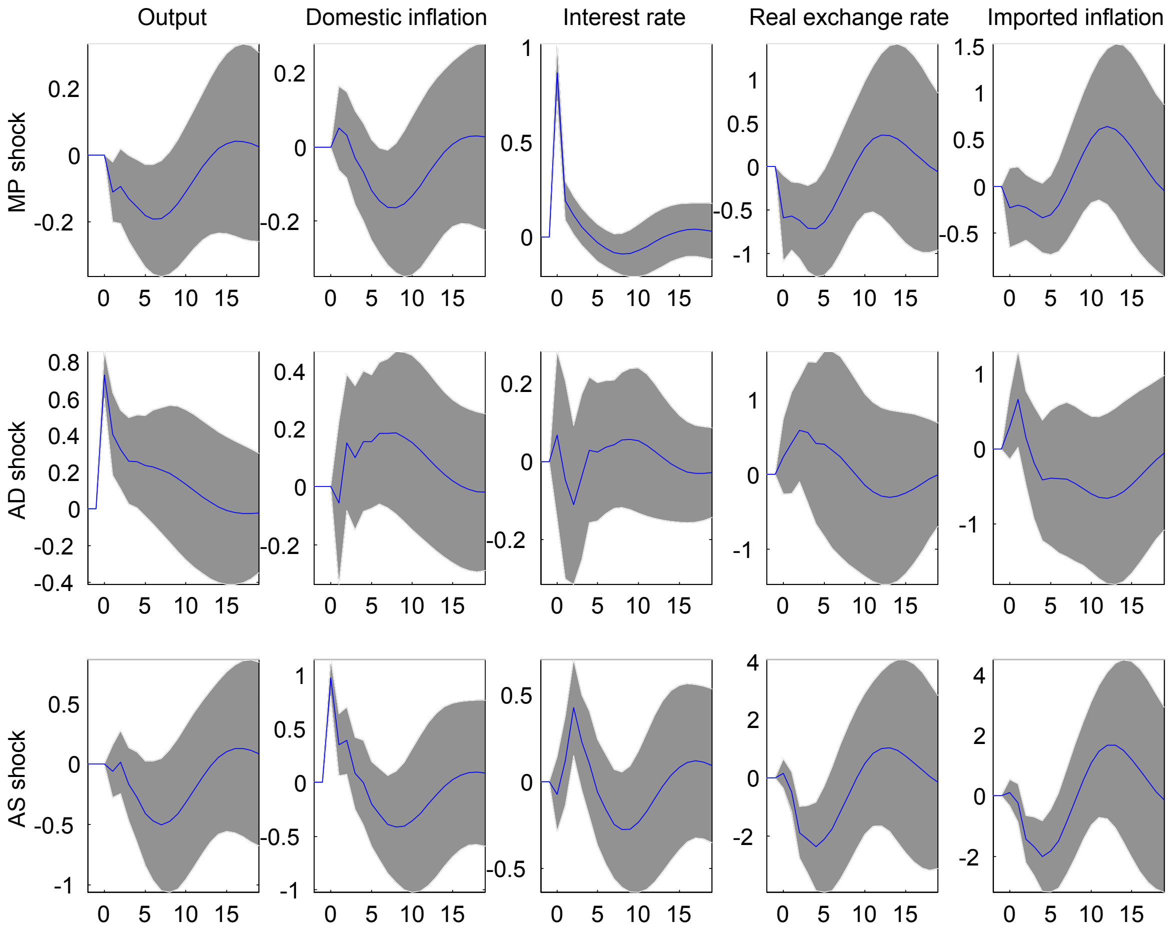

Figure 2: VAR and model responses to monetary policy shock, baseline model estimated on policy shock only

