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A medium-sized open economy DSGE model of South Africa

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Non-technical summary

Dynamic stochastic general equilibrium (DSGE) models have gained increasing prominence during the past two decades – not only in academic circles, but also in policymaking institutions such as central banks. The literature surrounding these models was birthed in the aftermath of Lucas's (1976) famous critique of the econometric models in use at the time. According to Lucas, these econometric models would fail once any changes in policy occur which alter the nature of the historical macroeconomic relationships on which the model was estimated. In fact, what was needed was a model where the parameters reflect the behavioural aspects of economic agents, such as their tastes and preferences, as these parameters would be policy invariant. Moreover, if these agents were rational and forward-looking, they would correctly anticipate the impact of the policy change and adjust their behaviour accordingly.

DSGE models largely succeeded in addressing the concerns of Lucas. Within these models, the macroeconomic relationships are derived from the microeconomic foundations of agents' intertemporal preferences. Moreover, agents' rational expectations play a central role in determining the macroeconomic outcomes. This theoretical consistency has created a highly credible tool in the hand of the policymaker, and therefore many central banks have adopted DSGE models into their policy analysis and forecasting frameworks.

The small open economy model developed for South Africa in this paper largely follows the lines of existing DSGE models that are operational in central banks. Essentially, the model consists of forward-looking agents which are made up by households, firms and the central bank. Households maximise their expected lifetime utility by consuming goods and supplying labour and capital to firms. In turn, firms produce goods and set their prices such as to maximise expected profits, while the central bank sets the short-term interest rate, based on the level of expected future inflation as well as current output. The rest of the world – or foreign economy – in the model has a similar structure to the domestic economy, but is assumed to be exogenous to developments in the domestic economy.

Model parameters are estimated with Bayesian techniques, and where necessary certain parameters are calibrated – either to pin down a specific long-run steady state value or due to lack of identification. The estimation sample covers the inflation targeting regime of the South African Reserve Bank (2000Q1 to 2012Q4), and includes 15 observable macroeconomic time-series.

DSGE models are well known for their story-telling ability, i.e. it is possible to determine exactly which shocks are driving the outcomes of variables that are of interest to the policymaker. For example, it is found within this model that upward pressure on CPI inflation could often be attributed to labour market and exchange rate risk premium shocks. Similarly, developments in the exchange rate appear to have affected GDP growth – especially during the first few years of the inflation targeting regime. Thereafter, in the immediate quarters following the onset of the global financial crisis, adverse shocks to total factor productivity seem to have reduced the economy's growth potential in excess of 2 percentage points. In addition, further downward pressure on economic growth in the wake of the crisis appears to have emanated from unfavourable labour market conditions – likely reflecting real wage increases that were not justified by gains in productivity at the time.

Apart from story-telling, DSGE models have proven to provide fairly accurate macroeconomic forecasts, especially over the medium to longer term. As a result, they are being widely used in central banks to achieve this end. The model developed in this paper lives up to this expectation. It's forecasting ability up to seven quarters ahead is compared to a random walk and to a consensus of professional forecasters, as surveyed by Reuters. With respect to year-on-year CPI inflation, the DSGE model outperforms the professional forecasters over the 5 to 7 quarter horizon, while it outperforms a random walk over the entire horizon. When forecasting GDP growth (quarter-on-quarter, annualised), a similar result is obtained: the model outperforms the professional forecasters over the outer quarters of the forecast horizon, while it outperforms the random walk over almost the entire horizon. However, when forecasting the Repo rate, the DSGE model fails to outperform the consensus of professional forecasters. Nevertheless, the model's Repo rate forecasts are in general more accurate than those of a random walk. This relative success of DSGE models in forecasting, specifically over longer-term horizons, points to the benefit that is to be had from theoretical consistency of these models in predicting longer-term economic outcomes.

In summary, this paper develops a macroeconomic model for South Africa that is grounded in both micro and macroeconomic theory, adequately captures the role of expectations in determining macroeconomic outcomes, has the ability to inform the policymaker on the various shocks that are contributing to these outcomes, and finally, is a reliable forecasting tool.

A medium-sized open economy DSGE model of South Africa

Stan du Plessis, Ben Smit and Rudi Steinbach*

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Abstract

In this paper a dynamic stochastic general equilibrium (DSGE) model is specified for the South African economy. Nominal and real frictions help to make the model estimable, and is then estimated on South African and global data using Bayesian techniques. The empirical fit of the model is validated through a forecast comparison with private sector consensus forecasts. The model is found to outperform the inflation forecasts of private sector economists.

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1 Introduction

The past two decades have seen the emergence of dynamic stochastic general equilibrium (DSGE) models – a new approach to macroeconometric modelling which has "taken centre stage in academic macroeconomic research" (Del Negro and Schorfheide, 2003). Given their theoretical consistency and inherently forward-looking nature, DSGE models offer a serious alternative to the Cowles Commission tradition of structural simultaneous equation models. In fact, the differences between DSGE models and the Cowles Commission tradition are so fundamental that the development of the DSGE approach has been described as a paradigm shift in macro-econometric modelling, which Fernández-Villaverde (2010) aptly calls the "New Macroeconometrics".

DSGE models are not only confined to academic circles, but are also being developed and used for actual monetary policy analysis and forecasting in many central banks, including the Bank of Canada (Murchison and Rennison, 2006), the Bank of England (Harrison et al., 2005), the Czech National Bank (Andrle et al., 2009), the European Central Bank (Christoffel et al., 2008), the Reserve Bank of New Zealand (Beneš et al., 2009) and the Swedish Riksbank (Adolfson et al., 2007), among others.

A number of DSGE models of the South African economy have lately been developed. Liu and Gupta (2007) calibrated the RBC model of Hansen (1985) to match South African data. The model is used to generate forecasts for a number of macroeconomic variables, which are then compared with the forecasts of a Bayesian and classical VAR. Steinbach et al. (2009) used Bayesian methods to estimate a small open economy DSGE model on South African data, while Ortiz and Sturzenegger (2007) used a version of the Gali and Monacelli (2003) model and Bayesian techniques to estimate the policy reaction function of the South African Reserve Bank (SARB). Finally, Alpanda et al. (2010a, 2010b) explored the role of the exchange rate in South African monetary policy, before evaluating the forecasting properties of the model in Alpanda et al. (2011).

This paper extends the South African literature by developing a DSGE model which could be operationalised in a policy institution such as the South African Reserve Bank. This is achieved by adding a number of variables and frictions to the standard small open economy DSGE model structure. First of all, as an extension to the aggregate demand components in Steinbach et al. (2009), investment (capital accumulation), exports and imports and their corresponding price deflators are added to the framework. In addition, the model includes a number of additional real and nominal frictions, such as investment adjustment costs, costly variation in the utilisation of capital and imperfect pass-through of import and export prices, to mention a few. The inclusion of these friction help make the model estimable. The model then is estimated with Bayesian methods, before its usefulness as a potential tool in a policy-making environment such as the South African Reserve Bank is assessed through a decomposition of historical developments in key variables, as well as the model's forecasting ability.

The paper is laid out as follows. The structure of the model is presented in Section 2. Section 3 describes the detail surrounding the estimation procedure, as well as the results thereof. Thereafter, the historical decomposition, the dynamic behaviour of the model and its forecasting ability are discussed in Sections 4 and 5, before Section 6 concludes.

2 The model

The small open economy model structure largely follows the lines of Adolfson et al. (2007), which in turn extended the models of Christiano et al. (2005) and Altig et al. (2011) into the open economy setting. More specifically, the general structure of Adolfson et al. (2007) is ideal for the purposes of this paper, as it forms the backbone of an operational DSGE model that is used for actual forecasting and policy analysis in an inflation-targeting central bank.[1] Nevertheless, the model laid out below departs from Adolfson et al. (2007) in four key aspects. Firstly, households do not derive utility from holding money. Secondly, allowance is made for the fact that on average, inflation in South Afica exceeds that of its trading partners. In the context of the model, this is achieved by assuming that South Africa has a higher steady state inflation rate. By implication, these differential inflation rates yield a nominal exchange rate depreciation in steady state, as predicted by purchasing power parity theory. Thirdly, it is assumed that there is no cost channel of monetary policy, hence firms do not borrow their wage bill.[2] Finally, apart from lump-sum transfers, the role of taxes in the model is disregarded.

Households consume both domestic and imported goods, whilst exhibiting habit formation in consumption. They have the option to save in domestic or foreign bonds. In addition, being the owners thereof, households rent capital to firms and decide how much to invest in each period. Changes to the rate of investment are subject to adjustment costs. Households can also vary the rate at which capital is utilised, subject to adjustment costs. Following Erceg et al. (2000), each household supplies a differentiated labour service to firms which enables them to set their wage in a Calvo (1983) manner.

In the model there are three types of firms: domestic producers, importers and exporters. Domestic firms employ labour and capital in production, whilst being exposed to both transitory and permanent technology shocks as in Altig et al. (2011). A differentiated good is produced by each type of firm, and subsequently prices are set following Calvo's (1983) model, with a variation of Rabanal and Rubio-Ramírez (2005) which allows for indexation to past inflation. The incorporation of these nominal rigidities in the price-setting behaviour of importing and exporting firms enables incomplete pass-through of exchange rate changes in the short-run.

The central bank is assumed to follow a Taylor-type rule in setting the short-term policy interest rate. And finally, consistent with the small-open economy setup, the foreign economy is assumed to be exogenous to developments in the domestic economy.

2.1 Firms

2.1.1 Domestic firms

Final good producers A final good producer transforms intermediate goods into a final homogeneous good, which in turn is used by households for either consumption or investment purposes. The

[1] RAMSES, the DSGE model used for forecasting and policy analysis at the Sveriges Riksbank is based on Adolfson et al. (2007).

[2] Liu (2013) finds evidence that the cost channel of monetary policy is at play in the South African economy. However, for the sake of simplicity this channel is not included here.

transformation process of intermediate goods into the final good takes the CES form

$$Y_t = \left[\int_0^1 Y_{i,t}^{\frac{1}{\lambda_{d,t}}} di \right]^{\lambda_{d,t}}, \tag{1}$$

where λ_t^d is the time-varying markup for domestic goods that is assumed to follow an AR(1) process

$$\lambda_t^d = (1-\rho_{\lambda^d})\lambda^d + \rho_{\lambda^d}\lambda_{t-1}^d + \epsilon_t^{\lambda^d}, \tag{2}$$

with λ^d being the steady-state level of the domestic goods markup, while ρ_{λ^d} measures the degree of persistence and $\epsilon_t^{\lambda^d} \sim N(0, \sigma_{\lambda^d})$. Profit maximisation by the final-good firm yields the demand function for intermediate goods

$$Y_{i,t} = \left(\frac{P_t}{P_{i,t}} \right)^{\frac{\lambda_{d,t}}{\lambda_{d,t}-1}} Y_t, \tag{3}$$

and the price of the final good as an index of intermediate goods' prices:

$$P_t = \left[\int_0^1 P_{i,t}^{\frac{1}{1-\lambda_{d,t}}} di \right]^{1-\lambda_{d,t}}. \tag{4}$$

Intermediate good producers A continuum of intermediate-good producers (indexed by i, where $i \in [0,1]$) operate in a monopolistically competitive environment and produce differentiated goods according to the production function:

$$Y_{i,t} = \varepsilon_t \left(K_{i,t}^s\right)^{\alpha} \left(z_t H_{i,t}\right)^{1-\alpha} - z_t \phi, \tag{5}$$

where z_t and ε_t are permanent and transitory technology shocks respectively. $K_{i,t}^s$ represents capital services that are rented from households, $H_{i,t}$ is a homogenised labour input, and ϕ captures fixed costs that grow in line with technology. Capital services K_t^s may differ from the actual capital stock K_t as a result of variation in the utilisation rate of capital, u_t, where $K_t^s = u_t K_t$. It is further assumed that the respective technology shocks follow autoregressive processes:

$$\begin{aligned} \frac{z_t}{z_{t-1}} &= \mu_t^z \\ &= (1-\rho_{\mu^z})\mu^z + \rho_{\mu^z}\mu_{t-1}^z + \epsilon_t^{\mu^z}, \end{aligned} \tag{6}$$

and

$$\hat{\varepsilon}_t = \rho_\varepsilon \hat{\varepsilon}_{t-1} + \varepsilon_t^\varepsilon, \tag{7}$$

where μ^z is the steady-state growth rate of technology, $E(\varepsilon_t) = 1$ and $\hat{\varepsilon}_t = (\varepsilon_t - 1)/1$. Since $\mu_t^z > 1$, the presence of the permanent technology shock z_t in the model implies that all real variables contain a unit root. To render the model stationary, real variables are therefore detrended with the permanent technology shock. Let the notational convention be such that lower case letters indicate detrended variables. Then, as an example, the detrended capital stock is expressed as $k_{t+1} = K_{t+1}/z_t$. Nominal variables also contain a stochastic trend, as the price level is non-stationary, and hence are detrended by the domestic price level P_t^d. Note that the nominal wage W_t contains both the permanent technology and nominal price level trend, as nominal wages grow in line with changes in the price level and technology. Therefore, the detrended real wage is expressed in the model as $w_t = W_t/(z_t P_t^d)$.

The intermediate firm rents capital services at the gross nominal rate R_t^k and compensates the homogenous labour service at the nominal wage rate W_t. Accordingly, the intermediate firm's cost-minimisation problem is as follows:

$$\min_{K_{i,t}^s, H_{i,t}} W_t H_{i,t} + R_t^k K_{i,t}^s + \lambda_t P_{i,t}^d \left[Y_{i,t} - \varepsilon_t \left(K_{i,t}^s\right)^\alpha \left(z_t H_{i,t}\right)^{1-\alpha} + z_t \phi \right]. \tag{8}$$

Optimization of Equation (8) with respect to $K_{i,t}^s$ and $H_{i,t}$ yields the familiar first-order conditions:

$$R_t^k = \alpha \lambda_t P_{i,t} z_t^{1-\alpha} \epsilon_t \left(K_{i,t}^s\right)^{\alpha-1} H_{i,t}^{1-\alpha} \tag{9}$$

and

$$W_t = (1-\alpha) \lambda_t P_{i,t} z_t^{1-\alpha} \epsilon_t \left(K_{i,t}^s\right)^{\alpha} H_{i,t}^{-\alpha}, \tag{10}$$

that equate the marginal returns of capital and labour to the cost of their compensation.

When combining Equations (9) and (10), the stationary real rental rate of capital is expressed as:

$$r_t^k = \frac{\alpha}{1-\alpha} \bar{w}_t \mu_t^z \left(\frac{H_t}{k_t}\right) \tag{11}$$

and real marginal cost as

$$mc_t = \left(\frac{1}{1-\alpha}\right)^{1-\alpha} \left(\frac{1}{\alpha}\right)^{\alpha} \epsilon_t^{-1} \left(r_t^k\right)^\alpha \left(\bar{w}_t\right)^{1-\alpha}, \tag{12}$$

where the Lagrange multiplier in Equation (8), $\lambda_t P_{i,t}^d$, is interpreted as nominal marginal cost MC_t.

Domestic price setting It is assumed that intermediate-good firms set prices in a staggered manner as proposed by Calvo (1983). In his model a firm gets the opportunity to adjust its price with a probability of $(1-\theta_d)$ in every period. Thus, in a given period t, not all firms are able to react to supply shocks immediately, which implies that the higher θ_d, the more sticky is the price adjustment process. In addition, following Adolfson et al. (2007), it is assumed that the intermediate-good firms who do not receive the Calvo signal to change their price, index their price in $t+1$ to period t's inflation rate and the current inflation target, as follows:

$$P_{t+1}^d = \left(\pi_t^d\right)^{\varkappa_d} \left(\bar{\pi}_{t+1}^c\right)^{1-\varkappa_d} P_t^d, \tag{13}$$

where $\pi_t^d = P_t^d / P_{t-1}^d$ is the gross inflation rate, $\bar{\pi}_t^c$ the inflation target and $\varkappa_d$ the degree of indexation to past inflation.[3,4] As it aims to maximise its expected discounted profit, the intermediate firm i's intertemporal optimisation problem is therefore:

$$\max_{\tilde{P}_t} E_t \sum_{s=0}^{\infty} (\beta\theta_d)^s \upsilon_{t+s} \left\{ \left[\left(\prod_{k=1}^{s} \pi_{t+k-1} \right)^{\varkappa_d} \left(\prod_{k=1}^{s} \bar{\pi}_{t+k}^c \right)^{1-\varkappa_d} \tilde{P}_t \right] Y_{i,t+s} \right.$$
$$\left. - MC_{i,t+s} \left(Y_{i,t+s} + z_{t+s}\phi \right) \right\}, \tag{14}$$

where $(\beta\theta_d)^s \upsilon_{t+s}$ is the stochastic discount factor. In addition, the price index of Equation (4) can be expressed as a weighted average of the new optimal price chosen by the firms that do receive the Calvo signal, and the backward indexed price set by the remaining firms:

$$P_t = \left[\theta_d \left(\left(\pi_{t-1} \right)^{\varkappa_d} \left(\bar{\pi}_t^c \right)^{1-\varkappa_d} P_{t-1} \right)^{\frac{1}{1-\lambda_{d,t}}} + (1-\theta_d) \tilde{P}_t^{\frac{1}{1-\lambda_{d,t}}} \right]^{1-\lambda_{d,t}}. \tag{15}$$

Optimising Equation (14), whilst taking account of the demand for intermediate goods in Equation (3), linearising the result and combing it with the linearised Equation (15), yields the New Keynesian Phillips curve for the domestic good:

$$\begin{aligned} \hat{\pi}_t - \hat{\bar{\pi}}_t^c &= \frac{\beta}{1+\varkappa_d\beta} \left(E_t \hat{\pi}_{t+1} - \rho_\pi \hat{\bar{\pi}}_t^c \right) + \frac{\varkappa_d}{1+\varkappa_d\beta} \left(\hat{\pi}_{t-1} - \hat{\bar{\pi}}_t^c \right) - \frac{\varkappa_d \beta (1-\rho_\pi)}{1+\varkappa_d\beta} \hat{\bar{\pi}}_t^c \\ &+ \frac{(1-\theta_d)(1-\beta\theta_d)}{(1+\varkappa_d\beta)\theta_d} \left(\hat{mc}_t + \hat{\lambda}_t^d \right). \end{aligned} \tag{16}$$

2.1.2 Importing firms

There are two types of importing firms: importing consumption and importing investment firms. Both of these importing firms purchase a homogeneous good in the world market at the international price P_t^*. Thereafter, the importing consumption firm turns the homogeneous good into a differentiated consumption good $C_{i,t}^m$, while a differentiated investment good $I_{i,t}^m$ is created by the importing investment firm. Let $J_t \in \{C_t^m, I_t^m\}$ denote aggregate quantities of the imported consumption and investment good, and $j \in \{c, i\}$, then the final imported good can be expressed as a CES composite of the differentiated import goods:

$$J_t = \left[\int_0^1 \left(J_{i,t} \right)^{\frac{1}{\lambda_t^{m,j}}} di \right]^{\lambda_t^{m,j}}. \tag{17}$$

[3]The time-varying inflation target is analogous to a flexible inflation targeting regime. More specifically, as discussed below in Section (3.1), it's role in this model is to facilitate the transition from high inflation and interest rates in the 1990s – prior to South Africa's implementation of an inflation targeting regime in February 2000 – to lower inflation and interest rates thereafter.

[4]$\varkappa_d = 1$ implies that indexation is completely backward-looking.

