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AN ESTIMATED SMALL OPEN ECONOMY MODEL WITH LABOUR MARKET FRICTIONS☆

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Abstract

We estimate small open economy models with involuntary unemployment using Australian data from 1993 to 2007, focusing on hiring costs and real wage rigidity. We find a strong preference for models with hiring costs, which account for 0.97% of GDP. The data favour models with real over nominal wage rigidity. Impulse responses to technology shocks reveal no productivity-employment puzzle for the preferred model. In the short run, technology shocks, operating through hiring costs via labour demand, explain most unemployment variance, while labour preference shocks explain most real wage variance. Demand shocks dominate supply shocks in explaining output variance. In the long run, these contributions reverse. Out-of-sample conditional forecasts perform well but cannot predict the confidence effects of the crisis.

Keywords: DSGE, Hiring cost, wage rigidities, Bayesian estimation, small open economy

JEL Classification: C11, C13, E32, F41, J64

1. Introduction

We estimate medium-scale small open economy models with labour market frictions using Australian data from 1993Q2 to 2007Q3. The small open economy features of the models are based on Adolfson et al. (2007), who analyze the Euro economies by incorporating various nominal and real rigidities including nominal price and wage rigidities, costly investment adjustment, habit formation and external risk premia. Further, we follow Blanchard and Gali (2010) by characterizing the labour market as searching and matching between firms and employees. In each period, there is a fixed chance of a worker separating from existing employment, and firms have to pay a hiring cost to employ a new worker. These hiring costs depend on current labour market conditions, which in turn depend on lagged and current unemployment. Forward-looking firms internalize this cost when making price decisions, and thus inflation depends on the lagged, current and future expected unemployment rate. These real labour market frictions create a monetary policy trade-off between output(or unemployment) and inflation, thus avoiding the

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so-called 'divine coincidence'.[1] In addition, equilibrium real wages are wedged by the hiring costs, but, as Shimer (2005) argues, real wages determined by Nash bargaining cannot generate the observed fluctuations of unemployment. To resolve this problem, we follow Hall (2005) in allowing a degree of real wage rigidity, and compare this to an assumption of nominal wage rigidity. These various labour market frictions permit involuntary unemployment in our small open economy model.

The main objectives of this paper are the following. Since we are unaware of any empirical evidence on the existence of hiring costs, we quantify these costs and test for their statistical significance using Australian data. We also evaluate whether nominal or real wage rigidity is supported by the data. Riggi (2010) and Riggi and Tancioni (2010) argue that real wage rigidities fail to account for the productivity-employment puzzle. Facing a positive technology shock, a model with real wage rigidity tends to exhibit a rise in employment, which contradicts most empirical findings as discussed in Gali (1999), Francis and Ramey (2005) and Basu et al. (2006). We test whether this puzzle holds in our New Keynesian model with labour market frictions, using Australian data.

Using Bayesian methods, our results indicate that the model with hiring costs fits the data better, regardless of the type of wage rigidity. We estimate that they account for a mean of 0.97 per cent of GDP, which is broadly consistent with the Australian Bureau of Statistics estimates (from ABS8558) that the total industry value-added by employment placement organisations contributed 1.3 per cent to Australian gross domestic product (GDP) in 2001-02. Using Bayes' factor as the guide, our results show that real wage rigidity is strictly preferred to nominal wage rigidity regardless of the existence of hiring costs.

Impulse responses following a positive permanent technology shock reveal that no productivity-employment puzzle is observed for all models except the one with nominal wage rigidity and hiring costs (which we do not prefer given the data), contradicting Riggi (2010) and Riggi and Tancioni (2010). The reason is that inflation rises following a positive permanent technology shock, which makes it harder for a model with nominal wage rigidity to account for the negative correlation between productivity and employment. Even with temporary technology shocks that induce a fall in inflation, all variants of our models do not exhibit a fall in unemployment.

[1] The concept, 'divine coincidence', was introduced by Blanchard and Gali (2007) who explained that it occurs in simple New Keynesian models where stabilizing inflation automatically stabilizes output, thus justifying simple inflation targetting.

The intuition is that following a positive technology shock, the increase in aggregate demand is sufficiently restricted by the various frictions we introduce, such as the hiring costs, nominal price rigidities, habit formation, costly installation of investment goods, variable capital utilization and the incomplete pass-through of export prices.

Decomposing variances using our preferred model reveals that technology shocks, which drive labour demand and incur hiring costs, dominate unemployment variance in the short run, but have little effect on real wages. Labour supply preference shocks have little effect on unemployment variance in the short run, but are important for real wage variance. In the long run, we find that the contributions of technology and labour preferences shocks reverse in their impacts on unemployment and real wage variance. Consistent with our description of the models as New Keynesian, we find that output variances are mostly explained by aggregate demand shocks in the short run, and by aggregate supply shocks in the long run.

To evaluate the performance of our preferred model, we obtain out-of-sample conditional forecasts from the end of 2007 through to 2012. Treating world variables as exogenous, the model performs remarkably well, with reasonable root mean square errors for domestic macroeconomic variables.

There are several related papers. Early attempts at estimating DSGE models for Australia include Buncic and Melecky (2008) and Nimark (2009), who construct and estimate a version of a small open economy New Keynesian model. Jääskelä and Nimark (2011) estimate a version of Adolfson et al. (2007) in a data-rich environment by incorporating the commodity market. However, these authors did not directly consider the labour market. Faccini et al. (2011) estimate a model with matching frictions and nominal wage rigidity for the UK economy, and they find nominal wage rigidity improves the model fit but are irrelevant for inflation dynamics at the estimated equilibrium. Using New Zealand data, Albertini et al. (2011) estimate the small open economy model of Gali and Monacelli (2005) with search and matching frictions, and find the majority of variation in the New Zealand labour market is solely explained by disturbances pertaining to the labour market. For the U.S. market, Gertler et al. (2008) estimate a model with indivisible, costly-to-adjust labour and staggered nominal wage bargaining, and find that the nominal wage rigidity fits the data well compared to the flexible wage version. Gali et al. (2011) extend Smets and Wouters (2007) with unemployment, and estimate the resulting model with unemployment data.

This paper is organized as follows. Section 2 outlines the model. Section 3 discusses the estimation procedures and analyzes the results. Section 4 concludes.

2. Model

Our model extends Adolfson et al. (2007) with labour market frictions as discussed in Blanchard and Gali (2010).[2] The economy consists of four types of representative firms: domestic goods-producing firms, consumption-importing firms, investment-importing firms and exporters. Each type of firm makes a Calvo-type price decision based on their respective markup and real marginal cost. Only domestic goods-producing firms employ labour and capital services, depending on the relative wage and rental price of capital. Households derive utility from both domestic and imported consumption, subject to habit formation. Households also enjoy leisure and real balances. They own the capital stock, the services of which they lease out to households. The supply of capital services are varied by households accumulating capital at a cost, by varying the utilization rate at a cost or by trading amongst themselves. A central bank conducts monetary policy by applying an interest rate rule, and supplies money to meet money demand. Alternative wage setting schemes are considered in this paper. Nominal wage rigidity arises from assuming labour is differentiated, thus giving workers the power to set wages according to the Calvo-type of nominal rigidity. The alternative of real wage rigidity is introduced by making real wages depend on a weighted average of the lagged real wage and the current Nash bargaining wage.

2.1. Domestic goods-producing firms

2.1.1. Final domestic goods

A final producer can costlessly combine intermediate goods, transforming them into a homogeneous good that can be used for consumption and investment, in both domestic and overseas economies. Domestic-produced goods compete with imported goods bought by the domestic-importing firms, and the domestic-exporting firms export a fraction of the final product abroad. Final goods are aggregated by:

$$Y_t = \left[\int_0^1 Y_{i,t}^{\frac{1}{\lambda_t^d}} di \right]^{\lambda_t^d}, \qquad 1 \leq \lambda_t^d < \infty$$

[2] We depart from Adolfson et al. (2007) in the following ways: 1. since inflation was well maintained within the Reserve Bank of Australia's inflation target range (2 to 3 per cent) for the period considered, we assume the past inflation rate is a good approximation for backward indexation in price setting; 2. we assume firms have to finance all of their wage bill by borrowing at the nominal cash rate; and 3. the government is assumed to distribute all tax revenue to households as a lump sum payment. We recognize the important role played by fiscal policy, especially during recessions and financial distress, and we leave that for future work.

where $Y_{i,t}$ denotes purchased intermediate product with $i \in [0,1]$. λ_t^d is the markup for the domestic goods market, which is assumed to follow a persistent stochastic process:

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

where $\bar{\lambda}^d$ is the steady-state level of markup, ρ_{λ^d} measures persistence and $\epsilon_t^{\lambda^d}$ is an i.i.d. shock. Profit maximization by the final-producing firm yields the following demand curve for the intermediate product i:

$$Y_{i,t} = \left[\frac{P_t^d}{P_{i,t}^d}\right]^{\frac{\lambda_t^d}{\lambda_t^d - 1}} Y_t \tag{2.1}$$

where $P_{i,t}^d$ is the output price of intermediate firm i, and P_t^d is the price of the final good compiled as:

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

2.1.2. Intermediate domestic goods

Intermediate firms are subject to monopolistic competition, with each using the following production technology:

$$Y_{i,t} = z_t^{1-\alpha}\epsilon_t K_{i,t}^{\alpha} N_{i,t}^{1-\alpha} - z_t\phi \tag{2.2}$$

ϕ is a fixed cost, scaled by the permanent technology shock z_t to ensure it grows at the economy-wide steady state rate. $K_{i,t}$ and $N_{i,t}$ are the capital and labour services used in the production process, and z_t and ϵ_t are permanent and temporary technology shocks with log-deviation processes:

$$\log\left(\frac{z_t}{z_{t-1}}\right) \equiv \hat{\mu}_t^z = \rho_{\mu^z}\mu_{t-1}^z + \epsilon_t^z$$
$$\hat{\epsilon}_t = \rho_\epsilon \hat{\epsilon}_{t-1} + \epsilon_t^\epsilon$$

$\mu_t^z = \frac{z_t}{z_{t-1}}$ is the source of the growth rate of real variables, ϵ_t^z and ϵ_t^ϵ are i.i.d. innovations and ρ_{μ^z} and ρ_ϵ are persistence parameters.

Hiring costs

Following Blanchard and Gali (2010), a fraction δ of the labour force is separated from existing employment in each period. Intermediate firms incur a *real* cost G_t if they hire a new worker:

$$G_t = z_t \epsilon_t B x_t^{\vartheta} \zeta_t^x \tag{2.3}$$

where B is a positive constant that measures the scale of the hiring cost. ζ_t^x is an AR(1) hiring cost shock that follows in log deviation form:

$$\hat{\zeta}_t^x = \rho_x \hat{\zeta}_{t-1}^x + \epsilon_t^x$$

The hiring cost depends on current labour market tightness x_t, defined as the ratio of the number of hires H_t to the number of unemployed *before* hiring proceeds at t:

$$x_t \equiv \frac{H_t}{(U_{t-1} + \delta N_{t-1})}$$

where $H_t \equiv \int_0^1 H_{i,t} di$ is aggregate hiring, $N_t \equiv \int_0^1 N_{i,t} di$ denotes aggregate employment, and $U_{t-1} = 1 - N_{t-1}$ is the number of unemployed *after* hiring ends in $t-1$, assuming the labour force is normalized at 1. Note x_t can be also interpreted as the job-finding rate from the perspective of the unemployed. The evolution of hiring is given by:

$$H_t = N_t - (1-\delta) N_{t-1}$$

where the number of hires is the difference between current and lagged employment, after accounting for separation. Note G_t is indexed to technology, so it grows with other real variables. It is convenient to work with the stationary hiring cost:

$$g_t = \frac{G_t}{z_t} = \epsilon_t B x_t^{\vartheta} \zeta_t^x$$

Optimal factor usage

Assume the intermediate firm i has to borrow in advance to fund its wage bill.[3] Therefore its nominal wage bill is $R_{t-1} W_t N_{i,t}$ at time t, where W_t is the nominal wage and R_{t-1} is the gross nominal interest rate. To optimally allocate resources across factors, firm i minimizes its expected present discounted cost subject to the production technology (2.2):

$$\min_{K_{i,t} N_{i,t}} \sum_{s=0}^{\infty} \beta^s \left(R_{t-1} W_t N_{i,t} + P_t^d G_t H_{i,t} + R_t^k K_{i,t} + \lambda_t P_{i,t}^d \left[Y_{i,t} - z_t^{1-\alpha} \epsilon_t K_{i,t}^{\alpha} N_{i,t}^{1-\alpha} + z_t \phi \right] \right)$$

where R_t^k is the gross nominal rental rate on capital service and λ_t is the Lagrange multiplier. The permanent technology shock implies that all real variables in the model have a stochastic

[3] Borrowing in *advance* to fund the wage bill simply delays the effect of monetary policy changes on marginal cost and thus unemployment.

trend. Let $k_{t+1} \equiv \frac{K_{t+1}}{z_t}$ represent the de-trended (predetermined) capital service stock. In addition, since the price level is not stationary, nominal variables will share a nominal stochastic trend. To stationarize the model, let $w_t \equiv \frac{W_t}{P_t^d z_t}$ denote the de-trended real wage rate, and $r_t^k \equiv \frac{R_t^k}{P_t^d}$ as the real rental rate of capital earned by households, and define the gross domestic inflation rate as $\pi_t^d \equiv \frac{P_t^d}{P_{t-1}^d}$. The real marginal cost for an intermediate producer, mc_t^d, can be defined as $mc_t^d = \lambda_t \frac{P_{i,t}^d}{P_t^d}$, which from the first order conditions becomes:

$$mc_t^d = \left(\frac{1}{1-\alpha}\right)^{1-\alpha} \left(\frac{1}{\alpha}\right)^{\alpha} \frac{\left(r_t^k\right)^{\alpha}}{\epsilon_t} \left(R_{t-1} w_t + g_t - \beta(1-\delta)\mu_{t+1}^z \pi_{t+1}^d g_{t+1}\right)^{1-\alpha}$$

The real marginal cost depends on the rental rate of capital, wage rate, and both current and future expected hiring costs. This cost will appear subsequently in the new Keynesian Phillips curve (NKPC), which links labour market conditions with inflation.

Price setting

Following Calvo (1983), each intermediate firm faces a random probability ξ_d of not receiving a 'price signal' to re-optimize its price at $P_{t,new}^d$ in period t, in which case it simply indexes its price to the intermediate firm inflation rate π_{t-1}^d:

$$P_{t,idx}^d = (\pi_{t-1}^d) P_{t-1}^d$$

Otherwise, with probability $(1-\xi_d)$, the intermediate firm i receives a 'price signal' to re-optimize, and so it sets its price at the level that maximizes its expected discounted profit:

$$\max_{P_{t,new}^d} E_t \sum_{s=0}^{\infty} (\beta\xi_d)^s \nu_{t+s} \left[(\pi_t^d \pi_{t+1}^d \dots \pi_{t+s-1}^d) P_{t,new}^d Y_{i,t+s} - MC_{i,t+s}^d (Y_{i,t+s} + z_{t+s}\phi) \right] \tag{2.4}$$

where $MC_{t+s}^d = mc_{t+s}^d P_{t+s}^d$ represents the nominal marginal cost and $(\beta\xi_d)^s \nu_{t+s}$ is the stochastic discount factor.[4] Substituting the demand for intermediate good i, (2.1) into (2.4), differentiating with respect to $P_{t,new}^d$, setting that to 0, and then linearizing around the steady state gives the optimal price-setting rule when an intermediate firm re-optimizes its price.

The aggregate price index is a weighted-average of the indexed and re-optimized intermediate prices:

$$P_t^d = \left[\xi_d \left(P_{t-1}^d \pi_{t-1}^d \right)^{\frac{1}{1-\lambda_t^d}} + (1-\xi_d) \left(P_{t,new}^d \right)^{\frac{1}{1-\lambda_t^d}} \right]^{1-\lambda_t^d}$$

Linearizing this and combining it with the re-optimized price gives the NKPC for the domestic goods market:

$$\hat{\pi}_t^d = \frac{\beta}{1+\beta} E_t \left[\hat{\pi}_{t+1}^d \right] + \frac{1}{1+\beta} \hat{\pi}_{t-1}^d + \frac{(1-\xi_d)(1-\beta\xi_d)}{\xi_d(1+\beta)} \left[\hat{\lambda}_t^d + \widehat{mc}_t^d \right]$$

[4]Since households own firms, profits are valued at the household's discounted marginal utility of income, $\beta^s \nu_{t+s}$.

2.1.3. Domestic-importing firms

Importing firms buy homogeneous goods at the given world price, and transform them into differentiated consumption C^m and investment I^m goods. Incomplete price pass-through arises because importing firms also follow Calvo (1983) pricing. Both aggregate imported consumption and investment goods are a composite of a continuum of i differentiated imported goods through a CES function. Let $IM_t \in \{C_t^m, I_t^m\}$ denotes the aggregate quantity for consumption and investment imports, with IM_{it} the imports of firm i with respective index $a \in \{cm, im\}$, where:

$$IM_t = \left[\int_0^1 (IM_{it})^{\frac{1}{\lambda_t^a}} di\right]^{\lambda_t^a}, \qquad 1 \leq \lambda_t^a < \infty$$

Profit maximization ensures the demand for imported consumption good i is:

$$IM_{it} = \left(\frac{P_t^a}{P_{i,t}^a}\right)^{\frac{\lambda_t^a}{\lambda_t^a - 1}} IM_t$$

where P_t^a denotes the aggregate price of the imported goods and $P_{i,t}^a$ is the price of the imported goods set by the firm i. The time-varying markup λ_t^a follows:

$$\lambda_t^a = (1 - \rho_{\lambda^a})\bar{\lambda}^a + \rho_{\lambda^a}\lambda_{t-1}^a + \epsilon_t^{\lambda^a}$$

In each period, only $1 - \xi^a$ portion of the importing firms can re-optimize their price. For the rest ξ^a, they simply index their price to the respective import inflation $P_t^a = \pi_{t-1}^a P_{t-1}^a$. Denote S_t^n as the nominal exchange rate (domestic currency per unit of foreign currency) and P^* as the foreign aggregate price level. Since importing firms can differentiate and repack imported goods costlessly, the marginal cost is the relative price between the cost and selling price: $mc_t^a = \frac{P_t^* S_t^n}{P_t^a}$. Similar to the domestic intermediate firms, profit maximizing leads to a New Keynesian Phillips curve for import prices:

$$\hat{\pi}_t^a = \frac{\beta}{1+\beta} E_t\left[\hat{\pi}_{t+1}^a\right] + \frac{1}{1+\beta}\hat{\pi}_{t-1}^a + \frac{(1-\xi^a)(1-\beta\xi^a)}{\xi^a(1+\beta)}\left[\hat{\lambda}_t^a + \widehat{mc}_t^a\right]$$

2.1.4. Domestic-exporting firms

Export firms buy domestic final goods at price P_t^d, differentiate and sell them abroad. Firm i faces the following demand for its product, $X_{i,t}$:

$$X_{i,t} = \left(\frac{P_t^x}{P_{i,t}^x}\right)^{\frac{\lambda_t^x}{\lambda_t^x - 1}} X_t$$

where P_t^x is the aggregate foreign currency price for exports, $P_{i,t}^x$ is the price set by firm i and X_t is the total export volume. The stochastic time-varying markup for export firms is:

$$\lambda_t^x = (1 - \rho_{\lambda^x})\bar{\lambda}^x + \rho_{\lambda^x}\lambda_{t-1}^x + \epsilon_t^{\lambda^x}$$

Given the domestic economy is small, the total demand for domestic exports is:

$$X_t = \left[\frac{P_t^x}{P_t^*}\right]^{-\eta_f} Y_t^* \tag{2.5}$$

where Y_t^* is foreign output, η_f is the elasticity of substitution in the foreign economy, and P_t^* is the aggregate foreign price level. As for importing firms, with only $1-\xi_x$ probability can an export firm re-optimize its price to $P_{t,new}^x$ in each period, and for the rest, firms index their price to the past export inflation: $P_t^x = \pi_{t-1}^x P_{t-1}^x$. Since no labour and capital services are employed, the marginal cost for the exporting firms is $mc_t^x = \frac{P_t^d}{S_t^n P_t^x}$. Profit maximization leads to a New Keynesian Phillips curve for export prices:

$$\hat{\pi}_t^x = \frac{\beta}{1+\beta} E_t\left[\hat{\pi}_{t+1}^x\right] + \frac{1}{1+\beta}\hat{\pi}_{t-1}^x + \frac{(1-\xi_x)(1-\beta\xi_x)}{\xi_x(1+\beta)}\left[\hat{\lambda}_t^x + \widehat{mc}_t^x\right]$$

2.2. Households

A representative household j with a continuum of members indexed by $\iota \in [0,1]$ maximizes the following utility function:

$$E_0^j \sum_{t=0}^{\infty} \beta^t \left[\zeta_t^c \ln(C_{j,t} - bC_{j,t-1}) - \zeta_t^N A_L \frac{N_{j,t}^{1+\sigma_L}}{1+\sigma_L} + A_q \frac{\left(\frac{Q_{j,t}}{z_t P_t^d}\right)^{1-\sigma_q}}{1-\sigma_q}\right] \tag{2.6}$$

Households get utility from habitual consumption $C_{j,t}$, with the degree of habit persistence measured by b, disutility from work [5], and utility from real cash balances scaled by the permanent technology shock $\frac{Q_{j,t}}{z_t P_t^d}$. ζ_t^l for $l \in \{c, N\}$ are preference shocks for consumption and labour supply, with a steady-state value $E[\zeta_t^l] = 1$.