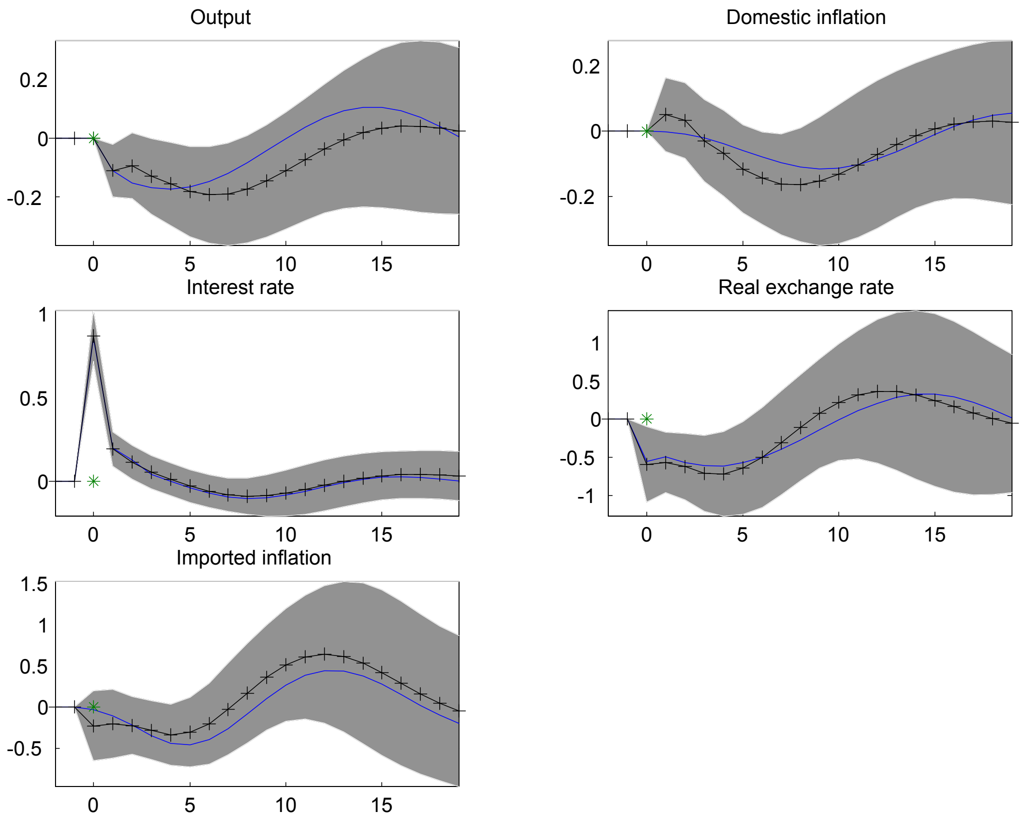

Figure 3: Sensitivity analysis: restrictions on the foreign exchange premium. VAR and model responses to monetary policy shock, baseline model estimated on policy shock only

