Monetary Policy in an Estimated Open-Economy Model with Imperfect Pass-Through*

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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 we find that a modified version of our model (that allows for inertia also in the exchange rate) matches the empirical impulse responses very well.

Keywords: Structural open-economy model, exchange rate pass-through, estimation, calibration.

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1 Introduction

Small-scale structural models with optimizing agents and nominal rigidities have proved very useful as tools to study the effects of monetary policy both in 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, Eichenbaum, and Evans (2001), Ireland (2001), and Smets and Wouters (2002a). At the same time, there are relatively few empirical applications for open economies (exceptions are Ghironi (2000), Bergin (2003), and, to some extent, Bouakez (2002) and Smets and Wouters (2002b)).

For many practical policy issues, it is of course important to obtain quantitative predictions from a reasonably well-specified model. 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 (e.g., 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. Our model is similar to those of Svensson (2000), Adolfson (2001), Galí and Monacelli (2002), and Monacelli (2003). As in Adolfson (2001) and Monacelli (2003), the model allows for gradual exchange rate pass-through, assuming that also import firms face sticky prices. In addition, we introduce inertia in output (originating in 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.

We then move on to estimate the model on Swedish data. In the estimation we follow Christiano, Eichenbaum, and Evans (2001) and Smets and Wouters (2002b) 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.

Our results are encouraging. Although a baseline model does not fully capture the behavior of the exchange rate, a slightly modified version of the model is rather successful in matching the dynamic behavior of all variables in the VAR model. The main problem with the baseline model originates in the rational expectations uncovered interest parity (UIP) condition, which makes the real and nominal exchange rates respond very rapidly to shocks. UIP is well-known to find weak empirical support. As we modify the UIP condition to allow for more gradual behavior of exchange rate expectations (in line with the empirical literature) our model implies a more gradual response of the real exchange rate to shocks, which is more consistent with the data. We conclude that although our model is a very stylized description of a small open economy, it is rather successful in describing the dynamic behavior of the Swedish economy.

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

In this section we lay out the general structure of our theoretical model and present the main equations. The interested reader is referred to Appendix A for details.

We formulate a model of a small open economy with imperfect exchange rate pass-through. 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. Our model also introduces inertia in aggregate demand through habit formation in consumer preferences.

A key feature of our model is the imperfect pass-through of nominal exchange rates changes to the domestic currency price of imported goods. This feature com-

[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.

plicates the notation somewhat and we begin here with a short account of the main prices. 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, i.e., $p_t^m \neq p_t^f + s_t$, 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 prices means that we can identify two different terms of trade in the model. The first is the *domestic terms of trade*, i.e., the relative 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*, defined as

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

i.e., the relative price between the domestically produced good and the imported good on the world market. 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

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

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

[2] Our way of defining the terms of trade accords well with the custom in the recent literature on open-economy models (see, e.g., 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 $p_t^d - p_t^m$, meaning that 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.

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 terms of trade changes on consumer price inflation.

The real exchange rate is defined as the ratio between the domestic and foreign aggregate price levels:

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

where we have used the assumption that the domestic economy plays a negligible role in the world economy. In the case of perfect pass-through we would have $q_t = (1 - \omega_m)\,\tau_t$, implying that terms of trade changes have smaller impact on the real exchange rate in a more open economy. This is because as the degree of openness increases, domestic inflation becomes more correlated with world inflation, meaning that the real exchange rate will vary less. Having gone through some simple definitions we now turn to more fundamental aspects of our theoretical model.

2.1 Households

Households obtain utility not only from current and future consumption, but also from current consumption in relation to past consumption. More specifically, household preferences display external habit formation of the "Catching up with the Joneses" type (see Abel (1990) or Smets and Wouters (2002a)). Thus household i's utility depends on consumption C_t^i relative to lagged aggregate consumption C_{t-1} according to

$$u\left(C_t^i\right) = \Upsilon_t \frac{\left(C_t^i - hC_{t-1}\right)^{1-\sigma}}{1-\sigma}, \tag{2.7}$$

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

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

where C_t^d and C_t^m are consumption of the domestic and imported good, respectively, ω_m is the share of imports in consumption, and η is the elasticity of substitution across goods. By assumption, $\eta > 1$.

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

$$\max_{C_t^i, B_t^i, B_t^{if}} \mathrm{E}_t \sum_{s=0}^{\infty} \beta^s u\left(C_{t+s}^i\right), \tag{2.9}$$

subject to the flow budget constraint

$$P_t^c C_t^i + (1+i_t)^{-1} B_t^i + \left(1+i_t^f\right)^{-1} S_t B_t^{if} = B_{t-1}^i + S_t B_{t-1}^{if}, \tag{2.10}$$

where B_t^i and B_t^{if} are holdings of one-period nominal bonds denominated in the domestic and foreign currency, respectively; domestic bonds give the return i_t and foreign bonds give the return i_t^f; S_t is the nominal exchange rate (the domestic currency price of foreign currency); and P_t^c is the aggregate price of consumption goods (i.e., the consumer price index) defined as

$$P_t^c = \left[(1-\omega_m)\left(P_t^d\right)^{1-\eta} + \omega_m \left(P_t^m\right)^{1-\eta}\right]^{1/(1-\eta)}. \tag{2.11}$$

The household's maximization problem yields the consumption Euler equation

$$1 = \beta(1+i_t)\mathrm{E}_t\left[\frac{\Upsilon_{t+1}}{\Upsilon_t}\left(\frac{C_{t+1}^i - hC_t}{C_t^i - hC_{t-1}}\right)^{-\sigma}\frac{P_t^c}{P_{t+1}^c}\right], \tag{2.12}$$

and the UIP condition

$$\frac{1+i_t}{1+i_t^f} = \frac{\mathrm{E}_t S_{t+1}}{S_t}. \tag{2.13}$$

Optimal intratemporal allocation is given by

$$C_t^d = (1-\omega_m)\left[\frac{P_t^d}{P_t^c}\right]^{-\eta} C_t, \tag{2.14}$$

$$C_t^m = \omega_m \left[\frac{P_t^m}{P_t^c}\right]^{-\eta} C_t. \tag{2.15}$$

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, foreign demand for the domestic good is given by

$$C_t^{df} = \left[\frac{P_t^d / S_t}{P_t^f} \right]^{-\eta} C_t^f, \tag{2.16}$$

where both the numerator and the denominator are in units of foreign currency and where the foreign elasticity of substitution η is assumed to be the same as in the domestic economy.

Log-linearizing the model around its steady state (see Appendix A for details) gives the following expression for the output gap (the log deviation of aggregate output from steady state):

$$\begin{aligned} y_t &= (1-a_y)\, y_{t-1} + a_y \mathrm{E}_t y_{t+1} + a_r \left[i_t - \mathrm{E}_t \pi_{t+1}^d \right] + a_{\tau 1} \tau_{t-1} + a_{\tau 2} \tau_t \\ &\quad + a_{\tau_3} \mathrm{E}_t \tau_{t+1} + a_{\tau f1} \tau_{t-1}^f + a_{\tau f2} \tau_t^f + a_{\tau f3} \mathrm{E}_t \tau_{t+1}^f + a_{yf1} y_{t-1}^f + a_{yf2} y_t^f \\ &\quad + a_{yf3} \mathrm{E}_t y_{t+1}^f + u_t^y, \end{aligned} \tag{2.17}$$

where lower case letters denote log deviation from steady state, the parameters are

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

and the demand shock u_t^y is given by

$$u_t^y = \frac{(1-h)(1-\omega_x)}{(1+h)\sigma} \left[\upsilon_t - \mathrm{E}_t \upsilon_{t+1} \right], \tag{2.18}$$

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 is similar to Svensson (2000), and the closed-economy version of (2.17) without habit formation is given by the standard expression

$$y_t = \mathrm{E}_t y_{t+1} - \sigma^{-1} \left[i_t - \mathrm{E}_t \pi_{t+1} \right] + \sigma^{-1} \left[\upsilon_t - \mathrm{E}_t \upsilon_{t+1} \right]. \tag{2.19}$$

2.2 Firms

Our model has two sets of firms. As in Smets and Wouters (2002b), we have a monopolistically competitive *imported goods sector* with sticky prices. Firms in this sector purchase a foreign good at given world prices and turn it into a differentiated import good for domestic consumption and production. Firms in the *domestic sector* produce a differentiated good 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 each period, while the remaining firms follow a simple rule of thumb when resetting their prices, as in Galí and Gertler (1999), Steinsson (2002), and Amato and Laubach (2002).