The demand function faced by each importing firm i is given by:

$$J_{i,t} = \left(\frac{P_{i,t}^{m,j}}{P_t^{m,j}} \right)^{-\frac{\lambda_t^{m,j}}{\lambda_t^{m,j}-1}} J_t, \tag{18}$$

while the time-varying markup for the imported consumption and investment goods is:

$$\lambda_t^{m,j} = (1-\rho_{\lambda^{m,j}})\lambda^{m,j} + \rho_{\lambda^{m,j}} \lambda_{t-1}^{m,j} + \epsilon_{\lambda^{m,j},t}. \tag{19}$$

As with domestic firms, it is assumed that importing firms face a Calvo probability when setting their price. Hence, importing consumption firms may change their price with probability $(1-\theta_{m,c})$ and investment firms with probability $(1-\theta_{m,i})$. Firms who cannot reoptimise, index their price in period $t+1$ to a combination of the previous period's imported price inflation rate $\pi_t^{m,j}$ and the current inflation target $\bar{\pi}_{t+1}^c$ as follows:

$$P_{t+1}^{m,j} = \left(\pi_t^{m,j}\right)^{\varkappa_{m,j}} \left(\bar{\pi}_{t+1}^c\right)^{1-\varkappa_{m,j}} P_t^{m,j}. \tag{20}$$

In a similar vein to the domestic intermediate firm, the respective importing firm's optimisation problem is therefore given by:

$$\begin{aligned} \max_{\tilde{P}_t^{m,j}} E_t \sum_{s=0}^{\infty} \left(\beta\theta_{m,j}\right)^s \upsilon_{t+s} \Bigg\{ \Bigg[\left(\prod_{k=1}^{s} \pi_{t+k-1}^{m,j} \right)^{\varkappa_{m,j}} \left(\prod_{k=1}^{s} \bar{\pi}_{t+k}^{j} \right)^{1-\varkappa_{m,j}} \tilde{P}_t^{m,j} \Bigg] J_{i,t+s} \\ -S_{t+s} P_{t+s}^{*} \left(J_{i,t+s} + z_{t+s} \phi^{m,j} \right) \Bigg\}, \end{aligned} \tag{21}$$

where S_t is the nominal exchange rate expressed as the number of domestic currency units needed to buy one unit of the foreign currency, and hence, $S_t P_t^*$ is the importing firm's marginal cost. The respective aggregate imported goods price indices in period t are therefore a weighted average of firms who reoptimise and firms who set their price to the indexing scheme of Equation (20):

$$\begin{aligned} P_t^{m,j} &= \left[\int_0^1 \left(P_{i,t}^{m,j} \right)^{\frac{1}{1-\lambda_t^{m,j}}} di \right]^{1-\lambda_t^{m,j}} \\ &= \left[\theta_{m,j} \left(P_{t-1}^{m,j} \left(\pi_{t-1}^{m,j} \right)^{\varkappa}_{m,j} \left(\bar{\pi}_t^j \right)^{1-\varkappa_{m,j}} \right)^{\frac{1}{1-\lambda_t^{m,j}}} + \left(1-\theta_{m,j}\right) \left(\tilde{P}_t^{m,j} \right)^{\frac{1}{1-\lambda_t^{m,j}}} \right]^{1-\lambda_t^{m,j}}. \end{aligned} \tag{22}$$

Combining Equations (21) and (18), linearising the result before inserting it in the linearised Equation (22), yields dynamic inflation equations for imported consumption and investment goods:

$$\begin{aligned}\hat{\pi}_t^{m,j} - \hat{\bar{\pi}}_t^c &= \frac{\beta}{1+\varkappa_{m,j}\beta}\left(E_t\hat{\pi}_{t+1}^{m,j} - \rho_\pi\hat{\bar{\pi}}_t^c\right) + \frac{\varkappa_{m,j}}{1+\varkappa_{m,j}\beta}\left(\hat{\pi}_{t-1}^{m,j} - \hat{\bar{\pi}}_t^c\right) - \frac{\varkappa_{m,j}\beta(1-\rho_\pi)}{1+\varkappa_{m,j}\beta}\hat{\bar{\pi}}_t^c \\ &+ \frac{\left(1-\theta_{m,j}\right)\left(1-\beta\theta_{m,j}\right)}{\left(1+\varkappa_{m,j}\beta\right)\theta_{m,j}}\left(\hat{mc}_t^{m,j} + \hat{\lambda}_t^{m,j}\right), \end{aligned} \tag{23}$$

where $j = \{c, i\}$ and the importing firms' real marginal cost deviation from its steady state is given by $\hat{mc}_t^j = \hat{s}_t + \hat{p}_t^* - \hat{p}_t^{m,j}$.

2.1.3 Exporting firms

Exporting firms purchase the final good, differentiate it and then sell this continuum of differentiated export goods to households abroad. The demand faced by the individual exporting firm is given by:

$$\tilde{X}_{i,t} = \left(\frac{P_{i,t}^x}{P_t^x}\right)^{-\frac{\lambda_t^x}{\lambda_t^x-1}}\tilde{X}_t, \tag{24}$$

where P_t^x is the foreign currency price of exports, and the time-varying markup for the exporting firm is:

$$\lambda_t^x = (1-\rho_{\lambda^x})\lambda^x + \rho_{\lambda^x}\lambda_{t-1}^x + \varepsilon_{\lambda^x,t}. \tag{25}$$

We assume that exporters also set their prices in a staggered manner as proposed by Calvo (1983), and that the proportion of firms who cannot reoptimise in a given period, index their price to the previous period's export price inflation rate, as follows:[5]

$$P_{t+1}^x = \pi_t^x P_t^x. \tag{26}$$

Hence, the optimisation problem of the individual exporting firm is given by:

$$\max_{\tilde{P}_t^x} E_t \sum_{s=0}^{\infty}(\beta\theta_x)^s \upsilon_{t+s}\left\{\left(\prod_{k=1}^{s}\pi_{t+k-1}^x\tilde{P}_t^x\right)\tilde{X}_{i,t+s} - \frac{P_{t+s}}{S_{t+s}}\left(\tilde{X}_{i,t+s} + z_{t+s}\phi^x\right)\right\}, \tag{27}$$

where P_{t+s}/S_{t+s} is the nominal marginal cost of the exporting firm as it buys the final good at the domestic price P_t^d before differentiating it and selling it in the foreign market's currency. The aggregate export price is once again a weighted combination of the two pricing schemes which exporting firms

[5]Since exporting firms set their prices for the foreign market, they do not consider the domestic inflation target when indexing.

face: reoptimise with probability $(1-\theta_x)$, or else index with probability θ_x. Hence,

$$
\begin{aligned}
P_t^x &= \left[\int_0^1 \left(P_{i,t}^x\right)^{\frac{1}{1-\lambda_t^x}} di\right]^{1-\lambda_t^x} \\
&= \left[\theta_x \left(\pi_{t-1}^x P_{t-1}^x\right)^{\frac{1}{1-\lambda_t^x}} + (1-\theta)\left(\tilde{P}_t^x\right)^{\frac{1}{1-\lambda_t^x}}\right]^{1-\lambda_t^x}. \qquad (28)
\end{aligned}
$$

As before, optimising the combination of Equations (27) and (24), and thereafter linearising the result and inserting the linearised Equation (22), yields the dynamic inflation equation for exported goods:

$$
\hat{\pi}_t^x = \frac{\beta}{1+\beta} E_t \hat{\pi}_{t+1}^x + \frac{1}{1+\beta}\hat{\pi}_{t-1}^x + \frac{(1-\theta_x)(1-\beta\theta_x)}{(1+\beta)\theta_x}\left(\hat{mc}_t^x + \hat{\lambda}_t^x\right), \qquad (29)
$$

where $\hat{mc}_t^x = \hat{p}_t^d - \hat{s}_t - \hat{p}_t^x$ is the real marginal cost of the exporting firm.

In the foreign economy, the exported good may either be used for consumption C_t^* or investment I_t^*. The assumption that the domestic economy is so small that its contribution to aggregate demand in the foreign economy becomes negligible, allows us to express foreign demand for the exported consumption and investment goods as

$$
C_t^x = \left[\frac{P_t^x}{P_t^*}\right]^{-\eta_f} C_t^* \quad \text{and} \quad I_t^x = \left[\frac{P_t^x}{P_t^*}\right]^{-\eta_f} I_t^*. \qquad (30)
$$

Since we assume that the elasticiy of substitution η_f is the same for both the exported consumption and investment good, their respective contributions to aggregate exports is irrelevant. Therefore, the individual demand functions for the exported consumption and investment goods can be simplified in terms of aggregate exports and aggregate foreign demand as follows:

$$
\begin{aligned}
\tilde{X}_t &= C_t^x + I_t^x = \left[\frac{P_t^x}{P_t^*}\right]^{-\eta_f}\left(C_t^* + I_t^*\right) \\
&= \left[\frac{P_t^x}{P_t^*}\right]^{-\eta_f} Y_t^*. \qquad (31)
\end{aligned}
$$

2.2 Households

A continuum of infinitely-lived households (indexed by j, where $j \in [0,1]$) populate the domestic economy. They derive utility from consuming a basket of imported and domestic consumption goods and holding cash balances, while they exhibit disutility in supplying labour services. In every period, the j^{th} household maximises expected lifetime utility according to following intertemporal utility function

$$
E_0^j \sum_{t=0}^{\infty} \beta^t \left[\xi_t^c \ln\left(C_{j,t} - bC_{j,t-1}\right) - \xi_t^h A_L \frac{(h_{j,t})^{1+\sigma_L}}{1+\sigma_L}\right] \qquad (32)
$$

where $C_{j,t}$ denotes consumption by the household, $h_{j,t}$ is the labour it supplies. The parameter β represents the household's subjective discount factor, b captures the degree of habit formation in consumption, A_L pins down the steady state level of disutility from supplying labour, while σ_L is the inverted Frisch elasticity of labour supply. ξ_t^c and ξ_t^h represent consumption preference and labour supply shocks, respectively, and are assumed to follow AR(1) processes as follows:

$$\xi_t^c = \rho_c \xi_{t-1}^c + \varepsilon_t^c$$
$$\xi_t^h = \rho_c \xi_{t-1}^h + \varepsilon_t^h$$

Consumption The aggregate consumption basket from which households derive utility is given by the CES index:

$$C_t = \left[(1-\vartheta_c)^{\frac{1}{\eta_c}} \left(C_t^d \right)^{\frac{\eta_c - 1}{\eta_c}} + \vartheta_c^{\frac{1}{\eta_c}} \left(C_t^m \right)^{\frac{\eta_c - 1}{\eta_c}} \right]^{\frac{\eta_c}{\eta_c - 1}}, \tag{33}$$

where C_t^d and C_t^m denote domestic and imported consumption goods, η_c is the substitution elasticity between the two goods and ϑ_c is the imports share in aggregate consumption. The respective demand functions for the domestic and imported consumption goods are given by

$$C_t^d = (1-\vartheta_c) \left[\frac{P_t^d}{P_t^c} \right]^{-\eta_c} C_t \quad \text{and} \quad C_t^m = \vartheta_c \left[\frac{P_t^{m,c}}{P_t^c} \right]^{-\eta_c} C_t, \tag{34}$$

and the price index for the consumption basket (CPI) is:

$$P_t^c = \left[(1-\vartheta_c)(P_t^d)^{1-\eta_c} + \vartheta_c (P_t^{m,c})^{1-\eta_c} \right]^{\frac{1}{1-\eta_c}}. \tag{35}$$

Labour supply and wage setting The differentiated labour service $h_{j,t}$ that is supplied by each household, is transformed by a labour aggregating firm into a homogeneous input good H_t as follows:

$$H_t = \left[\int_0^1 \left(h_{j,t} \right)^{\frac{1}{\lambda_w}} \right]^{\lambda_w}, \tag{36}$$

where H_t is then used by intermediate firms in production. By supplying a differentiated labour service, each household has monopoly power when setting its nominal wage $W_{j,t}$. However, in doing so it faces the following demand for its labour services:

$$h_{j,t} = \left[\frac{W_{j,t}}{W_t} \right]^{\frac{\lambda_w}{1-\lambda_w}} H_t, \tag{37}$$

where W_t is the aggregated nominal wage rate for the homogeneous labour input good H_t, expressed as the CES aggregate:

$$W_t = \left[\int_0^1 W_{j,t}^{\frac{1}{1-\lambda_w}} dj\right]^{1-\lambda_w}. \tag{38}$$

Moreover, it is assumed that a household cannot optimally set its wage in every period, but rather faces a Calvo probability $1-\theta_w$ of doing so. Hence, with probability θ_w household j will not be able to change its wage in period t, and as such will index its wage in period $t+1$ to a combination of the previous period's CPI inflation rate, the current inflation target and the current economy-wide technology growth rate, as follows:

$$W_{j,t+1} = \left(\pi_t^c\right)^{\varkappa_w} \left(\bar{\pi}_{t+1}^c\right)^{(1-\varkappa_w)} \mu_{t+1}^z W_{j,t}, \tag{39}$$

where $\varkappa_w$ is the degree of indexation to CPI inflation.

$$\max_{\tilde{W}_{j,t}} E_t \sum_{s=0}^{\infty} (\beta\theta_w)^s \left\{ \begin{array}{c} -\xi_{t+s}^h A_L \frac{(h_{j,t+s})^{1+\sigma_L}}{1+\sigma_L} \\ +\upsilon_{t+s} h_{j,t+s} \left[\left(\prod_{k=1}^s \pi_{t+k-1}^c\right)^{\varkappa_w} \left(\prod_{k=1}^s \bar{\pi}_{t+k}^c\right)^{(1-\varkappa_w)} \left(\prod_{k=1}^s \mu_{t+k}^z\right) \tilde{W}_{j,t}\right] \end{array} \right\}, \tag{40}$$

where $\tilde{W}_{j,t}$ is the optimal reset wage. Optimisation of Eq. (40) subject to the demand for individual household labour given by Eq. (37), yields first-order condition for wage setting

$$E_t \sum_{s=0}^{\infty} (\beta\theta_w)^s h_{j,t+s} \left\{ \begin{array}{c} \xi_{t+s}^h A_L \left(h_{j,t+s}\right)^{\sigma_L} \\ +\frac{\tilde{W}_t}{z_t P_t} \frac{z_{t+s}\upsilon_{t+s} P_{t+s}}{\lambda_w} \frac{\left(\frac{P_{t+s-1}^c}{P_{t-1}^c}\right)^{\varkappa_w} \left(\prod_{k=1}^s \bar{\pi}_{t+k}^c\right)^{(1-\varkappa_w)}}{\frac{P_{t+s}^d}{P_t^d}} \end{array} \right\} = 0, \tag{41}$$

where we make use of the fact that in equilibrium, all households choose the same optimal reset wage $\tilde{W}_t$. In addition, the aggregate wage index from Eq. (38) can be expressed as a weighted average of households who reoptimise their wage in period t and those that set their wage to the indexing scheme of Eq. (39):

$$W_t = \left[\theta_w \left(\left(\pi_{t-1}^c\right)^{\varkappa_w} \left(\bar{\pi}_t^c\right)^{1-\varkappa_w} \mu_t^z W_{t-1}\right)^{\frac{1}{1-\lambda_w}} + (1-\theta_w)\tilde{W}_t^{\frac{1}{1-\lambda_w}}\right]^{1-\lambda_w}. \tag{42}$$

Combining the loglinearised versions of Eqs. (41) and (42), whilst also stationarising the nominal wage such that $w_t = W_t / P_t^d z_t$ is the real wage, yields the wage equation

$$\hat{w}_t = -\frac{1}{\eta_1} \left[\begin{array}{l} \eta_0 \hat{w}_{t-1} + \eta_2 E_t \hat{w}_{t+1} + \eta_3 \left(\hat{\pi}_t^d - \hat{\bar{\pi}}_t^c\right) + \eta_4 \left(E_t \hat{\pi}_{t+1}^d - \rho_\pi \hat{\bar{\pi}}_t^c\right) \\ +\eta_5 \left(\hat{\pi}_{t-1}^c - \hat{\bar{\pi}}_t^c\right) + \eta_6 \left(\hat{\pi}_t^c - \rho_\pi \hat{\bar{\pi}}_t^c\right) + \eta_7 \hat{\psi}_t^z + \eta_8 \hat{H}_t + \eta_9 \hat{\xi}_t^h \end{array} \right] \tag{43}$$

where $b_w = \frac{\lambda_w \sigma_L - (1-\lambda_w)}{(1-\beta\theta_w)(1-\theta_w)}$

$$\begin{pmatrix} \eta_0 \\ \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \\ \eta_6 \\ \eta_7 \\ \eta_8 \\ \eta_9 \end{pmatrix} = \begin{pmatrix} b_w \theta_w \\ \left[\lambda_w \sigma_L - b_w(1+\beta\theta_w^2)\right] \\ b_w \beta \theta_w \\ -b_w \theta_w \\ b_w \beta \theta_w \\ b_w \theta_w \varkappa_w \\ -b_w \beta \theta_w \varkappa_w \\ (1-\lambda_w) \\ -(1-\lambda_w)\sigma_L \\ -(1-\lambda_w) \end{pmatrix} \tag{44}$$

and ψ_t^z is the stationarised Lagrange multiplier.

Asset holdings Households allocate their wealth among domestic and foreign risk-free bonds, B_t and B_t^*. The prices of these bonds are inversely proportional to their respective gross nominal interest rates, R_t and R_t^*, while they have a maturity of one period. However, as in Benigno (2009), the interest rate at which households purchase foreign bonds is adjusted with a risk premium that depends on the domestic economy's indebtedness in the international asset market, as measured by its net foreign asset position:

$$A_t \equiv \frac{S_t B_t^*}{P_t^d}. \tag{45}$$

Schmitt-Grohé and Uribe (2003) show that the inclusion of this debt-elastic risk premium is crucial for the determination of a well-defined steady state in small open economy models. In addition, following Adolfson et al. (2008), we assume that the risk premium is not only a function of the net foreign asset position, but also the expected depreciation of the domestic currency, S_{t+1}/S_{t-1}. The inclusion of the expected exchange rate in the risk premium aims to account for the "forward premium puzzle": an empirical anomaly according to which currencies with higher risk premiums *ex ante* often tend to appreciate *ex post*, and hence a negative relationship exists between risk premia and expected depreciations. Consequently, it is assumed that the risk premium has the following functional form

$$\Phi(\frac{A_t}{z_t}, S_t, \tilde{\phi}_t) = \exp\left\{-\tilde{\phi}_a(a_t - a) - \tilde{\phi}_s\left[\frac{E_t S_{t+1}}{S_t}\frac{S_t}{S_{t-1}} - \left(\frac{\pi}{\pi^*}\right)^2\right] + \tilde{\phi}_t\right\}, \tag{46}$$

such that households will pay a premium on the foreign interest rate if the domestic economy is a net borrower in the international asset market, and conversely they receive a lower remuneration if the domestic economy is a net lender. In addition, the negative sign on the expected change in the exchange rate could be interpreted as a willingness by households to accept a lower return on their foreign bond holdings, if they expected the exchange rate depreciation to exceed the steady state inflation differential $\frac{\pi}{\pi^*}$, as a depreciation would increase the domestic currency return of their foreign assets.[6] Finally, the term $\tilde{\phi}_t$ in Eq. (46) represents an AR(1) shock to the risk premium, while in the steady state, the risk premium has the property $\Phi(0,0,0) = 1$.

Investment and capital accumulation Households own the capital stock, and as a result, in every period t they make a decision on how much to invest, I_t. As with consumption, households may purchase domestic (I_t^d) or imported investment goods (I_t^m), which is given by the CES aggregate:

$$I_t = \left[(1-\vartheta_i)^{\frac{1}{\eta_i}}\left(I_t^d\right)^{\frac{\eta_i-1}{\eta_i}} + \vartheta_i^{\frac{1}{\eta_i}}\left(I_t^m\right)^{\frac{\eta_i-1}{\eta_i}}\right]^{\frac{\eta_i}{\eta_i-1}}, \tag{47}$$

where η_i is the substitution elasticity between domestic and imported investment goods and ϑ_i is the share of imports in aggregate investment. The respective demand functions for domestic and imported investment goods are given by

$$I_t^d = (1-\vartheta_i)\left[\frac{P_t^d}{P_t^i}\right]^{-\eta_i} I_t \quad \text{and} \quad I_t^m = \vartheta_i\left[\frac{P_t^{m,i}}{P_t^i}\right]^{-\eta_i} I_t, \tag{48}$$

and subsequently, the price deflator for aggregate investment is:

$$P_t^i = \left[(1-\vartheta_i)(P_t^d)^{1-\eta_i} + \vartheta_i(P_t^{m,i})^{1-\eta_i}\right]^{\frac{1}{1-\eta_i}}. \tag{49}$$

Note that the domestic consumption and investment good share the same price P_t^d, while differences between the CPI and investment price deflators emanate from the fact that the imported consumption good's price $P_t^{m,c}$ may differ from the imported investment good's $P_t^{m,i}$. Given the household's investment decision, the capital stock K_{t+1} accumulates as follows:

$$K_t = (1-\delta)K_{t-1} + \xi_t^i F(I_t, I_{t-1}) + \Delta_t, \tag{50}$$

where ξ_t^i is an investment specific technology shock, with the property $E[\xi_t^i] = 1$, that follows the AR(1) process:

$$\hat{\xi}_t^i = \rho_c \hat{\xi}_{t-1}^i + \varepsilon_t^i,$$

with $\hat{\xi}_t^i = (\xi_t^i - 1)/1$. Δ_t represents installed capital that households may purchase in the secondary market from other households. Although $\Delta_t = 0$ in equilibrium, as all households make indentical capital accumulation decisions, its inclusion facilitates the calculation of the price of installed capital $P_t^{k'}$. The term $F(I_t, I_{t-1})$ in Eq. (50) captures the investment adjustment cost that is paid by households whenever the rate of change in the level of investment deviates from the economy-wide steady

[6] Adolfson et al. (2008) assume that the domestic and foreign inflation rates are identical in steady state, hence $\frac{\pi}{\pi^*} = 1$.

state growth rate μ^z. Christiano et al. (2005) specify this adjustment cost function as follows:

$$F(I_t, I_{t-1}) = \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t, \tag{51}$$

where

$$S\left(\frac{I_t}{I_{t-1}}\right) = \frac{\phi_i}{2}\left(\frac{I_t}{I_{t-1}} - \mu^z\right)^2, \tag{52}$$

such that in steady state $S(\cdot)$ satisfies $S(\mu^z) = S'(\mu^z) = 0$ and $S''(\mu^z) \equiv \phi_i$, with $\phi_i > 0$. In addition to the investment decision, households may also choose to vary the rate at which the current capital stock is utilised, u_t. The effective capital stock that is rented to firms, K_t^s, is therefore defined as:

$$K_t^s = u_t K_{t-1}. \tag{53}$$

However, as with investment, households pay a capital adjustment cost $a(u_t)$ when varying the level of capital utilisation. It is assumed that the utilisation adjustment cost function has the following properties in steady state: $a(1) = 0$, $a'(1) = r^k$ and $a''(1) \geq 0$.[7]

Budget constraint Given the set of variables introduced above, the household's budget constraint can be formulated as follows:

$$\begin{aligned}
&\frac{B_{j,t}}{R_t} + \frac{S_t B^*_{j,t}}{R^*_t \Phi\left(\frac{A_t}{z_t}, S_t, \tilde{\phi}_t\right)} + P^c_t C_{j,t} + P^i_t I_{j,t} + P^d_t \left[a(u_{j,t}) K_{j,t} + P^{k'}_t \Delta_t\right] \\
&\quad = B_{j,t-1} + S_t B^*_{j,t-1} + W_{j,t} h_{j,t} + R^k_t u_{j,t} K_{j,t-1} + \Pi_t - T_t
\end{aligned} \tag{54}$$

where the expression on the left of the equality represents nominal expenditure by the household in period t, while to the right we have nominal income earned by the household in period t as well as wealth carried over from $t-1$. Hence, households purchase new domestic and foreign assets, nominal consumption goods, nominal investment goods, they pay adjustment costs on capital utilisation and also purchase installed capital. The wealth households carry over from $t-1$ consists of their portfolio of domestic and foreign bond holdings. Households are remunerated for the labour they supply and the capital services they rent to firms. In addition, they receive profits from firm ownership, Π_t, while they pay lump-sum taxes to the government, T_t.

