Endogenous Money or Sticky Wages: A Bayesian Approach

Guangling 'Dave' Liu[1]

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[1] Contact Details: Department of Economics, University of Stellenbosch, Stellenbosch, 7602, South Africa. Tel: +27 21 808 2238; fax: +27 21 808 4637. E-mail address: daveliu@sun.ac.za (G.Liu)

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Guangling "Dave" Liu*

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Abstract

This paper attempts to answer question similar to that asked by Ireland (2003): What explains the correlations between nominal and real variables in postwar US data? More precisely, this paper aims to investigate whether endogenous money, sticky wages, or some combination of the two, are necessary features in a dynamic New Keynesian model in explaining the correlations between nominal and real variables in postwar US data. To do so, we estimate a medium-scale dynamic stochastic general equilibrium model of endogenous money. The model is estimated using Bayesian maximum likelihood and compared with a restricted version of the structural model, in which wages are flexible. We conclude that both endogenous money and sticky wages are necessary features in a dynamic New Keynesian model in explaining the variation in key macroeconomic variables, both nominal and real.

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1 Introduction

In a classical model economy, real variables are independent of monetary policy. However, monetary policy plays an important role in explaining the behavior of nominal variables, such as prices. As pointed out by Ireland (2003), under a Taylor-type interest rate rule, money supply and nominal interest rate become endogenous, at least most if not all, and the effects of changes in monetary policy can be interpreted plausibly as how nominal variables respond to real variables, not the other way around [1]. On the other hand, nominal rigidities provide a channel through which nominal variables drive movements in real variables. Ireland (2003) uses maximum likelihood to estimate a structural model of endogenous money with Rotemberg-type (quadratic costs) sticky prices (Rotemberg, 1982), and suggests that the nominal price rigidity, over and above endogenous money, plays a role in accounting for the key features of postwar US data.

*Contact Details: Department of Economics, University of Stellenbosch, Stellenbosch, 7602, South Africa. Tel: +27 21 808 2238; fax: +27 21 808 4637. E-mail address: daveliu@sun.ac.za (G. Liu)

[1] Gali (2008) also argues that, with a Taylor-type monetary policy rule, the simple correlations of interest rates and real variables cannot be used as evidence of non-neutralities. The causal effects can, at least partially, run the other way around.

Recently, the New Keynesian model with both Calvo-type sticky prices and sticky wages (Erceg *et al.*, 2000) has become the framework in the literature in monetary policy analysis (e.g. Giannoni and Woodford, 2003). The model has also been used in studying the persistence of effects of monetary policy shocks. For instance, both studies by Huang and Liu (2002) and Christiano *et al.* (2005) suggest that it is the staggered wage, not staggered price, which plays an important role in generating the observed inertia in inflation and persistent output movements in response to a monetary policy shock.

The objective of this paper is to investigate whether a dynamic New Keynesian model without nominal wage rigidities, but with an augmented Taylor-type interest rate rule, is capable of explaining the joint behavior of nominal and real variables and their connection to monetary policy. In other words, the paper aims to find out whether endogenous money, sticky wages, or some combination of the two, are necessary features in a dynamic New Keynesian model in explaining the correlations between nominal and real variables in postwar US data. To do so, we incorporate real balances and staggered wage contracts into a dynamic New Keynesian model [2]. We employ the Bayesian technique to estimate the structural model, using postwar US data from 1959:01 to 2008:02. We then compare the estimated structural models of endogenous money with and without staggered wage contracts. We conclude that both endogenous money and sticky wages are necessary features in a dynamic New Keynesian model in explaining the variation in key macroeconomic variables, both nominal and real.

The remainder of the paper is organized as follows. Section 2 lays out the structural model. Section 3 discusses the prior and posterior parameters and the robustness of the estimation results. Section 4 answers the question asked in the present paper, while Section 5 concludes.

2 A Structural Model with Money

The model presented here has many features typical to a standard dynamic New Keynesian model with nominal and real rigidities, particularly along the lines of Erceg *et al.* (2000), Christiano *et al.* (2005), and Smets and Wouters (2007). These common features such as Calvo-type sticky prices and wages, partial price and wage indexation, and capital utilization are documented below. Among them, in order to study the role for money in the model economy, we include real balances in the structural model. Since money becomes an argument of the utility function, the money demand function can be derived explicitly. Given that the effects arising with non-separable utility are negligible (McCallum and Nelson, 1999, Woodfood, 2001, and Andres *et al.*, 2007), the utility function is assumed to be separable in consumption and real balances[3]. The model is closed by assuming that the monetary authority follows an augmented Taylor-type interest rate rule.

The Taylor rule, an empirical observation about the Fed's behavior [4], became a theory of inflation determinacy after it had been introduced into the New Keynesian framework. However, Cochrane (2007)

[2]The structural model is documented in detail in the next section. For a dynamic New Keynesian model with real balances, see Ireland (2003, 2004), Andres *et al.* (2005, 2007), and Gali (2008).