Following Gertler et al. (2008) and Gali et al. (2011), we model labour so that it varies on its extensive rather than intensive margin (as assumed in Adolfson et al. (2007) and Jääskelä and Nimark (2011)). This turns out to be broadly consistent with Australian experience during the period we study, since the correlation between employment and hours worked is 0.818.

The budget constraint for the representative household is:

$$\begin{aligned} &R_{t-1}(M_t - Q_t) + Q_t + \Pi_t + W_t N_t + R_t^k u_t \tilde{K}_t + R_{t-1}^* \Phi\left(\frac{A_{t-1}}{z_{t-1}}, \tilde{\phi}_{t-1}\right) S_t^n B_t^* \\ &= M_{t+1} + S_t^n B_{t+1}^* + P_t^c C_t + P_t^i I_t + P_t^d \left(\tilde{a}(u_t)\tilde{K}_t + P_t^{k'} \Delta_t\right) \end{aligned} \tag{2.7}$$

[5] A household member ι can either be employed or unemployed. If employed, she incurs a disutility of $A_L \zeta_t^N \iota^{\sigma_L}$ and 0 otherwise, where A_L is a positive constant. Since agents are ex ante homogeneous, integrating over the members who are employed gives $\int_0^{N_{j,t}} A_L \zeta_t^N \iota^{\sigma_L} d\iota = A_L \zeta_t^N \frac{N_{j,t}^{1+\sigma_L}}{1+\sigma_L}$

where M_t is total nominal domestic assets (either in the form of cash Q_t or domestic interest earning assets $(M_t - Q_t)$.) B_t^* is foreign bonds held by the household at time t earning R_t^*. Π_t is profits from domestic firms.[6]

The household has three options in varying capital services: 1. purchase new investment goods at price P_t^i, with a cost of installation; or 2. pay the capital utilization cost $\tilde{a}(u_{j,t})$ to change the utilization rate of existing capital stock, where the capital utilization cost is assumed to satisfy $\tilde{a}(1) = 0$, $\tilde{a}'(1) = \bar{r}^k$ and $a''(1) \geq 0$[7]; or 3. go to the market to purchase existing installed capital stocks at cost $P_t^{k'} \Delta_t$.

The function $\Phi(.)$ represents the risk premium on holding foreign bonds, which depends on the real aggregate net foreign asset position of the domestic economy $A_t \equiv \frac{S_t^n B_{t+1}^*}{P_t^d}$:

$$\Phi\left(\frac{A_t}{z_t}, \tilde{\phi}_t\right) = \Phi\left(a_t, \tilde{\phi}_t\right) = \exp\left(-\tilde{\phi}_a(a_t - \bar{a}) + \tilde{\phi}_t\right)$$

where $\tilde{\phi}_t$ is a time-varying shock to the risk premium.[8] The function $\Phi(.)$ is assumed to be strictly decreasing in a_t, so that domestic households are charged a premium on the foreign interest rate if the home country is a net borrower ($B_{t+1}^* < 0$). This risk premium ensures a well-defined steady state in the model (for details see Schmitt-Grohe and Uribe (2003)).

2.2.1. Consumption and investment

Households derive utility from an aggregate of domestic and imported consumption goods:

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

where ω_c is the share of imports in aggregate consumption and η_c is the elasticity of substitution between domestic and foreign consumption goods. Optimal consumption is:

$$C_t^d = (1-\omega_c)\left[\frac{P_t^d}{P_t^c}\right]^{-\eta_c} C_t \tag{2.8}$$

$$C_t^m = \omega_c \left[\frac{P_t^{m,c}}{P_t^c}\right]^{-\eta_c} C_t \tag{2.9}$$

where P_t^c is the aggregate price for consumption goods (CPI):

[6] ϕ is set to ensure the steady-state value of this profit equals to 0.
[7] Recall $u_t = \frac{K_t}{\bar{K}_t}$ is the utilization rate with a steady-state value of 1.
[8] In the case of no borrowing at the steady state, $\Phi(0,0) = 1$.

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

Similarly, households make investment decisions, with aggregate investment being:

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

The aggregate investment price level P_t^i can deviate from the aggregate consumption price level P_t^c:

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

The allocation of demand between domestic and imported investment is:

$$I_t^d = (1-\omega_i)\left[\frac{P_t^d}{P_t^i}\right]^{-\eta_i} I_t \tag{2.10}$$

$$I_t^m = \omega_i\left[\frac{P_t^{m,i}}{P_t^i}\right]^{-\eta_i} I_t \tag{2.11}$$

Aggregate imports is the sum of consumption and investment imports:

$$M_t^m = C_t^m + I_t^m$$

2.2.2. Capital accumulation

The accumulation of physical capital stock by households $\tilde{K}_{t+1}$ is governed by depreciation δ_k and new investments with an installation cost.

$$\tilde{K}_{t+1} = (1-\delta_k)\tilde{K}_t + \Gamma_t\left[1 - \tilde{S}\left(\frac{I_t}{I_{t-1}}\right)\right] I_t + \Delta_t$$

where Γ_t is a stationary investment-specific technology shock with $E[\Gamma_t] = 1$. Δ_t reflects households with access to a market where they can purchase new, installed capital $\tilde{K}_{t+1}$ from other households. Since households are representative, $\Delta_t = 0$ in equilibrium. The existence of this market facilitates calculation of the price of second-hand physical capital, $P_t^{k'}$. $1-\tilde{S}\left(\frac{I_t}{I_{t-1}}\right)$ describes the installation technology, with $\tilde{S}(\bar{\mu}^z) = \tilde{S}'(\bar{\mu}^z) = 0$ and $\tilde{S}''(\mu_t^z) = \tilde{S}'' > 0$. Since the capital stock is pre-determined and has a trend component, we stationarize it by dividing by z_t on both sides of the above equation to give:

$$\tilde{k}_{t+1} = (1-\delta_k)\frac{\tilde{k}_t}{\mu_t^z} + \Gamma_t f(i_t, i_{t-1}, \mu_t^z) + \frac{\Delta_t}{z_t} \tag{2.12}$$

2.2.3. Optimality conditions

The household j maximizes the utility function (2.6), subject to the budget constraint (2.7) and the capital accumulation identity (2.12). Defining $\psi_t^z \equiv z_t P_t^d \nu_t$ as the stationarized marginal utility from income, the first-order-conditions with respect to $c_t, m_{t+1}, \Delta_t, \tilde{k}_{t+1}, i_t, u_t, q_t$ and b_{t+1}^* are:

$$\frac{\zeta_t^c}{c_t - \frac{bc_{t-1}}{\mu_t^z}} - \beta b E_t \left[\frac{\zeta_{t+1}^c}{c_{t+1}\mu_{t+1}^z - bc_t} \right] - \psi_t^z \frac{P_t^c}{P_t^d} = 0$$

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

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

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

$$-\psi_t^z \frac{P_t^i}{P_t^d} + \psi_t^z P_t^{k'} \Gamma_t f_1(i_t, i_{t-1}, \mu_t^z) + \beta E_t \left[P_{t+1}^{k'} \psi_{t+1}^z \Gamma_{t+1} f_2(i_{t+1}, i_t, \mu_{t+1}^z) \right] = 0$$

$$(\mu_t^z)^{-1} \psi_t^z \left(r_t^k - \tilde{a}'(u_t) \right) \tilde{k}_t = 0$$

$$A_q q_t^{-\sigma_q} - \psi_t^z (R_{t-1} - 1) = 0$$

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

The optimal decisions on domestic asset and foreign bond holding yield a risk-adjusted uncovered interest rate parity condition:

$$\hat{R}_t - \hat{R}_t^* = E_t \left[\hat{S}_{t+1}^n - \hat{S}_t^n \right] - \tilde{\phi}_a \hat{a}_t + \hat{\tilde{\phi}}_t$$

where $\hat{\tilde{\phi}}_t$ is the time-varying shock to the risk premium, which is assumed to follow a stationary AR(1) process.

2.3. Wage determination under alternative rigidity assumptions

We consider real and nominal wage rigidities as alternatives. We construct real wage rigidity in the spirit of Hall (2003, 2005), where the real wage is a weighted average of the lagged real wage and the equilibrium Nash-bargaining wage. We construct nominal wage rigidity with labour assumed differentiated and organized possibly through unions, and following the Calvo (1983)-type of wage-setting.

2.3.1. Real wage rigidity

For this alternative, in the absence of any rigidity, the equilibrium real wage would be determined by Nash bargaining. In each period, both firms and workers calculate the surplus from an established employment relationship. Because firms can replace any worker immediately after paying a hiring cost, the stationarized surplus for a firm is the hiring cost:

$$S_t^F = g_t = B\epsilon_t x_t^{\vartheta}\zeta_t^x$$

The worker's surplus from the existing match depends on the wage rate, the opportunity cost measured by the marginal rate of substitution and the future discounted prospect of the existing relationship:[9]

$$V_t^N = w_t - \frac{\zeta_t^N A_L N_t^{\sigma_L}}{\psi_t^z} + \beta E_t\left[\frac{\psi_{t+1}^z}{\psi_t^z\mu_{t+1}^z\pi_{t+1}^d}\left\{(1-\delta(1-x_{t+1}))\,V_{t+1}^N + \delta(1-x_{t+1})V_{t+1}^U\right\}\right] \quad (2.13)$$

The term $\beta E_t\left[\frac{\psi_{t+1}^z}{\psi_t^z\mu_{t+1}^z\pi_{t+1}^d}\right]$ is the stochastic discount factor, while x_{t+1} can be interpreted as the job-finding rate in period $t+1$. The value of a worker who is unemployed is given by:

$$V_t^U = \beta E_t\left[\frac{\psi_{t+1}^z}{\psi_t^z\mu_{t+1}^z\pi_{t+1}^d}\left\{x_{t+1}V_{t+1}^N + (1-x_{t+1})V_{t+1}^U\right\}\right] \quad (2.14)$$

Therefore the net surplus to the worker from an existing relationship is the difference between (2.13) and (2.14):

$$S_t^H \equiv V_t^N - V_t^U = w_t - \frac{\zeta_t^N A_L N_t^{\sigma_L}}{\psi_t^z} + \beta(1-\delta)E_t\left[\frac{\psi_{t+1}^z}{\psi_t^z\mu_{t+1}^z\pi_{t+1}^d}(1-x_{t+1})S_{t+1}^H\right]$$

The gains induced by the matching friction generates a wedge between the maximum wage that the firm is willing to pay and the minimum wage that a worker is willing to accept:[10]

$$\begin{aligned} w_t^{UB} &= w_t + S_t^F = w_t + B\epsilon_t x_t^{\vartheta}\zeta_t^x \\ w_t^{LB} &= w_t - S_t^H = \frac{\zeta_t^N A_L N_t^{\sigma_L}}{\psi_t^z} - \beta(1-\delta)E_t\left[\frac{\psi_{t+1}^z}{\psi_t^z\mu_{t+1}^z\pi_{t+1}^d}(1-x_{t+1})S_{t+1}^H\right] \end{aligned}$$

The firm would be willing to pay up to a premium given by the hiring cost of an additional replacement worker. The worker would accept going down not just to the current marginal rate of substitution, but even further to accommodate the benefit of the probability of not being separated next period when one might not otherwise find another job. Any wage rate within this wage band could be an equilibrium wage. In particular, if the worker and firm have the

[9] If labour does not have any monopoly power, the flexible wage should equal in equilibrium the marginal rate of substitution between consumption and work, as well as the net marginal product of labour.

[10] We could rewrite the surpluses as $S_t^F = w_t^{UB} - w_t$ and $S_t^H = w_t - w_t^{LB}$.

same bargaining power, they would share the surplus equally $S_t^F = S_t^H$, and thus a symmetric Nash-bargaining wage lies at the centre of the wage band:

$$w_t^* = \frac{w_t^{UB} + w_t^{LB}}{2} = B\epsilon_t x_t^{\vartheta}\zeta_t^x + \frac{\zeta_t^N A_L N_t^{\sigma_L}}{\psi_t^z} - \beta(1-\delta)E_t\left[\frac{\psi_{t+1}^z}{\psi_t^z\mu_{t+1}^z\pi_{t+1}^d}(1-x_{t+1})\left(B\epsilon_{t+1}x_{t+1}^{\vartheta}\zeta_{t+1}^x\right)\right] \tag{2.15}$$

Equation (2.15) implies that when the hiring cost decreases, firms can fill a job more cheaply and are therefore less willing to pay a higher wage. Similarly, if workers' opportunity cost increases, they demand a higher wage. In addition, if the future expected gain increases, which may due to lower future opportunity costs, workers are less resistant to a wage cut today, and therefore the wage rate is lower. In the case of no hiring cost ($B = 0$), the Nash bargaining wage only depends on workers' marginal rate of substitution, and so $w_t^* = \frac{\zeta_t^N A_L N_t^{\sigma_L}}{\psi_t^z}$.

However, as argued by Shimer (2005), the real wage determined by Nash bargaining cannot generate the observed fluctuations of unemployment. The reason is that the real wage is determined by splitting the surplus with fixed portions between firm and household. As the upper and lower bounds of the wage band fluctuate due to the driving forces at the business cycle frequency, the real wage determined by Nash bargaining also fluctuates, often by a substantial amount. A volatile real wage scheme thus absorbs most of the driving forces, leaving unemployment relatively (too) stable. Recognizing the problem, Hall (2003, 2005) motivates a rigid real wage from wage norms, which insulates the real wage from movements of the upper and lower bounds insofar as it remains inside the bounds. Since the real wage lies inside the bounds, the real wage is consistent with equilibrium and there is no unrealized gain. However, this specification induces discrete movements in the real wage, which makes estimation hard. Instead, Hall (2003) shows that the aggregate real wage has an adaptive component once we allow for idiosyncratic random shifts in the bargaining set, and we aggregate over individual wage decisions. To further motivate the real wage following an adaptive process, we note that, in reality, firms and workers negotiate a wage bargain based on available information. Most likely, neither knows the actual value of unobserved technology parameters, particularly as they apply over the future life of the negotiated contract. Both may be able to make inferences from various signals received about productivity, but they will be aware of potential errors. These errors may lead them to take a more cautious approach to real wage changes, adjusting them only partly in response to any received productivity signals, thus making the real wage history-dependent. To cope with these ideas, we use the following rule:

$$w_t = f w_{t-1} + (1-f) w_t^*$$

where f measures the degree of the real wage rigidity and $f = 0$ corresponds to the flexible Nash bargaining wage.[11]

2.3.2. Nominal wage rigidity

For this alternative, we assume there is a 'firm' that aggregates and transforms differentiated labour into a homogeneous labour service N_t, which can be used in the production of intermediate goods. The transformation process uses the following technology:

$$N_t = \left[\int_0^1 N_{j,t}^{\frac{1}{\lambda_t^w}} \, dj \right]^{\lambda_t^w}, \qquad 1 \leq \lambda_t^w < \infty$$

where $N_{j,t}$ is monopolistic labour supply by household j at time t and λ_t^w is the wage markup that follows:

$$\lambda_t^w = (1 - \rho_{\lambda^w}) \bar{\lambda}^w + \rho_{\lambda^w} \lambda_{t-1}^w + \epsilon_t^{\lambda^w}$$

where $\epsilon_t^{\lambda^w}$ is an i.i.d. shock. Profit maximization ensures the demand for labour j is:

$$N_{j,t} = \left(\frac{W_t}{W_{j,t}} \right)^{\frac{\lambda_t^w}{\lambda_t^w - 1}} N_t$$

where W_t is the nominal wage rate of the homogeneous labour service and $W_{j,t}$ is the nominal wage rate for household j. Since labour supply is differentiated, households have the power to set their nominal wage, but are subject to the Calvo (1983) type of nominal rigidity. In each period, household j faces a random probability ξ_w that she cannot change her nominal wage, and she simply indexes the wage according to:

$$W_{j,t} = \pi_{t-1}^c \mu_t^z W_{j,t-1}$$

where π_t^c is the CPI inflation rate. For the rest $1 - \xi_w$, household j receives a 'price signal' that she can re-optimize her wage at W_t^{new}. The aggregate wage rate is:

[11] Gali and van Rens (2010), on the other hand, introduce an endogenous wage rigidity rule:

$$w_t = f_{t-1} w_{t-1} + (1 - f_{t-1}) w_t^*$$

where w_t^* is the symmetric Nash bargaining wage as discussed above, and f_{t-1} measures the degree of the endogenous real wage rigidity, given by:

$$f_t = \bar{f} \left[1 - \left(\frac{w_t - w_t^*}{\frac{1}{2}(w_t^{UB} - w_t^{LB})} \right)^{2\rho_f} \right]$$

Given symmetric bargaining, this rule captures the idea that the wage is more likely to adjust when it approaches the boundaries of the bargaining set.

$$W_t = \left[\xi_w \left(\pi_{t-1}^c \mu_t^z W_{t-1} \right)^{\frac{1}{1-\lambda_t^w}} + (1-\xi_w) \left(W_t^{new} \right)^{\frac{1}{1-\lambda_t^w}} \right]^{1-\lambda_t^w}$$

If the household cannot re-optimize her wage for s periods, the time $t+s$ wage is thus $W_{j,t+s} = (\pi_t^c \dots \pi_{t+s-1}^c)(\mu_{z,t+1} \dots \mu_{z,t+s})W_{j,t}^{new}$. Once the nominal wage is set, households inelastically meet firms' demand for labour. Stationarizing by dividing both side by $P_t^d z_t$, and then linearizing, gives:

$$\hat{w}_t = \xi_w \left(\hat{w}_{t-1} + \hat{\pi}_t^c - \hat{\pi}_t^d \right) + (1-\xi_w)\hat{w}_t^{new}$$

The re-optimized wage decision hinges on the balance between marginal utility from wage income and marginal disutility from working, and applying this yields the equilibrium aggregate real wage rate:

$$\hat{w}_t = \tau_b \left(\hat{w}_{t-1} + \hat{\pi}_{t-1}^c - \hat{\pi}_t^d \right) + \tau_f \left(E_t \left[\hat{w}_{t+1} \right] - \hat{\pi}_t^c + E_t \left[\hat{\pi}_{t+1}^d \right] \right) + \tau_c \left(\hat{\zeta}_t^N + \sigma_L \hat{N}_t - \hat{\psi}_t^z + \hat{\lambda}_t^w \right) \tag{2.16}$$

where $\tau_b \equiv \frac{(1+\tau)\xi_w}{1+\xi_w\tau+\beta\xi_w^2}$, $\tau_f \equiv \frac{\beta\xi_w}{1+\xi_w\tau+\beta\xi_w^2}$, $\tau_c \equiv \frac{(1-\beta\xi_w)(1-\xi_w)}{1+\xi_w\tau+\beta\xi_w^2}$, $\tau_b+\tau_f+\tau_c = 1$, and $\tau \equiv \frac{\bar{\lambda}^w\sigma_L(1-\beta\xi_w)}{\bar{\lambda}^w-1}$.