First-order conditions Optimisation of the household's utility function, Eq. (32), subject to the budget constraint and capital's law of motion, Eqs. (54) and (50), yields the following set of first-order conditions with respect to each of the choice variables:[8]

[7] $u = 1$ in steady state, since $K^s = K$.

[8] Since all households make identical decisions in equilibrium, the subscript j is no longer needed.

Consumption, c_t

$$\frac{\xi_t^c}{c_t - bc_{t-1}\frac{1}{\mu_t^z}} - \beta b E_t \frac{\xi_{t+1}^c}{c_{t+1}\mu_{t+1}^z - bc_t} - \psi_t^z \frac{P_t^c}{P_t} = 0 \tag{55}$$

Investment, i_t

$$-\psi_t^z \frac{P_t^i}{P_t} + \psi_t^z P_t^{k'} \xi_t^i F_1\left(i_t, i_{t-1}, \mu_t^z\right) + \beta E_t \left[\frac{\psi_{t+1}^z}{\mu_{t+1}^z} P_{t+1}^{k'} \xi_{t+1}^i F_2\left(i_{t+1}, i_t, \mu_{t+1}^z\right)\right] = 0 \tag{56}$$

Capital stock, k_t

$$-\psi_t^z P_t^{k'} + \beta E_t \left[\frac{\psi_{t+1}^z}{\mu_{t+1}^z}\left(r_{t+1}^k u_{t+1} + (1-\delta)P_{t+1}^{k'} - a(u_{t+1})\right)\right] = 0 \tag{57}$$

Installed capital, Δ_t

$$-\psi_t^z P_t^{k'} + \omega_t = 0 \tag{58}$$

Capital utilisation, u_t

$$\psi_t^z \left[r_t^k - a'(u_t)\right] = 0 \tag{59}$$

Domestic bond holdings, b_t

$$-\psi_t^z + \beta E_t \left[\frac{\psi_{t+1}^z}{\mu_{t+1}^z} \frac{R_t}{\pi_{t+1}}\right] = 0 \tag{60}$$

Foreign bond holdings, b_t^*

$$-\psi_t^z S_t + \beta E_t \left[\frac{\psi_{t+1}^z}{\mu_{t+1}^z \pi_{t+1}}\left(S_{t+1} R_t^* \Phi(a_t, S_t, \tilde{\phi}_t)\right)\right] = 0 \tag{61}$$

where all trending variables have been rendered stationary, as represented by their lower case counterparts, and $\psi_t^z = z_t P_t^d \upsilon_t$ is the stationary Lagrange multiplier. In addition, the log-linearised combination of the first-order conditions for domestic assets and foreign bond holdings, Eqs. (60) and (61), yield the UIP condition

$$\hat{R}_t - \hat{R}_t^* = (1-\tilde{\phi}_s)E_t \Delta\hat{S}_{t+1} - \tilde{\phi}_s \Delta\hat{S}_t - \tilde{\phi}_a \hat{a}_t + \hat{\tilde{\phi}}_t, \tag{62}$$

such that an increase (decrease) in the net foreign asset position of the domestic economy – *ceteris paribus* – leads to an appreciation (depreciation) of its currency.[9]

[9] If $\tilde{\phi}_s = 0$ the standard UIP condition is obtained.

2.3 The Central Bank

When setting the short-term interest rate, it is assumed that the central bank responds to the expected deviation of year-on-year CPI inflation $\hat{\pi}^{c,4}_{t+1}$ from its target as well as the current quarter's change in the price level, $\hat{\pi}^{c}_{t}$. In addition, the central bank also takes into account the current level and rate of change in output. Based on the findings of Alpanda et al. (2010b) for South Africa, it is assumed that the central bank's policy rule does not respond to fluctuations in the real exchange rate – in contrast with studies such as Smets and Wouters (2003). Consequently, the monetary policy rule is specified as follows:

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1-\rho_R)\left[\hat{\bar{\pi}}^c_t + \phi_\pi\left(\hat{\pi}^{c,4}_{t+1} - \hat{\bar{\pi}}^c_t\right) + \phi_{\Delta\pi}\hat{\pi}^c_t + \phi_y \hat{y}_t + \phi_{\Delta y}\Delta\hat{y}_t\right] + \varepsilon^R_t \tag{63}$$

where year-on-year CPI inflation is defined as $\hat{\pi}^{c,4}_t = \frac{1}{4}\prod_{j=1}^{4}\pi_{t+1-j}$.

2.4 Market clearing

In equilibrium, quantities demanded equal quantities supplied to ensure that markets clear. This applies to both the domestic final goods market and the foreign bond market.

Goods market Clearing in the domestic final goods market implies that the supply of the final-good firm should match the demand from households, government and the export market, as follows:

$$C^d_t + I^d_t + G_t + C^x_t + I^x_t \leq \varepsilon_t \left(K^s_t\right)^\alpha \left(z_t H_t\right)^{1-\alpha} - z_t\phi - a\left(u_t\right)K_{t-1}, \tag{64}$$

where government spending G_t is assumed to be determined exogenously. Stationarising Eq. (64), after having substituted the relevant demand functions from Eqs. (30), (34) and (48), yields

$$\begin{aligned} &(1-\vartheta_c)\left[\frac{P^c_t}{P^d_t}\right]^{\eta_c} c_t + (1-\vartheta_i)\left[\frac{P^i_t}{P^d_t}\right]^{\eta_i} i_t + g_t + \left[\frac{P^x_t}{P^*_t}\right]^{\eta_f} y^*_t \frac{z^*_t}{z_t} \\ \leq\ & \varepsilon_t\left(\frac{k^s_t}{\mu^z_t}\right)^\alpha H^{1-\alpha}_t - \phi - a\left(u_t\right)\left(\frac{k_{t-1}}{\mu^z_t}\right), \end{aligned} \tag{65}$$

where $Y^*_t = C^*_t + I^*_t$ and since Y^*_t is detrended with the level of permanent technology in the foreign economy, z^*_t, the term $\frac{z^*_t}{z_t}$ captures temporary asymmetry in the relative technological progress between the foreign and domestic economy. Let $\tilde{z}^*_t = \frac{z^*_t}{z_t}$, and assuming that permananent technology growth in the domestic and foreign economy is equal in steady state, *i.e.*, $\mu^{z*} = \mu^z$, then $\tilde{z}^* = 1$.[10] The asymmetric technology shock is assumed to follow an AR(1) process as follows:

$$\hat{\tilde{z}}^*_t = \rho_{\tilde{z}^*}\hat{\tilde{z}}^*_{t-1} + \varepsilon^{\tilde{z}^*}_t, \tag{66}$$

where $\hat{\tilde{z}}^*_t = (\tilde{z}^*_t - 1)/1$.

[10] To hold, this result implicitly assumes $z^*_0 = z_0$.

Foreign bond market Clearing in the foreign bond market requires foreign bond holdings by households to equal the combined net position of importing and exporting firms. As such, the balance of payments identity for the evolution of (nominal) net foreign assets may be formulated as follows:

$$\frac{S_t B^*_{j,t}}{R^*_t \Phi\left(\frac{A_t}{z_t}, S_t, \tilde{\phi}_t\right)} = S_t P^x_t \left(C^x_t + I^x_t\right) + S_t P^*_t \left(C^m_t + I^m_t\right) + S_t B^*_{t-1}. \tag{67}$$

As before, the stationary (real) net foreign asset position is given by $a_t \equiv \frac{S_t B^*_t}{P^d_t z_t}$.

2.5 Relative prices

In addition to the model's real variables, the various price levels also need to be rendered stationary. This is achieved by dividing these price levels through a numeraire. In the domestic economy, prices are rendered stationary by dividing with the domestic price level P^d_t, while prices that are relevant for the foreign economy, are divided with the foreign price level P^*_t. As a result, the following relative prices are defined:

Relative prices of consumption and investment goods:

$$\gamma^{c,d}_t \equiv \frac{P^c_t}{P^d_t} \tag{68}$$

$$\gamma^{i,d}_t \equiv \frac{P^i_t}{P^d_t}. \tag{69}$$

Relative prices of imported consumption and investment goods:

$$\gamma^{mc,d}_t \equiv \frac{P^{m,c}_t}{P^d_t} \tag{70}$$

$$\gamma^{mi,d}_t \equiv \frac{P^{m,i}_t}{P^d_t}. \tag{71}$$

Relative price of exported goods:

$$\gamma^{x,*}_t \equiv \frac{P^x_t}{P^*_t}. \tag{72}$$

In addition, it is convenient to express both the importing and exporting firms' marginal cost as functions of the domestic-foreign relative price γ^f_t. Hence, let

$$\gamma^f_t \equiv \frac{P^d_t}{S_t P^*_t}. \tag{73}$$

Consequently, the marginal cost of the importing consumption and investment good firms are given as:

$$
\begin{aligned}
mc_t^{m,c} &\equiv \frac{S_t P_t^*}{P_t^{m,c}} = \left(\gamma_t^f \gamma_t^{mc,d}\right)^{-1} && (74)\\
mc_t^{m,i} &\equiv \frac{S_t P_t^*}{P_t^{m,i}} = \left(\gamma_t^f \gamma_t^{mi,d}\right)^{-1}, && (75)
\end{aligned}
$$

while that of the exporting firm is given as:

$$
mc_t^x = \frac{\gamma_t^f}{\gamma_t^{x,*}}. \tag{76}
$$

2.6 Foreign economy

Being exogenous, the foreign economy is modelled as a standard three-equation closed economy DSGE model which is broadly similar to the log-linearised structure of An and Schorfheide (2007):

$$
\begin{aligned}
\hat{y}_t^* &= E_t\hat{y}_{t+1}^* - \frac{1}{\sigma^*}\left(\hat{R}_t^* - E_t\hat{\pi}_{t+1}^* + \xi_t^{y,*}\right) && (77)\\
\hat{\pi}_t^* &= \beta E_t\hat{\pi}_{t+1}^* + \varkappa^*\hat{y}_t^* + \xi_t^{\pi,*} && (78)\\
\hat{R}_t^* &= \rho_R^*\hat{R}_{t-1}^* + (1-\rho_R^*)\left[\phi_{\hat{\pi}}^*\pi_t^* + \phi_y^*\hat{y}_t^*\right] + \varepsilon_t^{R,*}, && (79)
\end{aligned}
$$

where $\hat{y}_t^*$, $\hat{\pi}_t^*$ and $\hat{R}_t^*$ represent output, inflation and the policy rate of the foreign economy. $\xi_t^{y,*}$ and $\xi_t^{\pi,*}$ are AR(1) shock processes.

2.7 The model in state space form

In order to solve the model, its equations are log-linearised.[11] It is then possible to write the solved model in state space form, as follows:

$$
\begin{aligned}
\mathbf{S_t} &= \mathbf{F}\mathbf{S_{t-1}} + \mathbf{Q}\epsilon_\mathbf{t}, && (80)\\
\mathbf{Y_t} &= \mathbf{M} + \mathbf{H}\mathbf{S_t} + \eta_\mathbf{t}, && (81)
\end{aligned}
$$

with

$$
\begin{bmatrix} \epsilon_\mathbf{t} \\ \eta_\mathbf{t} \end{bmatrix} \sim N\left(0, \begin{bmatrix} \sigma & 0 \\ 0 & \mathbf{R} \end{bmatrix}\right), \tag{82}
$$

where the m dimensional state vector $\mathbf{S_t}$ contains the model's endogenous variables, while $\mathbf{Y_t}$ is an n dimensional vector of observable data which is discussed in greater detail in the following section. The matrices $\mathbf{F}$ and $\mathbf{Q}$ are functions of the model's parameters, $\mathbf{M}$ holds the steady-state information of the observed data, and $\mathbf{H}$ serves to map the endogenous variables of the model to the data. $\epsilon_\mathbf{t}$ is a vector of innovations to the model's structural shocks, while $\eta_\mathbf{t}$ is a vector of measurement errors, with $\mathbf{R} = E(\eta_\mathbf{t}\eta_\mathbf{t}')$.

[11] See the Appendix for the entire set of log-linearised equations.

3 Estimation

3.1 Data

In order to estimate the model, a total of fifteen observable domestic and international macro-economic time series for the sample period 2000Q1 to 2012Q4 are used.[12] The choice of sample period yields 52 quarterly observations and coincides with the inflation-targeting regime of the South African Reserve Bank (SARB), which officially commenced in the first quarter of 2000.[13]

Data for the South African economy was largely obtained from the SARB Quarterly Bulletin, however, CPI and producer price inflation were obtained from StatsSA. GDP, inflation and the interest rate of the foreign economy are all calculated as trade-weighted averages of South Africa's main trading partner countries. The data for South Africa's trading partners was sourced from the Global Projection Model of the Center for Economic Research and its Applications (CEPREMAP).[14] In order to calculate the trade weights, bilateral trade data from the South African Revenue Service's Customs and Excise was used. The trade weight for each country j was calculated as the sum of imports and exports between South Africa and country j as a share of total South African exports and imports from January 2006 to December 2010. Table (1) lists the time series used, as well as their respective sources.

3.1.1 Reconciling the high inflation of the early 2000s with the model structure

Given the legacy of high inflation (and interest rates) which characterised the 1990s, as well as a severe adverse exchange rate shock in December 2001, the measure of CPI inflation then targeted by the SARB only entered the 3 to 6 per cent target range for the first time in the fourth quarter of 2003 - almost four years after the implementation of inflation targeting.[15] Therefore, in order to reconcile the excessively high inflation rates at the start of the sample with the model's steady state inflation rate of 4.5 per cent (i.e. the midpoint of the inflation target range), it is assumed that the *unofficial* midpoint of the inflation target band most likely exceeded 4.5 per cent over this initial period. As such, the model's inflation target variable $\tilde{\bar{\pi}}^c_{t+1}$ is utilised as an additional observable variable and is calculated by means of a Hodrick-Prescott filter which then converges to the 4.5 per cent midpoint in 2004. Similarly, Klein (2012) estimates that the implicit inflation target of the SARB only reached the midpoint of the target band three years after the inflation targeting framework was adopted. Figure (4) in the Appendix plots the estimated inflation target midpoint and CPI inflation.

[12]Data plots of the fifteen series and their corresponding model predictions are in Figure (5) of the Appendix.

[13]Having announced its intention to adopt the inflation targeting framework in August 1999, it was officially implemented by the SARB in February 2000.

[14]In partnership with the Modelling Unit at the International Monetary Fund (IMF), the CEPREMAP modelling team have developed the Global Projection Model (GPM) – a quarterly model of around 35 countries which have been aggregated into 6 regions(see Carabenciov et al., 2012).

[15]After having averaged 10 per cent during the 1990s, CPI inflation had declined to 7.6 per cent by February 2000, but accelerated to a peak of 12.7 per cent in Novemeber 2002.

Table 1: Observable variables

Variable	Series	Source
South Africa		
$\Delta\ln(\tilde{Y}_t)$	Real GDP	South African Reserve Bank
$\Delta\ln(\tilde{C}_t)$	Private consumption	
$\Delta\ln(\tilde{I}_t)$	Total fixed investment	
$\Delta\ln(\tilde{X}_t)$	Total exports	
$\Delta\ln(\tilde{M}_t)$	Total imports	
$\Delta\ln(\tilde{S}_t)$	Nominal effective exchange rate	
$\Delta\ln(\tilde{E}_t)$	Non-agricultural employment	
$\Delta\ln(\tilde{W}_t)$	Compensation of employees	
$\tilde{R}_t$	Repo rate	
$\tilde{\pi}^i_t$	Fixed investment deflator	
$\tilde{\pi}^c_t$	CPI inflation	StatsSA
$\tilde{\pi}^d_t$	PPI inflation, domestic manufacturing	
$\tilde{\bar{\pi}}^c_{t+1}$	Inflation target midpoint	Author's own calculations
Foreign economy		
$\Delta\ln(\tilde{Y}^*_t)$	Real GDP (trade weighted)	GPM, CEPREMAP
$\tilde{\pi}^*_t$	CPI inflation (trade weighted)	
$\tilde{R}^*_t$	Policy interest rates (trade weighted)	

3.2 Measurement equations

Since the theoretical model is stationary, the observable variables need to be rendered stationary before matching them to their model counterparts. To this end, all trending observable variables are loaded as first differences. In addition, the construction of the observable variables may differ from that of their theoretical counterparts in the model. For example, the data on consumption ($\tilde{C}_t$) is constructed as the sum of imported and domestic consumption:

$$\tilde{C}_t = C^m_t + C^d_t, \tag{83}$$

where the ˜ above a variable denotes that it is observable. However, the theoretical measure of consumption in the model is a CES aggregate of imported and domestic consumption, and hence the observed measure of consumption needs to be adjusted in order to take account of the relative prices included in the theoretical measure. As a result, Eq. (83) is expressed as:

$$\tilde{C}_t = \left((1-\vartheta_c) \left[\frac{P^d_t}{P^c_t} \right]^{-\eta_c} + \vartheta_c \left[\frac{P^{m,c}_t}{P^c_t} \right]^{-\eta_c} \right) C_t. \tag{84}$$

Consequently, the need to account for relative prices also applies to observable investment, imports and exports, as follows:

$$\begin{aligned}\tilde{I}_t &= I_t^m + I_t^d \\ &= \left((1-\vartheta_i)\left[\frac{P_t^d}{P_t^i}\right]^{-\eta_i} + \vartheta_i\left[\frac{P_t^{m,i}}{P_t^i}\right]^{-\eta_i}\right) I_t,\end{aligned} \tag{85}$$

$$\begin{aligned}\tilde{M}_t &= C_t^m + I_t^m \\ &= \vartheta_c\left[\frac{P_t^{m,c}}{P_t^c}\right]^{-\eta_i} C_t + \vartheta_i\left[\frac{P_t^{m,i}}{P_t^i}\right]^{-\eta_i} I_t,\end{aligned} \tag{86}$$

$$\begin{aligned}\tilde{X}_t &= C_t^x + I_t^x \\ &= \left[\frac{P_t^x}{P_t^*}\right]^{-\eta_f} Y_t^*.\end{aligned} \tag{87}$$

Moreover, the aggregate resource constraint from Eq. (64) can be expressed as:

$$\begin{aligned}&\left(C_t^d + C_t^m\right) + \left(I_t^d + I_t^m\right) + G_t + \left(C_t^x + I_t^x\right) - \left(C_t^m + I_t^m\right) \\ &\qquad \leq \varepsilon_t\left(K_t^s\right)^{\alpha}\left(z_t H_t\right)^{1-\alpha} - z_t\phi - a\left(u_t\right)K_t.\end{aligned} \tag{88}$$

The presence of capital utilisation costs in Eq. (88) implies that observable GDP is not directly comparable with its theoretical counterpart and, as a result, the measurement equation for observed GDP needs to account for them. Appendix A contains the full set of log-linearised measurement equations. Of the fifteen observable variables, nine are included with measurement error, to allow for the fact that the data is merely an approximation of the actual underlying series.[16] Following Jääskelä and Nimark (2011), **R** in Eq. (82) is calibrated such that 10 per cent of the variation in the observed data is explained by measurement error.

3.3 Estimation methodology

The model is estimated with Bayesian techniques, as this approach offers a number of advantages. An and Schorfheide (2007) highlight some of them: First, Bayesian analysis is system based and therefore fits the complete solved DSGE model to actual data, as opposed to generalised method of moments (GMM), which estimates individual equilibrium relationships of the model. Second, it allows for the incorporation of additional information in parameter estimation by means of prior distributions which are specified by the researcher, whereas structural parameter estimates generated through maximum likelihood estimation are often significantly different from the additional prior information that the researcher might have. Therefore, Bayesian estimation serves as a bridge between pure calibration and maximum likelihood. Lubik and Schorfheide (2005) also emphasise the benefit of Bayesian es-

[16]It is assumed that $\tilde{\pi}_t^c$, $\tilde{\pi}_t^d$, $\tilde{\pi}_t^*$, $\tilde{R}_t$, $\tilde{R}_t^*$ and $\Delta\ln(\tilde{S}_t)$ are free from measurement error.

timation from a practical perspective, along with Sims (2008) who believes that the use of Bayesian methods can greatly improve macro-econometric modelling in central banks. In the light of these findings, the parameters of the model are estimated with Bayesian techniques.