[3]For a detailed discussion on the separable and non-separable utility functions, see Walsh (2003) and Gali (2008).

[4]Clarida *et al.* (2000) use a single-equation regression to show that the Fed sufficiently controlled inflation by reacting more than one-for-one to inflation in the post-Volker era.

points out that the Taylor coefficient required to stabilize inflation in the New Keynesian Taylor-rule setup is not identified in the data. Using the three-equation benchmark New Keynesian model, Cochrane (2007) argues that in a forward-looking New Keynesian model the Taylor principle is the condition for unstable dynamics, which rules out multiple equilibria and forces forward-looking solutions. We leave to a future study the question of whether the Taylor principle holds in a medium-size New Keynesian DSGE model in which both backward-looking and forward-looking terms appear in the Phillips curve, as is the case in the current study. Nonetheless, we assume the monetary authority follows an augmented Taylor-type interest rate rule, in which the short-term nominal interest rate is adjusted in response to the deviation of the money growth rate as well. Bernanke (2006) argues that although monetary and credit aggregates have not played a central role in formulation of the US monetary policy since 1982, money growth may still contain important information about the state of the future economy. Therefore, attention to money growth is sensible as part of the eclectic modelling framework used by the Fed.

2.1 The representative household

The economy consists of a continuum of infinitely-lived households. In each period $t = 0, 1, 2, ...$, a representative household makes a sequence of decisions to maximize the expected utility over a composite consumption good C_t, real money balance M_t/P_t, and leisure $1 - N_t$:

$$E\sum_{t=0}^{\infty}\beta^t\Big[\frac{(C_t - hC_{t-1})^{1-\eta_c}}{1-\eta_c} + \xi_{m,t}\frac{(M_t/P_t)^{1-\eta_m}}{1-\eta_m} - \frac{(N_t)^{1+\eta_n}}{1+\eta_n}\Big] \tag{1}$$

where β is the subjective discount factor and η_n is the inverse of the elasticity of work effort with respect to the real wage. The habit formation parameter h measures the importance of the reference level relative to current consumption. As suggested by Fuhrer (2000), Amato and Thomas (2004), and Bouakez *et al.* (2005), including habit formation in the household's utility function improves the short-run dynamic of the model in terms of replicating the hump-shaped response of consumption to monetary policy and other shocks. η_c is the coefficient of relative risk aversion of household, and η_m is the inverse of the interest elasticity of real money demand. The preference shock, $\xi_{m,t}$, acts as a shock to money demand, which follows a first-order autoregressive (AR(1)) process :

$$\xi_{m,t} = \rho_m\xi_{m,t-1} + \epsilon_{m,t}, \qquad 0 \le \rho_m < 1, \qquad \epsilon_{m,t} \sim i.i.d.(0, \sigma_m^2) \tag{2}$$

The representative household carries money M_{t-1} and bonds B_{t-1} from the previous period into the current period t. In time period t, the household receives a lump-sum transfer T_t from the monetary authority and the nominal profit or dividend payment D_t from the intermediate-good firms. In addition, the household also receives its usual labor income W_tN_t, where W_t denotes the nominal wage. The model assumes that households own capital stock K_t and supply capital to the intermediate-good firms at a rental rate $R_{k,t}$. Following Christiano *et al.* (2005), the model further assumes that households can adjust the capital utilization at rate μ_t in each time period but face a cost $\psi(\mu_t)K_{t-1}$ [5]. Therefore, in each time period,

[5] The $\psi(\cdot)$ function is increasing and convex, whereas $\psi(1) = 0$.

the representative household maximizes her expected utility (1) subject to the following budget constraint:

$$C_t + X_t + \frac{B_t}{P_t} + \frac{M_t}{P_t} + \psi(\mu_t)K_{t-1} \leq \frac{W_t}{P_t}N_t + \frac{B_{t-1}(1+i_{t-1})}{P_t} + \frac{M_{t-1}}{P_t} + \frac{D_t}{P_t} + \frac{T_t}{P_t} + R_{k,t}(\mu_t)K_{t-1} \quad (3)$$

The first-order conditions result in the following linearized [6] equations:

$$c_t = \frac{h}{1+h}c_{t-1} + \frac{1}{1+h}E_t c_{t+1} - \frac{1-h}{(1+h)\eta_c}r_t \quad (4)$$

$$m_t = \frac{\eta_c}{\eta_m}(c_t - hc_{t-1}) - \frac{1}{\eta_m}\frac{1}{i}i_t + \frac{1}{\eta_m}\xi_{m,t} \quad (5)$$

Equation (4) is the consumption Euler equation with external habit formation. It represents the intertemporal allocation consumption, where the current period consumption depends on a weighted average of previous and expected future consumption. The habit persistence parameter captures the impact of the real rate on consumption given an intertemporal elasticity of substitution, i.e. the higher the habit persistence, the less the impact of the real rate on consumption (Smets and Wouters, 2007)

The money demand equation (5) states that the optimal condition of money holding requires that the marginal rate of substitution between money and consumption must equalize with the opportunity cost of holding money.