Equation (2.16) shows the real wage is set as a weighted average of lagged and future expected wages and the current marginal rate of substitution. Unlike under real wage rigidity—recall (2.15)—hiring costs do not directly affect the real wage under nominal wage rigidities. This is because the wage is here being set by households, not by employers. Instead, hiring costs work indirectly by restricting labour demand, thus limiting the movement in N_t.

Setting $\xi_w = 0$ gives the real wage without nominal wage rigidity:

$$\hat{w}_t = \hat{\zeta}_t^N + \sigma_L \hat{N}_t - \hat{\psi}_t^z + \hat{\lambda}_t^w$$

in which case the real wage only depends on the markup and the marginal rate of substitution between labour and consumption.

2.4. Monetary policy

As in Smets and Wouters (2003), monetary policy follows:

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1-\rho_R)[r_\pi \hat{\pi}_{t-1}^c + r_y \hat{y}_{t-1} + r_s \hat{s}_{t-1}^r] + r_\Delta^\pi \Delta \hat{\pi}_t^c + r_\Delta^y \Delta \hat{y}_t + \epsilon_t^R$$

where $\hat{\pi}_t^c$ is the CPI inflation, $\hat{y}_t$ is the output gap and $\hat{s}_t^r$ denotes the log-linearized real exchange rate with $S_t^r = S_t^n \frac{P_t^*}{P_t^c}$. The parameter ρ_R measures the persistence in the interest rate. r_π, r_y

and r_s measure the interest rate responses to lagged CPI inflation, output gap and real exchange rate respectively. $\Delta\hat{\pi}_t^c$ and $\Delta\hat{y}_t$ are the current changes in the inflation and output gap. Since the central bank sets the interest rate, it adjusts the outstanding money supply to match money demand by buying and selling domestic interest-earning assets. The government through the central bank issues all forms of money—cash and interest-earning assets—and continuously balances its budget with endogenous lump-sum taxes or transfers to households.

2.5. Goods and financial market-clearing

2.5.1. Goods market-clearing

Since intermediate firms are inherently similar, they make identical decisions at equilibrium. Therefore (2.2) can be expressed as $Y_t = \epsilon_t z_t^{1-\alpha} K_t^{\alpha} N_t^{1-\alpha} - z_t\phi$. The aggregate resource constraint is given by:

$$C_t^d + I_t^d + X_t \leq Y_t - \tilde{a}(u_t)\tilde{K}_t - G_t H_t \tag{2.17}$$

so that net aggregate production accounts for the capital utilization cost $\tilde{a}(u_t)$ and the hiring cost $G_t H_t$. Substituting the demand for domestic consumption goods (2.8), domestic investment good (2.10), exports (2.5), and the hiring costs (2.3) into (2.17), and dividing both sides by z_t gives:

$$(1-\omega_c)\left[\frac{P_t^d}{P_t^c}\right]^{-\eta_c} c_t + (1-\omega_i)\left[\frac{P_t^d}{P_t^i}\right]^{-\eta_i} i_t + \left[\frac{P_t^x}{P_t^*}\right]^{-\eta_f} y_t^* \frac{z_t^*}{z_t} \leq y_t - \tilde{a}(u_t)\frac{\tilde{k}_t}{\mu_t^z} - g_t H_t$$

For simplicity, assume the foreign steady-state growth rate is the same as for the domestic economy. Define $\tilde{z}_t^* = \frac{z_t^*}{z_t}$ as a stationary shock that measures the degree of asymmetry in permanent shocks to technological progress between the foreign and the domestic economy. At the steady state, $\tilde{z}_t^* = 1$. Its log-linearized stochastic process is:

$$\hat{\tilde{z}}_{t+1}^* = \rho_{\tilde{z}^*}\hat{\tilde{z}}_t^* + \epsilon_{t+1}^{\tilde{z}^*}$$

2.5.2. Evolution of net foreign assets

Aggregate foreign assets must satisfy:

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

where $R_{t-1}^*\Phi(a_{t-1}, \tilde{\phi}_{t-1})$ represents the risk-adjusted gross interest rate and $a_t \equiv \frac{S_t^n B_{t+1}^*}{P_t^d z_t}$, which represents the stationarized real net foreign asset position in domestic value.

2.5.3. Loan market-clearing

Domestic loan market-clearing requires the borrowing in the form of the wage bill to equal the lending of the monetary system:

$$W_t N_t = \mu_t^m M_{t-1} - Q_t$$

where Q_t is nominal cash holding by households as defined in (2.6) and M_t is total domestic assets held including interest-earning bonds. μ_t^m is the gross monetary growth rate at time t:

$$\mu_t^m = \frac{M_t}{M_{t-1}}$$

Dividing both sides by z_t and P_t^d gives:

$$w_t N_t = \frac{\mu_t^m m_{t-1}}{\pi_t^d \mu_t^z} - q_t$$

2.6. Foreign economy

The foreign economy is summarized by three variables—inflation π_t^*, the output growth $\hat{y}_t^*$ and the short-term interest rate R_t^*. They are modelled as a VAR(1) process: $(F_t^* \equiv [\hat{y}_t^* \ \pi_t^* \ R_t^*]')$

$$F_t^* = \rho_F^* F_{t-1}^* + \epsilon_t^*$$

3. Estimation

We use quarterly Australian data from 1993Q2 to 2007Q3, including CPI inflation, nominal cash rate, real GDP, consumption, investment, imports and exports, G7-weighted real exchange rate, unemployment rate and real wages, G7 real GDP, G7 average inflation and nominal cash rate (Appendix Appendix A lists the sources of the data). This period was chosen because it begins when the Reserve Bank of Australia commenced inflation targeting and ends just before the global financial crisis began to have an impact. The CPI inflation is measured as the quarterly percentage growth of the CPI price index. Real GDP, consumption, investment, import and export are chain-volume measures, and the real wage is measured by nominal average weekly earnings per adult divided by the GDP deflator. The estimation maps Θ in the theoretical model to the data, where:

$$\Theta \in \left\{ \hat{\pi}_t^c,\ \hat{w}_t,\ \hat{y}_t,\ \hat{c}_t,\ \hat{i}_t,\ \hat{X}_t,\ \hat{M}_t^m,\ \hat{R}_t,\ \hat{s}_t^r,\ \hat{U}_t,\ \hat{R}_t^*,\ \hat{y}_t^*,\ \hat{\pi}_t^* \right\}$$

where a variable with a caret (ˆ) represents its log-linearized counterpart.

3.1. Measurement

All variables in Θ are stationary by construction, but some data series have a trend component and thus we need to transform these before mapping into the variables. In our theoretical model, the source of growth in real variables stems from growth in technology, thus all real variables share the same trend. Instead of estimating the model with pre-filtered data (eg: the Hodrick-Prescott filter), we can identify this growth component by mapping the model to the first-difference of the logged variable. Denote a variable with a tilde (˜) as the observation of the corresponding variable in the theoretical model. For domestic and foreign real GDP and real wages:

$$\begin{aligned}
\ln\left(\tilde{Y}_t/\tilde{Y}_{t-1}\right) &= \hat{y}_t - \hat{y}_{t-1} + \hat{\mu}_t^z + \ln\bar{\mu}^z - \alpha(\hat{k}_t - \hat{k}_{t-1} + \hat{\bar{k}}_t - \hat{\bar{k}}_{t-1}) \\
&\quad - \frac{\delta\bar{N}\bar{g}}{\bar{y}}(\hat{g}_t - \hat{g}_{t-1} + \hat{H}_t - \hat{H}_{t-1}) \\
\ln\left(\tilde{Y}_t^*/\tilde{Y}_{t-1}^*\right) &= \hat{y}_t^* - \hat{y}_{t-1}^* + \hat{\tilde{z}}_t^* - \hat{\tilde{z}}_{t-1}^* + \hat{\mu}_t^z + \ln\bar{\mu}^z \\
\ln\left(\frac{\widetilde{W}_t/P_t^d}{\widetilde{W}_{t-1}/P_{t-1}^d}\right) &= \hat{w}_t - \hat{w}_{t-1} + \hat{\mu}_t^z + \ln\bar{\mu}^z
\end{aligned}$$

Note our theoretical output concept does not take the capital utilization and hiring costs into consideration, and so we need to subtract these costs when matching with the data. Aggregate consumption and investment are mapped to the data according to:

$$\begin{aligned}
\ln\left(\tilde{C}_t/\tilde{C}_{t-1}\right) &= \left(\frac{\eta_c\bar{c}^d}{\bar{c}^m + \bar{c}^d}\right)\left(\frac{\bar{c}^m}{\bar{c}}\right)\left(\frac{\bar{\lambda}^{m,c}-1}{\bar{\gamma}^{c,d}}\right)(\hat{\pi}_t^{m,c} - \hat{\pi}_t^d) + \hat{c}_t - \hat{c}_{t-1} + \hat{\mu}_t^z + \ln\bar{\mu}^z \\
\ln\left(\tilde{I}_t/\tilde{I}_{t-1}\right) &= \left(\frac{\eta_i\bar{i}^d}{\bar{i}^m + \bar{i}^d}\right)\left(\frac{\bar{i}^m}{\bar{i}}\right)\left(\frac{\bar{\lambda}^{m,i}-1}{\bar{\gamma}^{i,d}}\right)(\hat{\pi}_t^{m,i} - \hat{\pi}_t^d) + \hat{i}_t - \hat{i}_{t-1} + \hat{\mu}_t^z + \ln\bar{\mu}^z
\end{aligned}$$

Similarly, we match export and import data with:

$$\begin{aligned}
\ln\left(\tilde{X}_t/\tilde{X}_{t-1}\right) &= -\eta_f\,(\hat{\pi}_t^x - \hat{\pi}_t^*) + \hat{y}_t^* - \hat{y}_{t-1}^* + \hat{\tilde{z}}_t^* - \hat{\tilde{z}}_{t-1}^* + \hat{\mu}_t^z + \ln\bar{\mu}^z \\
\ln\left(\tilde{M}_t^m/\tilde{M}_{t-1}^m\right) &= \frac{\bar{c}^m}{\bar{c}^m + \bar{i}^m}\left(-\eta_c(1-\omega_c)\left(\bar{\gamma}^{c,d}\right)^{\eta_c - 1}(\hat{\pi}_t^{m,c} - \hat{\pi}_t^d) + \hat{c}_t - \hat{c}_{t-1}\right) \\
&\quad + \frac{\bar{i}^m}{\bar{c}^m + \bar{i}^m}\left(-\eta_i(1-\omega_i)\left(\bar{\gamma}^{i,d}\right)^{\eta_i - 1}(\hat{\pi}_t^{m,i} - \hat{\pi}_t^d) + \hat{i}_t - \hat{i}_{t-1}\right) + \hat{\mu}_t^z + \ln\bar{\mu}^z
\end{aligned}$$

where $\bar{c}^m = \omega_c(\bar{\lambda}^{mc})^{-\eta_c}(\bar{\gamma}^{c,d})^{\eta_c}\bar{c}$ and $\bar{i}^m = \omega_i(\bar{\lambda}^{mi})^{-\eta_i}(\bar{\gamma}^{i,d})^{\eta_i}\bar{i}$. The interest rates, inflation and unemployment rates are matched with data through:

$$\tilde{R}_t = \hat{R}_t + \ln \bar{R}$$
$$\tilde{R}^*_t = \hat{R}^*_t + \ln \bar{R}$$
$$\tilde{\pi}^c_t = \hat{\pi}^c_t + \ln \bar{\pi}^d$$
$$\tilde{\pi}^*_t = \hat{\pi}^*_t + \ln \bar{\pi}^d$$
$$\tilde{U}_t = U_t + \bar{U}$$

The solved version of the whole model can be cast into the following state-space form:

$$\mathbf{S_t} = \mathbf{F}\mathbf{S}_{t-1} + \mathbf{V}\epsilon_\mathbf{t} \qquad \epsilon \sim \mathrm{N}(0, \sigma)$$
$$\tilde{\mathbf{\Upsilon}}_\mathbf{t} = \bar{\mathbf{\Upsilon}} + \mathrm{H}\mathbf{S_t} + \eta_\mathbf{t} \qquad \eta \sim \mathrm{N}(0, \Lambda)$$

where $\mathbf{S_t}$ is the vector that contains all endogenous variables, matrix $\mathbf{H}$ maps the endogenous variables Θ_t to observations $\mathbf{\Upsilon_t}$, where

$$\tilde{\mathbf{\Upsilon}}_\mathbf{t} \in \left\{\Delta \ln \tilde{Y}_t, \Delta \ln \tilde{C}_t, \Delta \ln \tilde{I}_t, \Delta \ln \tilde{X}_t, \Delta \ln \tilde{M}^m_t \Delta \ln \left(\tilde{W}_t/P_t\right), \tilde{R}_t, \tilde{U}^a_t, \hat{s}^r_t, \tilde{\pi}^c_t, \Delta \ln \tilde{Y}^*_t, \tilde{R}^*_t, \tilde{\pi}^*_t\right\}$$

and $\bar{\mathbf{\Upsilon}}$ contains the steady-state information of these variables:

$$\bar{\mathbf{\Upsilon}} \in \left\{\ln \bar{\mu}^z, \ln \bar{\mu}^z, \ln \bar{\mu}^z, \ln \bar{\mu}^z, \ln \bar{\mu}^z, \ln \bar{\mu}^z, \ln \bar{R}, \bar{U}, 0, \bar{\pi}^d, \ln \bar{\mu}^z, \ln \bar{R}, \bar{\pi}^d\right\}$$

3.2. Calibration and priors

We calibrate a number of parameters, which are shown in Table 1. $\beta = 0.996$ implies the steady-state nominal interest rate is 5.2 per cent, which matches the average interest rate in the sample period. Setting δ at 0.1 delivers a steady-state monthly separation rate of 3.45 per cent and a job-finding rate of 25 per cent, which is consistent with the Australian labour market in the period under discussion (see Ponomareva and Sheen (2010) for details).[12] As in Blanchard and Gali (2010), we set ϑ at 1, which implies the hiring cost is unit-elastic to current labour market conditions. We follow Jääskelä and Nimark (2011) in calibrating for the Australian economy by setting the depreciation rate δ_k at 0.013, the labour share of production α at 0.29,

[12] We calculate the implied monthly rate from the quarterly rate by solving $m+(1-m)m+(1-m)^2m = q$, where $q \in \{\delta, \bar{x}\}$. The steady-state job finding rate $\bar{x}$ is calculated based on a 7 per cent steady-state unemployment rate.

and the share of consumption and investment in imports, ω_c and ω_i at 0.2 and 0.5. Following Adolfson et al. (2007), we set the curvature of the money demand function σ_q at 10.62, the elasticity of labour supply σ_L at 1, and the constants that determine the level of utility from real balances Aq at 0.337. Since the steady-state markup for labour-producing firms $\bar{\lambda}^w$ is not jointly identified with the labour supply shock, we set the value at 1.05. We use the sample average for the steady-state level of the annual unemployment rate $\bar{U}$ (calibrated at 7 per cent) and for the inflation rate of domestic production (0.7 per cent). The utility parameter A_L is set to 1, which has implications for the steady state level of the marginal disutility of labour and thus the real wage, and then the capital to labour ratio.

Parameter	Description	Value	Source
β	discount factor	0.996	matches sample average interest rate
δ	separation rate	0.1	Ponomareva and Sheen (2010)
ϑ	elasticity of hiring cost to labour market condition	1	Blanchard and Gali (2010)
δ_k	depreciation rate	0.013	Jääskelä and Nimark (2011)
α	capital share	0.29	Jääskelä and Nimark (2011)
ω_c	import share of consumption good	0.2	Jääskelä and Nimark (2011)
ω_i	import share of investment good	0.5	Jääskelä and Nimark (2011)
σ_q	money demand curvature parameter	10.62	Adolfson et al. (2007)
$\bar{\lambda}^w$	steady-state labour markup	1.05	Adolfson et al. (2007)
σ_L	labour supply elasticity	1	Adolfson et al. (2007)
A_L	labour disutility constant	1	
Aq	money utility constant	0.3776	Adolfson et al. (2007)
$\bar{U}$	steady-state level of unemployment	0.07	sample average unemployment rate
$\bar{\pi}^d$	steady-state level of domestic goods inflation	1.005	Jääskelä and Nimark (2011)
ρ_{λ^d}	persistence of final domestic goods markup	0.5	
$\frac{a''(1)}{a'(1)}$	steady-state utilization cost parameter	0.049	Adolfson et al. (2007)

Table 1: Calibrated parameters

We follow Adolfson et al. (2007) and Jääskelä and Nimark (2011) in choosing priors. For parameters that ought to be bounded between 0 and 1, such as the persistence parameters, we use a beta distribution. For elasticities, steady-state markups and standard deviation of shocks, we expect the mass of the distribution to be concentrated at small values, but do not rule out possible large values; thus inverse gamma distributions are used. Some of the shocks appear in the model scaled by a non-linear function of deep parameters. We set the same prior for the 'reduced' form of these shocks as for unscaled shocks—with a mean 0.5 and standard deviation 2. For the rest, we simply employ normal distributions. Since we were unable to identify the hiring cost shock, ϵ_t^x, the imported investment good markup shock, $\epsilon_t^{\lambda^{im}}$, and the nominal wage markup shock, $\epsilon_t^{\lambda^w}$, we set their standard errors to zero.

3.3. Results

The model is solved numerically using Dynare. The Kalman filter is employed to evaluate the model likelihood, and the Markov Chain-Monte Carlo (MCMC) method is used to conduct the posterior simulations. One million draws are taken, of which 30 per cent are discarded to minimize the impact of initial values. We also control the variance of the candidate distribution, from which the simulation draws, to achieve an acceptance rate around 30 per cent.

The prior and posterior for the benchmark model (for real wage rigidity with hiring costs) are displayed in Table 2. A key parameter in our setup of the model is B, which determines the steady-state level of hiring costs. We find B is sharply estimated with a mean of 0.10 and a 90 per cent credibility interval bounded between 0.03 and 0.17. This implies the point estimate of the hiring costs to GDP ratio evaluated at the steady state ($\frac{\bar{g}\delta\bar{N}}{\bar{y}-\bar{g}\delta\bar{N}}$) is 0.97 per cent, with a 90 per cent credibility interval ranging from 0.30 to 1.61. Our estimation suggests statistically significant hiring costs in the Australian economy, and is consistent with the ABS estimates for the year 2001-2002 (Australian Bureau of Statistics (2003)).[13]

The point estimate of the habit formation parameter b is 0.68, indicating households prefer a relatively smooth consumption path. The investment adjustment cost $\tilde{S}''$ is 6.66. This implies the temporary elasticity of investment with respect to the current price of existing capital is 0.15, while the permanent elasticity is 37.

Our estimate of the risk premium parameter $\tilde{\phi}_a$ is 0.01, which indicates a 1 per cent increase in net foreign assets reduces the domestic rate of interest (ceteris paribus) by 0.01 per cent. Although this risk premium parameter is small in absolute value, it is statistically significant. The real wage persistence parameter f is tightly estimated at 0.44, indicating a substantial amount of real wage rigidity in the Australian economy. The elasticities of substitution of imported consumption and investment to domestic-produced goods are 2.82 and 1.26 respectively, which indicates the demand for imported consumer goods is substantially more sensitive to changes in relative price than imported investment goods. As the impulse response analysis will later show, this low price sensitivity of imported investment goods allows aggregate imports to rise following a positive technology shock, which restricts aggregate demand and results in unemployment. The mean estimate for $\bar{\mu}^z$ implies an annual growth rate of 2 per cent, with a 90 per cent confidence interval ranging from 1.2 to 2.4 percent. This is consistent with the sample

[13] According to the Australian Bureau of Statistics (2003), the total industry value-added by employment replacement firms was \$8866.7 million, which accounted for 1.3 per cent of GDP in 2001-2.