3.4 Calibration

Although the model is estimated with Bayesian methods, a large number of parameters are nevertheless still calibrated. The need to calibrate certain parameters may either depend on specific steady-state ratios which have to be pinned down, or result from insufficient identification of a specific parameter.[17] Table (2) lists the calibrated parameters.

Table 2: Calibrated parameters

β	Discount factor	0.9975	δ	Depreciation rate	0.025
A_L	Labour disutility constant	7.5	σ_L	Labour supply elasticity	5
σ_a	Capital utilisation cost	10	α	Capital share in production	0.23
ϑ_c	Consumption imports share	0.36	ϑ_i	Investment imports share	0.48
θ_w	Calvo: wage setting	0.69	$\varkappa_w$	Indexation: wage setting	0.5
λ_w	Wage setting markup	1.05	λ_d	Domestic price markup	1.1
η_c	Subst. elasticity: consumption	1.5	η_i	Subst. elasticity: investment	1.5
η_f	Subst. elasticity: foreign	1.25	μ^z	Permanent technology growth	1.0085
π	Steady state inflation	1.0114	g_y	Government spending to GDP	0.197
ρ_g	Government spending persistence	0.815	π^*	Foreign inflation	1.005

The discount factor β is calibrated to 0.9975. Although this value is higher than 0.99 that is standard in the literature, its high value is crucial to ensure that the steady-state nominal interest rate does not become unplausibly high. The deprecation rate δ is set to 0.025, which implies an annual depreciation of capital of 10 per cent. The constant in the disutility of labour, A_L, is calibrated to 7.5 which implies that households devote more or less 30 per cent of their time to working, while the calibration of the inverted Frisch elasticity of labour supply at 5 follows Martínez-García et al. (2012). Altig et al. (2011) estimate the parameter that governs the adjustment cost of capital utilisation, σ_a, at 2.02, while Adolfson et al. (2007) calibrate it to 1,000,000 – which effectively removes the capital utilisation channel from the model. Based on a comparison of the model's log marginal likelihood using both Altig et al. (2011) and Adolfson et al.'s 2007 capital utilisation parameter values, as well as some intermediate ones, the parameter is ultimately set to 10. The share of capital used in production α is set to 0.23. This value is lower than its actual sample mean, but is necessary to ensure that the model's steady-state ratios for both consumption and investment to GDP match their sample means of 60 and 20 per cent, respectively. Similarly, the shares of imports in aggregate consumption and investment, ϑ_c and ϑ_i, are calibrated to values slightly higher than their sample means. However, these calibrations ensure that the model's steady-state ratios of total imports and exports to GDP match their sample means of roughly 27 per cent. The parameters that guide the persistence in wage setting, θ_w and $\varkappa_w$, are not identified and as a result are both calibrated to 0.75 – implying that wage contracts are re-optimised once every four quarters, with a high degree of indexation to past inflation.

[17]Identification analysis of the model's parameters was carried out using the identification toolbox in Dynare, which is largely based on Iskrev (2010a, 2010b) as well as Andrle (2010).

The steady-state wage markup follows Adolfson et al. (2007) and is set at 1.05, while the markup for domestic prices is calibrated to 1.1. Estimates of the substitution elasticities for consumption, investment and foreign goods generally vary between 1 and 2, and are therefore calibrated to 1.5, 1.5 and 1.25 respectively. The steady-state growth rate of the model's stochastic trend, μ^z, is set to 1.0085, which implies a steady-state economy-wide growth rate of 3.4 per cent – roughly the average growth rate of GDP over the sample. Steady state growth of money, μ^m, is set to 1.02, *i.e.* an annualised rate of 8 per cent. Moreover, the steady-state rate of inflation π in the model is calibrated to yield an annual rate of 4.5 per cent. The nominal interest rate in steady state is $R = (\pi\mu^z)/\beta$. Hence, the calibrations for β, μ^z and μ^m together imply an annualised steady-state nominal interest rate of 8.9 per cent. The steady-state ratio of government spending to GDP, g_y, matches its sample mean, while the persistence of government spending is set to an OLS estimate of the AR(1) coefficient for government spending. The calibration for steady-state foreign inflation implies an annualised rate of 2 per cent.

3.5 Prior distributions

The prior means and their corresponding distributions are summarised in Table (3) and largely follow Adolfson et al. (2007) and Smets and Wouters (2003), where exceptions pertain to specifics of the South African economy. Consequently, the prior for the investment adjustment cost parameter ϕ_i, is assumed to follow a normal distribution around a mean of 7.694. The degree of habit persistence – being bounded between zero and unity – is assumed to follow a beta distribution around 0.65.

The Calvo price-setting parameters (θ's) as well as those governing backward indexation ($\varkappa$'s) are also bounded to lie between zero and one and are assumed to follow beta distributions. Moreover, the prior means for the Calvo parameters reflect the view that South African inflation is fairly sticky, such that domestic prices are re-optimised once every 3 to 4 quarters. Moreover, the firms that do not reset are assumed to place an equal weight on the previous period's inflation rate and the current inflation target. The elasticity of the risk premium in the UIP condition is assumed to follow an inverse-gamma distribution around a mean of 0.01, which equals Alpanda et al.'s 2010b calibration of this parameter. Given the lack of prior information on ϕ_s – the parameter that guides the expected exchange rate modification in the UIP condition – it is assumed to follow a uniform distribution and hence, may take any value between zero and one.

Following Smets and Wouters (2003), the priors for the Taylor-rule parameters are fairly standard. However, a larger weight is placed on both output parameters in order to allow for a more flexible approach to inflation targeting, especially during the period following the global financial crisis of 2008.

The persistence of structural shocks are all assumed to follow a beta distribution around a mean of 0.75 with standard deviation of 0.1, while the standard deviations of the shocks themselves are assumed to follow inverse-gamma distributions around means that are more or less in line with Adolfson et al. (2007). However, the risk-premium shock allows for a larger standard deviation, largely due to South Africa's emerging market status and the consequent exposure of the Rand to bouts of global risk aversion.

Table 3: Priors and posterior estimation results

Parameter description		Prior			Posterior	
		Density[a]	Mean	Std. Dev.	Mean	90% interval
Adjustment costs						
ϕ_i	Investment	N	7.694	1.5	10.517	[8.49 ; 12.6]
Consumption						
b	Habit formation	B	0.65	0.1	0.808	[0.75 ; 0.87]
Calvo parameters						
θ_d	Domestic prices	B	0.715	0.05	0.699	[0.62 ; 0.78]
θ_{mc}	Imported consumption prices	B	0.675	0.1	0.762	[0.66 ; 0.87]
θ_{mi}	Imported investment prices	B	0.675	0.1	0.805	[0.74 ; 0.87]
θ_x	Export prices	B	0.675	0.1	0.640	[0.55 ; 0.73]
θ_E	Employment	B	0.675	0.1	0.633	[0.53 ; 0.73]
Indexation						
$\varkappa_d$	Domestic prices	B	0.5	0.15	0.502	[0.31 ; 0.70]
$\varkappa_{mc}$	Imported consumption prices	B	0.5	0.15	0.329	[0.14 ; 0.49]
$\varkappa_{mi}$	Imported investment prices	B	0.5	0.15	0.283	[0.11 ; 0.44]
Exchange rate						
ϕ_a	Risk premium	IG	0.01	Inf	0.006	[0.00 ; 0.01]
ϕ_s	Modified UIP	U	0.5	[0,1]	0.192	[0.09 ; 0.30]
Taylor Rule						
ρ_R	Smoothing	B	0.8	0.05	0.830	[0.79 ; 0.87]
ϕ_π	Inflation	G	1.7	0.15	1.728	[1.49 ; 1.95]
$\phi_{\Delta\pi}$	Inflation (change)	G	0.3	0.1	0.271	[0.13 ; 0.41]
ϕ_y	Output gap	G	0.25	0.05	0.249	[0.17 ; 0.33]
$\phi_{\Delta y}$	Output gap (change)	G	0.125	0.05	0.170	[0.07 ; 0.27]
Persistence parameters						
ρ_{μ^z}	Permanent technology	B	0.75	0.1	0.835	[0.73 ; 0.93]
ρ_ε	Transitory technology	B	0.75	0.1	0.765	[0.62 ; 0.92]
ρ_i	Investment technology	B	0.75	0.1	0.786	[0.70 ; 0.88]
$\rho_{\tilde{z}^*}$	Asymmetric technology	B	0.75	0.1	0.783	[0.63 ; 0.94]
ρ_c	Consumption preference	B	0.75	0.1	0.682	[0.54 ; 0.84]
ρ_H	Labour supply	B	0.75	0.1	0.486	[0.35 ; 0.62]
ρ_a	Risk premium	B	0.75	0.1	0.699	[0.59 ; 0.81]
ρ_{λ^d}	Imported cons. price markup	B	0.75	0.1	0.648	[0.49 ; 0.80]
$\rho_{\lambda^{mc}}$	Imported cons. price markup	B	0.75	0.1	0.816	[0.66 ; 0.97]
$\rho_{\lambda^{mi}}$	Imported invest. price markup	B	0.75	0.1	0.651	[0.47 ; 0.83]
ρ_{λ^x}	Export price markup	B	0.75	0.1	0.591	[0.42 ; 0.77]
Structural shocks						
σ_{μ^z}	Permanent technology	IG	0.4	Inf	0.298	[0.20 ; 0.39]
σ_ε	Transitory technology	IG	0.7	Inf	1.548	[0.79 ; 2.27]
σ_i	Investment technology	IG	0.4	Inf	0.303	[0.21 ; 0.39]
$\sigma_{\tilde{z}^*}$	Asymmetric technology	IG	0.4	Inf	0.237	[0.11 ; 0.37]
σ_c	Consumption preference	IG	0.4	Inf	0.130	[0.09 ; 0.17]
σ_H	Labour supply	IG	0.2	Inf	0.355	[0.26 ; 0.46]
σ_a	Risk premium	IG	0.5	Inf	1.507	[0.97 ; 2.02]
σ_d	Domestic price markup	IG	0.3	Inf	0.648	[0.48 ; 0.82]
σ_{mc}	Imported cons. price markup	IG	0.3	Inf	0.942	[0.63 ; 1.25]
σ_{mi}	Imported invest. price markup	IG	0.3	Inf	0.646	[0.33 ; 0.95]
σ_x	Export price markup	IG	0.3	Inf	1.528	[1.06 ; 1.98]
σ_R	Monetary policy	IG	0.15	Inf	0.137	[0.11 ; 0.16]

[a] B – Beta, G – Gamma, IG – Inverse Gamma, N – Normal, U – Uniform

3.6 Estimation results

The posterior estimation results are summarised in Table (3), while Figure (3) in the Appendix contains the prior and posterior distributions. From the posterior results it can firstly be seen that investment adjustment costs are substantially higher than the prior mean, which implies an elasticity of investment of around 0.1 to a one per cent change in the price of installed capital. At 0.757, the degree of habit formation is found to be higher than Adolfson et al. (2007), but in line with the estimate of Jääskelä and Nimark (2011) for Australia.

The Calvo parameter estimates indicate that import and export price contracts are generally reoptimised every 4 quarters, while domestic contracts are reoptimised at a lower frequency – between 2 and 3 quarters. The Calvo estimate for domestic contracts compares favourably with Creamer, Farrell, and Rankin (2012) who find that the average producer price duration in South Africa is around 6 months. The inflation indexation parameters are all estimated to be around 0.5, which implies that an equal weight is placed on past inflation and the current inflation target during indexation. Although the posterior estimate of the risk premium elasticity ϕ_a is lower than its prior, the data nevertheless to some degree favours the endogenous persistence in the risk premium induced by ϕ_s.

Turning to the estimates for Taylor-rule parameters, it appears as if the SARB places a high weight on interest rate stabilisation. In addition, its reaction to changes in inflation and the output gap are less pronounced than what is indicated by the prior on these two parameters.

The estimates for the persistence of shocks indicate that the various technology shocks are most persistent, while export and imported investment markup shocks are least persistent. The standard deviations of the innovations to these shocks vary substantially. Consistent with the high weight placed on interest rate stabilisation, monetary policy shocks exhibit low volatility. However, export markup shocks are the most volatile, which possibly reflects the large weight of commodities in South Africa's export basket.

3.7 Model fit: moments, cross- and autocorrelations

The theoretical standard deviations, cross correlations and autocorrelations implied by the model are compared to those of the observed variables in order to assess how well the model structure conforms to the data.[18] A comparison of the standard deviations in Table (5) indicates that the model generally predicts a slightly greater degree of volatility than is observed in the actual data. Nevertheless, the relative magnitudes of the standard deviations correspond. Moreover, notoriously volatile variables such as imports, exports and especially the nominal exchange rate, are accurately portrayed by the model. The second column of Table (5) contains the cross correlation of the selected variables with the Repo rate.[19] Here there is a large degree of similarity – both in terms of sign and magnitude. More specifically, the model matches both GDP growth and CPI inflation's correlation with the Repo rate. Finally, the first and second coefficients of autocorrelation in Table (5) compare the model-implied persistence with the actual persistence observed in the data.[20] Apart from exports and wages, the

[18]This is standard practise in especially the RBC literature – see for instance Cooley (1995).

[19]Table (6) contains the cross-correlations of all the observed variables.

[20]Figure (6) displays up to the fifth coefficient of autocorrelation.

model generally succeeds in matching the persistence observed in the remaining variables.

3.8 Variance decomposition

Table (7) reports the contribution of the structural shocks' innovations to the variation in the model's key endogenous variables. Innovations to temporary technology $\varepsilon_t^{\varepsilon}$, as well to the domestic and imported price markup shocks (ε_t^{d}, $\varepsilon_t^{m,c}$ and $\varepsilon_t^{m,i}$) are regarded as *supply* shocks, while innovations to the components of aggregate demand (ε_t^{c}, ε_t^{i} and ε_t^{g}) are grouped as *demand* shocks. Columns 8 to 13 in Table (7) contains the individual contributions of the remaining shocks.[21]

Variation in the Repo rate is dominated by innovations to domestic and imported consumption price markups, developments in the labour market and the exchange rate. These shocks also explain a significant proportion of the variation in CPI inflation. Variation in output is dominated by shocks to the labour market. In the light of the adverse impact that widespread labour market turmoil during 2012 is perceived to have had on economic activity, this is a highly intuitive result. In addition, domestic and export price markups are also of importance. The latter likely reflects the impact of variations in international commodity prices – more specifically precious metals – on domestic economic activity. Shocks to imported consumption markups, demand, labour and permanent technology explain the majority of variation in consumption and investment. Not surprisingly, labour market shocks explain a large proportion of the variation in employment. However, domestic price markups also play a significant role, which intuitively reflects the adverse impact that pressure on firms' profit margins has on employment. Innovations to the country risk premium and imported consumption markups dominate variation in both the nominal and real exchange rate. The significant role of the risk premium reflects the Rand's well-documented exposure to global risk aversion, whilst the role of price markups likely points to the theoretical underpinning of purchasing power parity. Innovations to export markups are the largest contributor to export variation, while labour market shocks also play a role. Although imported consumption markups explain the majority of the variation in imports, innovations to domestic price markups, investment and the exchange rate risk premium also contribute. Interestingly, innovations to domestic price markups dominate variation in the real wage, possibly reflecting the high degree of indexation to inflation during the setting of wage agreements.

3.9 Historical shock decomposition

Given the parameter estimates and the state space representation of the model in Equations (80) and (81), the historical evolution of the unobservable variables of the model, as well as the innovations to the structural shocks may be obtained through the Kalman filter.[22] An analysis of the contibutions of these structural shocks to CPI inflation and GDP growth (both year-on-year) may shed some light on the model's interpretation of historical developments in these variables.

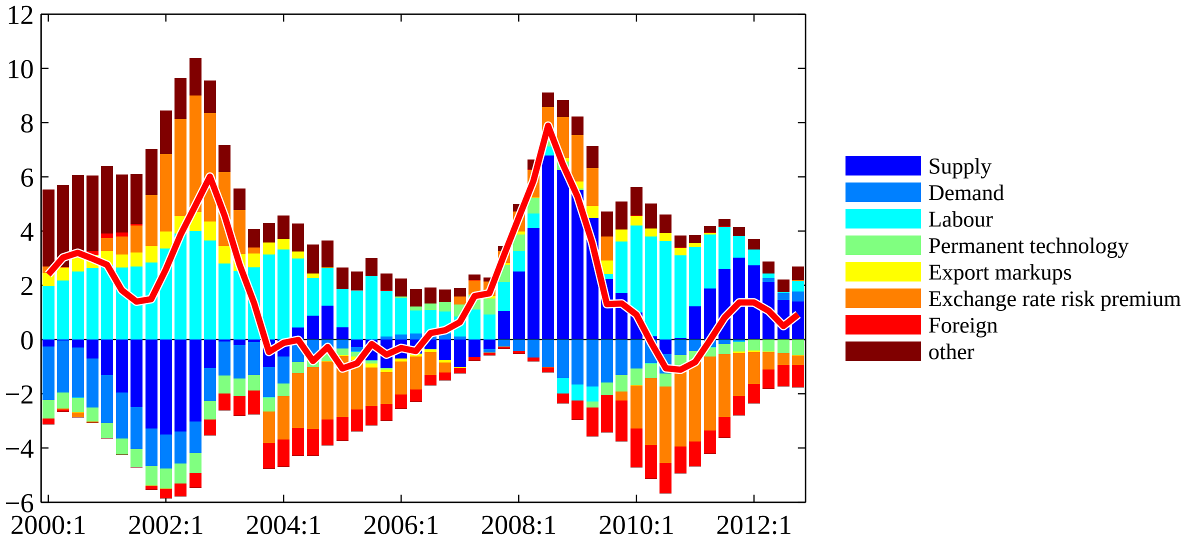
Applying a similar grouping as seen in the variance decomposition in Table 7, the historical shock decomposition of CPI inflation in Figure 1 highlights the main shocks that contributed to inflation's

[21]Innovations to the assymetric technology and inflation target shock, $\varepsilon_t^{\tilde{z}^*}$ and $\varepsilon_t^{\bar{\pi}^c}$, have negligible contributions to the variation in the key variables and are therefore not reported in Table (7).

[22]The historical evolution of the individual structural shocks and their innovations are in Figure (7) of the Appendix.

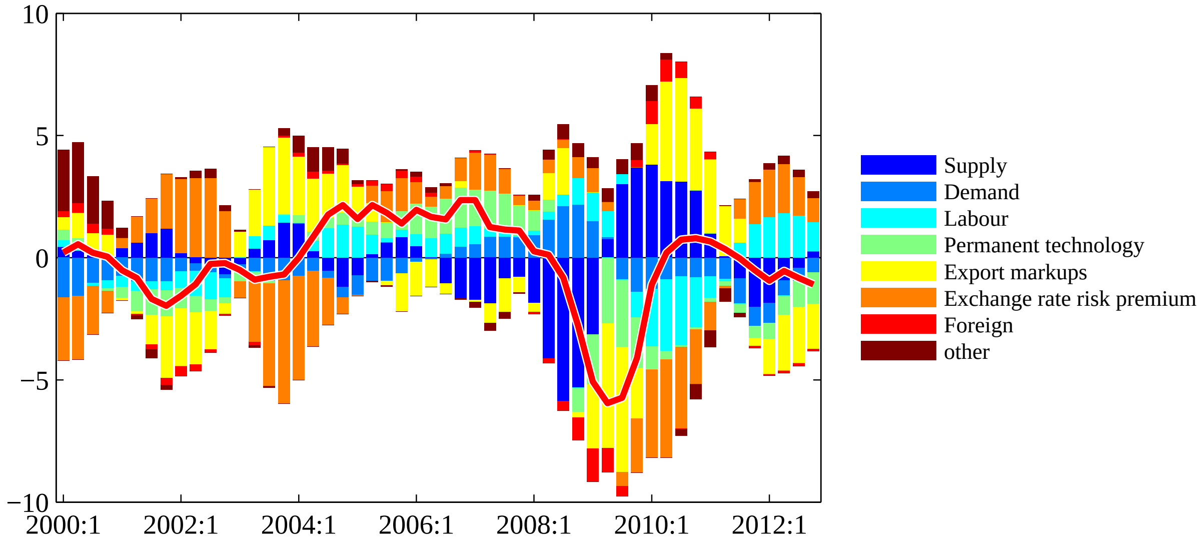
deviations from the midpoint of the inflation target band during the inflation-targeting regime. In the context of the model, the rise in inflation following the Rand's sudden depreciation towards the end of 2001 could be attributed to risk premium shocks and the ensuing domestic cost-push shocks following the depreciation. The decline in inflation from 2003 to 2005 is partly attributed to reductions in the risk premium which led to the Rand's appreciation over this period. Favourable global economic conditions also contributed to the lowering of CPI inflation over this period. Nevertheless, throughout both of these periods the labour market has placed upward pressure on inflation. The model largely ascribes the rise in inflation from 2006 to 2008 to supply shocks, which possibly reflect the rising international oil price and subsequent rise in domestic fuel prices over this period. The onset of the global financial crisis in late 2008 led to a sudden depreciation of the Rand, a fall in international commodity prices, and a sharp decline in demand – global and domestic. The impact thereof can clearly be seen, as the falling commodity prices (more specifically oil prices) and adverse demand shocks contributed to CPI inflation's sudden decline during 2009. This decline in inflation would have been even steeper were it not for the depreciated exchange rate over this period. Nevertheless, by late 2009 a protracted reversal in the currency had begun, which – along with weak global conditions – had a favourable impact on inflation throughout the remainder of the sample period. However, this downward pressure was largely countered to the upside by supply shocks owing to renewed increases in international commodity prices, as well as adverse shocks to the domestic labour market.