Beginning with the category of firms that do reoptimize each period, they will adjust prices such that inflation in sector j follows the familiar first-order condition

$$\pi_t^{opt,j} = \beta \mathrm{E}_t \pi_{t+1}^{opt,j} + \frac{1}{\gamma_j}\left(\hat{p}_t^j - p_t^{opt,j}\right), \qquad j = d, m, \tag{2.20}$$

where γ_j is the cost of price adjustment in sector j, $\hat{p}_t^j$ is the price that is optimal under flexible prices, and the superscripts d and m refer to domestic and importing firms, respectively. (Again, see Appendix A for details.) For the domestic firm the optimal flexible price is given by

$$\hat{p}_t^d = (1-\kappa)p_t^d + \kappa p_t^m + \frac{\theta}{1-\theta} y_t, \tag{2.21}$$

where κ is the share of imported goods in inputs and θ is a technology parameter that determines the returns to scale in domestic production ($\theta = 1$ implies constant returns to scale). For the importing firm the optimal flexible price is

$$\hat{p}_t^m = p_t^f + s_t. \tag{2.22}$$

The first two terms in the optimal domestic flexible price in (2.21) reflects input costs, and the third term reflects demand pressure. The optimal flexible price in the import sector is simply the foreign currency price converted into domestic currency at the prevailing nominal exchange rate.

In 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:

$$p_t^{rule,j} = p_{t-1}^j + \pi_{t-1}^j, \qquad j = d, m. \tag{2.23}$$

The aggregate rate of inflation is then given by

$$\pi_t^j = (1-\alpha_j)\pi_t^{opt,j} + \alpha_j \pi_t^{rule,j}, \qquad j = d, m. \tag{2.24}$$

Combining the above and solving for the inflation rate in the domestic and imported sectors, we obtain (after adding aggregate supply, or cost-push, shocks)

$$\begin{aligned} \pi_t^d &= b_{\pi 1}\mathrm{E}_t\pi_{t+1}^d + b_{\pi 2}\pi_{t-1}^d + b_{\pi 3}\pi_{t-2}^d + b_y y_t + b_\tau \tau_t + u_t^d, & (2.25)\\ \pi_t^m &= c_{\pi 1}\mathrm{E}_t\pi_{t+1}^m + c_{\pi 2}\pi_{t-1}^m + c_{\pi 3}\pi_{t-2}^m + c_\tau\left[\tau_t + \tau_t^f\right] + u_t^m, & (2.26)\end{aligned}$$

where

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

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. Without rule-of-thumb price setters (setting $\alpha_d = \alpha_m = 0$), we obtain the same expressions as Adolfson (2001), and in the closed-economy case without rule-of-thumbers we obtain the usual New-Keynesian Phillips curve

$$\pi_t^d = \beta\mathrm{E}_t\pi_{t+1}^d + \frac{\theta}{\gamma_d(1-\theta)}y_t. \tag{2.27}$$

2.3 The foreign economy, exogenous shocks and monetary policy

We are primarily interested in the workings of the small open economy, and therefore we find it sufficient to 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

$$y_t^f = a_y^f(L)y_{t-1}^f + b_y^f(L)\pi_{t-1}^f + c_y^f(L)i_{t-1}^f + \varepsilon_t^{yf}, \tag{2.28}$$
$$\pi_t^f = a_\pi^f(L)y_{t-1}^f + b_\pi^f(L)\pi_{t-1}^f + c_\pi^f(L)i_{t-1}^f + \varepsilon_t^{\pi f}, \tag{2.29}$$
$$i_t^f = a_i^f(L)y_t^f + b_i^f(L)\pi_t^f + c_i^f(L)i_{t-1}^f + \varepsilon_t^{if}, \tag{2.30}$$

where the lag length 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 monetary policy:

$$i_t = f z_t, \tag{2.31}$$

where z_t is a vector of relevant variables, including a monetary policy shock.

Finally, in the general case we allow for first-order serial correlation in all four shocks:

$$u_{t+1}^j = \rho_j u_t^j + \varepsilon_{t+1}^j, \qquad j = y, d, m, i, \tag{2.32}$$

where u_t^y is the shock to aggregate demand, u_t^d is the domestic cost-push shock, u_t^m is the cost-push shock for imported goods, and u_t^i is the monetary policy shock. 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 (2.17), domestic and imported inflation in equations (2.25) and (2.26), the consumer price index in equation (2.4), the real exchange rate in equation (2.6), the domestic and foreign terms of trade in equations (2.1) and (2.2) and the deviation from the law of one price in equation (2.3), the three equations (2.28)-(2.30) describing the foreign sector, the shocks in (2.32), monetary policy in equation (2.31) and a log-linearized version of the UIP condition in (2.13), i.e.,

$$s_t = \mathrm{E}_t s_{t+1} + i_t^f - i_t. \tag{2.33}$$

To solve the model, we use the "AIM" algorithm developed by Anderson and Moore (1985).

3 Estimation methodology

To parameterize the model, we match the theoretical impulse responses to those obtained from a VAR model estimated on Swedish data. In this section we first describe the VAR model and the identifying assumptions that we impose in order to identify three shocks: a monetary policy shock, an "aggregate demand" shock, and an "aggregate supply" (or "cost-push") shock. We then discuss our methodology for estimating the model.

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.[3] The reduced-form VAR model is specified according to

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

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 the third quarter in 1992 is included to capture the exceptionally high interest rates enforced in order to defend the fixed exchange rate. 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 equivalence prior to June 1994); q_t is the average real trade-weighted exchange rate; π_t^m is the inflation rate for imported goods (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 (i.e., first differences),

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

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.[4]

To identify the aggregate demand and aggregate supply shocks in the data, 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. To identify the monetary policy shock we impose the "recursiveness assumption" that has become standard in the closed economy literature (see, e.g., Christiano, Eichenbaum, and Evans (1999), (2001) and Angeloni, Kashyap, Mojon, and Terlizzese (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 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

$$i_t = g_1(L) X_{1,t} + g_2(L) X_{2,t-1} + g_3(L) i_{t-1} + g_4(L) Z_t + \varepsilon_t^i, \tag{3.4}$$

where $X_{1,t}$ consists of y_t and π_t^d, $X_{2,t}$ consists of q_t and π_t^m, and ε_t^i is the monetary policy shock which is orthogonal to the information set in (3.4). To ensure that these identifying assumptions are consistent with the theoretical model, we need to make similar assumption for the theoretical model, see 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

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

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

[4] 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 are robust to these alternative specifications.