Parameter	Description	Priors			Posterior			
		Distribution	Mean	Std	Mean	Std	5%	95%
b	habit formation	Beta	0.65	0.10	0.68	0.06	0.58	0.78
B	tightness coefficient	Normal	0.12	0.20	0.10	0.04	0.03	0.17
$\tilde{S}$"	curvature of investment adjustment cost	Normal	7.69	2.50	6.66	2.29	3.12	10.07
$\tilde{\phi}_a$	risk premium	InvGamma	0.01	0.002	0.01	0.002	0.007	0.012
f	real wage AR(1) persistence	Normal	0.50	0.20	0.44	0.11	0.26	0.63
η_c	imported consumption elasticity	InvGamma	1.50	4.00	2.82	0.55	1.75	3.95
η_i	imported investment elasticity	InvGamma	1.50	4.00	1.26	0.07	1.12	1.40
η_f	export elasticity	InvGamma	1.50	4.00	1.41	0.10	1.11	1.72
$\bar{\mu}^z$	steady-state growth rate	Normal	1.005	0.002	1.005	0.001	1.003	1.006
$\bar{\lambda}^d$	steady-state markup: domestic	InvGamma	1.20	2.00	2.46	0.41	1.72	3.14
$\bar{\lambda}^{mc}$	steady-state markup: imported-consumption	InvGamma	1.20	2.00	1.23	0.10	1.07	1.38
$\bar{\lambda}^{mi}$	steady-state markup: imported-investment	InvGamma	1.20	2.00	4.74	1.35	1.68	7.05
Calvo lottery								
ξ_d	domestic firm	Beta	0.675	0.10	0.56	0.08	0.43	0.69
ξ_c^m	consumption import firm	Beta	0.675	0.10	0.65	0.07	0.38	0.85
ξ_i^m	investment import firm	Beta	0.675	0.10	0.66	0.10	0.50	0.83
ξ_x	exporter	Beta	0.675	0.10	0.74	0.05	0.64	0.84
Monetary policy parameters								
ρ_R	interest rate smoothing	Beta	0.80	0.05	0.85	0.03	0.81	0.90
r_π	inflation response	Normal	1.75	0.30	1.75	0.24	1.36	2.13
r_y	output response	Normal	0.125	0.05	0.04	0.03	-0.01	0.08
r_s	real exchange rate response	Normal	0.00	0.05	-0.03	0.01	-0.06	-0.00
r_{Δ_π}	inflation change response	Normal	0.00	0.10	0.12	0.05	0.04	0.20
r_{Δ_y}	output change response	Normal	0.00	0.10	0.01	0.02	-0.03	0.05
Persistence parameters								
ρ_{ζ^c}	consumption preference	Beta	0.50	0.15	0.74	0.11	0.56	0.94
ρ_{ζ^N}	labour preference	Beta	0.50	0.15	0.95	0.02	0.91	0.99
ρ_{μ^z}	permanent technology	Beta	0.50	0.15	0.76	0.08	0.64	0.89
ρ_ϵ	temporary technology	Beta	0.50	0.15	0.95	0.01	0.90	1.00
ρ_ϕ	risk premium	Beta	0.50	0.15	0.94	0.03	0.89	0.99
ρ_Γ	investment-specific technology	Beta	0.50	0.15	0.49	0.12	0.31	0.67
$\rho_{\tilde{z}^*}$	asymmetric foreign technology	Beta	0.50	0.15	0.89	0.07	0.77	1.00
$\rho_{\lambda^{cm}}$	markup: imported-consumption	Beta	0.50	0.15	0.45	0.05	0.05	0.94
ρ_{λ^x}	markup: export	Beta	0.50	0.15	0.14	0.06	0.01	0.25
Standard errors of exogenous shocks								
σ_{ζ^c}	preference shock: consumption	InvGamma	2.01	8.02	1.55	0.23	1.12	1.96
σ_{ζ^N}	preference shock: labour supply	InvGamma	0.50	2.00	0.79	0.13	0.57	1.01
σ_{μ^z}	permanent technology shock	InvGamma	0.50	2.00	0.17	0.03	0.12	0.21
σ_ϵ	temporary technology shock	InvGamma	0.50	2.00	0.32	0.06	0.21	0.43
σ_ϕ	risk premium shock	InvGamma	0.50	2.00	0.25	0.04	0.13	0.36
σ_Γ	investment specific technology shock	InvGamma	0.03	0.13	0.08	0.01	0.06	0.11
$\sigma_{\tilde{z}^*}$	asymmetric foreign technology shock	InvGamma	0.50	2.00	0.18	0.03	0.12	0.23
σ_R	monetary policy shock	InvGamma	0.50	2.00	0.11	0.01	0.09	0.14
σ_{λ^d}	markup shock: domestic production	InvGamma	6.33	25.3	1.68	0.28	1.21	2.13
$\sigma_{\lambda^{cm}}$	markup shock: imported-consumption	InvGamma	6.33	25.3	9.12	4.19	4.33	14.53
σ_{λ^x}	markup shock: export	InvGamma	6.33	25.3	35.45	5.89	21.90	49.05

Table 2: Priors and posteriors

average growth rate, which is 1.88 per cent. The point estimates of steady-state markups show that investment-importing firms have the most, and consumption-importing firms have the least market power compared to other types of firms.

Figure 1 plots the distributions for these deep parameters. In most cases, the posterior distributions are distinct from the corresponding priors, indicating that the data likelihood plays a

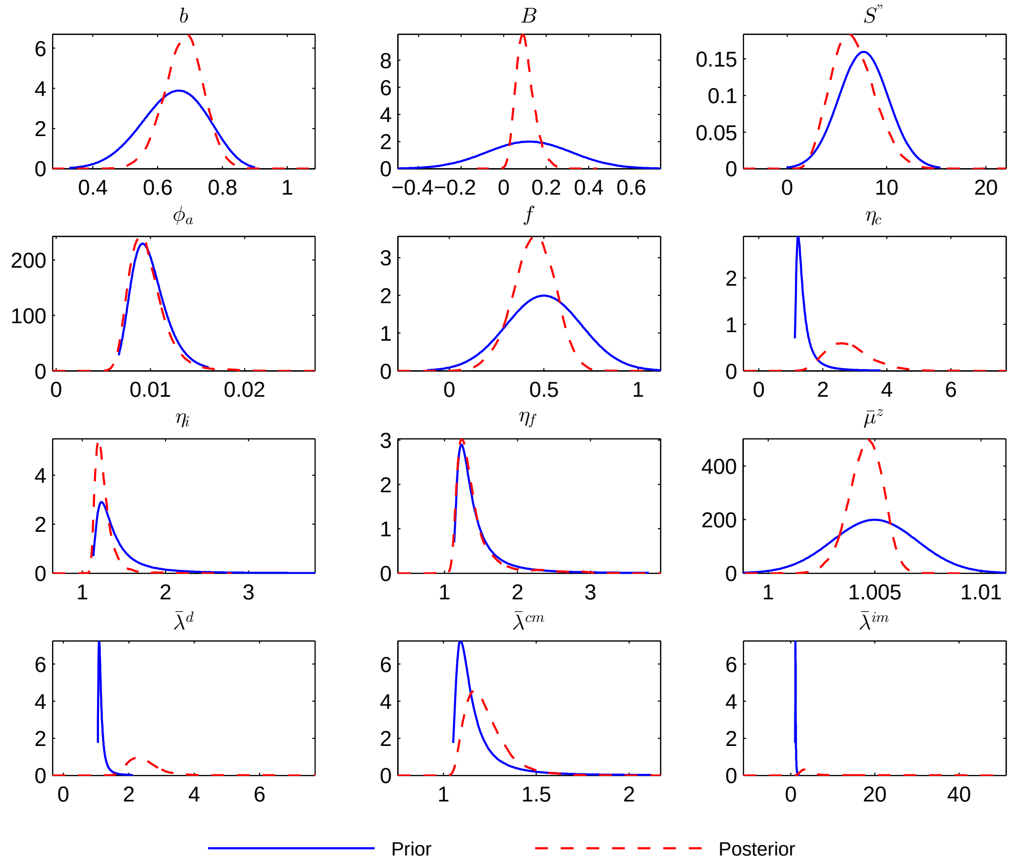

Figure 1: Prior and posterior: deep parameters

role in shaping the posterior distribution.

The point estimate of the Calvo lottery parameter for domestic firms is 0.56, which implies an average price fix duration of 2.3 quarters.[14] The Calvo parameter for consumption-importing firms and exporters are estimated at 0.65 (2.9 quarters) and 0.66 (2.9 quarters) respectively. However, the posterior of the parameter for investment-importing firms is dominated by its prior, which indicates the parameter is not well-identified. The Calvo parameter for exporters is significantly higher than other types of firms, with the mean centered at 0.74 (3.85 quarters), which suggests that exporters write longer-term contracts than domestic market suppliers.

The estimates of the interest rate rule suggest that the Reserve Bank of Australia (RBA) adjusted the nominal interest rate in response to inflation more than proportionately so as to influence the real interest rate (a policy requirement emphasized by Clarida et al. (1999, 2000)). The point estimate of the interest persistence parameter is 0.85, which indicates a substantial

[14]If ξ as the probability that a firm cannot change its price at a given period, Calvo pricing implies the average price fix duration is $\frac{1}{1-\xi}$.

amount of interest rate smoothing. This may reflect the desire to affect the long-run interest rate (Goodfriend (1991); Woodford (1999)), or may approximate for a more complicated optimal monetary policy (Levin et al. (1999)), or may arise because monetary policy is conducted under uncertainty (Sack and Wieland (2000)). The point estimates also suggest the RBA placed little weight on the real exchange rate and output directly. Inflation change had a modest but relevant effect, but output change had little.

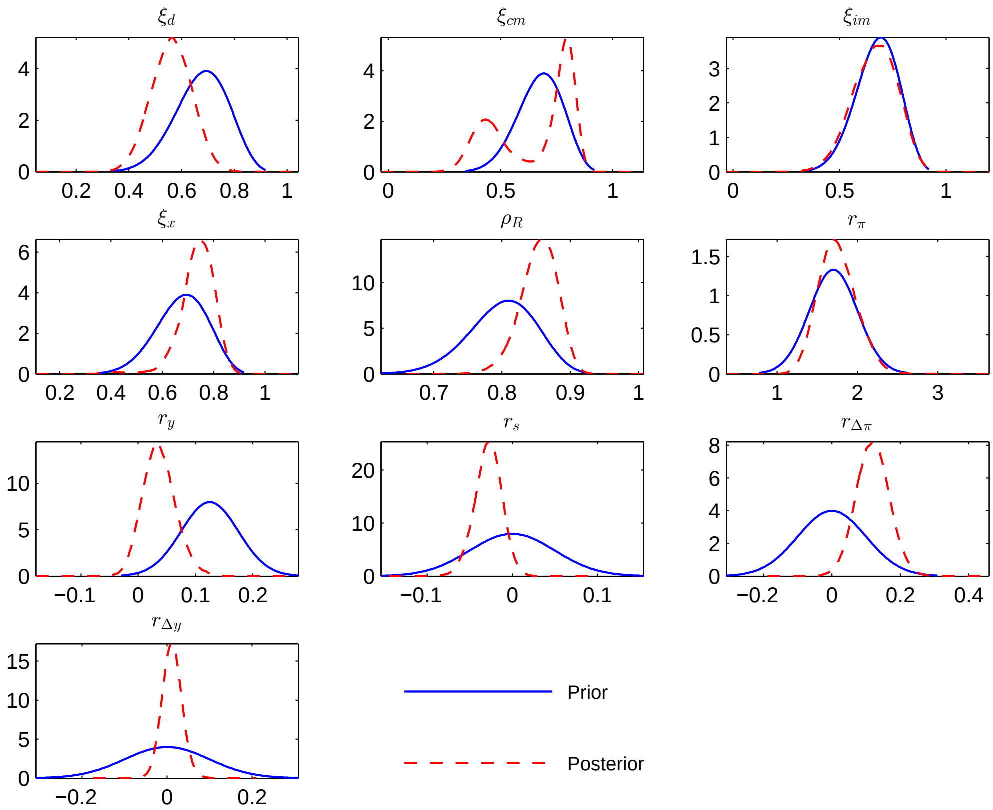

Figure 2: Prior and posterior: Calvo lottery and monetary policy parameters

Figure 2 shows the prior and posterior distributions for Calvo lottery and monetary policy parameters. All parameters are sharply estimated beside ξ_i^m (the Calvo lottery for imported investment), for which the distribution is almost identical to its prior, and ξ_c^m (the Calvo lottery for imported consumption), for which the posterior exhibits two modes. This bi-modal feature is also reflected in the persistence parameter for the imported consumption markup as shown in 3. This suggests a possible structural break in the sample period for the process driving imported consumption. An explanation could be that globalization (possibly through the advent of China) has enhanced competition in global consumer goods markets, reducing markups with higher price fix durations.

Our results indicate high persistence for shocks to labour supply preference (ρ_{ζ^N}), temporary technology (ρ_ϵ), the risk premium on foreign bonds (ρ_ϕ) and asymmetric technology ($\tilde{z}^*$), with point estimates between 0.89 and 0.95. The consumption preference shock ρ_{ζ^c} and the permanent technology shock ρ_{μ^z} are less persistent (0.74 and 0.76 respectively). In sharp contrast, the investment-specific technology and markup shocks have low persistence (between 0.14 and 0.49). Figure 3 shows the prior and posterior distributions for these persistence parameters, indicating that these parameters are identified.

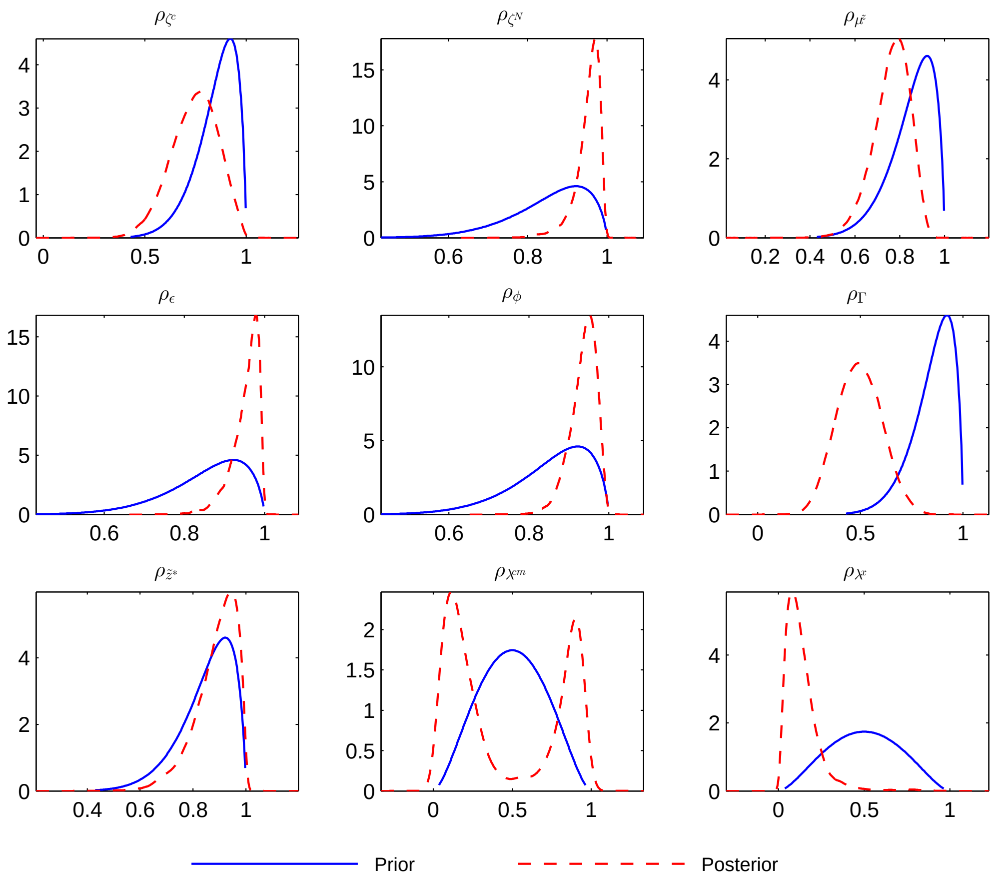

Figure 3: Prior and posterior: persistence parameters

Figure 4 shows the prior and posterior distributions for the standard deviations of all of the shocks, which appear to be identified by the data.[15]

[15]Two of the estimated means of the standard deviations are large—$\sigma_{\lambda^{m,c}}$ and $\sigma_{\lambda^{m,i}}$—simply because they appear in the model scaled by a small estimated coefficient which is a non-linear function of deep parameters. The standard deviation of the labour preference shock, σ_{ζ^N} is quite large due to the fact that non-modeled labour market reforms led to a decline in the unemployment rate over the period.

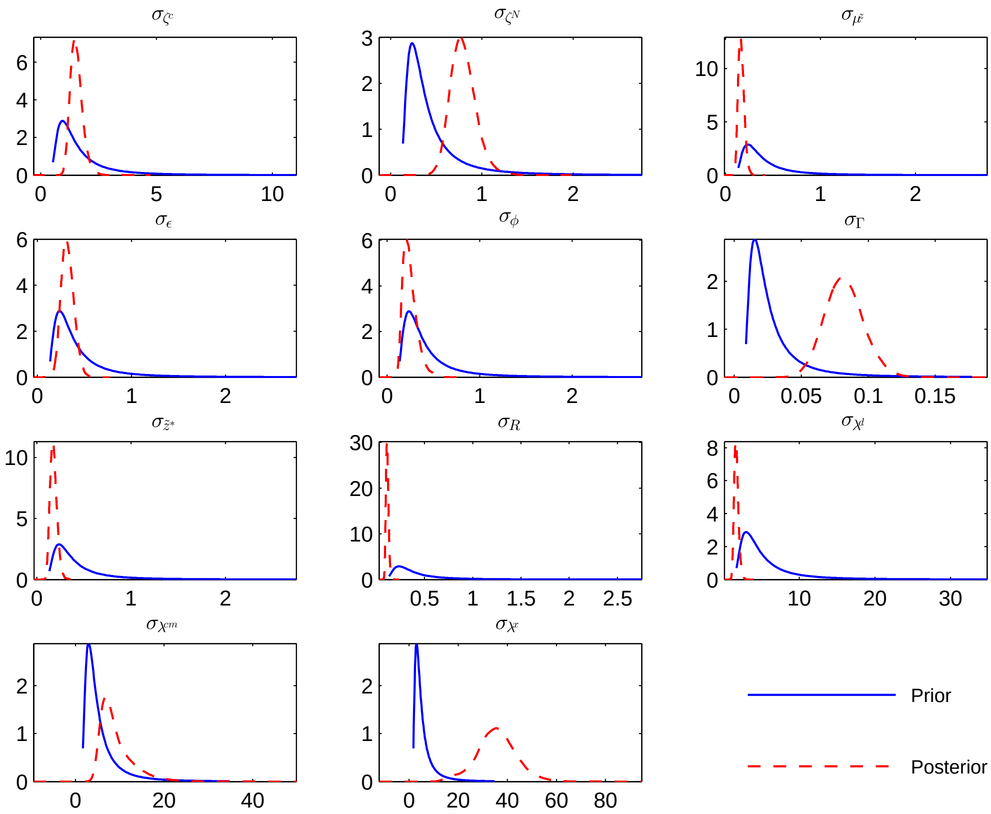

Figure 4: Prior and posterior: standard deviation of exogenous shocks

3.4. Hiring costs and wage rigidity

In this section we analyze the effect of hiring costs and types of wage rigidity on the parameter estimates. Four alternative models are investigated, namely the model with and without hiring costs and where either has real or nominal wage rigidity. The benchmark model was reported in the previous section and is the model with hiring costs and real wage rigidity. In Table 3, we show that the benchmark model is preferred against the other alternatives.