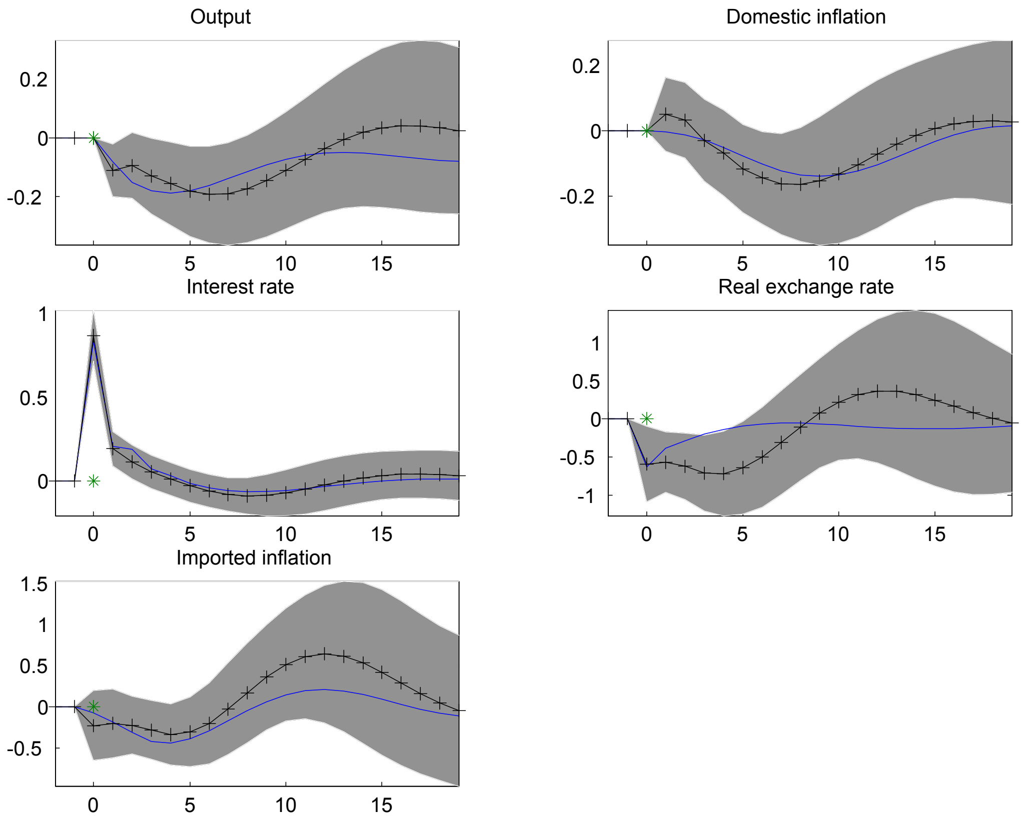

Figure 4: Sensitivity analysis: no habits in consumption. VAR and model responses to monetary policy shock, baseline model estimated on policy shock only

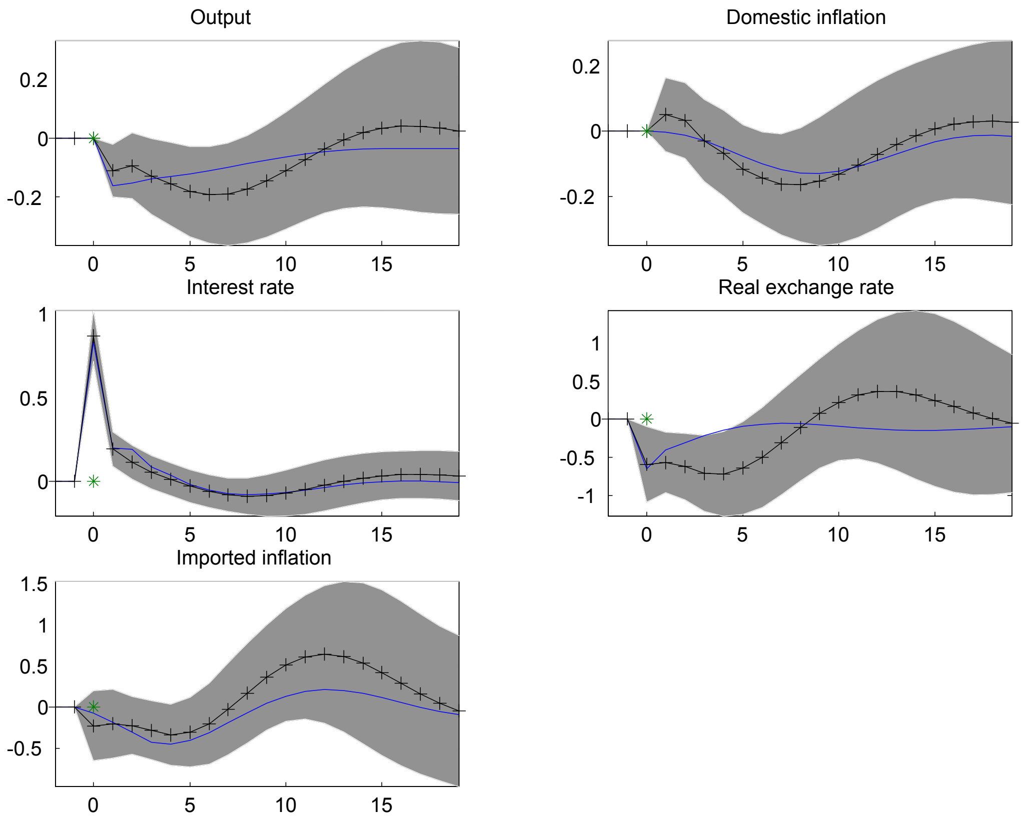

Figure 5: Sensitivity analysis: no backward-looking firms in the domestic sector. VAR and model responses to monetary policy shock, baseline model estimated on policy shock only