Figure 1: CPI inflation: historical shock decomposition



Decomposing the model's estimate of year-on-year GDP growth indicates that developments surrounding the exchange rate dominated South African GDP during the first 4 to 5 years of the sample (see Figure 2). From 2006 to 2008, innovations to demand and permanent technology – the economy's trend growth rate – contributed favourably to growth, while being countered by significant adverse supply shocks during this period. Around the time of the onset of the financial crisis, the adverse impact of global developments becomes evident. Firstly through a decline in global demand, but also through a shock to export markups. It seems plausible that these export-markup shocks reflect the substantial fall in international commodity prices at the time, and the subsequent impact thereof on South Africa's terms of trade. It also appears as if the economy's growth potential was adversely affected by some negative shocks to permanent technology that lasted from the end of 2008 to the beginning of 2010. In addition, whereas demand shocks contributed positively to growth while supply shocks hampered growth in the build-up to the financial crisis, their respective roles reversed during 2009 and 2010. Moreover, the strengthening of the Rand as well as unfavourable labour market conditions placed further pressure on economic growth during the wake of the financial crisis.

Figure 2: GDP growth: historical shock decomposition



4 Model dynamics

In order to analyse the dynamic reaction of the model in response to shocks, we discuss the impact of a selected number of structural shocks. In response to a 100 basis point increase in the Repo rate (see Figure 8), the exchange rate (both real and nominal) appreciates on impact by a similar magnitude. The appreciation reduces imported inflation which lowers CPI inflation. In addition, the higher nominal interest rate, coupled with falling inflation, implies that the real interest rate increase exceeds that of the Repo rate. The higher real interest rate slows down consumption and investment, and hence output. This slowdown in the real economy reduces domestic inflation, which lowers CPI inflation even further. Moreover, the relative price change brought about by the exchange rate appreciation leads to a substantial decline in net exports, as imports surge while exports fall. This serves to amplify the decline in output. The fall in output peaks after 3 quarters at around -0.3 per cent, followed by the year-on-year fall in CPI inflation which peaks in the fourth quarter at roughly -0.2 per cent.

A one percentage point (annualised) shock to the risk premium depreciates the exchange rate by almost 3/4 of a per cent on impact (see Figure 9). This sudden depreciation leads to a rise in imported inflation, and subsequently CPI inflation. In addition, exports rise in response to the favourable exchange rate, while the opposite holds for imports. Output rises as a result of the improvement in net exports, which in turn has a positive impact on employment. The central bank responds to rising inflation and output by increasing the Repo rate. This tightening of the policy rate cools down the domestic economy, as can be seen from the declines in consumption and investment. After more or less 16 quarters, output and CPI inflation return to their pre-shock levels.

Increasing transitory technology by 1 per cent increases output by almost half a per cent after one year in Figure (10). Simultaneously, this positive supply shock reduces domestic inflation. The gain in international competitiveness caused by falling domestic inflation lead to a real exchange rate depreciation, which in turn improves exports and reduces import demand. This general improvement in net exports improves the net foreign asset position which, through a reduction in the risk premium, leads an appreciation of the nominal exchange rate. The combination of lower import demand and an appreciated nominal exchange rate induce a lowering of imported consumer inflation, which further lowers CPI inflation. Monetary policy accommodates the falling CPI inflation, and after 16 quarters the economy has more-or-less returned to its steady state.

As expected, an annualised 1 percentage point shock to permanent technology μ_t^z – the economy's trend growth rate – leads to a permanent increase in all real variables. Given the unique nature of this shock, as well as its high degree of persistence, the model's long-run (25 years) reaction to the shock is shown in Figure (11). Although all inflation rates increase during the initial periods, largely as a result of rising real wages and a depreciating nominal exchange rate, they return to their steady-state values in the long run.

An adverse labour supply shock in Figure (12) increases the real wage, which in turn raises domestic inflation and subsequently CPI inflation. Rising inflation in the domestic economy appreciates the real exchange rate, fuelling imports while constraining exports. The fall in net exports deteriorates the economy's net foreign asset position, which puts pressure on the nominal exchange rate. Imported inflation rises in response to the nominal depreciation, and further contributes to the rise in CPI inflation. Monetary policy reacts by raising the Repo rate in order to contain rising inflation. The combined effect of contractionary policy and declining net exports cause a substantial decline in output.

Figure (13) shows the response to a sudden 1 per cent increase in foreign output. The overheating of the foreign economy leads to a rise in foreign inflation which necessitates appropriate policy reaction by the foreign central bank. The rise in foreign inflation implies that the real exchange rate in the domestic economy depreciates. As a result there are now two channels at play in the domestic economy: an income effect owing to increased foreign demand; and a price effect caused by the depreciating real exchange rate. Hence, exports rise substantially, which has a direct impact on domestic output. Moreover, the real depreciation reduces import demand which is of further benefit to output. Nevertheless, higher inflation abroad is reflected in higher imported inflation domestically. Monetary policy tightens in response to higher inflation and output, and as such cools down the domestic economy. After 20 quarters the economy has returned to its steady-state level.

5 Forecasting performance

According to Del Negro et al. (2007), improvements in the time-series fit of DSGE models have contributed substantially to their increasing popularity in policy-making institutions such as central banks. Consequently, in order to gauge the usefulness of the DSGE model developed in this paper as a potential forecasting tool, its forecasting ability is assessed. Adolfson, Lindé, and Villani (2007), Alpanda et al. (2011) and Christoffel et al. (2010) compare the forecasting ability of open economy DSGE models with other reduced form models, and find that the DSGE models perform favourably. More specifically, the results of Alpanda et al. (2011) are based on a DSGE model that is estimated for South Africa.[23] In this paper we compare the DSGE model's forecasts of CPI inflation, GDP growth (quarter-on-quarter, annualised) and the Repo rate to both a random walk and consensus forecasts of private sector economists as polled by Reuters over the period 2006Q1 to 2012Q3. To this end, the model is re-estimated recursively every four quarters – once per year – where the first recursive estimation spans the sample 1993Q1 to 2005Q4, and the last is from 1999Q1 to 2011Q4. The model is then forecast 7 quarters ahead at each quarter.[24] Since the actual observations end in 2012Q4, there are 28 one-quarter-ahead and 22 seven-quarter-ahead forecast errors.

Table 4: Forecasting performance of the DSGE model

	Quarters ahead						
Relative RMSE statistics	1	2	3	4	5	6	7
CPI inflation, year-on-year							
DSGE/Reuters	1.549	1.066	*0.980*	1.029	*0.913*	*0.798*	*0.704*
DSGE/Random walk	*0.720*	*0.733*	*0.747*	*0.799*	*0.701*	*0.597*	*0.523*
GDP growth (quarter-on-quarter, ann.)							
DSGE/Reuters	1.520	1.528	1.200	1.078	1.012	*0.991*	*0.945*
DSGE/Random walk	1.226	*0.963*	*0.788*	*0.715*	*0.695*	*0.706*	*0.689*
Repo rate							
DSGE/Reuters	3.203	2.092	1.447	1.253	1.166	1.096	1.052
DSGE/Random walk	1.007	*0.967*	*0.941*	*0.970*	*0.991*	*0.978*	*0.938*

Accordingly, these forecast errors from the DSGE model are compared to the corresponding errors of the Reuters consensus poll of private sector economists as well as a random walk (see Table 4). The relative RMSE statistics indicate that the consensus forecasts of CPI inflation from the private sector outperform the DSGE model over the first two quarters of the forecast horizon. At the third quarter the DSGE model becomes competitive, and after the fifth quarter is consistently superior. In addition, the DSGE model's inflation forecasts outperform the random walk over all seven quarters of the forecast horizon. Turning to GDP growth, the consensus forecasts once again outperform the DSGE model over the near term, while the DSGE model is superior at a horizon of six and seven quarters. Moreover, the DSGE model outperforms the random walk from the second quarter onwards. When compared to consensus forecasts of the Repo rate, the DSGE model is less successful. Consensus forecasts are superior over all seven quarters of the forecast horizon, although this superiority decreases as the horizon increases. Nevertheless, the DSGE model is marginally superior to the random walk forecasts of the Repo rate from the second quarter onwards. This general ability of the DSGE model to forecast key macroeconomic variables over the medium to longer term affirms the

[23] Alpanda et al. (2011) abstract from the role of capital, and as a result have fewer frictions than the model in this paper.
[24] The Reuters poll of consensus forecasts covers a seven quarter horizon.

increasing popularity and value of these models in policy-making institutions.

6 Conclusion

In recent years, dynamic stochastic general equilibrium (DSGE) models have become an intergral part of the toolbox of models used in policymaking institutions. This paper estimates an open economy New Keynesian DSGE model – that includes a large variety of frictions and structural shocks – for South Africa. The general structure of the model is similar to operational DSGE models used for forecasting and policy analysis in other central banks. Through the use of Bayesian methods, prior information pertaining to the South African economy is incorporated into the parameter estimates. It is found that the estimated model is able to decompose historical developments in variables of interest in a coherent and useful manner. In addition, the model is able to outperform professional forecasts of CPI inflation and GDP growth, especially at longer horizons. The estimated model is clearly suitable for storytelling as well as forecasting in the South African context and would be valuable to a policy institution such as the South African Reserve Bank.

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A The linearised model

Firms

Domestic goods

Production

$$\hat{y}_t = \lambda^d \left(\hat{\varepsilon}_t + \alpha \left(\hat{k}^s_t - \hat{\mu}^z_t\right) + (1-\alpha)\hat{H}_t\right) \tag{89}$$

Rental rate of capital

$$\hat{r}^k_t = \hat{w}_t + \hat{\mu}^z_t - \hat{k}^s_t + \hat{H}_t \tag{90}$$

Real marginal cost

$$\hat{mc}^d_t = \alpha\, \hat{r}^k_t + (1-\alpha)\left(\hat{w}_t\right) - \hat{\varepsilon}_t \tag{91}$$

New Keynesian Phillips curve

$$\begin{aligned}\hat{\pi}^d_t - \hat{\bar{\pi}}^c_t &= \frac{\beta}{1+\beta\varkappa_d}\left(E_t\hat{\pi}^d_{t+1} - \rho_\pi\hat{\bar{\pi}}^c_t\right) + \frac{\varkappa_d}{1+\beta\varkappa_d}\left(\hat{\pi}^d_{t-1} - \hat{\bar{\pi}}^c_t\right) - \frac{\beta\varkappa_d(1-\rho_\pi)}{1+\beta\varkappa_d}\hat{\bar{\pi}}^c_t \\ &+ \frac{(1-\theta_d)(1-\beta\theta_d)}{(1+\beta\varkappa_d)\theta_d}\left(\hat{mc}^d_t + \hat{\lambda}^d_t\right)\end{aligned} \tag{92}$$

Imported goods

New Keynesian Phillips curve: imported consumption goods

$$\begin{aligned}\hat{\pi}^{m,c}_t - \hat{\bar{\pi}}^c_t &= \frac{\beta}{1+\beta\varkappa_{m,c}}\left(E_t\hat{\pi}^{m,c}_{t+1} - \rho_\pi\hat{\bar{\pi}}^c_t\right) + \frac{\varkappa_{m,c}}{1+\beta\varkappa_{m,c}}\left(\hat{\pi}^{m,c}_{t-1} - \hat{\bar{\pi}}^c_t\right) - \frac{\varkappa_{m,c}\beta(1-\rho_\pi)}{1+\beta\varkappa_{m,c}}\hat{\bar{\pi}}^c_t \\ &+ \frac{\left(1-\theta_{m,c}\right)\left(1-\beta\theta_{m,c}\right)}{\left(1+\beta\varkappa_{m,c}\right)\theta_{m,c}}\left(\hat{mc}^{m,c}_t + \hat{\lambda}^{m,c}_t\right)\end{aligned} \tag{93}$$

Marginal cost: imported consumption goods

$$\hat{mc}^{m,c}_t = -\hat{\gamma}^f_t - \hat{\gamma}^{mc,d}_t \tag{94}$$

New Keynesian Phillips curve: imported investment goods

$$\begin{aligned}\hat{\pi}^{m,i}_t - \hat{\bar{\pi}}^c_t &= +\frac{\beta}{1+\beta\varkappa_{m,i}}\left(E_t\hat{\pi}^{m,i}_{t+1} - \rho_\pi\hat{\bar{\pi}}^c_t\right) + \frac{\varkappa_{m,i}}{1+\beta\varkappa_{m,i}}\left(\hat{\pi}^{m,i}_{t-1} - \hat{\bar{\pi}}^c_t\right) - \frac{\varkappa_{m,i}\beta(1-\rho_\pi)}{1+\beta\varkappa_{m,i}}\hat{\bar{\pi}}^c_t \\ &+ \frac{\left(1-\theta_{m,i}\right)\left(1-\beta\theta_{m,i}\right)}{\left(1+\beta\varkappa_{m,i}\right)\theta_{m,i}}\left(\hat{mc}^{m,i}_t + \hat{\lambda}^{m,i}_t\right)\end{aligned} \tag{95}$$

Marginal cost: imported investment goods

$$\hat{mc}^{m,i}_t = -\hat{\gamma}^f_t - \hat{\gamma}^{mi,d}_t \tag{96}$$

Exported goods

New Keynesian Phillips curve: exported goods

$$\begin{aligned}\hat{\pi}_t^x - \hat{\bar{\pi}}_t^c &= \frac{\beta}{1+\beta\varkappa_x}\left(E_t\hat{\pi}_{t+1}^x - \rho_\pi\hat{\bar{\pi}}_t^c\right) + \frac{\varkappa_x}{1+\beta\varkappa_x}\left(\hat{\pi}_{t-1}^x - \hat{\bar{\pi}}_t^c\right) - \frac{\varkappa_x\beta(1-\rho_\pi)}{1+\beta\varkappa_x}\hat{\bar{\pi}}_t^c \\ &+ \frac{(1-\theta_x)(1-\beta\theta_x)}{(1+\beta\varkappa_x)\theta_x}\left(\hat{mc}_t^x + \hat{\lambda}_t^x\right)\end{aligned} \tag{97}$$

Marginal cost: exported goods

$$\hat{mc}_t^x = \hat{mc}_{t-1}^x + \hat{\pi}_t^d - \hat{\pi}_t^x - \Delta\hat{S}_t \tag{98}$$

Households

Wage setting

$$\hat{w}_t = -\frac{1}{\eta_1}\begin{bmatrix} \eta_0\hat{w}_{t-1} + \eta_2 E_t\hat{w}_{t+1} + \eta_3\left(\hat{\pi}_t^d - \hat{\bar{\pi}}_t^c\right) + \eta_4\left(E_t\hat{\pi}_{t+1}^d - \rho_\pi\hat{\bar{\pi}}_t^c\right) \\ +\eta_5\left(\hat{\pi}_{t-1}^c - \hat{\bar{\pi}}_t^c\right) + \eta_6\left(\hat{\pi}_t^c - \rho_\pi\hat{\bar{\pi}}_t^c\right) + \eta_7\hat{\psi}_t^z + \eta_8\hat{H}_t + \eta_9\hat{\xi}_t^h \end{bmatrix} \tag{99}$$

Consumption Euler equation

$$\begin{aligned}\hat{c}_t &= \frac{\mu^z b}{(\mu^z)^2+\beta b^2}\hat{c}_{t-1} + \frac{\beta\mu^z b}{(\mu^z)^2+\beta b^2}E_t\hat{c}_{t+1} - \frac{\mu^z b}{(\mu^z)^2+\beta b^2}\left(\hat{\mu}_t^z - \beta E_t\hat{\mu}_{t+1}^z\right) \\ &- \frac{(\mu^z-b)(\mu^z-\beta b)}{(\mu^z)^2+\beta b^2}\left(\hat{\psi}_t^z + \hat{\gamma}_t^{c,d}\right) + \frac{\mu^z-b}{(\mu^z)^2+\beta b^2}\left(\mu^z\hat{\xi}_t^c - \beta b E_t\hat{\xi}_{t+1}^c\right)\end{aligned} \tag{100}$$

Investment Euler equation

$$\hat{i}_t = \frac{1}{1+\beta}\left[\beta E_t\hat{i}_{t+1} + \hat{i}_{t-1} + \beta E_t\hat{\mu}_{t+1}^z - \mu_t^z\right] + \frac{1}{(\mu^z)^2\phi_i(1+\beta)}\left(\hat{P}_t^k - \hat{\gamma}_t^{i,d} + \hat{\xi}_t^i\right) \tag{101}$$

Price of installed capital

$$\hat{P}_t^k = E_t\left[\frac{(1-\delta)\beta}{\mu^z}\hat{P}_{t+1}^k + \hat{\psi}_{t+1}^z - \hat{\psi}_t^z - \hat{\mu}_{t+1}^z + \frac{\mu^z-(1-\delta)\beta}{\mu^z}\hat{r}_{t+1}^k\right] \tag{102}$$

Capital's law-of-motion

$$\hat{k}_{t+1} = \frac{1-\delta}{\mu^z}\left(\hat{k}_t - \hat{\mu}_t^z\right) + \left(1 - \frac{1-\delta}{\mu^z}\right)\left(\hat{i}_t + \hat{\xi}_t^i\right) \tag{103}$$

Capital utilisation

$$\hat{u}_t = \frac{1}{\sigma_a}\hat{r}_t^k \tag{104}$$

Capital services

$$\hat{k}_t^s = \hat{k}_t + \hat{u}_t \tag{105}$$

Optimal asset holdings

$$\hat{\psi}_t^z = E_t\left(\hat{\psi}_{t+1}^z - \hat{\mu}_{t+1}^z\right) + \left(\hat{R}_t - E_t\hat{\pi}_{t+1}^d\right) \tag{106}$$

Modified UIP condition

$$\hat{R}_t - \hat{R}_t^* = (1-\tilde{\phi}_s)E_t\Delta\hat{S}_{t+1} - \tilde{\phi}_s\Delta\hat{S}_t - \tilde{\phi}_a\hat{a}_t + \hat{\tilde{\phi}}_t, \tag{107}$$

The Central Bank

Taylor rule

$$\hat{R}_t = \rho_R\hat{R}_{t-1} + (1-\rho_R)\left[\hat{\bar{\pi}}_t^c + \phi_\pi\left(\hat{\pi}_{t+1}^{c,4} - \hat{\bar{\pi}}_t^c\right) + \phi_{\Delta\pi}\hat{\pi}_t^c + \phi_y\hat{y}_t + \phi_{\Delta y}\Delta\hat{y}_t\right] + \varepsilon_t^R. \tag{108}$$

where CPI inflation is given by

$$\hat{\pi}_t^c = \left(1-\vartheta_c\right)\left(\frac{1}{\gamma^{c,d}}\right)^{1-\eta_c}\hat{\pi}_t^d + \vartheta_c\left(\gamma^{mc,c}\right)^{1-\eta_c}\hat{\pi}_t^{m,c} \tag{109}$$

Relative prices

Consumption and investment goods

$$\hat{\gamma}_t^{c,d} = \hat{\gamma}_{t-1}^{i,d} + \hat{\pi}_t^c - \hat{\pi}_t^d \tag{110}$$

$$\hat{\gamma}_t^{i,d} = \hat{\gamma}_{t-1}^{i,d} + \hat{\pi}_t^i - \hat{\pi}_t^d \tag{111}$$

Imported consumption and investment goods

$$\hat{\gamma}_t^{mc,d} = \hat{\gamma}_{t-1}^{mc,d} + \hat{\pi}_t^{m,c} - \hat{\pi}_t^d \tag{112}$$

$$\hat{\gamma}_t^{mi,d} = \hat{\gamma}_{t-1}^{mi,d} + \hat{\pi}_t^{m,i} - \hat{\pi}_t^d \tag{113}$$

Export goods

$$\hat{\gamma}_t^{x,*} = \hat{\gamma}_{t-1}^{x,*} + \hat{\pi}_t^x - \hat{\pi}_t^* \tag{114}$$

Domestic-foreign goods relative price

$$\hat{\gamma}_t^f = \hat{mc}_t^x + \hat{\gamma}_t^{x,*} \tag{115}$$

Real exchange rate

$$\hat{\gamma}_t^s = -\vartheta_c\left(\frac{1}{\gamma^{mc,c}}\right)^{\eta_c-1}\hat{\gamma}_t^{mc,d} - \hat{\gamma}_t^{x,*} - \hat{mc}_t^x \tag{116}$$