	RWR, HC	RWR, NHC	NWR, HC	NWR, NHC
Log-Likelihood	-889.11	-896.54	-891.79	-899.56
BF(Null: NHC)	7.43	—	7.78	—
BF(Null: NWR)	2.68	3.02	—	—

RWR: Real wage rigidity; NWR: Nominal wage rigidity
HC: Hiring cost; NHC: No hiring cost; BF: Bayes factor

Table 3: Comparison of models

Comparing posterior log-likelihoods, the model with hiring costs and real wage rigidity fits the data the best, with a value of -889.11. Using the Bayes factor as the criterion, models with the hiring costs are very strongly favoured by the data regardless of the type of wage rigidity.[16] Assuming a null hypothesis of no hiring costs, the Bayes factor is 7.43 (-889.11-(-896.54)) under real wage rigidity and 7.78(-891.79-(-899.56)) under nominal wage rigidity, indicating very strong evidence favouring the inclusion of hiring costs. Comparing types of wage rigidities, the data suggests models with real wage rigidity outperform those under nominal wage rigidities regardless of the existence of hiring costs. Assuming a null hypothesis that nominal wage rigidity prevails in the economy, the Bayes factor is 2.68 (-889.11-(-891.79)) with hiring costs and 3.02 (-896.54-(-899.56)) without hiring costs.[17]

The estimates of the parameters relating to the wage rate, domestic markup, habit formation and labour supply preference shocks depend on the assumptions of the existence of hiring costs and the type of wage rigidity. Figure 5 shows the effects on these parameters.[18] For details of the estimation results, see Appendix Appendix C.

The role of wage rigidity

As shown in section 2.3, nominal wage rigidity fixes the nominal wage via Calvo-pricing while real wage rigidity dampens the real wage responses by placing some weight on the lagged real wage rate. Movements in prices induce fluctuations in real wages under nominal wage rigidity. Therefore real wage rigidity requires more adjustments in employment after exogenous shocks, which in turn affects labour preferences more. The top panel of Figure 5 shows the persistence (ρ_{ζ^N}) and the standard deviation (σ_{ζ^N}) of the labour preference shock ζ^N. Compared to nominal wage rigidity, real wage rigidity tends to increase the point estimate of the persistence and standard deviation of the labour preference shock. The real marginal cost of domestic firms is relatively more persistent under hiring cost models, implying a smaller average price fix duration to match the observed inflation persistence, and thus a lower value of the Calvo nominal rigidity parameter ξ_d.

[16] Kass and Raftery (1995) show the Bayes factor is equivalent to the posterior odds ratio if one places an equal prior weight on the two competing models. Denote $B_{10} = \frac{p(Data|H_1)}{p(Data|H_0)}$ as the Bayes factor, where $p(Data|H_0)$ is the likelihood of data conditional on the null hypothesis H_0 and $p(Data|H_1)$ is the likelihood conditional on the alternative model H_1. They suggest a value of $\ln B_{10}$ between 1 and 3 indicates positive evidence against model H_0, 3 and 5 indicates strong evidence, whereas a value greater than 5 indicates very strong evidence in favour of that model.

[17] We compared the results for the reported models with ones where the real wage rule in 2.3.1 includes a separate persistent shock. The parameter estimates are similar, and the conclusions are unchanged. However, because models without hiring costs are limited to shocks in labour preferences in explaining actual variations in real wages, they are helped when adding a separate real wage shock. Thus the Bayes factors change to improve the role of models without hiring costs, but not decisively.

[18] Appendix Appendix D plots the posterior distributions for all parameters.

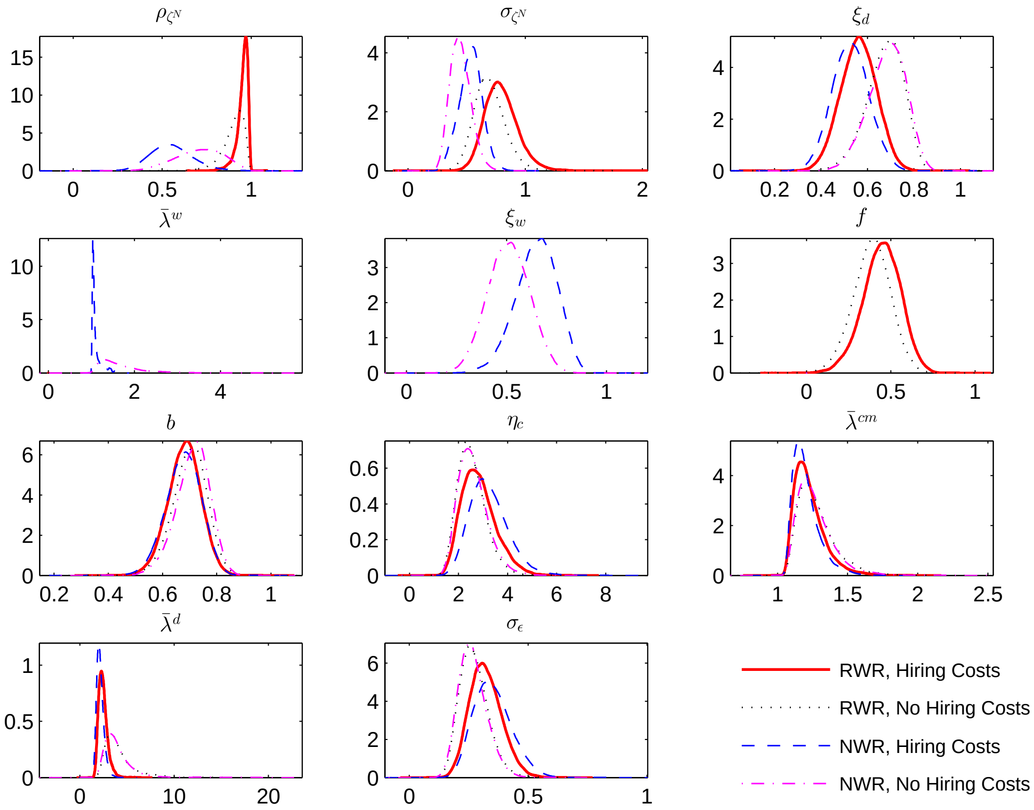

Figure 5: Comparison of posterior distributions: effects of types of wage rigidities and the existence of hiring costs

The role of hiring costs

The introduction of hiring costs increases labour costs and thus dampens firms' demand for labour.[19] Under nominal wage rigidity, this reduces the endogenous market power of the labour union, which results in a more rigid nominal wage. The second row of Figure 5 shows the impact on wages. Muting the hiring cost induces an increase of the mean of the nominal wage markup $\bar{\lambda}^w$ from 1.10 to 1.66, which indicates lower market power of the 'labour union' under the model with hiring costs. At the same time, the mean of the Calvo parameter in wage-setting ξ_w falls from 0.65 to 0.51, implying an average price fix duration reduced from 2.9 to 2 quarters, indicating a less rigid nominal wage. Under Nash bargaining, the hiring cost makes firms and workers consider both current and future expected hiring costs in the bargaining process, which leads to the Nash-bargaining wage w_t^* being directly indexed to the temporary technology shock. Since the shock is robustly estimated between 0.95 and 0.96, real wages are inherently persistent with the hiring cost.[20] This is evident from the persistence parameter under real

[19] Since labour demand is restricted, fluctuations in unemployment have to be attributed to higher labour preference volatility σ_{ζ^N}, as shown on the first row of Figure 5.

[20] Besides the hiring costs inducing more persistence in real wages, they also amplify its fluctuations. Comparing

wage rigidity, f,—with the introduction of the hiring costs, the estimate increases from 0.38 to 0.44.

The effects of the hiring costs on consumption-related parameters are shown in the third row of Figure 5. Since hiring costs increase the persistence in real wages, they in turn increase the persistence in the marginal rate of substitution and thus aggregate consumption. Therefore, less habit formation is needed to force a match of the observed persistence in aggregate consumption. The parameter b measures the degree of habit formation, which reduces from 0.70 (0.71) to 0.68 (0.68) under real (nominal) wage rigidity. Although hiring costs reduce the amount of habit formation, all models still require a substantial amount of the latter to match the persistence of consumption. The presence of the hiring costs also makes consumers more sensitive to the relative price between imported and domestically produced consumption goods, since the hiring costs add a wedge to the underlying marginal cost of domestic goods. The price elasticity η_c increases from 2.52 (2.59) to 2.82 (3.23) under real (nominal) wage rigidity, which in turn reduces the steady-state markup for consumption-importing firms $\bar{\lambda}^{cm}$ from 1.28 (1.27) to 1.23 (1.20).

The last row of Figure 5 shows the impact on domestic producers' steady-state markup $\bar{\lambda}^d$ and the standard deviation of the temporary technology shock σ_ϵ. Regardless of the type of wage rigidity, hiring costs reduce the point estimate of the steady-state domestic-producing firms' markup $\bar{\lambda}^d$ from 4.12(3.98) to 2.46(2.16) under real (nominal) wage rigidity. This is because the introduction of hiring costs increases marginal costs, and thus reduces firms' markup. The hiring costs restrict labour demand, thus requiring a bigger technology shock to shift labour demand and induce further fluctuations in the labour market. The point estimate of the standard deviation of the temporary technology shock increases from 0.16(0.17) to 0.17(0.18) under real (nominal) wage rigidity.

3.5. Impulse responses

3.5.1. A positive temporary technology shock

Figure 6 shows the impulse responses to a positive one-standard-deviation temporary shock to technology ϵ_t^ϵ for the four types of models (i.e. pairs of nominal or real wage rigidity, hiring

equation (2.15) when B is positive and zero, the introduction of hiring costs induces the Nash-bargaining wage w_t^* to respond to current and future expected hiring costs, which makes w_t^* more sensitive to the current state of economy. For example, a rise in employment increases w_t^* regardless of the existence of the hiring costs. However, the rising employment is also associated with an increase in hiring, which increases labour market tightness x_t. As the labour market becomes tighter, firms are willing to pay higher wages, which further increases w_t^*.

costs or none). Following the shock, output expands and peaks after 5 quarters with real wage rigidities and 9(10) quarters with nominal wage rigidities with (without) hiring costs. The real marginal cost mc^d decreases, which drives down the domestic producers' inflation π^d. This allows the central bank to decrease the interest rate R, which causes the exchange rate S^N to depreciate.

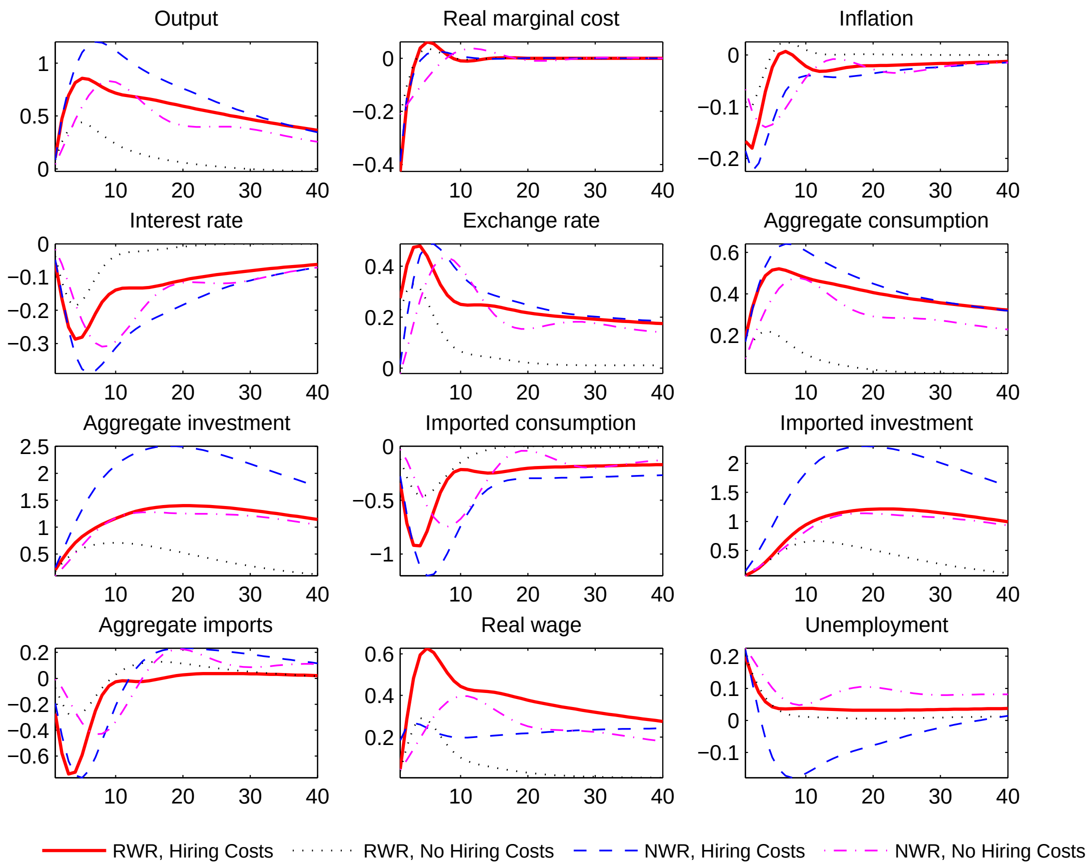

Figure 6: Impulse responses: 1 standard deviation temporary technology shock

Although both aggregate consumption c and investment i rise following the positive temporary technology shock, the shock decreases imported-consumption c^m, but increases imported-investment i^m despite the exchange rate depreciation. This different response between consumption and investment imports is due to the different price elasticities of the associated goods as well as macroeconomic 'income effects'.[21] However, the estimates of our model imply only 20

[21] According to equation (2.9) and (2.11), the response of imported consumption and investment depends on the respective relative price between imported and aggregate goods, and the respective quantity of aggregate

per cent of imports are associated with investment, and so aggregate imports still fall.[22]

Following the shock, productivity increases and thus real wages rise in all models. However, the increase in aggregate demand is restricted by the various rigidities present in the economy: hiring costs that add a premium to employment change; nominal price rigidities that constrain the decrease in price thus limiting the aggregate demand change; habit formation that dampens the increase in aggregate consumption; costly installation of investment goods and variable capital utilization that limit the increase in aggregate investment; and incomplete pass-through of export prices that restricts the increase in export demand. Further, due to its low estimated elasticity, the increase in aggregate investment is mainly in the form of imports rather than domestic demand. Therefore, the combination of rising wages and restricted aggregate demand reduces the demand for labour, and thus raises unemployment. Although output and unemployment move on impact in the same direction with this shock, we will show later that this apparent contravention of Okun's law is not a prediction of the overall model.

3.5.2. A positive permanent technology shock

Figure 7 shows the impulse responses after a positive permanent technology shock ϵ_t^z. Following the shock, the productivity gain increases the real wage, which in turn drives up the real marginal cost.[23] A rising real marginal cost pushes up inflation, and thus induces the central bank to raise the interest rate. The higher interest rate causes appreciation of the currency, which in turn lifts aggregate imports. As in the case under the temporary technology shock, the combination of restricted aggregate demand and rising real wage induces an increase in

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goods:

$$\hat{c}_t^m = \eta_c(\hat{\gamma}^{c,d} - \hat{\gamma}^{mc,d}) + \hat{c}_t$$
$$\hat{i}_t^m = \eta_i(\hat{\gamma}^{i,d} - \hat{\gamma}^{mi,d}) + \hat{i}_t$$

where the first term on the right hand side represents the 'substitution effect' on imported goods, and the second term represents the 'income effect'. As shown in Table 3, the point estimate of the elasticity parameter for investment-importing firms η_i (which ranges from 1.25 to 1.26) is significantly lower than for consumption-importing firms η_c (which ranges from 2.52 to 3.23). Following the positive technology shock, the relative prices for both imported consumption and investment goods fall, indicating that imported goods are more expensive. However the magnitude of the substitution effect is much larger for imported-consumption than imported-investment goods, mainly due to households being more sensitive to relative price changes for consumption goods. On the other hand, the technology shock stimulates both aggregate consumption and investment as shown in Figure 6. The net effects on imported-consumption and investment depend on which effect dominates. Since our estimates suggest households are much more sensitive to relative price changes for consumption goods, the substitution effect dominates for imported-consumption goods and the income effect for imported-investment goods.

[22]Due to the depreciation, aggregate exports also rise, as do net exports and the current account. Therefore, our model confirms that the general equilibrium Marshall-Lerner condition holds for the sample period in Australia.

[23]The rental price of capital r_t^k also increases, but to a lesser extent. For example, under real wage rigidity with hiring cost, r_t^k jumps to 0.011 on the impact of the shock, peaks at 0.032 in period 14 and then gradually return zero.

unemployment in all variants except nominal wage rigidity with hiring costs (which our tests using the Bayes factor did not support).

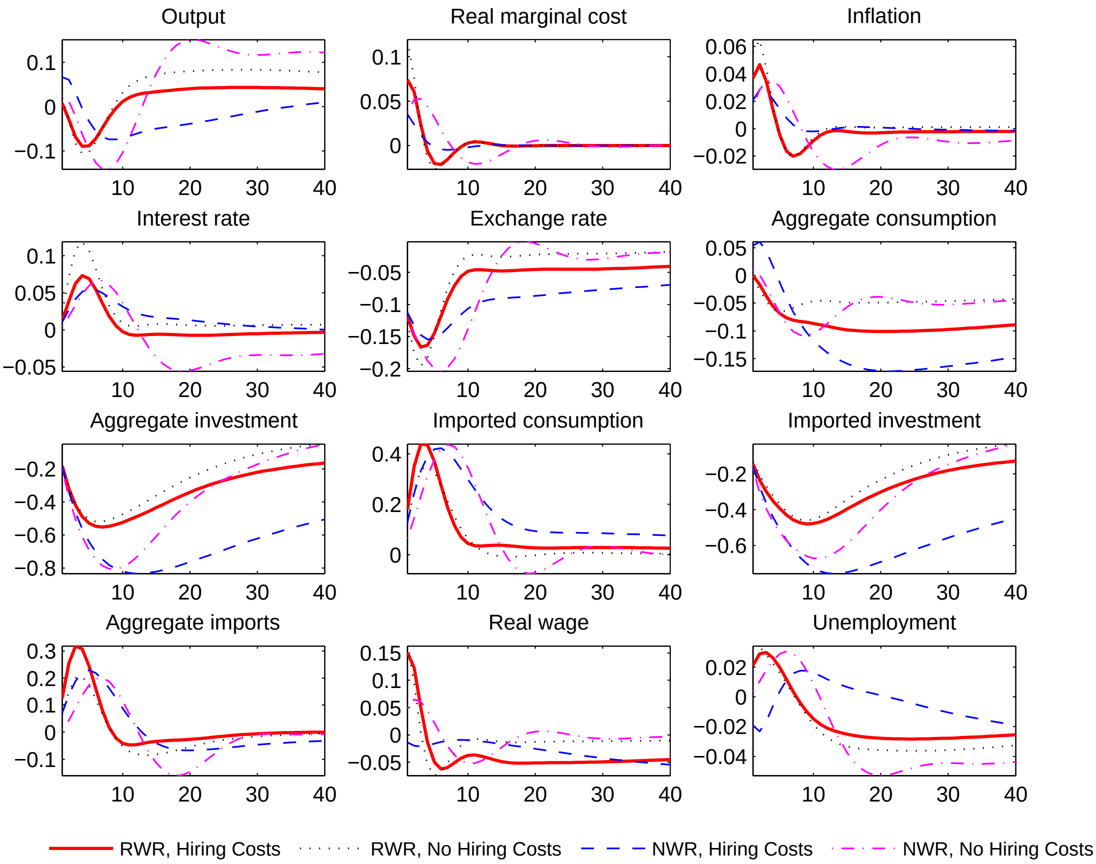

Figure 7: Impulse responses: 1 standard deviation permanent technology shock

Comparing to its temporary counterpart, a permanent technology shock increases real marginal cost, causing different responses of inflation, the interest rate, exchange rate and aggregate imports. This is because a temporary technology increase serves as a discrete 'helicopter drop' of production into the stationarized economy, with decreasing real marginal costs despite a rising real wage. On the other hand, a permanent technology shock changes the growth rate and does not deliver this discrete 'helicopter drop' into the deviation of production from the new steady state, leaving the rising factor prices to dominate the real marginal cost.