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 column implies that aggregate demand shocks affect all variables contemporaneously except inflation on domestic goods. When we estimate the structural VAR, we impose the normalization $a_{45} = 0$, otherwise the last two shocks are not identified. But since we are using only the first three shocks in the analysis this has no effect on our results. 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, e.g., Christiano, Eichenbaum, and Evans (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. The effects on imported inflation are similar to those on the real exchange rate. 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 rather than 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.[5] The three identified shocks account for roughly

[5] The variance decompositions have roughly converged after 20 quarters, so those numbers can

Table 1: Fraction of variance attributed to various 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.

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 (e.g., Altig, Christiano, Eichenbaum, and Lindé (2002)), shocks to monetary policy contribute to only a small fraction of the fluctuations in other variables.[6]

3.2 The methodology

When estimating 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, Eichenbaum, and Evans (2001) and Smets and Wouters (2002b). 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.

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 aggregate demand (the output gap) are not affected contemporaneously by shocks to the other variable, nor by

also be interpreted as the long-run fraction of variability due to different shocks.

[6] 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.

Table 2: Fixed parameters

Parameter	Value
κ	0.86
ω_m	0.33
ω_x	0.36
β	0.99

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 empirical VAR (in Figure 1) and the theoretical model. Let the set of these parameters be defined by

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

where the vector Γ contains the parameters in the monetary policy rule (3.4). Next, let $\Phi(\xi)$ denote the mapping from the parameter vector ξ to the vector of model impulse responses, and $\hat{\Phi}$ the vector of impulse responses from the VAR. The estimator for ξ is then given by

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

where V is a diagonal matrix with the sample variances of $\hat{\Phi}$ on the diagonal. 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 parameters in the theoretical model, 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 parameters estimated in the VAR.

4 Results

4.1 The baseline model

The results from estimating the model to match the only impulse responses to a policy shock are displayed in Figure 2. Each panel shows the impulse response in the theoretical model (the grey solid line) along with those from the VAR model (the dark crossed line) and the 95% confidence interval.

The results are mixed. The theoretical model is very successful in matching the response of domestic inflation and the interest rate, and also the initial decline in imported inflation. However, the preferred parameterization implies that the output gap is completely unresponsive to the policy shock, and the real exchange rate is much less persistent than in the data.

It seems that the movements in the interest rate and the real exchange rate are not sufficient to create the negative values of the output gap seen in the VAR model. Partly this is because both the interest rate and the real exchange rate revert relatively quickly to their steady-state values after the initial impulse. Instead the model chooses to match the initial increase in domestic inflation, yielding a zero response in the output gap.

4.2 A modified model

It is of course difficult to identify the exact features of the model that are responsible for this failure to match the data. Given the behavior of the real exchange rate in Figure 2, however, one likely explanation is the UIP condition. In its pure form UIP implies that the exchange rate is an extremely forward-looking variable that jumps in response to all shocks in the model. With sticky prices this behavior is reflected in the real exchange rate, which jumps after the policy shock and then quickly reverts to the steady-state level. Such a behavior is in stark contrast to the response in the VAR model, which is rather slow and persistent.

The empirical failure of UIP is a well-known fact (see, e.g., Froot and Thaler (1990)) and several alternative specifications of the UIP condition have been suggested. One avenue is to introduce endogenous movements in a foreign exchange risk premium, which then would vary in response to shocks to other variables. An alternative is to introduce inertia in exchange rate expectations, moving away from the assumption of rational expectations.

Several studies reject the hypothesis that exchange rate expectations are rational, e.g., MacDonald (1990), Cavaglia, Verschoor, and Wolff (1993), Ito (1990) and Froot and Frankel (1989). We therefore choose to introduce inertia in exchange rate expectations by specifying a more general model that allows for both rational expectations and more backward-looking expectation formation mechanisms that have been suggested in the literature.[7]

First, under *equilibrium expectations*, the nominal exchange rate is expected to revert to its long-run fundamental value:

$$\hat{\mathrm{E}}_t^e s_{t+1} = (1 - \zeta_e) s_t + \zeta_e s_t^*, \tag{4.1}$$

where s_t^* is the long-run equilibrium rate (defined by $q_t^* = 0$), given by $s_t^* = p_t^c - p_t^f = s_t - q_t$. Thus, when the real exchange rate is weak (so $q_t > 0$), $s_t^* < s_t$, so the nominal exchange rate is expected to appreciate (and vice versa). Second, under *distributed-lag expectations*, observed exchange rate movements are expected to be reversed:

$$\hat{\mathrm{E}}_t^d s_{t+1} = (1 - \zeta_d) s_t + \zeta_d s_{t-1}, \tag{4.2}$$

and third, with *chartists*, observed exchange rate movements are extrapolated into the future:

$$\hat{\mathrm{E}}_t^c s_{t+1} = (1 + \zeta_c) s_t - \zeta_c s_{t-1}. \tag{4.3}$$

Thus, chartist and distributed-lag expectations are special cases of the more general process

$$\hat{\mathrm{E}}_t^{cd} s_{t+1} = (1 + \zeta_{cd}) s_t - \zeta_{cd} s_{t-1}, \tag{4.4}$$

where the parameter ζ_{cd} is positive with chartists and negative with distributed-lag expectations.

We combine these different models of expectation formation into a general process for partially non-rational expectations, written as

$$\hat{\mathrm{E}}_t s_{t+1} = (1 - \mu_e - \mu_{cd}) \mathrm{E}_t s_{t+1} + \mu_e \hat{\mathrm{E}}_t^e s_{t+1} + \mu_{cd} \hat{\mathrm{E}}_t^{cd} s_{t+1}, \tag{4.5}$$

[7] Using survey data, Frankel and Froot (1987) test the validity of alternative expectation formation mechanisms on the foreign exchange market: adaptive expectations, equilibrium (or regressive) expectations, and distributed-lag expectations. Their results indicate that expectations at the 3-month, 6-month and 12-month horizon can be explained by any of the three models.

where $\mu_e, \mu_{cd} \in [0, 1]$ are the weights on equilibrium and chartist/distributed-lag expectations, respectively, and the remaining weight is given to rational expectations. Replacing the rational expectations in the UIP condition (2.33) we get a *modified UIP condition* given by

$$s_t = \hat{\mathrm{E}}_t s_{t+1} + i_t^f - i_t. \tag{4.6}$$

We then let the data determine the parameters μ_e, μ_{cd}, ζ_e, and ζ_{cd}, which are included in the parameter vector ξ to be estimated.

Figure 3 shows the impulse responses from the modified model when matching the response after a monetary policy shock. As before, domestic inflation, imported inflation and the interest rate are all fairly close to the responses from the VAR model. Now, however, also output and the real exchange rate are very close to the empirical responses. To be specific, there is considerable inertia in the real exchange rate response: instead of immediately moving back towards the steady state after an initial jump, the real exchange rate remains relatively strong for several quarters before depreciating back to the steady state. This response is very much in line with the dynamic behavior of the real exchange rate in the data. Allowing for more exchange rate inertia also has a strong impact on the output gap, which now falls for several periods before gradually moving back to steady state, yielding a hump-shaped response that is very similar to the VAR response. The results when using the modified UIP condition are thus considerably more favorable than when using the standard UIP condition, and the modified model captures very well the dynamic behavior of all variables in the VAR.