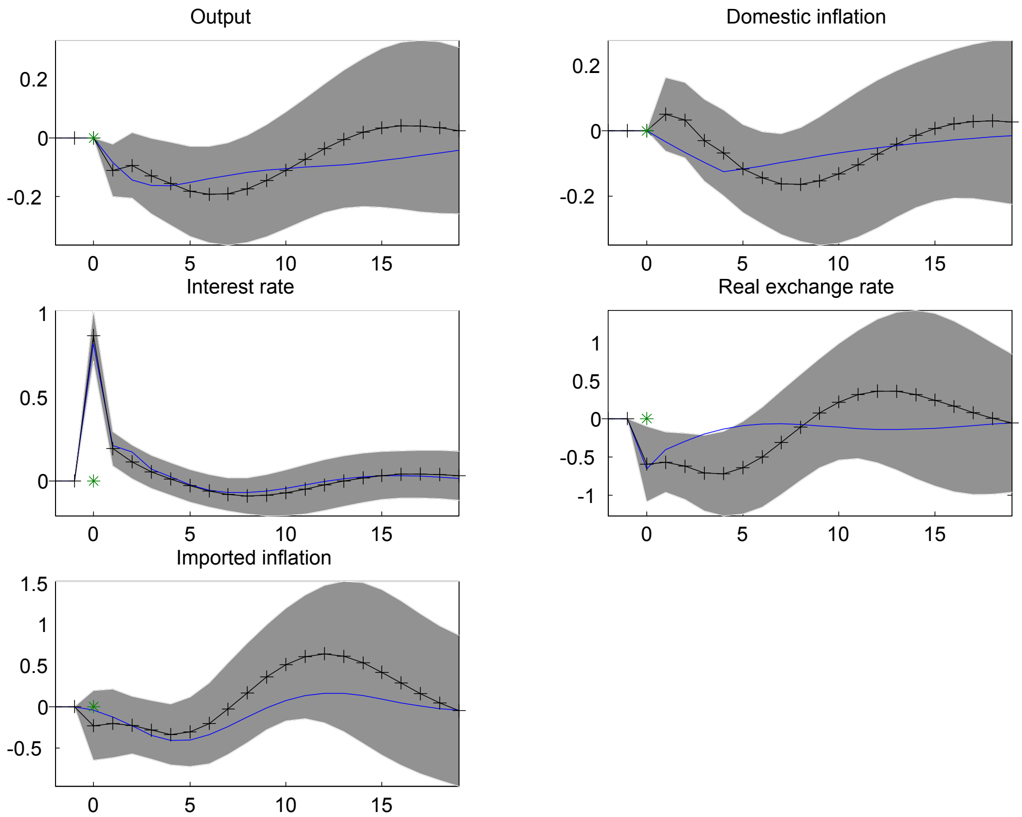

Figure 6: Sensitivity analysis: no backward-looking firms in the import sector. VAR and model responses to monetary policy shock, baseline model estimated on policy shock only