Riggi (2010) and Riggi and Tancioni (2010) argue that real wage rigidity fails to account for the 'productivity-employment' puzzle, in which a positive technology shock should generate a fall in labour inputs as found in many empirical studies (for example see Gali (1999), Francis and Ramey (2005) and Basu et al. (2006)). Following the shock, they explain that prices decrease and aggregate demand rises. Nominal wage rigidity prevents nominal wage changes, and thus a decrease in the price level increases the real wage, which results in a reduction in labour demand thus lowering the labour input. On the other hand, real wage rigidity prevents the real wage increasing much after the positive technology shock. The combination of rising aggregate demand and a lower than otherwise real wage increases the demand for labour, and thus results in more employment. We do not observe this productivity-employment puzzle for all models except the non-preferred one with nominal wage rigidity and hiring costs. In fact, our models indicate instead a rise in inflation after the shock, which makes the model with nominal wage rigidity incapable of accounting for the puzzle. The result obtained in Riggi (2010) and Riggi and Tancioni (2010) crucially relied on their setup for the technology shock, in which they use temporary rather than permanent technology shocks (and thus they obtain a fall in inflation after the positive technology shock). However, even with temporary technology shocks, our models exhibit a rise in unemployment, because the sluggish response of aggregate demand due to the various restrictions are sufficient to reduce labour demand.

Note that output falls and unemployment rises initially with a permanent shock, consistent with Okun's law.

3.5.3. A monetary policy contraction shock

Figure 8 shows the impulse responses for the four models after a positive one-standard-deviation shock to the interest rate. Following the shock, the interest rate rises, which reduces aggregate output, consumption and investment. The reduction in production cost decreases the real marginal cost, which in turn lowers inflation. The increase in the interest rate makes the domestic bond more attractive, which results in an appreciation of the domestic currency. The sign of the response of imports crucially depends on the assumptions of the model. Under real wage rigidity with hiring costs (which is the model most preferred by our tests), the substitution effect dominates the income effect (of the appreciation), which results in an immediate increase in aggregate imports. This response is what one would normally expect. However, under real wage rigidity without hiring costs and under nominal wage rigidity, we see a decrease in aggregate imports. In the model with real wage rigidity but no hiring costs, the reduction in output is the least, while imported consumption falls the most, combining to affect labour demand and supply, resulting in lower unemployment, which contradicts most empirical studies. This further underlines the importance of including hiring costs in the presence of real wage rigidity. Once again, this shock is consistent with Okun's law.

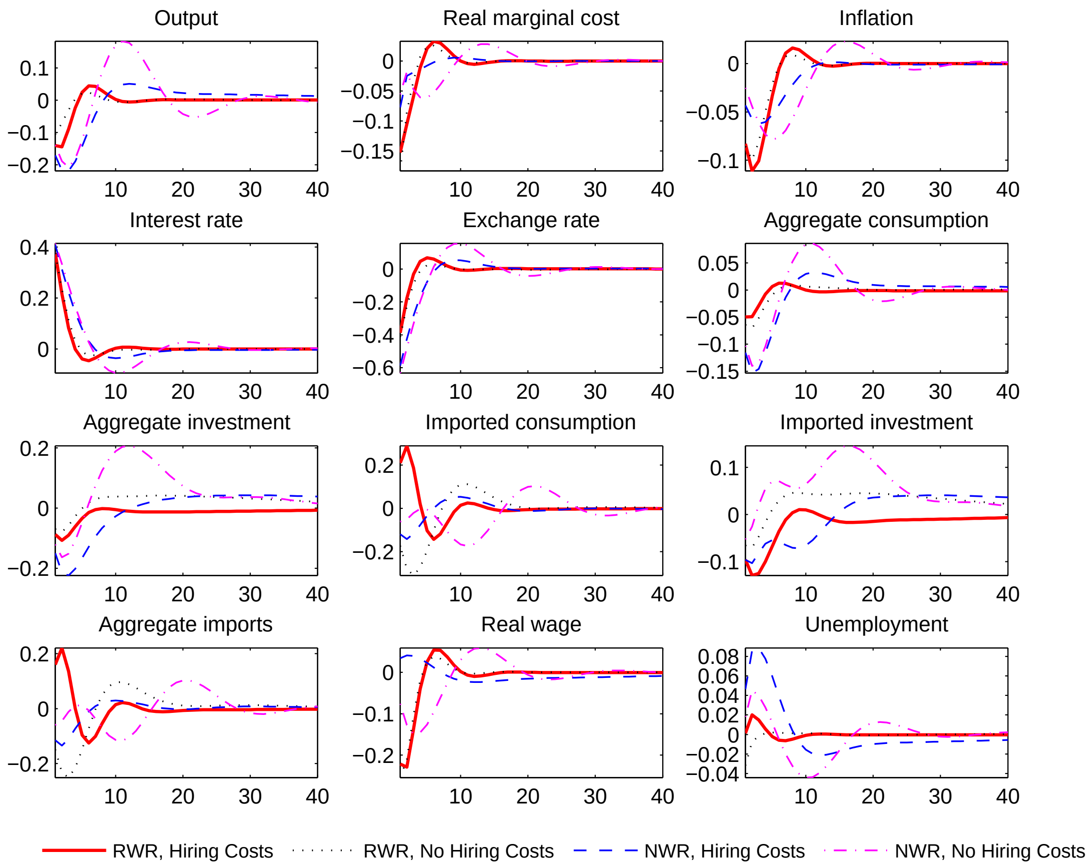

Figure 8: Impulse responses: 1 standard deviation monetary policy shock

3.6. Variance decomposition

Figure 9 shows the forecast variance decomposition both on impact and in the long run of the various shocks on key endogenous variables. We aggregate the effects of both temporary and permanent technology shocks into one single measure (defined as Tech), and aggregate over all shocks related to the small open economy (SOE). The other shocks relate to consumption preferences (Pref-C), labour supply preferences (Pref-L), investment (Inv), monetary policy (MP) and the domestic markup (Markup-Dom). There are a number of notable results.

Almost 50% of the variance of unemployment ($\hat{U}$) on impact is explained by technology shocks (all most all temporary), which are reflected in variations of labour demand and thus hiring costs ($\hat{g}$). In the long run equilibrium, this contribution declines to about 10%, with the contribution of labour supply preference shocks jumping to a dominant 58%. In contrast, labour supply preferences contribute about 50% to real wage ($\hat{w}$) variation on impact, declining to 15% in the long run, replaced by technology shocks with 40% (almost all temporary). Note that about 50% of unemployment variance is explained by shocks other than technology.

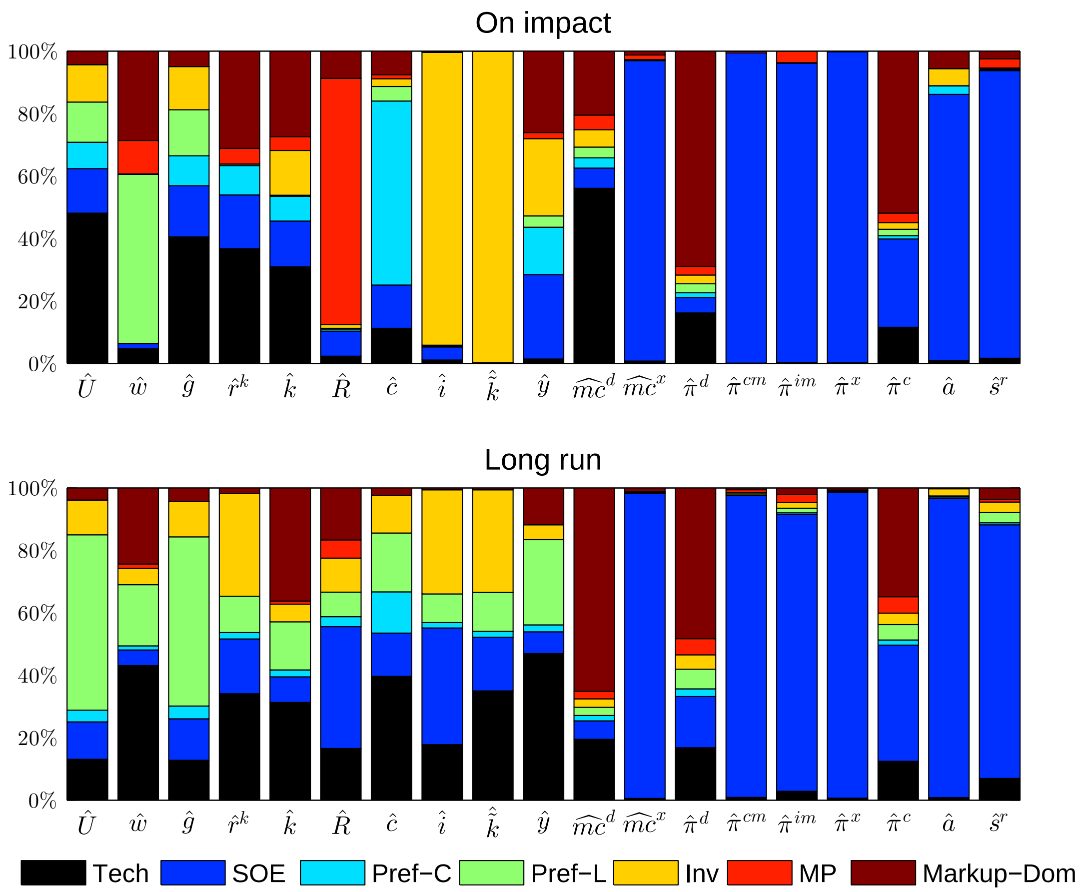

Figure 9: Variance decomposition

But, interestingly, technology shocks hardly play any role in driving short run output ($\hat{y}$) fluctuations, leaving aggregate demand-side factors to account for 67% (SOE: 27%, Pref-C: 15%, Inv: 25%) of output variance. In the long run however, technology and labour preference shocks on the aggregate supply side account for 74% (Tech: 47%, Pref-L: 27%) of output variations. Our results thus support the predictions by models from the new Keynesian tradition, which attribute short run output fluctuations to demand shocks and long run fluctuations to supply shocks.

Taking into account the effects of all shocks on output and unemployment, we find that estimated correlation between these two variables is -0.61, which is evidence that the model is consistent with Okun's law.

Investment shocks contributed significantly in the short run to investment ($\hat{i}$) and capital accumulation ($\hat{\bar{k}}$) variation, and to a much lesser extent capital services ($\hat{k}$, 10%), and thus output ($\hat{y}$, 12%) but nothing to the real rate of return on capital ($\hat{r}^k$). These effects reverse in the long run.

Consumption preference shocks have a large effect on consumption ($\hat{c}$) variation in the short run (65%), and less on output (11%), but negligible effects in the long run.

Taking into account all shocks, we find significant positive co-movement of the key domestic components of aggregate demand (with the correlation of consumption and investment being 0.32).

The variance of inflation (for all but domestic goods $\hat{\pi}^a, a \in \{cm, im, x, c\}$) is strongly dominated by open economy shocks both in the short and long run. Domestic goods inflation ($\hat{\pi}^d$) variance is heavily affected by markup shocks (almost 80% in the short run, 50% in the long).

The variance of (unexpected) monetary policy policy shocks only has an important impact on the short-term nominal interest rate ($\hat{R}$) variance. This indicates the Reserve Bank of Australia has communicated its intentions effectively, and has not caused significant surprises to the Australian economy, even in the short run.

3.7. Conditional forecasts

We now examine the out-of-sample performance of our preferred model, focusing on how well it does during the global financial crisis. Since this crisis was external to Australia, our conditional forecasts are calculated by imposing the actual data paths for foreign interest rates, foreign inflation and foreign output growth in the forecast period. In addition, since Australia experienced a boom in the real value of its mining exports from the mid-2000s mainly due to an ever-growing China, we also impose the actual values of export growth on our conditional forecasts.[24]

Figure 10 presents the actual data series (red solid line) and our preferred model's conditional forecasts (blue dashed line) from 2007Q4 to 2012Q2 with 90 per cent credible bands (thin solid lines). Despite the obvious difficulties that such a model faces in predicting well in such a major crisis, after 19 quarters, the forecast values of all the key macroeconomic variables are close to their actual values. The root mean square errors (shown in the sub-headers of each pane in Figure 10) are remarkably low for the main domestic macroeconomic variables. The model fails

[24] This assumption suppresses any potential effects of endogenous real exchange rate changes on exports. These changes were actually modest.

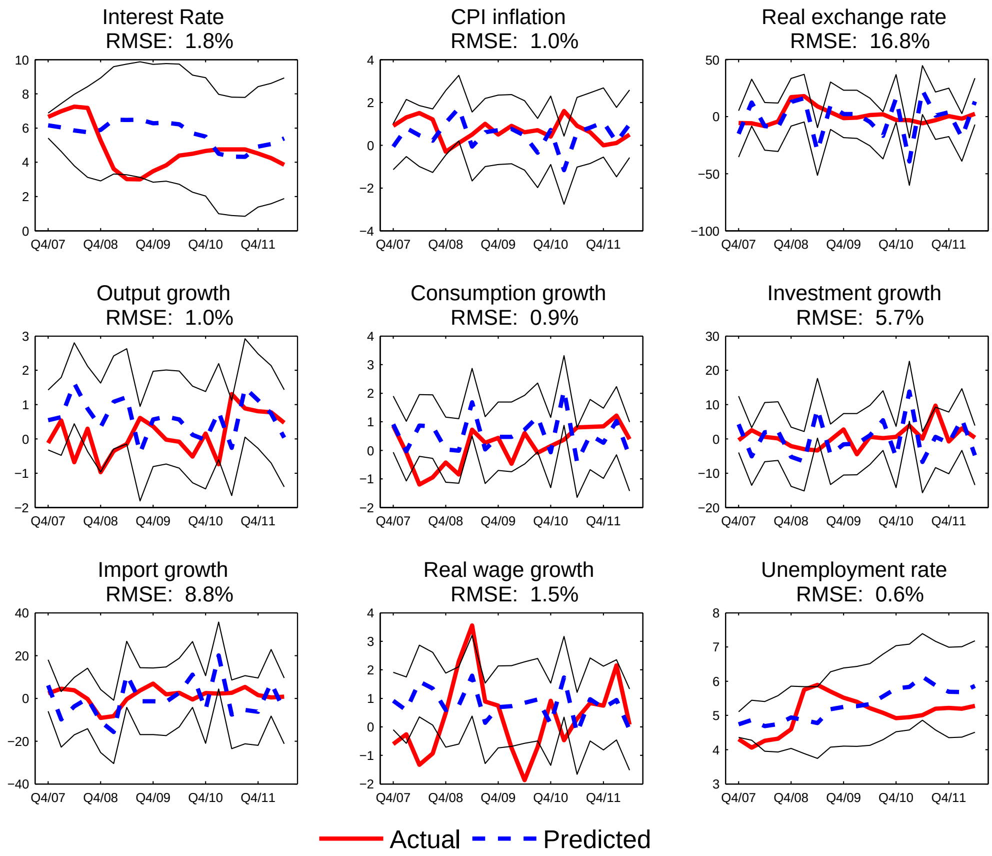

Figure 10: Conditional forecasts

to pick up the large fall in output and consumption growth through 2008. This is unsurprising if these are explained by the collapse in consumer confidence that actually occurred[25]. For the same reason, our model fails to predict the sharp decline in the cash rate and a sharp rise in unemployment in 2008. The immediate and large response of monetary policy and of fiscal policy (which we did not model), and the boom in mining exports helped the Australian economy to recover from this crisis in confidence. From then onwards, the model's conditional forecasts did well for all domestic macroeconomic variables.

Our model is able to track the sharp depreciation in the second half of 2008, which reduced imports. However the predicted real exchange rate then becomes much more volatile than the actual one. Our model predicts too smooth a real wage growth path. This is due to a relatively stable real wage growth path in the sample, which became far more volatile during the crisis.[26] Consequently, the sample implies a much higher real wage persistence (with the mean estimate

[25]The Westpac-Melbourne Institute consumer sentiment index fell from 112.5 in December 2007 to 79 in July 2008, recovering only in mid-2009.

[26]The variance of the real wage growth increased from 0.41 for the sample period between 1993Q2 to 2007Q3 to 1.79 in the forecast period between 2007Q4 to 2012Q2.

of f being 0.44) than we might expect if we had included the crisis period in estimation. Nevertheless, aside from confidence effects, the model successfully predicts the relatively small impact that the global financial crisis had on the Australian economy.

4. Conclusions

In this paper, we estimate a medium-scale, small, open economy, DSGE model with labour market frictions using quarterly Australian data from 1993 to 2007. We evaluate four alternatives of this model, with nominal or real wage rigidity and/or with and without hiring costs.

Our results confirm the existence of hiring costs in the Australian labour market, with the point estimates suggesting they account for 0.97 per cent of GDP, with a 90 per cent credibility interval ranging from 0.30 to 1.61. Using the Bayes factor as a guide, the Australian data strictly prefers real wage rigidity and the inclusion of hiring costs compared to the other paired alternatives. In other words, the model with both real wage rigidity and hiring costs best fits the data.

The credible mean estimates of the preferred model (real wage rigidity with hiring costs) imply a real wage rigidity parameter of 0.44 (or a half-life of just under 1 quarter after a shock), and 0.1 for the hiring cost scale. The results suggest sizable habit formation (with a point estimate of 0.68). The short-term elasticity of investment to the current price of existing capital is 0.15, and except for investment-importing firms, the point estimates of the Calvo parameters are sharply estimated, giving an average price fix duration for domestic, consumption-importing firms and exporters as 2.3, 2.9 and 2.9 quarters respectively. The exchange rate risk premium elasticity is tightly estimated but small. The monetary policy rule strongly indicates the existence of smoothing, and the targetting of the level and change of inflation.

Impulse responses to the permanent (and temporary) technology shock reveal no productivity-employment puzzle for all variants except the (rejected) model with nominal wage rigidity and hiring costs, a finding that contradicts Riggi (2010) and Riggi and Tancioni (2010). The reason is that inflation rises after a permanent technology shock, which makes it harder for the model with nominal wage rigidity to account for the puzzle. With a positive temporary technology shock that decreases inflation, our results indicate a rise in unemployment in all four models considered. Besides rising real wages after the shock, aggregate demand is also limited by various frictions in the economy including hiring costs, nominal price rigidity, habit formation, costly installation of capital, variable capital utilization and incomplete pass-through in exports. Therefore, the combination of rising wages and restricted aggregate demand limits the demand for labour, and thus increases unemployment.

The impulse responses to a monetary policy shock for our preferred model yield results consistent with the New Keynesian model for a small open economy. The unexpected increase in the interest rate immediately appreciates the exchange rate, lowers inflation, aggregate demand, output, real wages and marginal costs, while pushing up unemployment and imports.

Variance decompositions for our preferred model indicate that labour supply shocks are important for real wages in the short run and unemployment in the long run, with the reverse for labour demand shocks (arising from technology). These contrasting variance effects operate in conjunction with hiring costs, and depend on the extent of real wage rigidity. Output variations are driven by aggregate demand shocks in the short run, and by aggregate supply shocks in the long run, thus validating the New Keynesian description of our model.

The out-of-sample conditional forecast performance of the model shows that it was difficult to predict the immediate impact of the global financial crisis, which were probably due to confidence effects. However, once these had dissolved (probably on account of the un-modeled fiscal stimulus, the large response of monetary policy and the mining export boom), our model performed remarkably well in predicting domestic macroeconomic variables.