Market clearing

Domestic goods market

$$
\begin{aligned}
\hat{y}_t &= (1-\vartheta_c)\left(\gamma^{c,d}\right)^{\eta_c}\frac{c}{y}\left(\hat{c}_t+\eta_c\hat{\gamma}_t^{c,d}\right)+(1-\vartheta_i)\left(\gamma^{i,d}\right)^{\eta_i}\frac{i}{y}\left(\hat{i}_t+\eta_i\hat{\gamma}_t^{i,d}\right)\\
&+ g_y\hat{g}_t+\frac{y^*}{y}\left(\hat{y}_t^*-\eta_f\hat{\gamma}_t^{x,*}+\hat{\tilde{z}}_t^*\right)+\frac{r^k}{\mu^z}\frac{k}{y}\left(\hat{k}_t^s-\hat{k}_t\right) \qquad (117)
\end{aligned}
$$

Foreign bond market

$$
\begin{aligned}
\hat{a}_t &= -y^*\hat{mc}_t^x-\eta_f y^*\hat{\gamma}_t^{x,*}+y^*\hat{y}_t^*+y^*\hat{\tilde{z}}_t^*+(c^m+i^m)\hat{\gamma}_t^f\\
&- \left[c^m\left(-\eta_c(1-\vartheta_c)\left(\gamma^{c,d}\right)^{\eta_c-1}\right)\hat{\gamma}_t^{mc,d}+\hat{c}_t\right]\\
&- \left[i^m\left(-\eta_i(1-\vartheta_i)\left(\gamma^{i,d}\right)^{\eta_i-1}\right)\hat{\gamma}_t^{mi,d}+\hat{i}_t\right]\\
&+ \frac{\pi^*}{\pi}\frac{1}{\beta}\hat{a}_{t-1} \qquad (118)
\end{aligned}
$$

AR(1) shock processes

$$\Xi_t=\rho\Xi_{t-1}+\Gamma_t \qquad (119)$$

where

$$
\begin{aligned}
\Xi_t &= [\hat{\xi}_t^c \quad \hat{\xi}_t^i \quad \hat{\tilde{\phi}}_t \quad \hat{\varepsilon}_t \quad \hat{\xi}_t^H \quad \hat{\lambda}_t^x \quad \hat{\lambda}_t^d \quad \hat{\lambda}_t^{m,c} \quad \hat{\lambda}_t^{m,i} \quad \hat{\tilde{z}}_t^* \quad \hat{\mu}_t^z \quad \hat{g}_t \quad \hat{\bar{\pi}}_t^c]'\\
\rho &= [\rho_c \quad \rho_i \quad \rho_{\tilde{\phi}} \quad \rho_\varepsilon \quad \rho_H \quad \rho_{\lambda^x} \quad \rho_d \quad \rho_{\lambda^{m,c}} \quad \rho_{\lambda^{m,i}} \quad \rho_{\tilde{z}^*} \quad \rho_{\mu^z} \quad \rho_g \quad \rho_{\bar{\pi}^c}]'\\
\Gamma_t &= [\varepsilon_t^c \quad \varepsilon_t^i \quad \varepsilon_t^{\tilde{\phi}} \quad \varepsilon_t^\varepsilon \quad \varepsilon_t^H \quad \varepsilon_t^x \quad \varepsilon_t^d \quad \varepsilon_t^{m,c} \quad \varepsilon_t^{m,i} \quad \varepsilon_t^{\tilde{z}^*} \quad \varepsilon_t^{\mu^z} \quad \varepsilon_t^g \quad \varepsilon_t^{\bar{\pi}^c}]'
\end{aligned}
$$

Measurement equations

Output

$$\Delta\ln\left(\tilde{Y}_t\right)=\hat{y}_t-\hat{y}_{t-1}+\hat{\mu}_t^z+\ln(\mu^z) \qquad (120)$$

Consumption

$$
\begin{aligned}
\Delta\ln\left(\tilde{C}_t\right) &= \left(\frac{\eta_c}{c^d+c^m}\right)\left[c_d\vartheta_c(\gamma^{c,mc})^{\eta_c-1}-c^m(1-\vartheta_c)\left(\gamma^{c,d}\right)^{\eta_c-1}\right]\left(\hat{\pi}_t^{m,c}-\hat{\pi}_t^d\right)\\
&+ \hat{c}_t-\hat{c}_{t-1}+\mu_t^z+\ln(\mu^z) \qquad (121)
\end{aligned}
$$

Investment

$$
\begin{aligned}
\Delta\ln\left(\tilde{I}_t\right) &= \left(\frac{\eta_i}{i^d+i^m}\right)\left[i_d\vartheta_i\left(\gamma^{i,mi}\right)^{\eta_i-1}-i^m(1-\vartheta_i)\left(\gamma^{i,d}\right)^{\eta_i-1}\right]\left(\hat{\pi}_t^{m,c}-\hat{\pi}_t^d\right)\\
&+ \hat{i}_t-\hat{i}_{t-1}+\hat{\mu}_t^z+\ln(\mu^z) \qquad (122)
\end{aligned}
$$

Exports

$$\Delta\ln\left(\tilde{X}_t\right) = -\eta_f\left(\hat{\pi}_t^x-\hat{\pi}_t^*\right)+\hat{y}_t^*-\hat{y}_{t-1}^*+\hat{\tilde{z}}_t-\hat{\tilde{z}}_{t-1}+\hat{\mu}_t^z+\ln(\mu^z) \qquad (123)$$

Imports

$$
\begin{aligned}
\Delta \ln\left(\tilde{M}_t\right) &= \left(\frac{c^m}{c^m+i^m}\right)\left[\eta_c\left(1-\vartheta_c\right)\left(\gamma^{c,d}\right)^{\eta_c-1}\left[\hat{\pi}_t^d-\hat{\pi}_t^{m,c}\right]+\hat{c}_t-\hat{c}_{t-1}\right] \\
&+ \left(\frac{i^m}{c^m+i^m}\right)\left[\eta_i\left(1-\vartheta_i\right)\left(\gamma^{i,d}\right)^{\eta_i-1}\left[\hat{\pi}_t^d-\hat{\pi}_t^{m,i}\right]+\hat{i}_t-\hat{i}_{t-1}\right] \\
&+ \hat{\mu}_t^z+\ln(\mu^z) \qquad (124)
\end{aligned}
$$

Foreign GDP

$$\Delta \ln\left(\tilde{Y}_t^*\right) = \hat{y}_t^*-\hat{y}_{t-1}^*+\hat{\tilde{z}}_t-\hat{\tilde{z}}_{t-1}+\hat{\mu}_t^z+\ln(\mu^z) \qquad (125)$$

Wages

$$\Delta \ln\left(\tilde{W}_t\right) = \hat{w}_t-\hat{w}_{t-1}+\hat{\pi}_t^d+\hat{\mu}_t^z+\ln(\mu^m) \qquad (126)$$

Employment

$$\Delta \ln\left(\tilde{E}_t\right) = \hat{E}_t-\hat{E}_{t-1} \qquad (127)$$

CPI inflation

$$\tilde{\pi}_t^c = \hat{\pi}_t^c+\ln(\pi) \qquad (128)$$

Producer price inflation

$$\tilde{\pi}_t^d = \hat{\pi}_t^d+\ln(\pi) \qquad (129)$$

Investment deflator

$$\tilde{\pi}_t^i = \hat{\pi}_t^i+\ln(\pi) \qquad (130)$$

Foreign inflation

$$\tilde{\pi}_t^* = \hat{\pi}_t^*+\ln(\pi^*) \qquad (131)$$

Nominal exchange rate

$$\Delta \ln\left(\tilde{S}_t\right) = \Delta\hat{S}_t+\ln\left(\frac{\pi}{\pi^*}\right) \qquad (132)$$

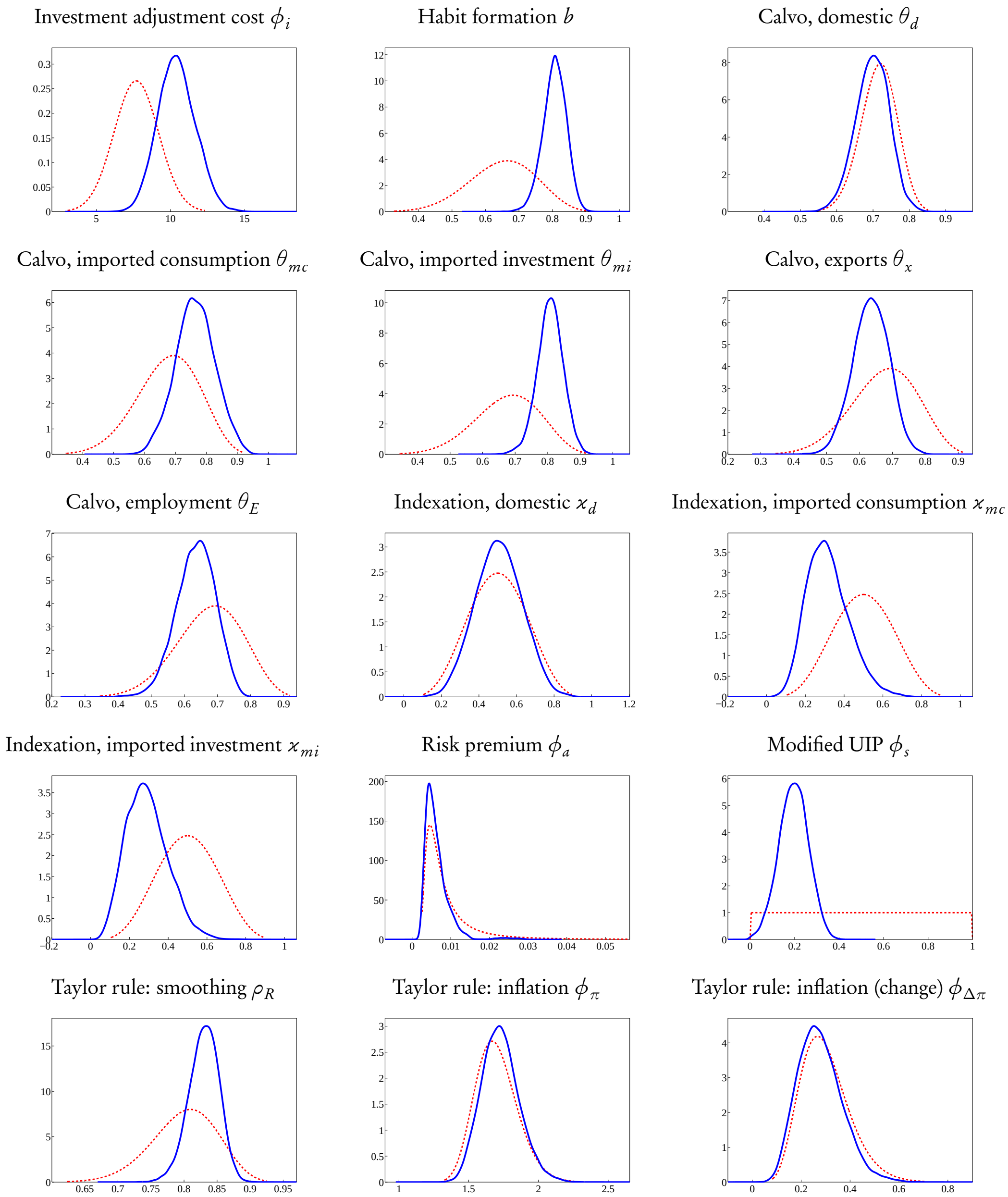
Repo rate

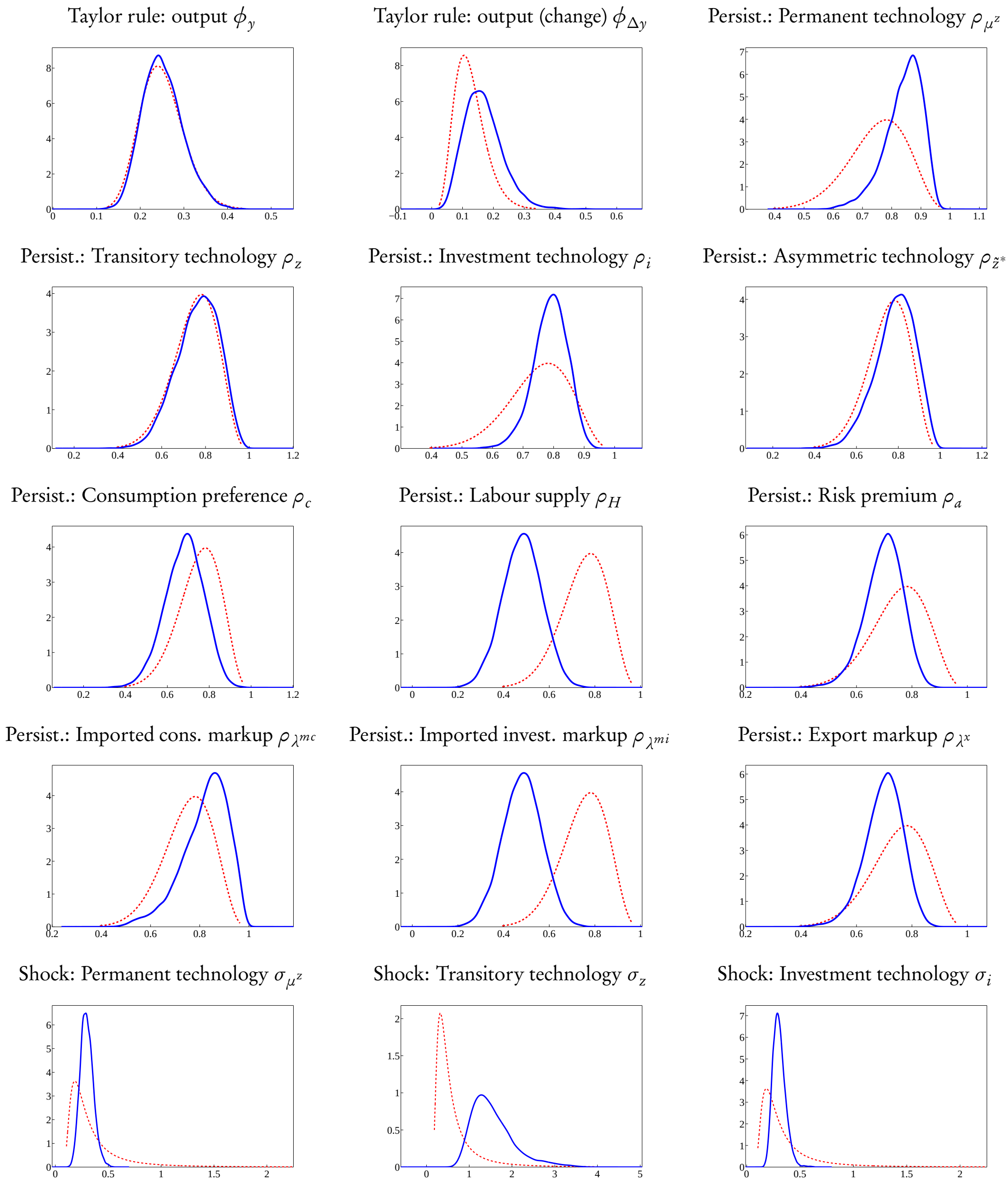
$$\tilde{R}_t^* = \hat{R}_t+\ln(R) \qquad (133)$$

Foreign interest rate

$$\tilde{R}_t^* = \hat{R}_t^*+\ln(R^*) \qquad (134)$$

Figure 3: Prior and posterior density plots




Taylor rule: output ϕ_y
Taylor rule: output (change) $\phi_{\Delta y}$
Persist.: Permanent technology ρ_{μ^z}
Persist.: Transitory technology ρ_z
Persist.: Investment technology ρ_i
Persist.: Asymmetric technology $\rho_{\tilde{z}^*}$
Persist.: Consumption preference ρ_c
Persist.: Labour supply ρ_H
Persist.: Risk premium ρ_a
Persist.: Imported cons. markup $\rho_{\lambda^{mc}}$
Persist.: Imported invest. markup $\rho_{\lambda^{mi}}$
Persist.: Export markup ρ_{λ^x}
Shock: Permanent technology σ_{μ^z}
Shock: Transitory technology σ_z
Shock: Investment technology σ_i