The obtained parameter estimates can be seen in the first column in Table 3. Beginning with the structural parameters in the top panel, we first note that the parameters σ (which is related to the elasticity of intertemporal substitution) and η (the elasticity of substitution across goods) tend to take on corner values. We therefore fix an upper bound of $\theta = 10$ and a lower bound of $\eta = 3$ (implying a steady-state markup of 50 percent), which we feel are reasonable bounds. From Table 3 we see that habit formation is important in the model ($h = 0.88$), yielding substantial inertia in the output gap, as seen in Figure 3. Domestic prices are very sticky ($\gamma_d = 153$), while import prices are much less sticky ($\gamma_m = 4.25$). In both the domestic and imported sectors there is a large fraction of rule-of-thumbers ($\alpha_d = 0.79$, $\alpha_m = 0.91$), giving rise to additional inertia in both domestic and imported inflation (again, see Figure 3).

The parameters in the exchange rate expectation formation mechanism imply

Table 3: Parameter estimates

	Policy shock	All shocks
Structural parameters		
h	0.86	0.96
σ	10.00	10.00
η	3.00	3.00
θ	0.66	0.81
γ_d	152.65	150.64
α_d	0.79	0.00
γ_m	4.25	12.87
α_m	0.91	0.86
Expectations parameters		
μ_e	0.43	0.00
μ_{cd}	0.57	0.97
ζ_e	0.18	0.00
ζ_{cd}	−0.39	−0.50
Shock parameters		
σ_i	0.89	0.85
ρ_y		0.00
σ_y		0.65
ρ_d		0.00
σ_d		0.97

that the weight on rational expectations is essentially zero, and the weights on equilibrium and chartist/distributed-lag expectations are roughly fifty-fifty. The chartist/distributed-lag parameter is negative ($\zeta_{cd} = -0.50$), so the model prefers distributed-lag expectations to chartists. Finally, the rate of updating of equilibrium expectations is fairly slow ($\zeta_e = 0.18$). These expectations parameters together imply that the expected nominal exchange rate follows

$$\begin{aligned} \hat{\mathrm{E}}_t s_{t+1} &= 0.43\,[0.82 s_t + 0.18 s_t^*] + 0.57\,[0.61 s_t + 0.39 s_{t-1}] \\ &= 0.70 s_t + 0.077 s_t^* + 0.222 s_{t-1}, \end{aligned} \tag{4.7}$$

so expectations are mainly a mixture of random walk expectations and backward-looking expectations, with a small component related to the equilibrium exchange rate.

There are very few papers that have tried to estimate similar open-economy models. Smets and Wouters (2002b) use a similar methodology to estimate the parameters in the equations for domestic and imported inflation in the euro area for the period 1977–1999. However, they take the responses of the other variables in their VAR (output, the real exchange rate, and net exports) as given, and therefore do not match the behavior of the real exchange rate. Although it is difficult to directly translate their results to our model, they obtain less price stickiness and inflation inertia in the domestic sector than we do, and a similar degree of price stickiness but a smaller degree of inertia in the import sector.

4.3 Matching all three shocks

We now 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.[8] 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 Figures 4–6, and the parameter values are presented in the second column of Table 3. The main difference when comparing the response to a policy shock in Figures 3 and 4 lies in the behavior of domestic inflation, which is somewhat less persistent when matching the response to all shocks. This is also clear from Table 3: the fraction of rule-of-thumbers in domestic price-setting (α_d) is zero when matching the response to all shocks, while it is 0.87 when matching only the response to the policy shock. The reason for this lies in the estimated response of domestic inflation to an aggregate supply shock, which is not very persistent in the VAR (see Figure 6). Thus, we obtain a smaller degree of inertia in domestic inflation when matching also the response to the aggregate demand and the aggregate supply shocks.

For the other parameters the differences in estimates are less significant. Import prices are slightly more sticky ($\gamma_m = 12.87$) and in exchange rate expectations the weight has shifted from equilibrium expectations to distributed-lag expectations. This shift has only minor consequences for exchange rate expectations: now these

[8] The results when matching the baseline model to match all three shocks are similar to those when matching only the policy shock, again due to the UIP condition.

are given by

$$\begin{aligned}\hat{\mathrm{E}}_t s_{t+1} &= 0.03\mathrm{E}_t s_{t+1} + 0.97\,[0.50 s_t + 0.50 s_{t-1}] \\ &= 0.03\mathrm{E}_t s_{t+1} + 0.485 s_t + 0.485 s_{t-1}, \end{aligned} \tag{4.8}$$

with a very small weight on rational expectations and a larger weight on the lagged exchange rate than before.

We conclude that our modified model is fairly successful in matching the dynamic behavior of the economy also after aggregate demand and aggregate supply shocks. Although it does not entirely capture the behavior of the real exchange rate and imported inflation after an aggregate demand shock or aggregate supply shock (see Figures 5 and 6), the model responses are almost everywhere inside the 95 percent confidence intervals around the VAR responses.

Thus, although our model is highly stylized and therfore excludes several potentially important mechanisms, it is very successful in reproducing the time-series behavior of the Swedish economy, as long as we introduce inertia in exchange rate expectations.

5 Concluding remarks

In this paper we formulate a small open-economy model with gradual exchange rate pass-through and endogenous inertia in domestic and imported inflation and output, extending the model of Adolfson (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. We document that in order for the model to reproduce the effects of a policy shock in the data, the uncovered interest parity (UIP) condition needs to be modified to allow for inertia in exchange rate expectations. This modification is consistent with the empirical evidence on expectation formation in foreign exchange markets. Importantly, the modified UIP condition improves the fit of the theoretical model not only for the exchange rate but also for other variables in the system, in particular for the output gap. The theoretical motivation for such inertia in exchange rate expectations is not obvious, however, and is left to future research.

We further demonstrate that parameters similar to those that enable the modified model to reproduce the dynamic effects of the policy shock are also able to replicate the effects of an aggregate demand and aggregate supply shock. Although the identifying assumptions for these shocks are less standard than for the policy shock, our results are encouraging and an additional indication that the version of UIP without inertia has problems in matching high degree of exchange rate persistence that seems to be a pervasive feature of the data.

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, perhaps with Bayesian methods as Smets and Wouters (2002a). 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 derives some important equations and presents the log-linearized version of the model.

A.1 Price-setting

Below we will assume that firms face a quadratic cost of price adjustment, following Rotemberg (1982), and minimize the log deviation of their price from the optimal flexible price. First, however, we need to derive the optimal flexible prices on domestically produced goods and imported goods.

A.1.1 Domestically produced goods

Domestic firms produce a differentiated good Y_t from intermediate domestic and imported inputs (Z_t^d, Z_t^m) using the production function

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

where κ is the share of imports in intermediate inputs. The aggregate (cost-minimizing) price of inputs, P_t^z, is given by

$$P_t^z = \frac{\left(P_t^d \right)^{1-\kappa} \left(P_t^m \right)^{\kappa}}{(1-\kappa)^{1-\kappa} \kappa^{\kappa}}. \tag{A.2}$$

Under flexible prices (denoted $\hat{P}_t^d$ etc.), firms choose prices for the domestic and foreign markets to maximize profits:

$$\max_{\hat{P}^d, \hat{P}^{df}} \hat{P}_t^d C_t^d + S_t \hat{P}_t^{df} C_t^{df} - P_t^z Z_t \tag{A.3}$$

subject to the production function (A.1) and the demand functions (2.14) and (2.16):

$$\begin{aligned} Y_t &= Z_t^{1-\theta} \\ &\geq C_t^d + C_t^{df} \\ &= (1-\omega_m) \left[\frac{\hat{P}_t^d}{\hat{P}_t^c} \right]^{-\eta} C_t + \left[\frac{\hat{P}_t^{df}}{\hat{P}_t^f} \right]^{-\eta} C_t^f, \end{aligned} \tag{A.4}$$

where the elasticity of substitution η is assumed to be the same at home and abroad.