Appendix A. Data description and sources

Variable	Description	Source (Series ID)
$\hat{\pi}_t^c$	Consumer Price Index (CPI) inflation	RBA (GCPIEITCQP)
$\Delta \ln \frac{W_t}{P_t^d}$	Nominal average weekly earnings per adult	RBA (GLCAWOET)
	deflated by GDP deflator	ABS (Cat 5206: A2303730T)
$\Delta \ln C_t$	Real final consumption expenditure	ABS (Cat 5206: A2304081W)
$\Delta \ln I_t$	Real private investment	ABS (Cat 5206: A2304100T)
$\Delta \ln X_t$	Real exports	ABS (Cat 5206: A2304114F)
$\Delta \ln M_t$	Real imports	ABS (Cat 5206: A2304115J)
$\Delta \ln Y_t$	Real GDP	ABS (Cat 5206: A2304402X)
$\hat{R}_t$	Target cash rate	RBA (FIRMMCRT)
$\hat{U}_t$	Unemployment rate	ABS (Cat 6202: A181525X)
$\hat{s}_t^f$	G7 trade-weighted real exchange rate	RBA (FRERGWI)
$\Delta \ln Y_t^*$	G7 real GDP	Datastream (G7OCFGDPD)
$\hat{\pi}_t^*$	G7 average inflation	Datastream: FRCONPRCE, BDCONPRCE, ITQ64...F JPCONPRCE, UKCONPRCF USCONPRCN, CNCONPRCF
$\hat{R}_t^*$	G7 average interest rate	Datastream: FRPRATE, BDPRATE, ITPRATE JPPRATE, UKPRATE USPRATE, CNPRATE

Optional Appendices:

Appendix B. The linearized economy

Appendix B.1. Domestic goods-producing firms

Appendix B.1.1. The labour market

After-hiring unemployment rate:

$$\hat{U}_t = -\left(1 - \bar{U}\right)\hat{N}_t \tag{B.1}$$

Labour market tightness:

$$\delta(1-\bar{U})\hat{x}_t = -\hat{U}_t + (1-\bar{x})(1-\delta)\hat{U}_{t-1} \tag{B.2}$$

Aggregate hiring:

$$\delta\hat{H}_t = \hat{N}_t - (1-\delta)\hat{N}_{t-1} \tag{B.3}$$

Stationary hiring cost:

$$\hat{g}_t = \hat{\epsilon}_t + \vartheta\hat{x}_t + \hat{\zeta}_t^x \tag{B.4}$$

Hiring cost shock:

$$\zeta_t^x = \rho_x\zeta_{t-1}^x + \epsilon_t^x \tag{B.5}$$

Appendix B.1.2. Domestic intermediate-producing firms

Intermediate producers' production function:

$$\hat{y}_t = \bar{\lambda}^d\left(\hat{\epsilon}_t + \alpha(\hat{k}_t - \hat{\mu}_t^z) + (1-\alpha)\hat{N}_t\right) \tag{B.6}$$

Permanent technology growth:

$$\hat{\mu}_t^z = \rho_{\mu^z}\hat{\mu}_{t-1}^z + \epsilon_t^z \tag{B.7}$$

Temporary technology shock:

$$\hat{\epsilon}_t = \rho_\epsilon\hat{\epsilon}_{t-1} + \epsilon_t^\epsilon \tag{B.8}$$

Optimal factor share:

$$\hat{r}_t^k = \hat{\epsilon}_t - (1-\alpha)(\hat{k}_t - \hat{\mu}_t^z - \hat{N}_t) + \widehat{mc}_t^d \tag{B.9}$$

Real marginal cost:

$$\begin{aligned}\widehat{mc}_t^d =& -\hat{\epsilon}_t + \alpha\hat{r}_t^k + \kappa_1\left[\hat{w}_t + \hat{R}_{t-1}\right] + \kappa_2\left[\hat{\epsilon}_t + \vartheta\hat{x}_t + \hat{\zeta}_t^x\right]\\ &+ \kappa_3 E_t\left[\hat{\epsilon}_{t+1} + \hat{\mu}_{t+1}^z + \hat{\pi}_{t+1}^d + \hat{\zeta}_{t+1}^x + \vartheta\hat{x}_{t+1}\right]\end{aligned} \tag{B.10}$$

where $\kappa = \frac{1-\alpha}{\left[\bar{w}\bar{R} + \left(1+\beta(1-\delta)\bar{\mu}^z\bar{\pi}^d\right)\bar{g}\right]}$, $\kappa_1 = \bar{w}\bar{R}\kappa$, $\kappa_2 = \bar{g}\kappa$ and $\kappa_3 = \beta(1-\delta)\bar{\mu}^z\bar{\pi}^d\bar{g}\kappa$.

New Keynesian Phillips curve for domestic intermediate producing firms:

$$\hat{\pi}_t^d = \frac{\beta}{1+\beta}E_t\left[\hat{\pi}_{t+1}^d\right] + \frac{1}{1+\beta}\hat{\pi}_{t-1}^d + \frac{(1-\xi_d)(1-\beta\xi_d)}{\xi_d(1+\beta)}\left[\hat{\lambda}_t^d + \widehat{mc}_t^d\right] \tag{B.11}$$

Appendix B.1.3. Domestic-importing firms

Let $a \in \{mc, mi\}$, the new Keynesian Phillips curve for the importing firms:

$$\hat{\pi}_t^a = \frac{\beta}{1+\beta}E_t\left[\hat{\pi}_{t+1}^a\right] + \frac{1}{1+\beta}\hat{\pi}_{t-1}^a + \frac{(1-\xi^a)(1-\beta\xi^a)}{\xi^a(1+\beta)}\left[\hat{\lambda}_t^a + \widehat{mc}_t^a\right] \tag{B.12}$$

which the associated real marginal cost $\widehat{mc}_t^a$:

$$\widehat{mc}_t^a = \hat{P}_t^* + \hat{S}_t^n - \hat{P}_t^a = -\widehat{mc}_t^x - \hat{\gamma}_t^{x,*} - \hat{\gamma}_t^{mc,d} \tag{B.13}$$

Appendix B.1.4. Domestic-exporting firms

New Keynesian Phillips curve for the exporting firms:

$$\hat{\pi}_t^x = \frac{\beta}{1+\beta} E_t \left[\hat{\pi}_{t+1}^x\right] + \frac{1}{1+\beta} \hat{\pi}_{t-1}^x + \frac{(1-\xi_x)(1-\beta\xi_x)}{\xi_x(1+\beta)} \left[\hat{\lambda}_t^x + \widehat{mc}_t^x\right] \tag{B.14}$$

where the real marginal cost $\widehat{mc}_t^x = \hat{P}_t^d - \hat{S}_t^n - \hat{P}_t^x$. Lagging one period then subtracting from itself gives:

$$\widehat{mc}_t^x = \widehat{mc}_{t-1}^x + \hat{\pi}_t^d - \hat{S}_t^n + \hat{S}_{t-1}^n - \hat{\pi}_t^x \tag{B.15}$$

Appendix B.2. Households

Let $l \in \{c, N\}$, the preference and investment-specific technology shock:

$$\hat{\zeta}_t^l = \rho_{\zeta^l} \hat{\zeta}_{t-1}^l + \epsilon_t^{\zeta^l} \tag{B.16}$$

$$\hat{\Gamma}_t = \rho_\Gamma \hat{\Gamma}_{t-1} + \epsilon_t^\Gamma \tag{B.17}$$

Consumption:

$$\begin{aligned}\hat{c}_t = {} & \frac{b\bar{\mu}^z}{(\bar{\mu}^z)^2 + \beta b^2} E_t \left[\hat{c}_{t-1} + \beta \hat{c}_{t+1}\right] - \frac{b\bar{\mu}^z}{(\bar{\mu}^z)^2 + \beta b^2} E_t \left[\hat{\mu}_t^z - \beta \hat{\mu}_{t+1}^z\right] \\ & + \frac{\bar{\mu}^z - b}{(\bar{\mu}^z)^2 + \beta b^2} E_t \left[\bar{\mu}^z \hat{\zeta}_t^c - \beta b \hat{\zeta}_{t+1}^c\right] - \frac{(\bar{\mu}^z - \beta b)(\bar{\mu}^z - b)}{(\bar{\mu}^z)^2 + \beta b^2} \left[\hat{\psi}_t^z + \hat{\gamma}_t^{c,d}\right]\end{aligned} \tag{B.18}$$

Optimal asset holding:

$$\hat{\psi}_t^z = \hat{R}_t + E_t[\hat{\psi}_{t+1}^z - \hat{\mu}_{t+1}^z - \hat{\pi}_{t+1}^d] \tag{B.19}$$

Price of the ready-to-install asset:

$$\hat{P}_t^{k'} = E_t \left[\frac{(1-\delta_k)\beta}{\bar{\mu}^z} \hat{P}_{t+1}^{k'} + \frac{\bar{\mu}^z - \beta(1-\delta_k)}{\bar{\mu}^z} \hat{r}_{t+1}^k + \hat{\psi}_{t+1}^z - \hat{\psi}_t^z - \hat{\mu}_{t+1}^z\right] \tag{B.20}$$

Optimal investment:

$$\hat{P}_t^{k'} = \hat{\gamma}_t^{i,d} - \hat{\Gamma}_t + (\bar{\mu}^z)^2 \tilde{S}''(.) \left[\left(\hat{i}_t - \hat{i}_{t-1} + \hat{\mu}_t^z\right) - \beta E_t \left[\left(\hat{i}_{t+1} - \hat{i}_t + \hat{\mu}_{t+1}^z\right)\right]\right] \tag{B.21}$$

Capital accumulation:

$$\hat{\bar{k}}_{t+1} = \frac{(1-\delta_k)}{\bar{\mu}^z}(\hat{\bar{k}}_t - \hat{\mu}_t^z) + \left(1 - \frac{(1-\delta_k)}{\bar{\mu}^z}\right)\left(\hat{\Gamma}_t + \hat{i}_t\right) \tag{B.22}$$

Let $\sigma_a \equiv \frac{a''(1)}{a'(1)}$. Capital utilization rate:

$$\hat{u}_t = \hat{k}_t - \hat{\bar{k}}_t = \frac{1}{\sigma_a} \hat{r}_t^k \tag{B.23}$$

Optimal real balance:

$$\hat{q}_t = -\frac{1}{\sigma_q} \hat{\psi}_t^z - \frac{\bar{R}}{\sigma_q(\bar{R}-1)} \hat{R}_{t-1} \tag{B.24}$$

Uncovered interest rate parity (with risk premium):

$$\hat{R}_t - \hat{R}_t^* = E_t \left[\hat{S}_{t+1}^n - \hat{S}_t^n\right] - \tilde{\phi}_a \hat{a}_t + \hat{\tilde{\phi}}_t \tag{B.25}$$

Risk premium shock:

$$\hat{\tilde{\phi}}_t = \rho_{\tilde{\phi}} \hat{\tilde{\phi}}_{t-1} + \epsilon_t^{\tilde{\phi}} \tag{B.26}$$

Appendix B.3. Wage rigidities

Appendix B.3.1. Real wage rigidity

Nash bargaining wage:

$$\hat{w}_t^* = \tau_1 \left(\hat{\epsilon}_t + \vartheta \hat{x}_t + \hat{\zeta}_t^x\right) + \tau_2 \left(\hat{\zeta}_t^N + \sigma_L \hat{N}_t - \hat{\psi}_t^z\right) - \tau_3 E_t \left[\hat{\epsilon}_{t+1} + \hat{\zeta}_{t+1}^x + \hat{\psi}_{t+1}^z - \hat{\psi}_t^z - \hat{\mu}_{t+1}^z - \hat{\pi}_{t+1}^d\right] + \tau_4 E_t \left[\hat{x}_{t+1}\right] \quad \text{(B.27)}$$

where $\tau_1 \equiv \frac{B\bar{x}^{\vartheta}}{\bar{w}^*}$, $\tau_2 \equiv \frac{A_L \bar{N}^{\sigma_L}}{\bar{\psi}^z \bar{w}^*}$, $\tau_3 \equiv \frac{\beta(1-\delta)B\bar{x}^{\vartheta}(1-\bar{x})}{\bar{\mu}^z \bar{\pi}^d \bar{w}^*}$ and $\tau_4 \equiv \frac{\beta(1-\delta)B\bar{x}^{\vartheta}(\bar{x}(1+\vartheta)-\vartheta)}{\bar{\mu}^z \bar{\pi}^d \bar{w}^*}$. The real wage follows:

$$\hat{w}_t = f\hat{w}_{t-1} + (1-f)\hat{w}_t^* \quad \text{(B.28)}$$

Appendix B.3.2. Nominal wage rigidity

The real wage under nominal wage rigidity:

$$\hat{w}_t = \tau_b \left(\hat{w}_{t-1} + \hat{\pi}_{t-1}^c - \hat{\pi}_t^d\right) + \tau_f \left(E_t \left[\hat{w}_{t+1}\right] - \hat{\pi}_t^c + E_t \left[\hat{\pi}_{t+1}^d\right]\right) + \tau_c \left(\hat{\zeta}_t^N + \sigma_L \hat{N}_t - \hat{\psi}_t^z + \hat{\lambda}_t^w\right) \quad \text{(B.29)}$$

where $\tau \equiv \frac{\bar{\lambda}^w \sigma_L (1-\beta\xi_w)}{\bar{\lambda}^w - 1}$, $\tau_b \equiv \frac{(1+\tau)\xi_w}{1+\xi_w\tau+\beta\xi_w^2}$, $\tau_f \equiv \frac{\beta\xi_w}{1+\xi_w\tau+\beta\xi_w^2}$, and $\tau_c \equiv \frac{(1-\beta\xi_w)(1-\xi_w)}{1+\xi_w\tau+\beta\xi_w^2}$.

Appendix B.4. Relative prices

$$\hat{\gamma}_t^{c,d} = \omega_c \left(\frac{\bar{\lambda}^{m,c}}{\bar{\gamma}^{c,d}}\right)^{1-\eta_c} \hat{\gamma}_t^{mc,d} = \left(1 - (1-\omega_c)\left(\bar{\gamma}^{c,d}\right)^{\eta_c - 1}\right) \hat{\gamma}_t^{mc,d} \quad \text{(B.30)}$$

$$\hat{\gamma}_t^{i,d} = \omega_i \left(\frac{\bar{\lambda}^{m,i}}{\bar{\gamma}^{i,d}}\right)^{1-\eta_i} \hat{\gamma}_t^{mi,d} = \left(1 - (1-\omega_i)\left(\bar{\gamma}^{i,d}\right)^{\eta_i - 1}\right) \hat{\gamma}_t^{mi,d} \quad \text{(B.31)}$$

$$\hat{\gamma}_t^{mc,d} = \hat{\gamma}_{t-1}^{mc,d} + \hat{\pi}_t^{cm} - \hat{\pi}_t^d \quad \text{(B.32)}$$

$$\hat{\gamma}_t^{mi,d} = \hat{\gamma}_{t-1}^{mi,d} + \hat{\pi}_t^{im} - \hat{\pi}_t^d \quad \text{(B.33)}$$

$$\hat{\gamma}_t^{x,*} = \hat{\gamma}_{t-1}^{x,*} + \hat{\pi}_t^x - \hat{\pi}_t^* \quad \text{(B.34)}$$

$$\hat{\gamma}_t^f = \widehat{mc}_t^x + \hat{\gamma}_t^{x,*} \quad \text{(B.35)}$$

Appendix B.5. Monetary policy

Monetary policy:

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1-\rho_R)[r_\pi \hat{\pi}_{t-1}^c + r_y \hat{y}_{t-1} + r_s \hat{s}_{t-1}^r] + r_\Delta^\pi \Delta\hat{\pi}_t^c + r_\Delta^y \Delta\hat{y}_t + \epsilon_t^R \quad \text{(B.36)}$$

Real exchange rate:

$$\hat{s}_t^r = -\widehat{mc}_t^x - \hat{\gamma}_t^{x,*} - \omega_c \left(\frac{\bar{\lambda}^{m,c}}{\bar{\gamma}^{c,d}}\right)^{1-\eta_c} \hat{\gamma}_t^{mc,d} \quad \text{(B.37)}$$

CPI inflation:

$$\hat{\pi}_t^c = \left[(1-\omega_c)\left(\bar{\gamma}^{c,d}\right)^{\eta_c - 1}\right] \hat{\pi}_t^d + \left[\omega_c \left(\frac{\bar{\gamma}^{c,d}}{\bar{\lambda}^{m,c}}\right)^{\eta_c - 1}\right] \hat{\pi}_t^{m,c} \quad \text{(B.38)}$$

Appendix B.6. Goods and financial market-clearing

Asymmetric technology shock:

$$\hat{\tilde{z}}_t^* = \rho_{\tilde{z}^*} \hat{\tilde{z}}_{t-1}^* + \epsilon_t^{\tilde{z}^*} \quad \text{(B.39)}$$

Aggregate resource constraint:

$$(1-\omega_c)\left[\bar{\gamma}^{c,d}\right]^{\eta_c} \frac{\bar{c}}{\bar{y}} \{\eta_c(\hat{\gamma}_t^{c,d}) + \hat{c}_t\} + (1-\omega_i)\left[\bar{\gamma}^{i,d}\right]^{\eta_i} \frac{\bar{i}}{\bar{y}} \{\eta_i(\hat{\gamma}_t^{i,d}) + \hat{i}_t\} + \frac{\bar{y}^*}{\bar{y}} \{\hat{y}_t^* - \eta_f(\hat{\gamma}_t^{x,*}) + \hat{\tilde{z}}_t^*\} = \hat{y}_t - \alpha\{\hat{k}_t - \hat{\bar{k}}_t\} - \frac{\delta \bar{N} \bar{g}}{\bar{y}} \{\hat{\epsilon}_t + \vartheta \hat{x}_t + \hat{\zeta}_t^x + \hat{H}_t\} \quad \text{(B.40)}$$

Assuming $\bar{R}^* = \bar{R}$, the evolution of net foreign assets:

$$\begin{aligned}\hat{a}_t =& \bar{y}^* \left(\hat{y}_t^* + \hat{\tilde{z}}_t^* - \widehat{mc}_t^x - \eta_f \hat{\gamma}_t^{x,*}\right) + (\bar{c}^m + \bar{i}^m)\hat{\gamma}_t^f - \bar{c}^m \left(-\eta_c(1-\omega_c)\left(\bar{\gamma}^{c,d}\right)^{-(1-\eta_c)} \hat{\gamma}_t^{mc,d} + \hat{c}_t\right) \\ & - \bar{i}^m \left(-\eta_i(1-\omega_i)\left(\bar{\gamma}^{i,d}\right)^{-(1-\eta_i)} \hat{\gamma}_t^{mi,d} + \hat{i}_t\right) + \frac{\bar{R}}{\bar{\pi}^d \bar{\mu}^z}\hat{a}_{t-1} \end{aligned} \tag{B.41}$$

Loan market clearing condition:

$$\bar{w}\bar{N}(\hat{w}_t + \hat{N}_t) = \bar{m}\left(\hat{\mu}_t^m + \hat{m}_t - \hat{\pi}_t^d - \hat{\mu}_t^z\right) - \bar{q}\hat{q}_t \tag{B.42}$$

Money growth:

$$\hat{\mu}_t^m = \hat{m}_t + \hat{\pi}_{t-1}^d + \hat{\mu}_{t-1}^z - \hat{m}_{t-1} \tag{B.43}$$

Appendix B.6.1. Foreign economy

The foreign economy is modeled as VAR(1). Let $F_t^* = [\hat{y}_t^*, \hat{\pi}_t^*, \hat{R}_t^*]'$:

$$F_t^* = \rho_F^* F_{t-1}^* + \epsilon_t^* \tag{B.44}$$

where ρ_F^* is a 3×3 autoregressive coefficients matrix.