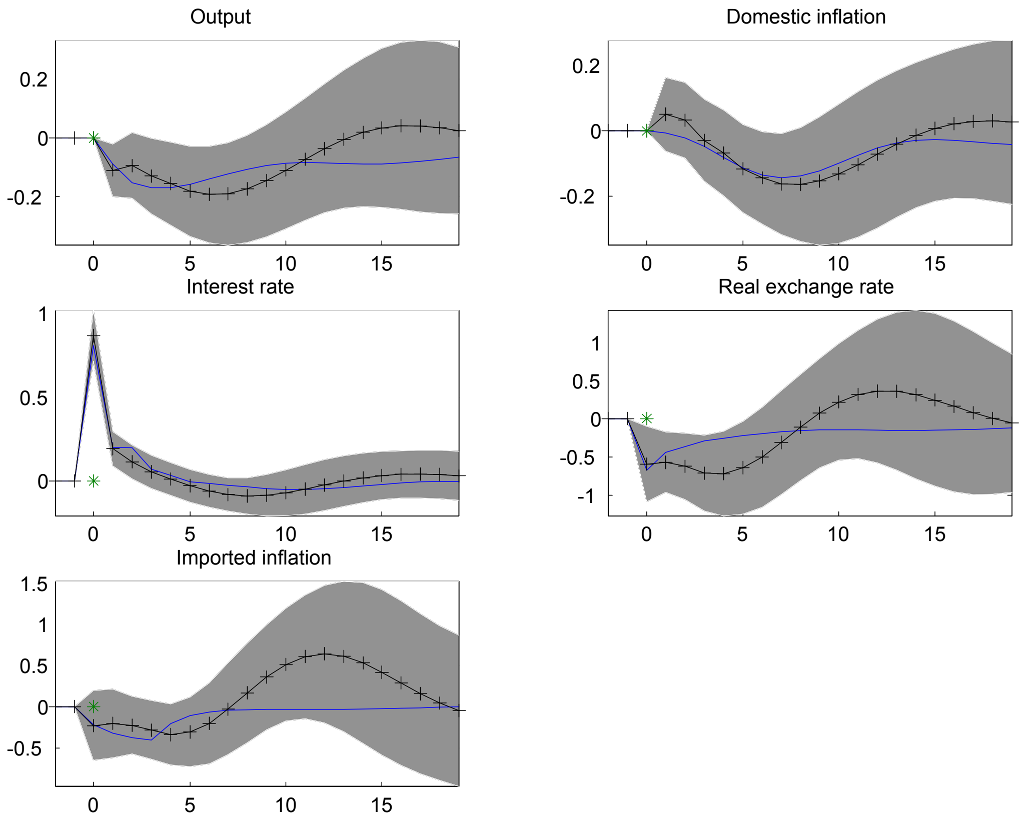

Figure 7: VAR and model responses to monetary policy shock, modified model estimated on policy shock only

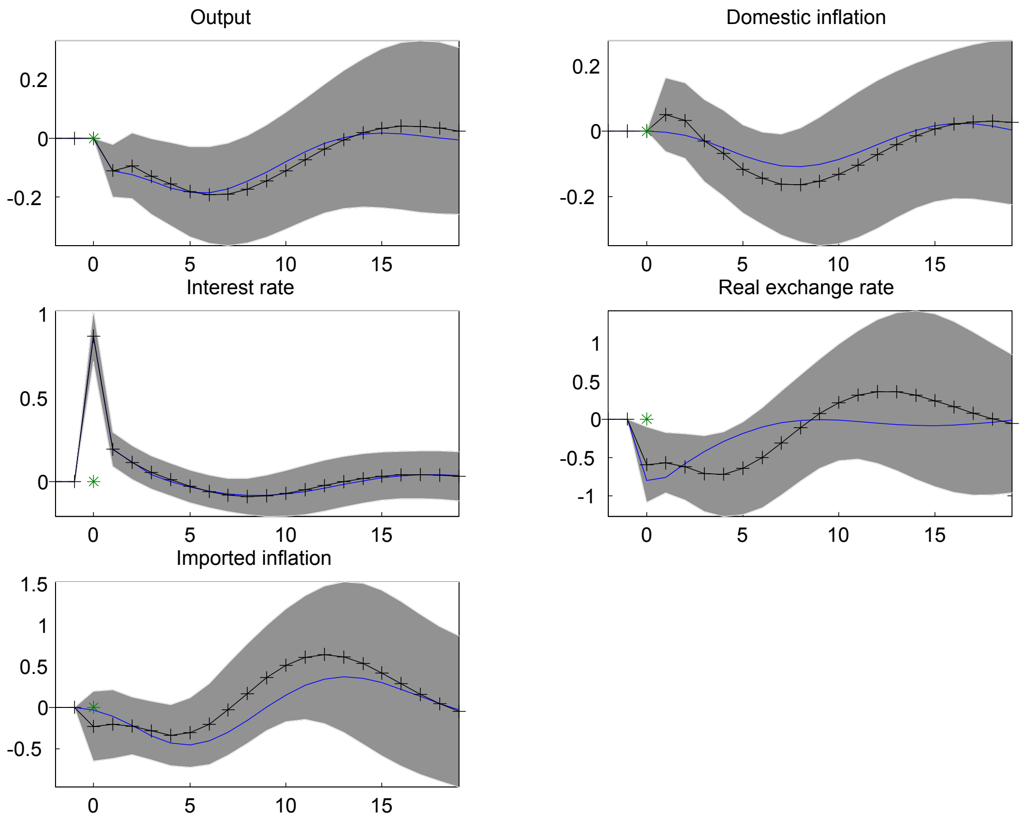

Figure 8: VAR and model responses, modified model estimated on all shocks