Substituting the demand functions and the inverted production function (assuming that the constraint is satisfied with equality) gives the maximization problem

$$\begin{aligned}\max_{\hat{P}_t^d,\hat{P}_t^{df}} \quad & (1-\omega_m)\left[\frac{\hat{P}_t^d}{\hat{P}_t^c}\right]^{-\eta} C_t\hat{P}_t^d + \left[\frac{\hat{P}_t^{df}}{\hat{P}_t^f}\right]^{-\eta} C_t^f S_t\hat{P}_t^{df} \\ & -P_t^z\left\{(1-\omega_m)\left[\frac{\hat{P}_t^d}{\hat{P}_t^c}\right]^{-\eta} C_t + \left[\frac{\hat{P}_t^{df}}{\hat{P}_t^f}\right]^{-\eta} C_t^f\right\}^{1/(1-\theta)}. \end{aligned} \tag{A.5}$$

The first-order conditions are

$$0 = (1-\eta)(1-\omega_m)\left[\frac{\hat{P}_t^d}{\hat{P}_t^c}\right]^{-\eta} C_t + \frac{\eta(1-\omega_m)}{1-\theta}\left[\frac{\hat{P}_t^d}{\hat{P}_t^c}\right]^{-\eta}\frac{P_t^z}{\hat{P}_t^d}C_tY_t^{\theta/(1-\theta)}, \tag{A.6}$$

$$0 = (1-\eta)\left[\frac{\hat{P}_t^{df}}{\hat{P}_t^f}\right]^{-\eta} S_tC_t^f + \frac{\eta}{1-\theta}\left[\frac{\hat{P}_t^{df}}{\hat{P}_t^f}\right]^{-\eta}\frac{P_t^z}{\hat{P}_t^{df}}C_t^fY_t^{\theta/(1-\theta)}, \tag{A.7}$$

and rearranging gives

$$\hat{P}_t^d = \frac{\eta}{\eta-1}\frac{1}{1-\theta}P_t^zY_t^{\theta/(1-\theta)}, \tag{A.8}$$

$$\hat{P}_t^{df} = \frac{\eta}{\eta-1}\frac{1}{S_t}\frac{1}{1-\theta}P_t^zY_t^{\theta/(1-\theta)}. \tag{A.9}$$

Thus, the optimal flexible prices are a markup $\eta/(\eta-1)$ on marginal cost, given by $(1-\theta)^{-1}P_t^zY_t^{\theta/(1-\theta)}$, and is adjusted for the exchange rate S_t in the case of export goods.

A.1.2 Imported goods

Import firms maximize

$$\max_{\hat{P}^m,\hat{P}^{mf}} \hat{P}_t^mC_t^m + S_t\hat{P}_t^{mf}C_t^{mf} - g\left(C_t^m + C_t^{mf}, P_t^{zf}\right) \tag{A.10}$$

subject to the demand functions

$$C_t^m = \omega_m\left[\frac{\hat{P}_t^m}{P_t^c}\right]^{-\eta} C_t \tag{A.11}$$

$$C_t^{mf} = \left[\frac{\hat{P}_t^m}{S_tP_t^f}\right]^{-\eta} C_t^f, \tag{A.12}$$

and the cost function $g(\cdot)$. In parallel with the optimal domestic flex-price this yields

$$\begin{aligned}\hat{P}_t^m &= \frac{\eta}{\eta-1}g'(\cdot)S_t \\ &= \hat{P}_t^f S_t. \end{aligned} \tag{A.13}$$

Because the import firm faces the same demand elasticity in both markets, there is no reason to deviate from the law of one price under flexible prices. Thus, the optimal flexible price is equal to the price charged in the foreign market adjusted for the exchange rate.

A.2 The log-linearization

To log-linearize the model around its steady state, let $\bar{X}$ denote the steady state value of a variable X_t, and x_t denote the log-deviation from steady state, i.e.,

$$x_t \equiv \log X_t - \log \bar{X}. \tag{A.14}$$

A.2.1 Steady state

First, normalize the steady-state domestic and foreign price levels to $\bar{P}^d = \bar{P}^f = 1$. For the real exchange rate $Q_t \equiv S_t P_t^f / P_t^c$ to be stationary (and thus $\bar{Q} = 1$), we must have $\bar{S} = \bar{P}^c / \bar{P}^f = \bar{P}^c$. From equation (A.13) the steady-state import price level is then given by $\bar{P}^m = \bar{S} = \bar{P}^c$, and from equation (2.11) the CPI level is

$$\left(\bar{P}^c\right)^{1-\eta} = (1-\omega_m) + \omega_m \left(\bar{P}^c\right)^{1-\eta}. \tag{A.15}$$

Thus, $\bar{P}^c = \bar{S} = \bar{P}^m = 1$, and the steady-state input price index is (using (A.2))

$$\bar{P}^z = \frac{1}{(1-\kappa)^{1-\kappa}\kappa^\kappa}. \tag{A.16}$$

Equation (A.8) then defines the steady-state level of output by

$$\begin{aligned}\bar{Y}^{\theta/(1-\theta)} &= \frac{(\eta-1)(1-\theta)}{\eta}\frac{\bar{P}^d}{\bar{P}^z} \\ &= \frac{(\eta-1)(1-\theta)(1-\kappa)^{1-\kappa}\kappa^\kappa}{\eta}. \end{aligned} \tag{A.17}$$

Finally, from the consumption Euler equation (2.12) we get $\bar{\beta} = 1/\left(1+\bar{\imath}\right)$.

A.2.2 Aggregate demand

Log-linearizing the Euler equation (2.12) gives

$$\begin{aligned} c_t &= \frac{h}{1+h}c_{t-1} + \frac{1}{1+h}\mathrm{E}_t c_{t+1} - \frac{1-h}{(1+h)\sigma}\left[i_t - \mathrm{E}_t\pi^c_{t+1}\right] \\ &\quad -\frac{1-h}{(1+h)\sigma}\mathrm{E}_t\Delta\upsilon_{t+1}, \end{aligned} \tag{A.18}$$

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

$$\begin{aligned} \pi^c_t &= (1-\omega_m)\pi^d_t + \omega_m\pi^m_t \\ &= \pi^d_t + \omega_m\Delta\tau_t, \end{aligned} \tag{A.19}$$

which is the first difference of the log-linearized CPI from (2.11):

$$\begin{aligned} p^c_t &= (1-\omega_m)p^d_t + \omega_m p^m_t \\ &= p^d_t + \omega_m\tau_t, \end{aligned} \tag{A.20}$$

using (2.1).

Linearizing domestic and foreign demand for domestic goods in (2.14) and (2.16) yields, using (A.20) and (2.2),

$$\begin{aligned} c^d_t &= c_t - \eta\left[p^d_t - p^c_t\right] \\ &= c_t + \eta\omega_m\tau_t, \end{aligned} \tag{A.21}$$

$$\begin{aligned} c^{df}_t &= c^f_t - \eta\left[p^d_t - s_t - p^f_t\right] \\ &= \chi_f y^f_t - \eta\tau^f_t, \end{aligned} \tag{A.22}$$

where χ_f is the income elasticity of foreign consumption.