Appendix B.6.2. Markups

Let $v \in \{d, mc, mi, x, w\}$, the markups follow the following dynamics:

$$\hat{\lambda}_t^v = \rho_{\lambda^v}\hat{\lambda}_{t-1}^v + \epsilon_t^{\lambda^v} \tag{B.45}$$

Appendix C. Comparison of posterior estimates

	RWR, HC				RWR, NHC				NWR, HC				NWR, NHC			
Parameter	Mean	Std	5%	95%	Mean	Std	5%	95%	Mean	Std	5%	95%	Mean	Std	5%	95%
b	0.68	0.06	0.58	0.78	0.70	0.06	0.60	0.80	0.68	0.07	0.57	0.78	0.71	0.07	0.61	0.81
B	0.10	0.04	0.03	0.17	—	—	—	—	0.17	0.05	0.08	0.25	—	—	—	—
S''	6.66	2.29	3.12	10.07	7.36	2.23	4.06	10.69	6.88	2.18	3.31	10.36	7.68	2.04	4.38	10.94
ϕ_a	0.010	0.002	0.007	0.012	0.010	0.002	0.007	0.012	0.010	0.001	0.007	0.012	0.010	0.002	0.007	0.013
f	0.44	0.11	0.26	0.63	0.38	0.11	0.20	0.57	—	—	—	—	—	—	—	—
η_c	2.82	0.55	1.75	3.95	2.52	0.61	1.60	3.37	3.23	0.76	1.98	4.43	2.59	0.60	1.64	3.50
η_i	1.26	0.07	1.12	1.40	1.25	0.07	1.12	1.38	1.26	0.07	1.12	1.40	1.25	0.07	1.12	1.38
η_f	1.41	0.10	1.11	1.72	1.36	0.09	1.12	1.60	1.35	0.09	1.12	1.61	1.37	0.09	1.12	1.68
$\bar{\mu}^z$	1.005	0.001	1.003	1.006	1.005	0.001	1.004	1.006	1.004	0.001	1.003	1.006	1.005	0.001	1.003	1.006
$\bar{\lambda}^d$	2.46	0.41	1.72	3.14	4.12	0.59	2.09	6.39	2.16	0.37	1.57	2.74	3.98	0.96	2.02	5.80
$\bar{\lambda}^{cm}$	1.23	0.10	1.07	1.38	1.28	0.10	1.08	1.47	1.20	0.07	1.07	1.34	1.27	0.09	1.09	1.45
$\bar{\lambda}^{im}$	4.74	1.35	1.68	7.05	3.50	0.78	1.73	5.23	3.80	0.94	1.87	5.75	3.45	0.75	1.67	5.18
$\bar{\lambda}^w$	—	—	—	—	—	—	—	—	1.10	0.01	1.01	1.25	1.66	0.28	1.04	2.36
Calvo lottery																
ξ_d	0.56	0.08	0.43	0.69	0.67	0.08	0.55	0.80	0.53	0.08	0.39	0.65	0.68	0.08	0.55	0.81
ξ_c^m	0.65	0.07	0.38	0.85	0.71	0.03	0.43	0.87	0.75	0.03	0.47	0.88	0.67	0.03	0.40	0.87
ξ_i^m	0.66	0.10	0.50	0.83	0.66	0.11	0.49	0.83	0.66	0.11	0.49	0.83	0.67	0.11	0.50	0.83
ξ_x	0.74	0.05	0.64	0.84	0.75	0.05	0.65	0.84	0.72	0.05	0.62	0.82	0.75	0.06	0.65	0.85
ξ_w	—	—	—	—	—	—	—	—	0.65	0.10	0.49	0.82	0.51	0.12	0.34	0.68
Monetary policy parameters																
ρ_R	0.85	0.03	0.81	0.90	0.85	0.03	0.81	0.90	0.87	0.03	0.83	0.91	0.87	0.03	0.83	0.92
r_π	1.75	0.24	1.36	2.13	1.64	0.21	1.26	2.03	1.71	0.26	1.30	2.11	1.64	0.26	1.25	2.04
r_y	0.04	0.03	-0.01	0.08	0.04	0.01	0.00	0.08	0.05	0.03	0.00	0.10	0.06	0.03	0.00	0.11
r_s	-0.03	0.01	-0.06	-0.00	-0.02	0.01	-0.05	0.00	-0.02	0.02	-0.05	0.01	-0.01	0.02	-0.04	0.02
$r_{\Delta\pi}$	0.12	0.05	0.04	0.20	0.12	0.05	0.04	0.20	0.10	0.05	0.02	0.17	0.09	0.05	0.01	0.17
$r_{\Delta y}$	0.01	0.02	-0.03	0.05	0.03	0.02	-0.02	0.07	0.02	0.02	-0.02	0.05	0.02	0.03	-0.02	0.06
Persistence parameters																
ρ_{ζ^c}	0.74	0.11	0.56	0.94	0.72	0.04	0.54	0.91	0.72	0.12	0.52	0.91	0.71	0.13	0.53	0.90
ρ_{ζ^N}	0.95	0.02	0.91	0.99	0.90	0.08	0.81	0.98	0.55	0.11	0.35	0.74	0.70	0.18	0.49	0.92
ρ_{μ^z}	0.76	0.08	0.64	0.89	0.73	0.08	0.60	0.87	0.81	0.08	0.68	0.93	0.77	0.09	0.64	0.91
ρ_ϵ	0.95	0.01	0.90	1.00	0.95	0.07	0.90	1.00	0.95	0.02	0.90	0.99	0.96	0.02	0.92	1.00
ρ_ϕ	0.94	0.03	0.89	0.99	0.92	0.03	0.87	0.98	0.94	0.03	0.89	0.99	0.92	0.03	0.86	0.97
ρ_Γ	0.49	0.12	0.31	0.67	0.49	0.14	0.31	0.68	0.49	0.12	0.31	0.67	0.51	0.12	0.32	0.69
$\rho_{\tilde{z}^*}$	0.89	0.07	0.77	1.00	0.91	0.07	0.80	1.00	0.88	0.07	0.77	1.00	0.89	0.07	0.77	1.00
$\rho_{\lambda^{cm}}$	0.45	0.05	0.05	0.94	0.34	0.07	0.03	0.89	0.27	0.07	0.02	0.89	0.45	0.07	0.05	0.94
ρ_{λ^x}	0.14	0.06	0.01	0.25	0.12	0.06	0.01	0.23	0.14	0.06	0.01	0.26	0.12	0.06	0.01	0.23
Standard errors of exogenous shocks																
σ_{ζ^c}	1.55	0.23	1.12	1.96	1.59	0.26	1.19	1.97	1.42	0.23	1.00	1.84	1.60	0.24	1.19	2.00
σ_{ζ^N}	0.79	0.13	0.57	1.01	0.69	0.16	0.48	0.90	0.53	0.07	0.37	0.69	0.45	0.10	0.31	0.59
σ_{μ^z}	0.17	0.03	0.12	0.21	0.16	0.03	0.11	0.21	0.18	0.03	0.12	0.23	0.17	0.03	0.12	0.22
σ_ϵ	0.32	0.06	0.21	0.43	0.27	0.06	0.18	0.37	0.35	0.07	0.22	0.48	0.27	0.05	0.17	0.36
σ_ϕ	0.25	0.04	0.13	0.36	0.24	0.05	0.13	0.36	0.27	0.06	0.14	0.39	0.27	0.06	0.14	0.40
σ_Γ	0.08	0.01	0.06	0.11	0.07	0.02	0.05	0.09	0.08	0.01	0.06	0.10	0.07	0.01	0.04	0.09
$\sigma_{\tilde{z}^*}$	0.18	0.03	0.12	0.23	0.19	0.04	0.13	0.25	0.17	0.03	0.12	0.22	0.17	0.03	0.12	0.23
σ_R	0.11	0.01	0.09	0.14	0.11	0.01	0.09	0.14	0.11	0.01	0.09	0.14	0.11	0.01	0.09	0.14
σ_{λ^d}	1.68	0.28	1.21	2.13	3.37	0.66	2.41	4.32	1.21	0.20	0.85	1.57	3.26	0.51	2.28	4.25
$\sigma_{\lambda^{cm}}$	9.12	4.19	4.33	14.53	14.33	2.42	7.66	20.99	16.02	2.91	8.12	22.93	10.56	1.76	5.25	16.35
σ_{λ^x}	35.45	5.89	21.90	49.05	39.12	6.53	26.16	52.94	32.38	5.33	21.49	43.10	39.00	6.55	24.17	52.21
Log-Likelihood	-889.11				-896.54				-891.79				-899.56			
BF(Null: NHC)	7.43				—				7.78				—			
BF(Null: NWR)	2.68				3.02				—				—			

RWR: Real wage rigidity; NWR: Nominal wage rigidity; HC: Hiring cost; NHC: No hiring cost
Std: Standard deviation; BF: Bayes factor

Table C.4: Comparison of estimates for alternative models

Appendix D. Comparison of posterior distributions

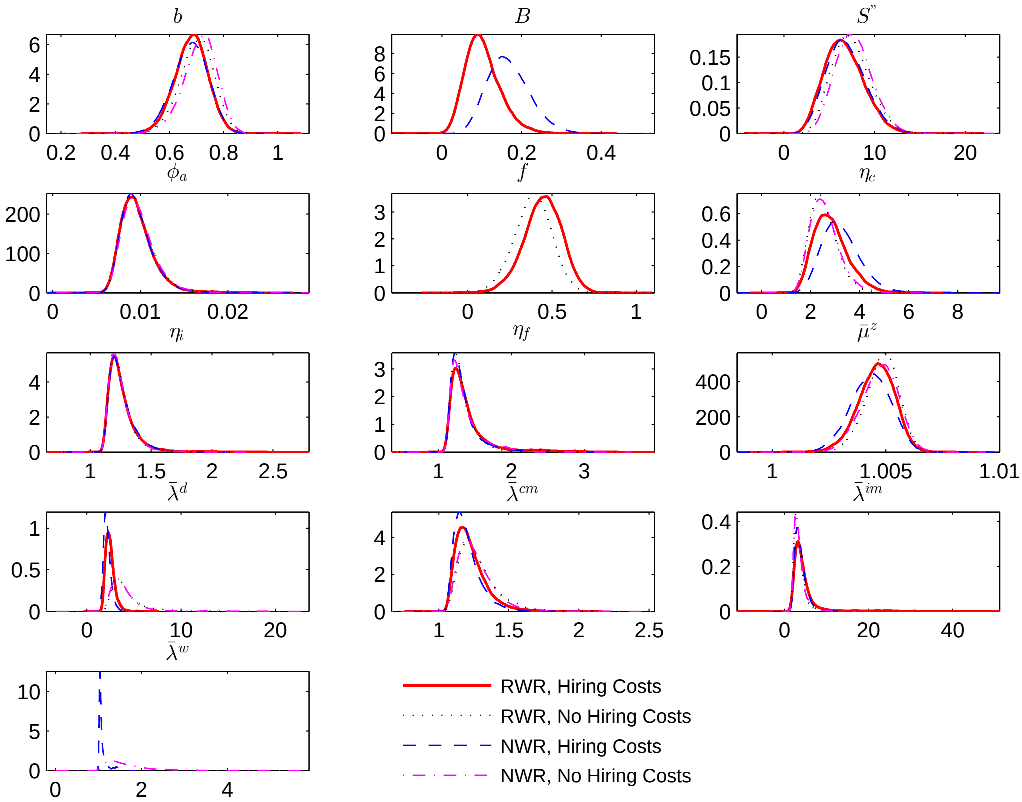

Figure D.11: Posterior distributions of alternative models: deep parameters

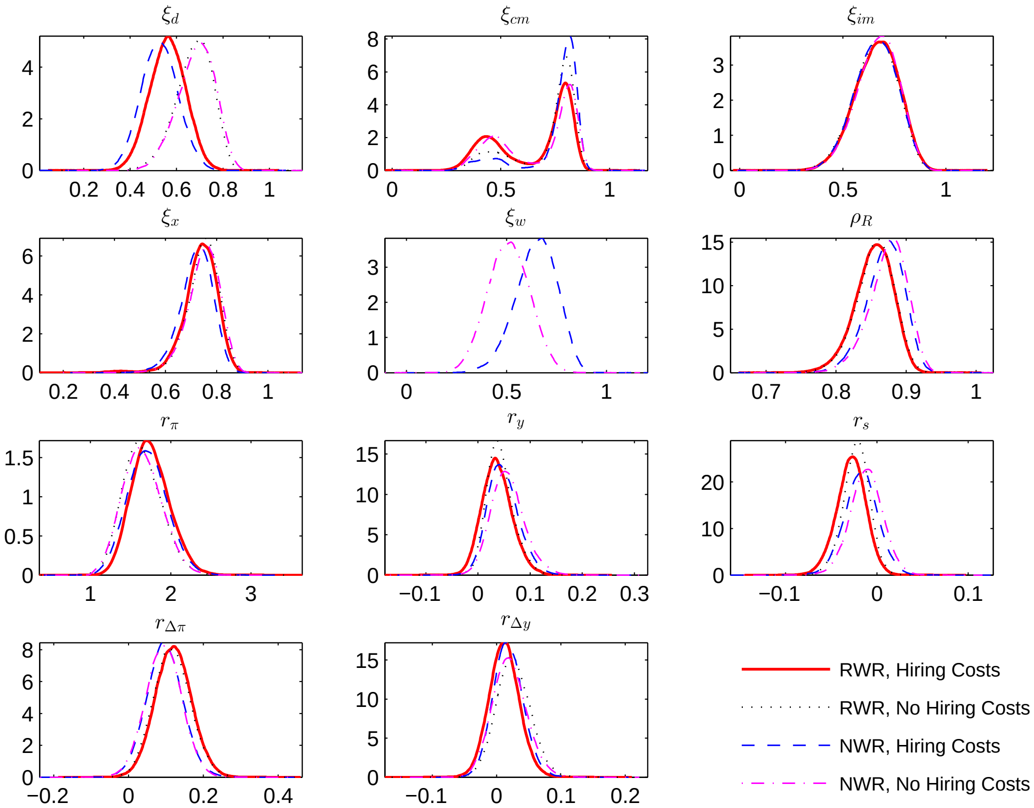

Figure D.12: Posterior distributions of alternative models: Calvo lottery and monetary policy parameters

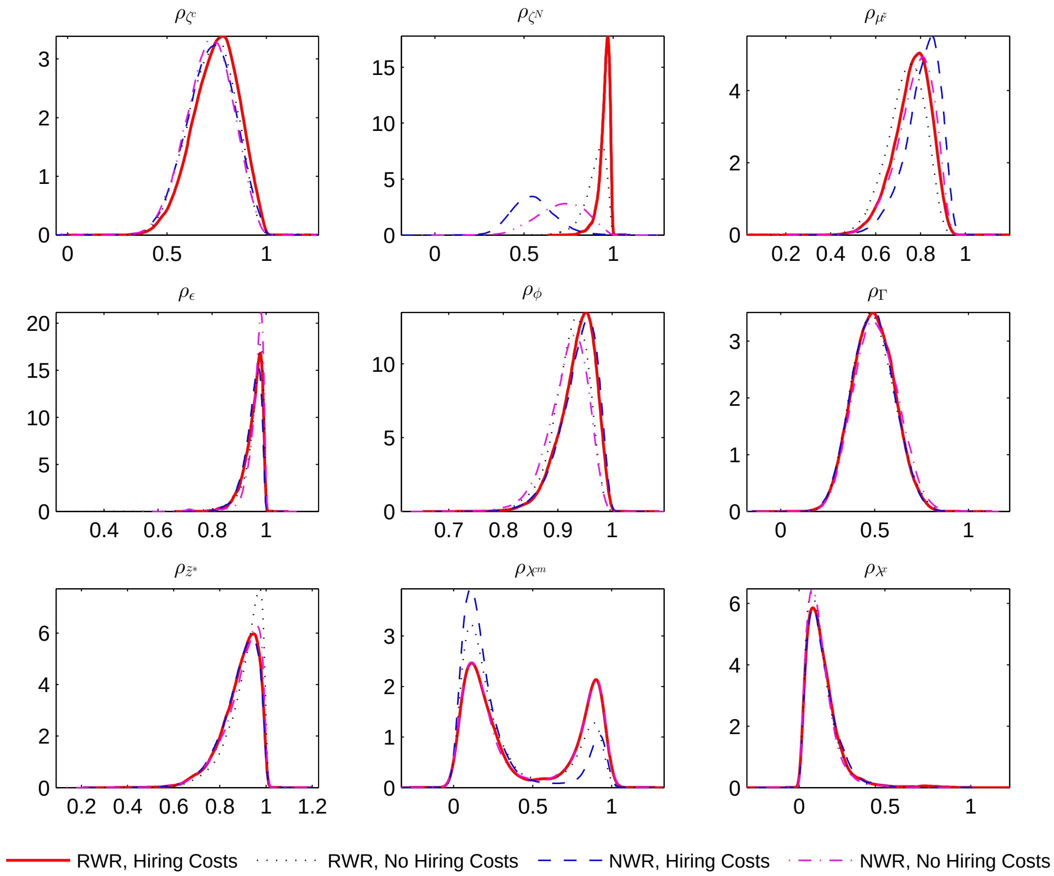

Figure D.13: Posterior distributions of alternative models: persistence parameters

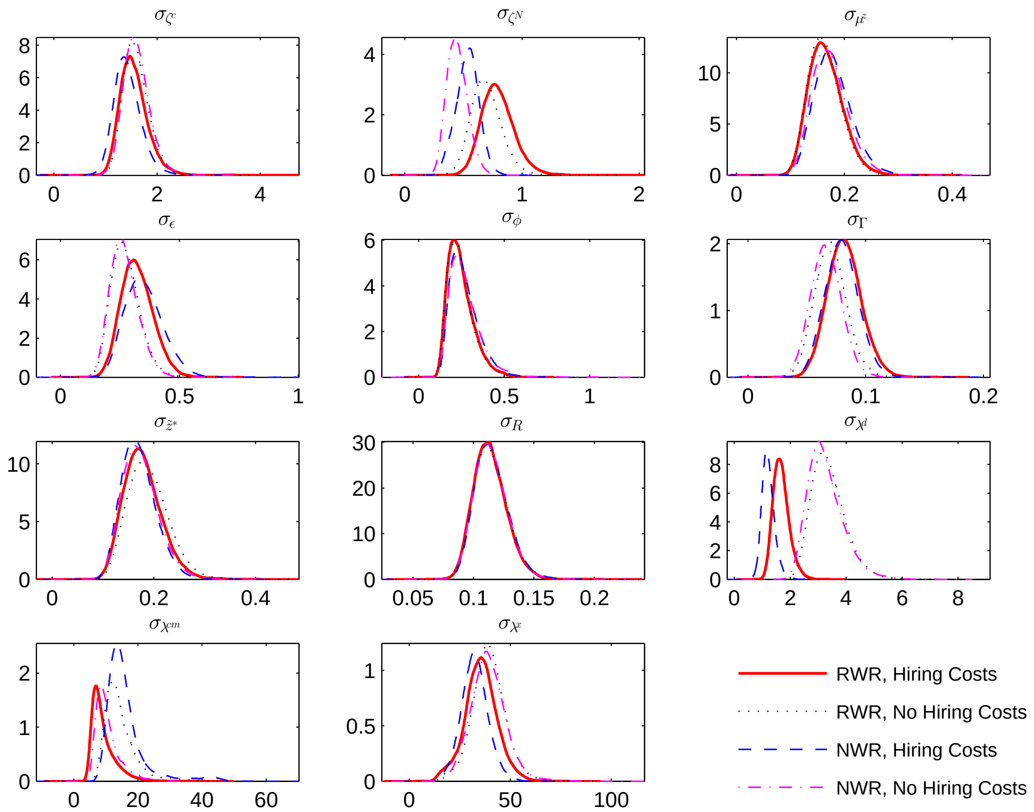

Figure D.14: Posterior distributions of alternative models: standard deviation of exogenous shocks

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