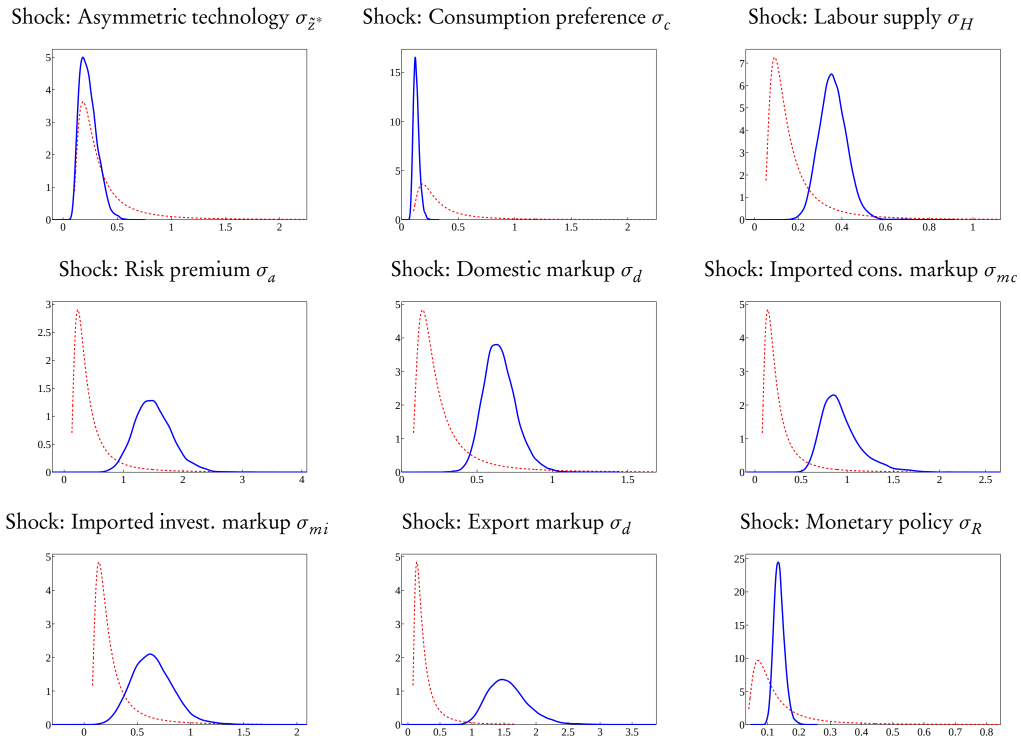


Figure 4: Inflation target midpoint estimate: Early 2000s and before

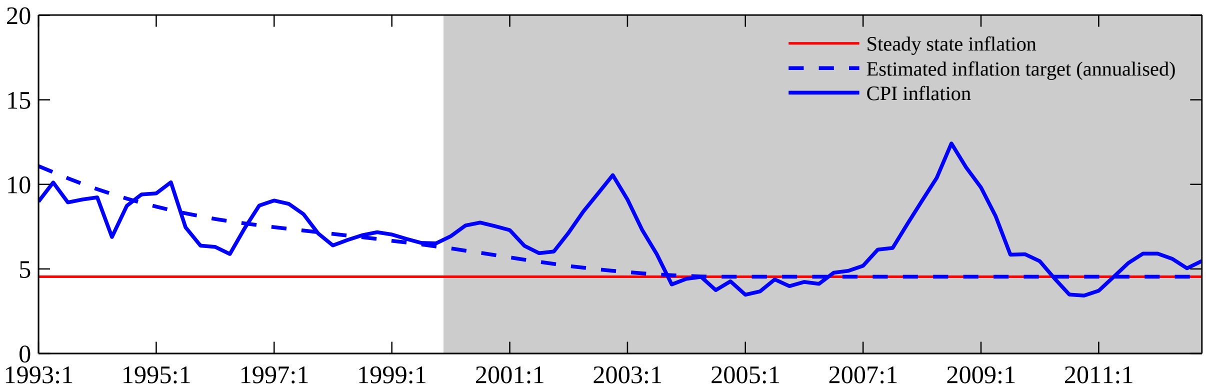


Figure 5: Data plots with corresponding values predicted by the model

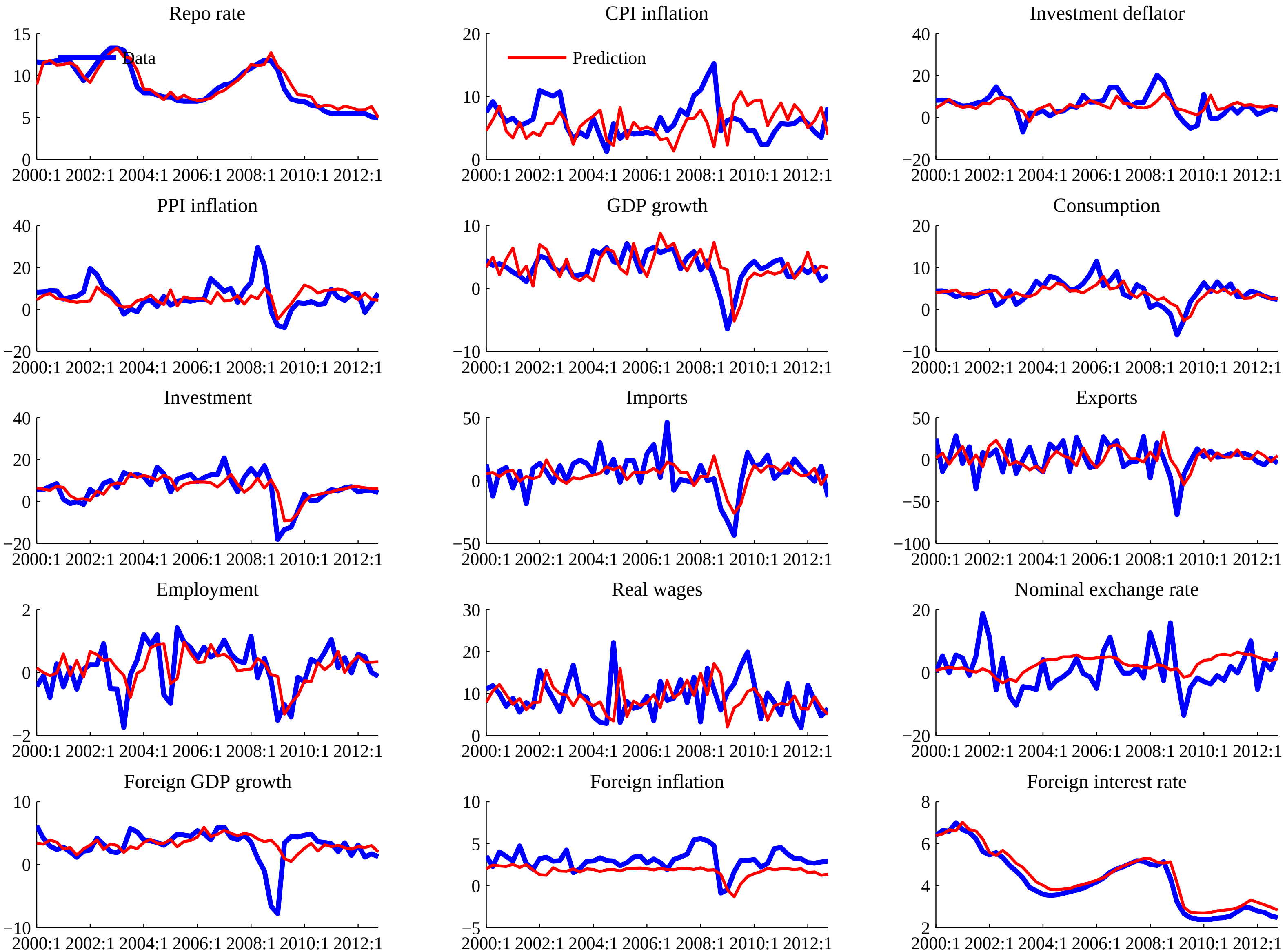


Table 5: Second moments, cross- and autocorrelations: model and data

	Standard deviation	$c(.,\tilde{R}_t)$	$ac(1)$	$ac(2)$
$\tilde{R}_t$	1.57	1	0.97	0.88
	0.63		*0.92*	*0.79*
$\tilde{\pi}_t^d$	2.14	0.69	0.82	0.61
	0.70	*0.49*	*0.60*	*0.39*
$\Delta\ln(\tilde{Y}_t)$	1.96	-0.15	0.77	0.44
	0.60	*-0.16*	*0.66*	*0.33*
$\Delta\ln(\tilde{C}_t)$	1.00	-0.20	0.71	0.50
	0.72	*-0.37*	*0.68*	*0.45*
$\Delta\ln(\tilde{I}_t)$	2.74	0.02	0.73	0.56
	1.85	*0.10*	*0.69*	*0.42*
$\Delta\ln(\tilde{X}_t)$	5.90	-0.13	0.70	0.35
	4.35	*-0.10*	*-0.03*	*0.05*
$\Delta\ln(\tilde{M}_t)$	2.99	-0.03	0.59	0.33
	3.72	*-0.20*	*0.23*	*0.24*
$\Delta\ln(\tilde{S}_t)$	5.96	0.20	0.18	0.00
	6.28	*0.00*	*0.22*	*-0.01*
$\Delta\ln(\tilde{E}_t)$	1.44	-0.20	0.76	0.51
	0.72	*-0.33*	*0.40*	*0.24*
$\Delta\ln(\tilde{W}_t)$	2.32	0.61	0.72	0.52
	1.12	*0.19*	*-0.03*	*-0.02*
$\tilde{\pi}_t^i$	1.92	0.62	0.78	0.57
	1.34	*0.32*	*0.63*	*0.31*
$\tilde{\pi}_t^d$	2.38	0.60	0.80	0.53
	1.63	*0.25*	*0.60*	*0.13*

Statistics for the data are in italics

Table 6: Matrix of variable cross correlations: model and data

Variables	$\tilde{R}_t$	$\tilde{\pi}^c_t$	$\Delta\ln(\tilde{Y}_t)$	$\Delta\ln(\tilde{C}_t)$	$\Delta\ln(\tilde{I}_t)$	$\Delta\ln(\tilde{E}_t)$	$\Delta\ln(\tilde{S}_t)$	$\Delta\ln(\tilde{X}_t)$	$\Delta\ln(\tilde{M}_t)$	$\Delta\ln(\tilde{W}_t)$	$\tilde{\pi}^i_t$	$\tilde{\pi}^d_t$
$\tilde{R}_t$	1	0.69 *0.49*	-0.15 *-0.16*	-0.20 *-0.37*	0.02 *0.10*	-0.20 *-0.33*	0.20 *0.00*	-0.13 *-0.10*	-0.03 *-0.20*	0.61 *0.19*	0.62 *0.32*	0.60 *0.25*
$\tilde{\pi}^c_t$	0.69 *0.49*	1	-0.44 *-0.05*	-0.51 *-0.37*	-0.15 *0.11*	-0.49 *-0.03*	0.04 *0.19*	-0.31 *0.01*	-0.04 *-0.23*	0.71 *0.26*	0.73 *0.60*	0.89 *0.72*
$\Delta\ln(\tilde{Y}_t)$	-0.15 *-0.16*	-0.44 *-0.05*	1	0.41 *0.76*	0.23 *0.61*	0.84 *0.59*	0.08 *0.10*	0.84 *0.63*	-0.12 *0.64*	-0.30 *-0.07*	-0.25 *0.29*	-0.50 *0.43*
$\Delta\ln(\tilde{C}_t)$	-0.20 *-0.37*	-0.51 *-0.37*	0.41 *0.76*	1	0.30 *0.47*	0.33 *0.46*	0.08 *-0.02*	0.17 *0.50*	0.32 *0.67*	-0.19 *-0.14*	-0.19 *0.06*	-0.39 *0.10*
$\Delta\ln(\tilde{I}_t)$	0.02 *0.10*	-0.15 *0.11*	0.23 *0.61*	0.30 *0.47*	1	0.15 *0.54*	0.02 *0.16*	0.00 *0.37*	0.30 *0.43*	0.03 *-0.15*	-0.19 *0.45*	-0.15 *0.43*
$\Delta\ln(\tilde{E}_t)$	-0.20 *-0.33*	-0.49 *-0.03*	0.84 *0.59*	0.33 *0.46*	0.15 *0.54*	1	0.10 *0.24*	0.75 *0.28*	-0.11 *0.38*	-0.46 *-0.44*	-0.27 *0.33*	-0.51 *0.30*
$\Delta\ln(\tilde{S}_t)$	0.20 *0.00*	0.04 *0.19*	0.08 *0.10*	0.08 *-0.02*	0.02 *0.16*	0.10 *0.24*	1	0.09 *-0.01*	0.05 *0.03*	0.07 *-0.24*	0.25 *0.41*	0.09 *0.35*
$\Delta\ln(\tilde{X}_t)$	-0.13 *-0.10*	-0.31 *0.01*	0.84 *0.63*	0.17 *0.50*	0.00 *0.37*	0.75 *0.28*	0.09 *-0.01*	1	0.04 *0.67*	-0.22 *0.09*	-0.07 *0.14*	-0.23 *0.37*
$\Delta\ln(\tilde{M}_t)$	-0.03 *-0.20*	-0.04 *-0.23*	-0.12 *0.64*	0.32 *0.67*	0.30 *0.43*	-0.11 *0.38*	0.05 *0.03*	0.04 *0.67*	1	0.18 *-0.08*	0.18 *0.08*	0.33 *0.24*
$\Delta\ln(\tilde{W}_t)$	0.61 *0.19*	0.71 *0.26*	-0.30 *-0.07*	-0.19 *-0.14*	0.03 *-0.15*	-0.46 *-0.44*	0.07 *-0.24*	-0.22 *0.09*	0.18 *-0.08*	1	0.61 *-0.11*	0.71 *0.15*
$\tilde{\pi}^i_t$	0.62 *0.32*	0.73 *0.60*	-0.25 *0.29*	-0.19 *0.06*	-0.19 *0.45*	-0.27 *0.33*	0.25 *0.41*	-0.07 *0.14*	0.18 *0.08*	0.61 *-0.11*	1	0.82 *0.76*
$\tilde{\pi}^d_t$	0.60 *0.25*	0.89 *0.72*	-0.50 *0.43*	-0.39 *0.10*	-0.15 *0.43*	-0.51 *0.30*	0.09 *0.35*	-0.23 *0.37*	0.33 *0.24*	0.71 *0.15*	0.82 *0.76*	1

Statistics for the data are in italics

Figure 6: Autocorrelations of the model compared to the data

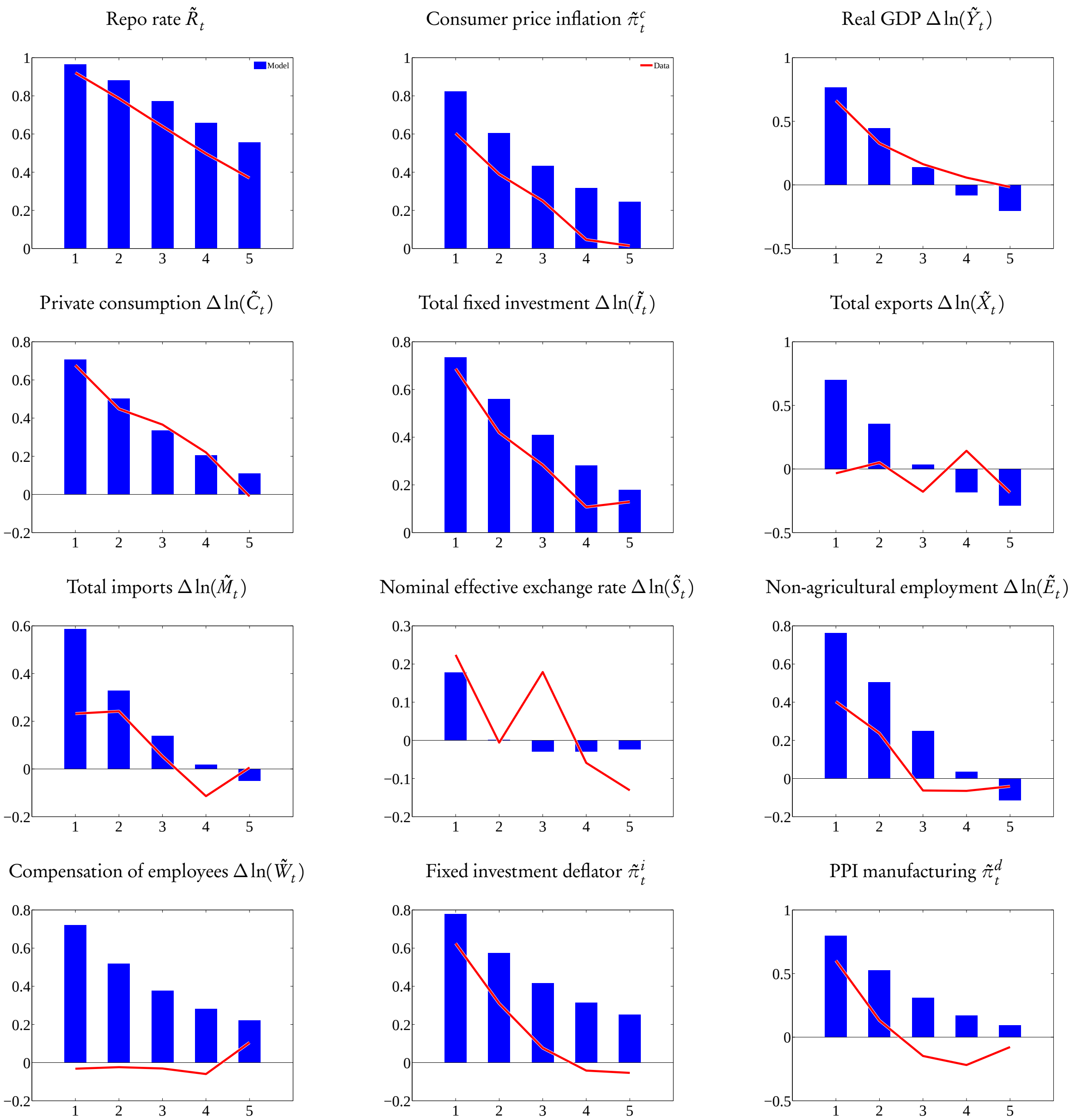
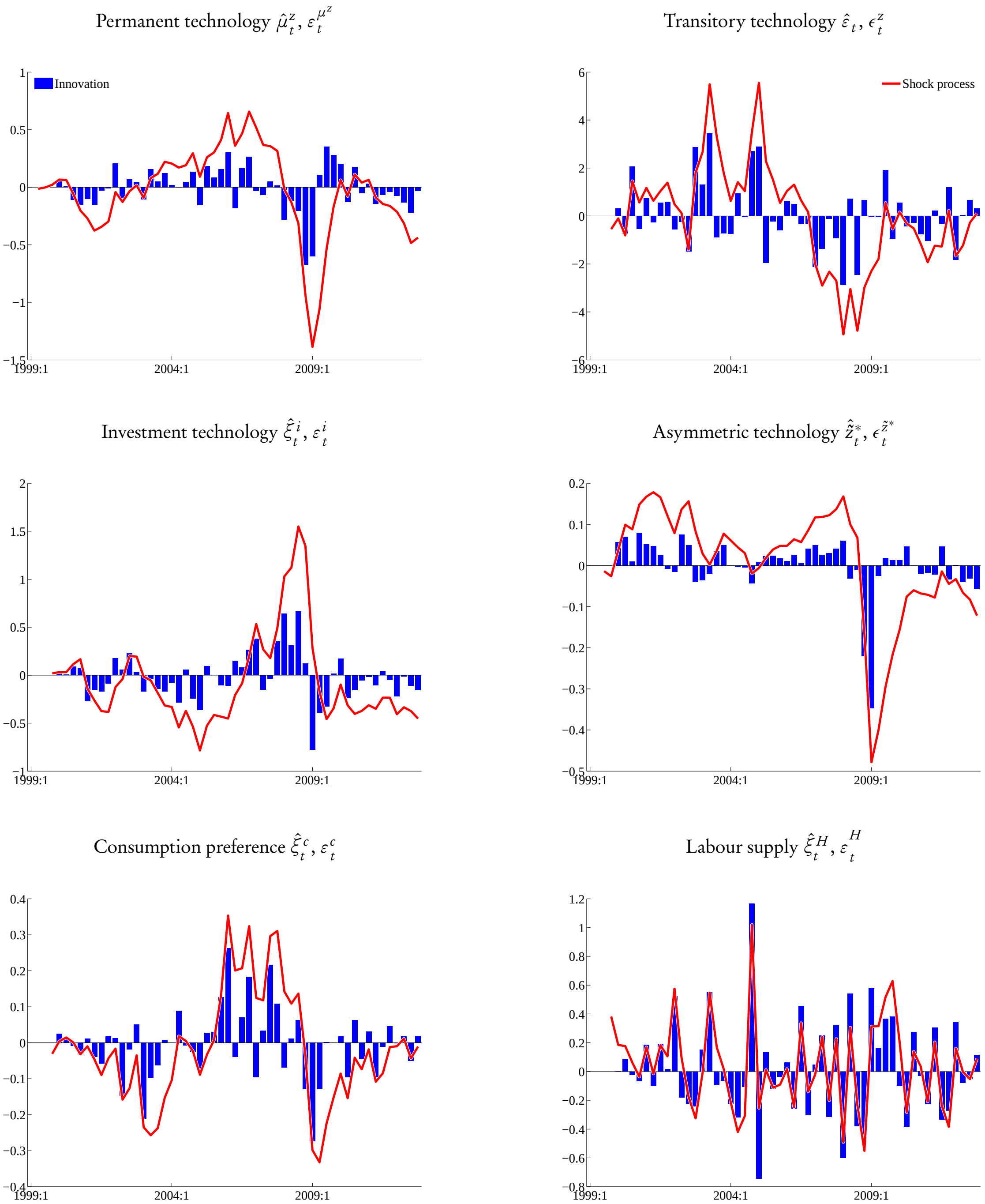


Table 7: Variance decomposition

	Supply				Demand			Labour	Permanent technology	Export markups	Exchange rate risk	Monetary policy	Foreign shocks
	ε_t^{ϵ}	ε_t^{d}	$\varepsilon_t^{m,c}$	$\varepsilon_t^{m,i}$	ε_t^{c}	ε_t^{i}	ε_t^{g}	ε_t^{H}	$\varepsilon_t^{\mu^z}$	ε_t^{x}	$\varepsilon_t^{\tilde{\phi}}$	ε_t^{r}	$\varepsilon_t^{i,*}$
Repo rate	2.4	12.7	35.9	0.0	0.2	1.7	0.0	28.6	3.3	2.9	9.9	1.1	1.2
CPI inflation	4.0	25.4	29.7	0.0	0.0	2.7	0.0	32.9	2.0	0.2	2.7	0.1	0.3
Output	3.6	19.3	10.0	0.2	0.3	5.9	0.1	43.6	2.6	10.8	3.0	0.2	0.2
Consumption	1.0	3.4	26.0	1.1	7.2	13.3	0.0	23.0	20.9	0.5	2.5	0.1	1.0
Investment	0.8	3.7	17.9	8.7	0.7	37.8	0.0	9.2	12.2	0.4	5.2	0.1	3.3
Employment	1.7	16.3	9.1	0.0	0.2	1.3	0.0	62.3	0.6	6.5	1.8	0.2	0.1
Nominal exch. Rate	0.4	2.0	24.7	0.1	0.1	0.3	0.0	3.6	0.4	3.8	62.5	0.8	1.5
Real exch. Rate	0.7	3.8	66.0	0.2	0.1	0.7	0.0	7.0	0.7	3.0	17.1	0.2	0.5
Exports	1.3	6.5	28.5	0.4	0.1	1.9	0.0	15.6	1.4	36.0	7.2	0.1	1.0
Imports	1.6	10.6	44.1	5.4	1.3	6.1	0.0	14.5	3.2	1.1	8.9	0.0	3.3
Real wage	7.4	49.9	5.2	0.3	0.1	10.2	0.0	19.5	6.7	0.5	0.2	0.0	0.1

Figure 7: Structural shock processes and their innovations



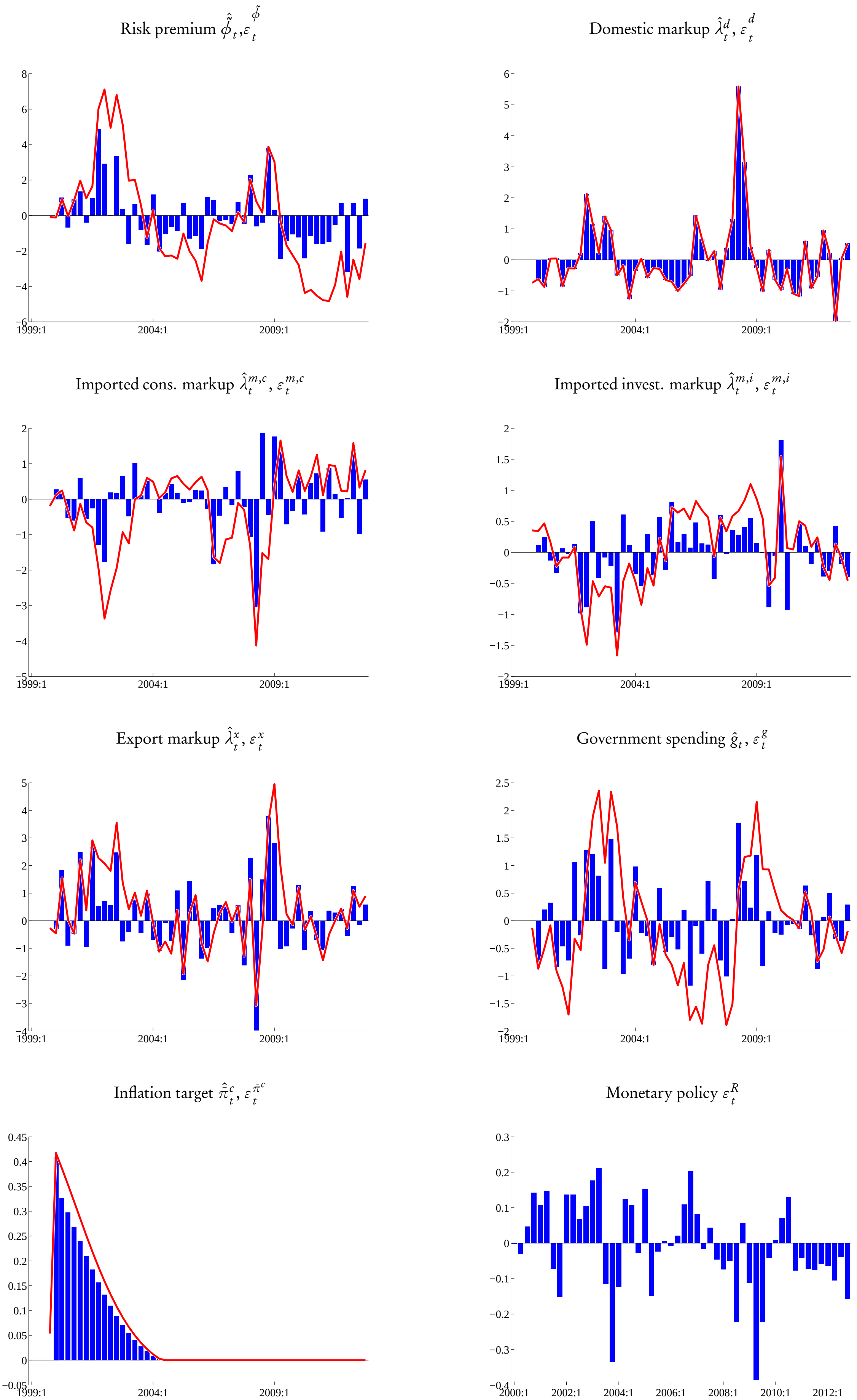

Risk premium $\hat{\tilde{\phi}}_t, \varepsilon_t^{\tilde{\phi}}$
Domestic markup $\hat{\lambda}_t^d, \varepsilon_t^d$
Imported cons. markup $\hat{\lambda}_t^{m,c}, \varepsilon_t^{m,c}$
Imported invest. markup $\hat{\lambda}_t^{m,i}, \varepsilon_t^{m,i}$
Export markup $\hat{\lambda}_t^x, \varepsilon_t^x$
Government spending $\hat{g}_t, \varepsilon_t^g$
Inflation target $\hat{\bar{\pi}}_t^c, \varepsilon_t^{\bar{\pi}^c}$
Monetary policy ε_t^R
1999:1
2004:1
2009:1
2000:1
2002:1
2004:1
2006:1
2008:1
2010:1
2012:1