Aggregate demand for domestic goods is then given by

$$\begin{aligned} y_t &= (1-\omega_x)c^d_t + \omega_x c^{df}_t \\ &= (1-\omega_x)\left[c_t + \eta\omega_m\tau_t\right] + \omega_x\left[\chi_f y^f_t - \eta\tau^f_t\right], \end{aligned} \tag{A.23}$$

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

$$c_t = \frac{1}{1-\omega_x}y_t - \eta\omega_m\tau_t - \frac{\omega_x}{1-\omega_x}\left[\chi_f y^f_t - \eta\tau^f_t\right], \tag{A.24}$$

and using this and (A.19) in the linearized Euler equation (A.18) we get

$$\begin{aligned}
&\frac{1}{1-\omega_x}y_t-\eta\omega_m\tau_t-\frac{\omega_x}{1-\omega_x}\left[\chi_f y_t^f-\eta\tau_t^f\right]\\
=\ &\frac{h}{1+h}\left\{\frac{1}{1-\omega_x}y_{t-1}-\eta\omega_m\tau_{t-1}-\frac{\omega_x}{1-\omega_x}\left[\chi_f y_{t-1}^f-\eta\tau_{t-1}^f\right]\right\}\\
&+\frac{1}{1+h}\left\{\frac{1}{1-\omega_x}\mathrm{E}_t y_{t+1}-\eta\omega_m\mathrm{E}_t\tau_{t+1}-\frac{\omega_x}{1-\omega_x}\left[\chi_f\mathrm{E}_t y_{t+1}^f-\eta\mathrm{E}_t\tau_{t+1}^f\right]\right\}\\
&-\frac{1-h}{(1+h)\sigma}\left[i_t-\mathrm{E}_t\pi_{t+1}^d-\omega_m\mathrm{E}_t\Delta\tau_{t+1}\right]-\frac{1-h}{(1+h)\sigma}\mathrm{E}_t\Delta\upsilon_{t+1}. \qquad \text{(A.25)}
\end{aligned}$$

Solving for y_t and collecting terms then gives

$$\begin{aligned}
y_t\ =\ &(1-a_y)\,y_{t-1}+a_y\mathrm{E}_t y_{t+1}+a_r\left[i_t-\mathrm{E}_t\pi_{t+1}^d\right]+a_{\tau1}\tau_{t-1}\\
&+a_{\tau2}\tau_t+a_{\tau_3}\mathrm{E}_t\tau_{t+1}+a_{\tau f1}\tau_{t-1}^f+a_{\tau f2}\tau_t^f+a_{\tau f3}\mathrm{E}_t\tau_{t+1}^f \qquad \text{(A.26)}\\
&+a_{yf1}y_{t-1}^f+a_{yf2}y_t^f+a_{yf3}\mathrm{E}_t y_{t+1}^f+u_t^y,
\end{aligned}$$

which is equation (2.17).

A.2.3 Aggregate supply

Log-linearizing the expression for the optimal domestic price in (A.8) yields

$$\hat{p}_t^d\ =\ p_t^z+\frac{\theta}{1-\theta}y_t, \qquad \text{(A.27)}$$

and log-linearizing the input price (A.2) yields

$$p_t^z=(1-\kappa)p_t^d+\kappa p_t^m. \qquad \text{(A.28)}$$

Thus, the optimal flexible domestic price is given by

$$\hat{p}_t^d\ =\ (1-\kappa)p_t^d+\kappa p_t^m+\frac{\theta}{1-\theta}y_t, \qquad \text{(A.29)}$$

and the optimal flexible import price is

$$\hat{p}_t^m=p_t^f+s_t. \qquad \text{(A.30)}$$

Firms that optimize their price minimize the expected log deviation of their price from the optimal flexible price given the adjustment cost γ_j:

$$\min_{p_t^{opt,j}} \mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \left\{ \left(p_{t+s}^{opt,j} - \hat{p}_{t+s}^j\right)^2 + \gamma_j \left(p_{t+s}^{opt,j} - p_{t+s-1}^{opt,j}\right)^2 \right\}, \tag{A.31}$$

for $j = d, m$. The first-order condition is

$$\left(p_t^{opt,j} - \hat{p}_t^j\right) + \gamma_j \left(p_t^{opt,j} - p_{t-1}^{opt,j}\right) - \beta\gamma_j \left(\mathrm{E}_t p_{t+1}^{opt,j} - p_t^{opt,j}\right) = 0, \tag{A.32}$$

yielding the inflation rate

$$\pi_t^{opt,j} = \beta \mathrm{E}_t \pi_{t+1}^{opt,j} + \frac{1}{\gamma_j} \left(\hat{p}_t^j - p_t^{opt,j}\right). \tag{A.33}$$

The fraction α_j of firms that does not reoptimize their price instead set their price equal to the observed aggregate price in the previous period, adjusted for the previous inflation rate:

$$p_t^{rule,j} = p_{t-1}^j + \pi_{t-1}^j, \tag{A.34}$$

or

$$\pi_t^{rule,j} = \pi_{t-1}^j + \pi_{t-1}^j - \pi_{t-2}^j. \tag{A.35}$$

The aggregate price level for domestic and imported goods is then given by

$$p_t^j = (1-\alpha_j)p_t^{opt,j} + \alpha_j p_t^{rule,j}, \tag{A.36}$$

and the inflation rate follows

$$\pi_t^j = (1-\alpha_j)\pi_t^{opt,j} + \alpha_j \pi_t^{rule,j}. \tag{A.37}$$

Note that (A.34)–(A.37) imply

$$\begin{aligned} p_t^{opt,j} &= \frac{1}{1-\alpha_j} p_t^j - \frac{\alpha_j}{1-\alpha_j} p_t^{rule,j} \\ &= p_t^j + \frac{\alpha_j}{1-\alpha_j}\left[\pi_t^j - \pi_{t-1}^j\right], \end{aligned} \tag{A.38}$$

$$\begin{aligned} \pi_t^{opt,j} &= \frac{1}{1-\alpha_j} \pi_t^j - \frac{\alpha_j}{1-\alpha_j} \pi_t^{rule,j} \\ &= \frac{1}{1-\alpha_j} \pi_t^j - \frac{\alpha_j}{1-\alpha_j}\left[2\pi_{t-1}^j - \pi_{t-2}^j\right]. \end{aligned} \tag{A.39}$$

Aggregate inflation is then given by

$$
\begin{aligned}
\pi_t^j &= (1-\alpha_j)\pi_t^{opt,j} + \alpha_j \pi_t^{rule,j} \\
&= (1-\alpha_j)\left\{\frac{\beta}{1-\alpha_j}\mathrm{E}_t\pi_{t+1}^j - \frac{\alpha_j\beta}{1-\alpha_j}\left[2\pi_t^j - \pi_{t-1}^j\right]\right\} \\
&\quad + \frac{1-\alpha_j}{\gamma_j}\left\{\hat{p}_t^j - p_t^j - \frac{\alpha_j}{1-\alpha_j}\left[\pi_t^j - \pi_{t-1}^j\right]\right\} \\
&\quad + \alpha_j\left\{2\pi_{t-1}^j - \pi_{t-2}^j\right\}. \qquad \text{(A.40)}
\end{aligned}
$$

Collecting terms, using the optimal flexible prices in (A.29) and (A.30) and the terms-of-trade in (2.1) and (2.2), and adding cost-push shocks, we can write domestic and imported inflation as

$$
\pi_t^d = b_{\pi 1}\mathrm{E}_t\pi_{t+1}^d + b_{\pi 2}\pi_{t-1}^d + b_{\pi 3}\pi_{t-2}^d + b_y y_t + b_\tau \tau_t + u_t^d, \qquad \text{(A.41)}
$$

$$
\pi_t^m = c_{\pi 1}\mathrm{E}_t\pi_{t+1}^m + c_{\pi 2}\pi_{t-1}^m + c_{\pi 3}\pi_{t-2}^m + c_\tau\left[\tau_t + \tau_t^f\right] + u_t^m, \qquad \text{(A.42)}
$$

as in equation (2.25) and (2.26).