Figure 8: Monetary policy shock

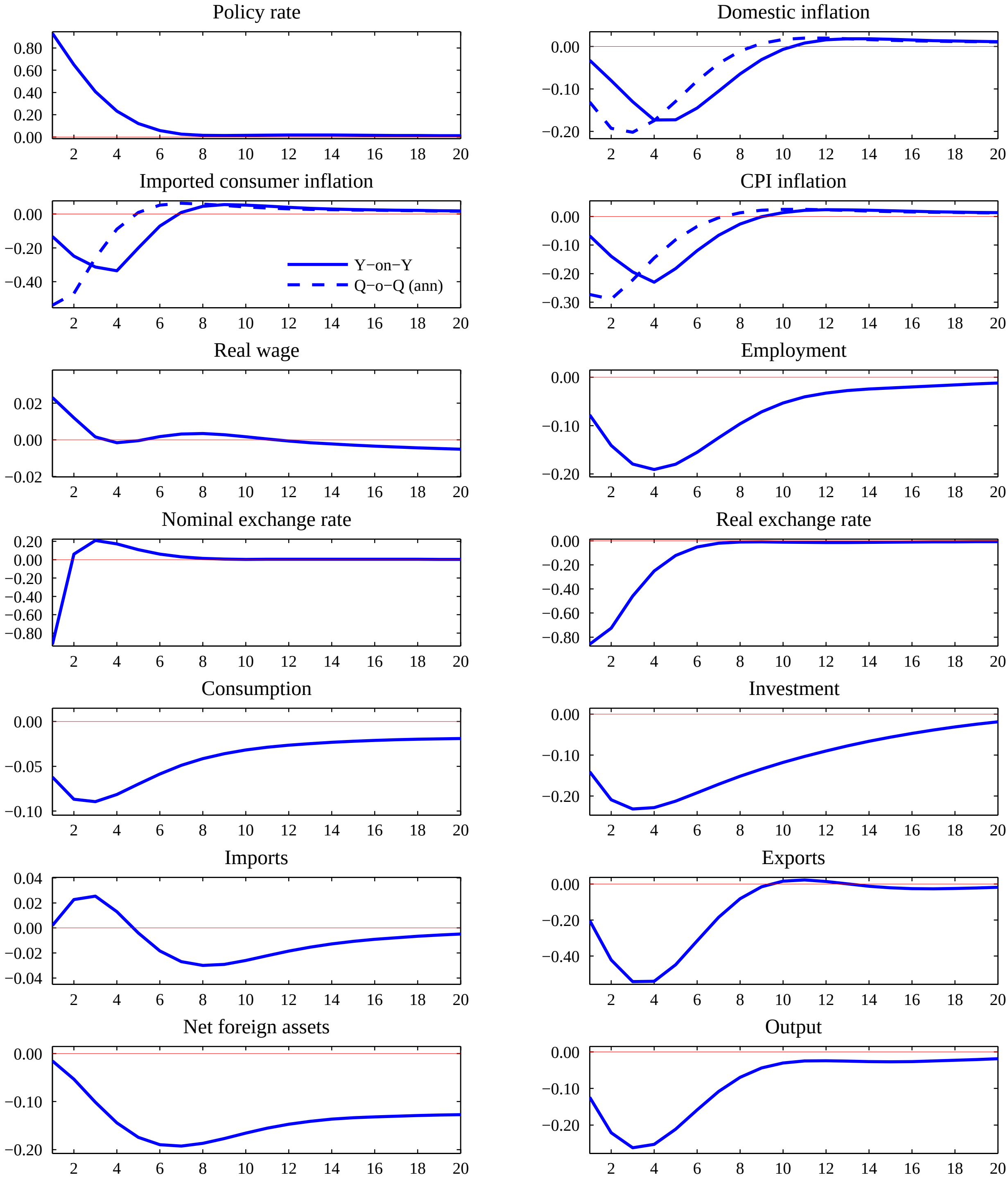


Figure 9: Risk premium shock

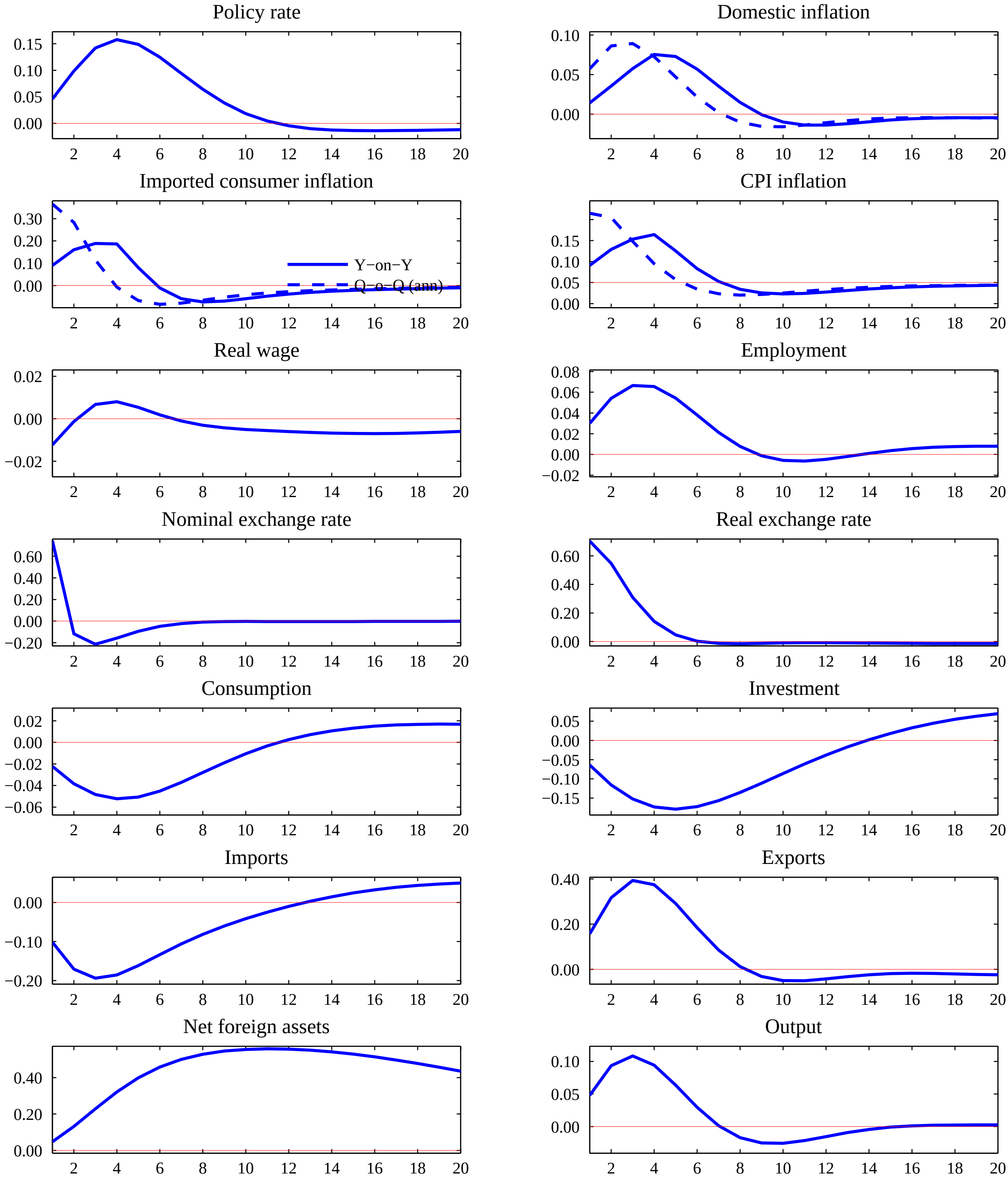


Figure 10: Transitory technology shock

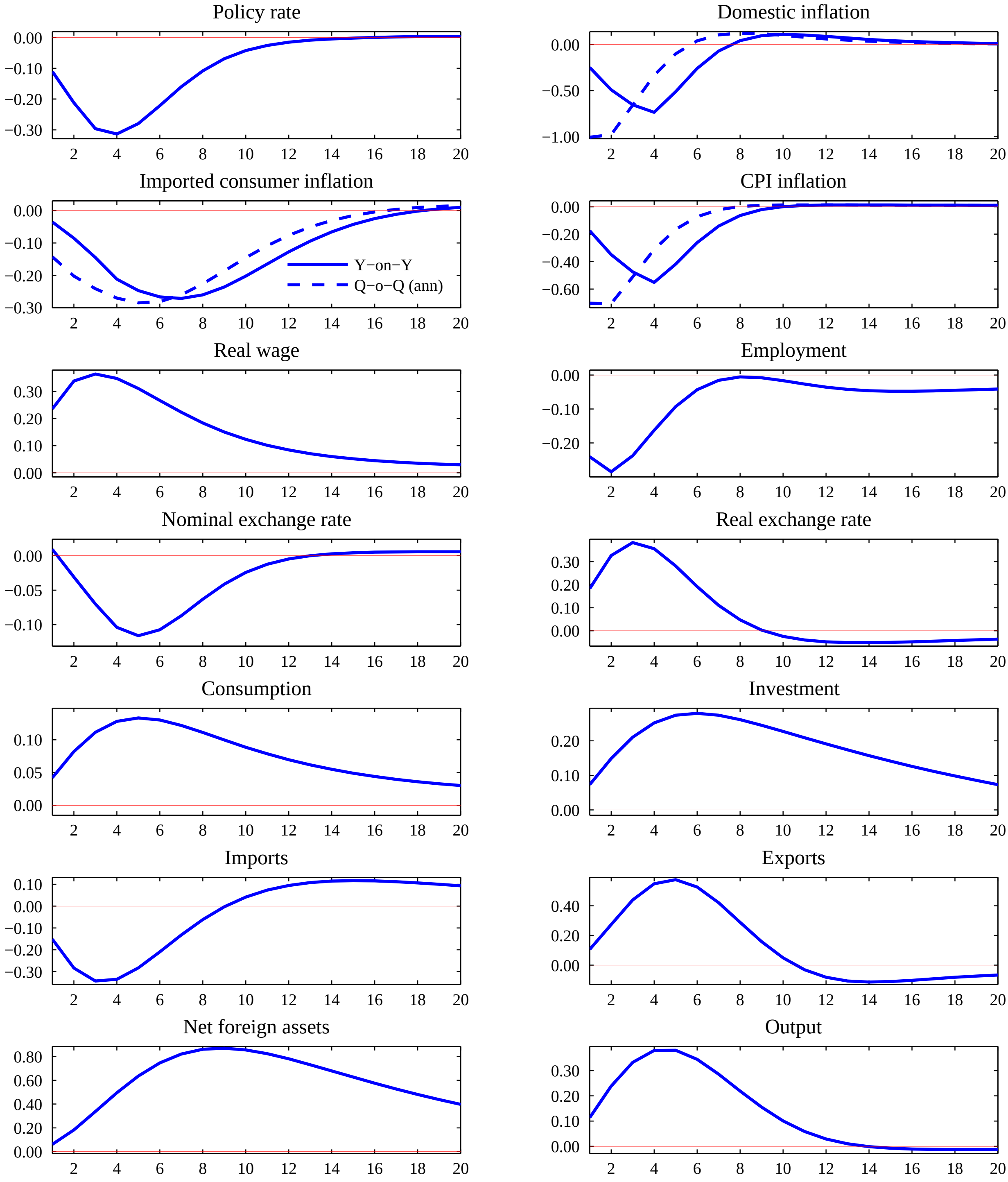


Figure 11: Permanent technology premium shock

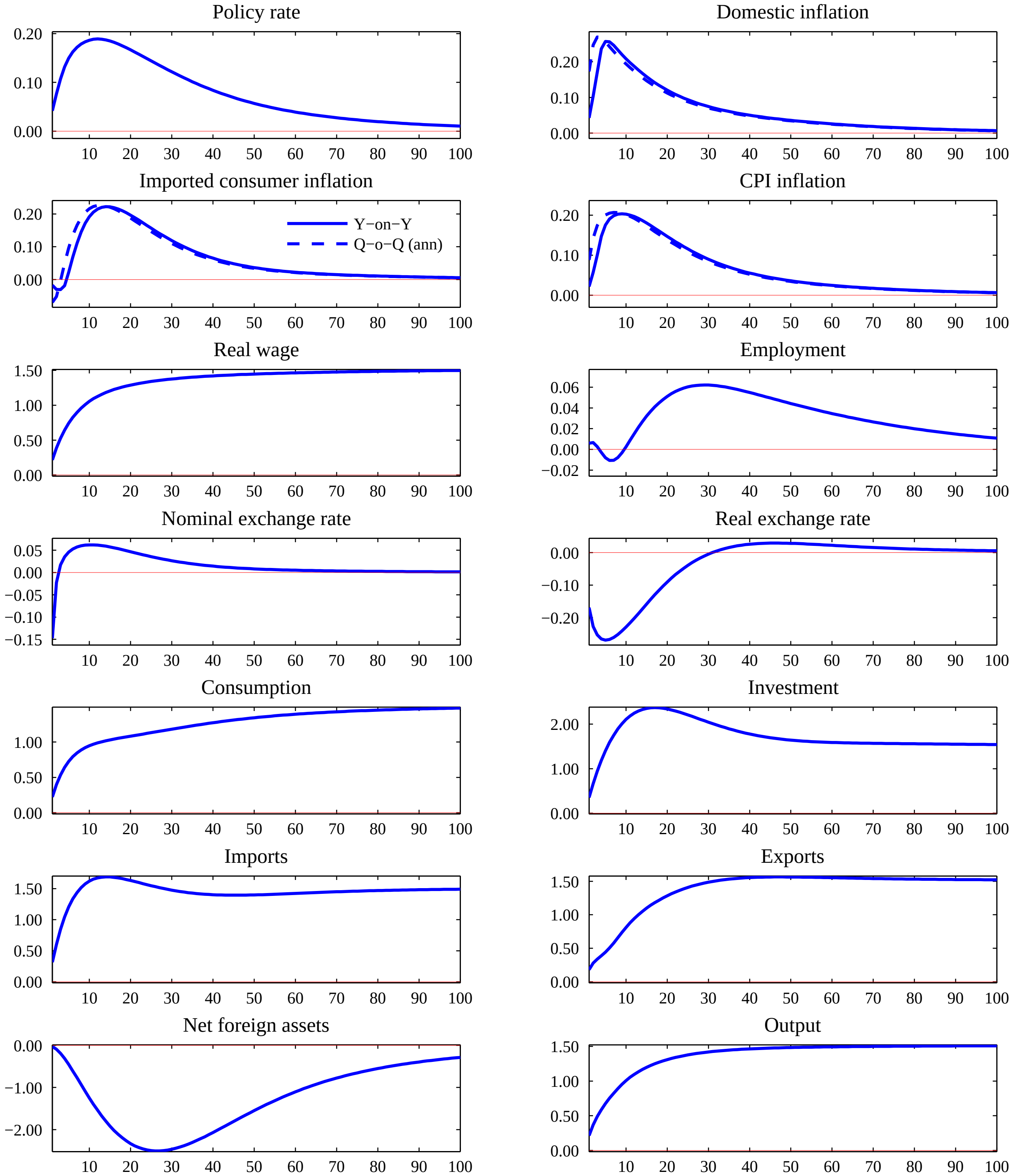


Figure 12: Labour supply shock

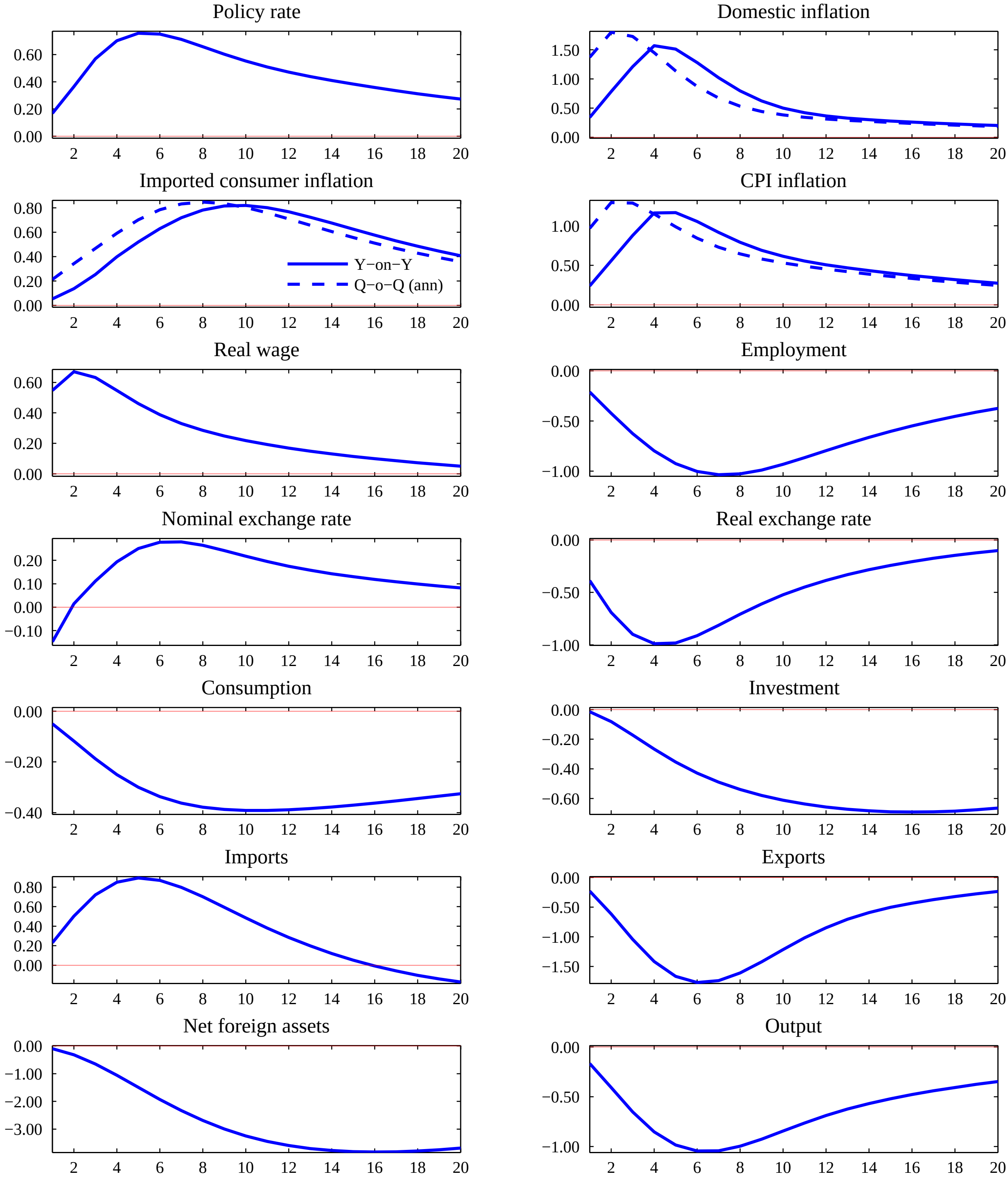


Figure 13: Foreign output shock