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 over 1986–2001 of exports/GDP, current prices. Source: Statistics Sweden.

B.2 Time series

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

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

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

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

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

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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Figure 1: Impulse responses in estimated VAR model

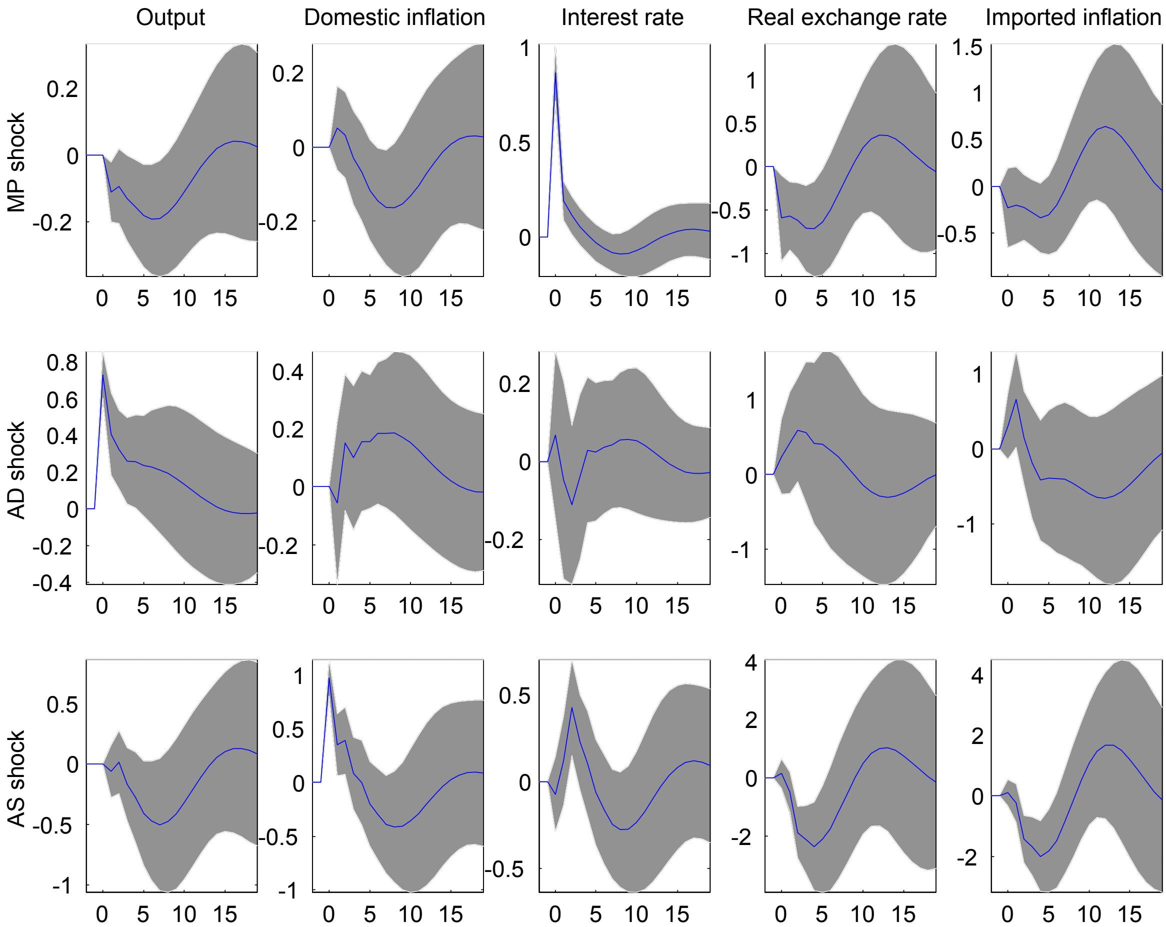

Figure 2: VAR and model responses to monetary policy shock, baseline model estimated on policy shock only

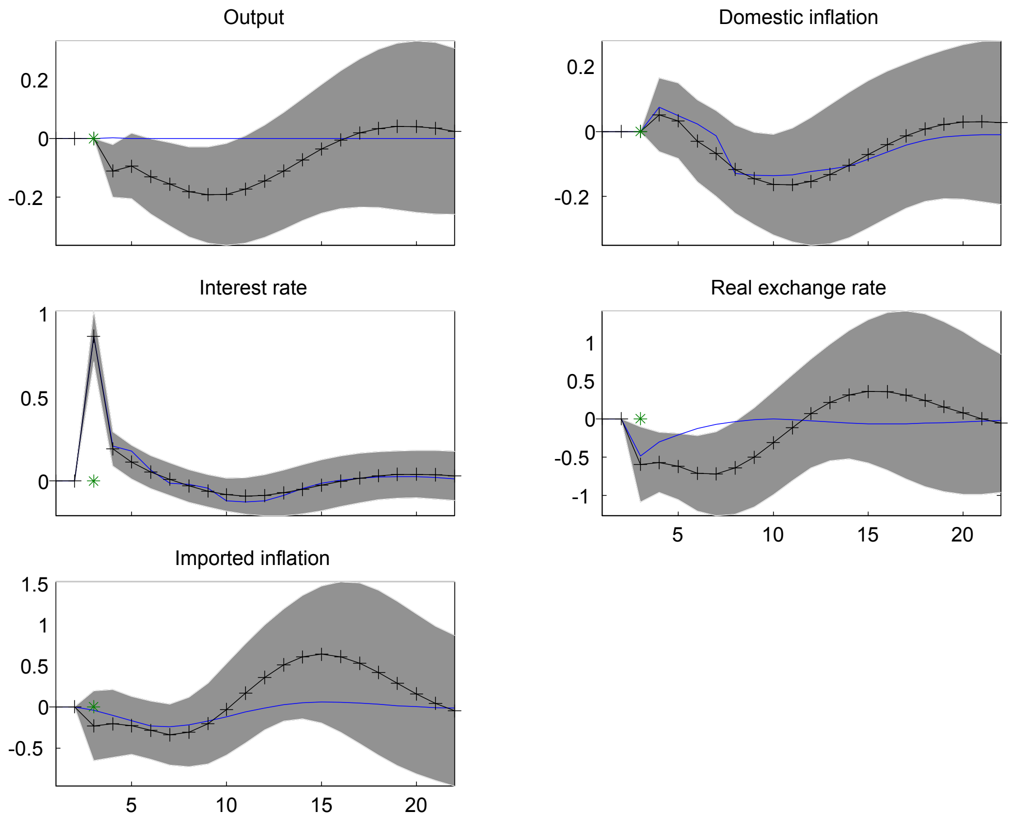

Figure 3: VAR and model responses to monetary policy shock, modified model estimated on policy shock only

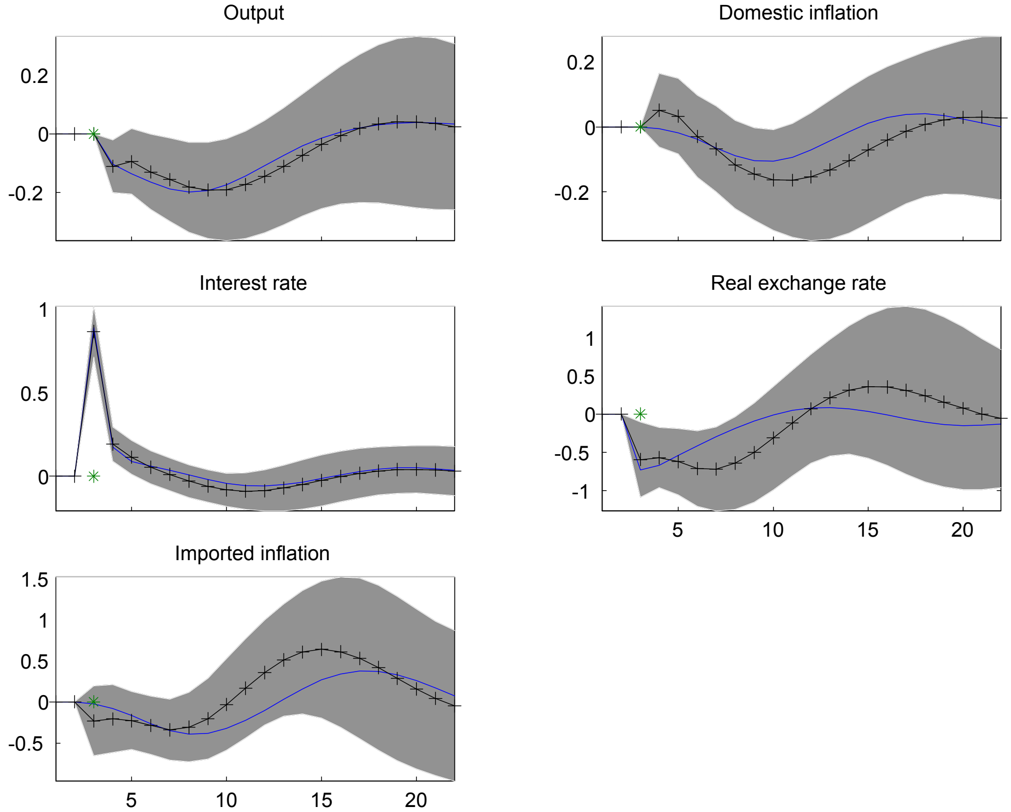

Figure 4: VAR and model responses to monetary policy shock, modified model estimated on all shocks

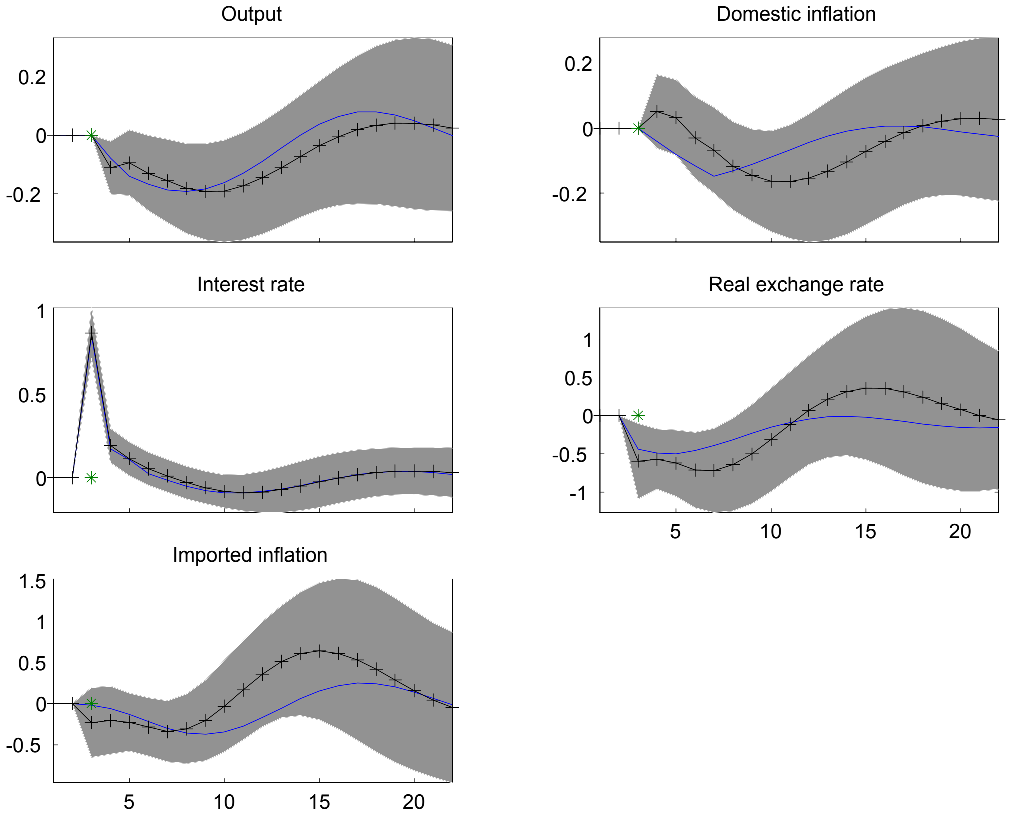

Figure 5: VAR and model responses to aggregate demand shock, modified model estimated on all shocks

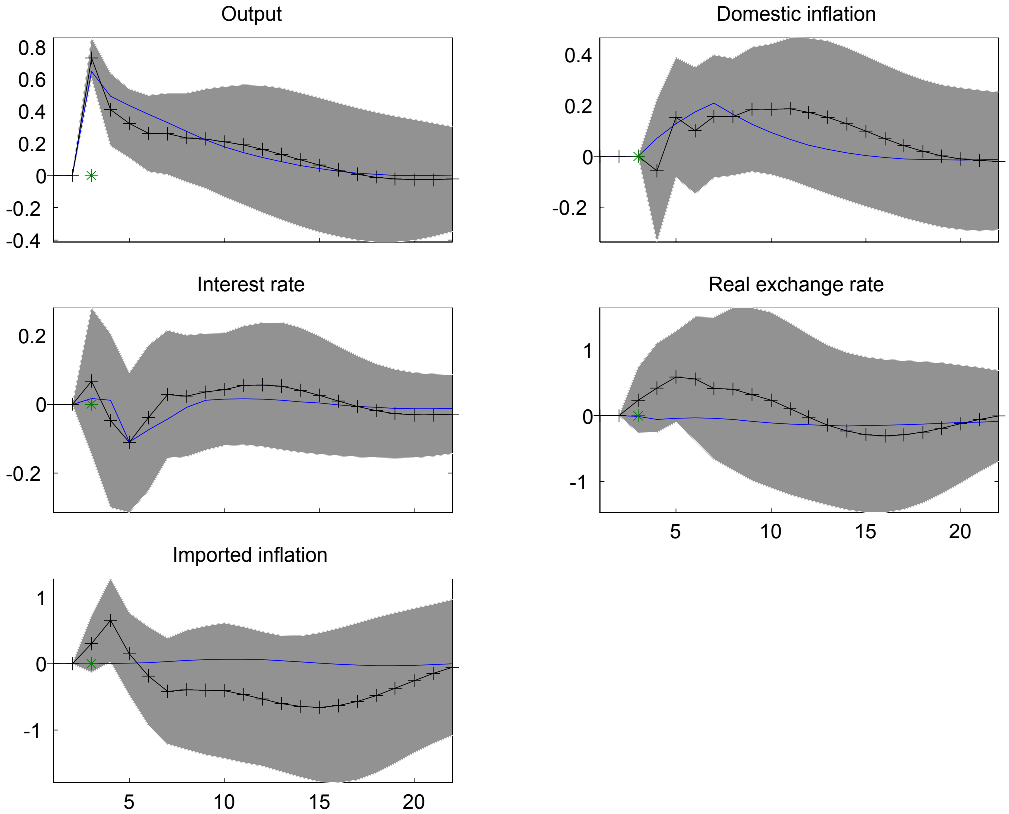

Figure 6: VAR and model responses to aggregate supply shock, modified model estimated on all shocks