Beside the intertemporal budget constraint (3), when the representative household maximizes her expected utility, she is also subject to the following capital accumulation equation as in Christiano *et al.* (2005):

$$K_t = (1-\delta)K_{t-1} + \xi_{x,t}\big[1 - S\big(\frac{X_t}{X_{t-1}}\big)\big]X_t \quad (6)$$

where δ is depreciation rate, X_t is gross investment. The function S captures the presence of investment adjustment cost [7]. The investment shock $\xi_{x,t}$ is assumed to follow an AR(1) process:

$$\xi_{x,t} = \rho_x \xi_{x,t-1} + \epsilon_{x,t}, \qquad 0 \leq \rho_x < 1, \qquad \epsilon_{x,t} \sim i.i.d.(0, \sigma_i^2) \quad (7)$$

The linearized first-order conditions are:

$$p_{k,t} = E_t\pi_{t+1} - r_t + [1 - \beta(1-\delta)]E_t r_{k,t+1} + \beta(1-\delta)E_t p_{k,t+1} \quad (8)$$

$$x_t = \frac{1}{1+\beta}(x_{t-1} + \beta E_t x_{t+1} + \frac{1}{\nu}p_{k,t}) + \xi_{x,t} \quad (9)$$

Equation (8) is the Lucas asset price equation for capital. $P_{k,t}$ is the shadow value of the installed capital, which depends on both the expected future value of capital and its return, taking into account the

[6] A lowercase letter represents its log deviation from steady state.

[7] In steady state, $S(\cdot) = 0,\ S'(\cdot) = 0,\ S''(\cdot) > 0$. See Christiano *et al.* (2005).

depreciation rate. The investment equation (9) describes the dynamics of investment, in which it contains both backward-looking and forward-looking components. ν is the investment adjustment cost parameter, $\nu = S''(\cdot)$.

2.2 Final goods production

In the final-good sector, firms are perfectly competitive. The representative firm produces the final good Y_t using a continuum of intermediate goods $Y_{j,t}$ indexed by j ($j \in [0, 1]$), according to a constant elasticity of substitution (CES) production function as suggested by Dixit and Stiglitz (1977):

$$Y_t = \left(\int_0^1 Y_{j,t}^{\frac{\varphi_{p,t}-1}{\varphi_{p,t}}} dj \right)^{\frac{\varphi_{p,t}}{\varphi_{p,t}-1}} \tag{10}$$

where $\varphi_{p,t}$ measures the time-varying price elasticity of demand for each intermediate good $Y_{j,t}$. It acts as a price markup shock in the goods market. The price markup shock is assumed to be IID.

The representative firm maximizes its profit, and the first-order condition implies the demand for each intermediate good as the following:

$$Y_{j,t} = (\frac{P_{j,t}}{P_t})^{-\varphi_{p,t}} Y_t \tag{11}$$

where $P_{j,t}$ is the price of the intermediate good j, and P_t is the price for the final good. Since the final-good firms operate in a perfectly competitive market, in equilibrium the representative firm's profit should equal to zero. Hence, the equilibrium market price for the final good is given as the following:

$$P_t = \left(\int_0^1 P_{j,t}^{1-\varphi_{p,t}} dj \right)^{1/1-\varphi_{p,t}} \tag{12}$$

2.3 Intermediate goods production

In the intermediate-good sector, firms are monopolistically competitive. In each time period, the representative firm produces $Y_{j,t}$ units of intermediate good j according to the following constant-returns-to-scale production function:

$$Y_{j,t} = \xi_{z,t}(\mu_t K_{j,t-1})^{\alpha} N_{j,t}^{1-\alpha}, \qquad 0 < \alpha < 1 \tag{13}$$

where the aggregate technology shock $\xi_{z,t}$ follows an AR(1) process:

$$\xi_{z,t} = \rho_z \xi_{z,t-1} + \epsilon_{z,t}, \qquad 0 \leq \rho_z < 1, \qquad \epsilon_{z,t} \sim i.i.d.(0, \sigma_z^2) \tag{14}$$

Households supply $N_{j,t}$ units of labor and $K_{j,t}$ units of utilized capital stock, where $K_{j,t} = \mu_t K_{j,t-1}$, to the representative firm j. The aggregate labor demand N_t is giving by the following Dixit-Stiglitz form:

$$N_t = \left(\int_0^1 N_{j,t}^{\frac{\varphi_{w,t}-1}{\varphi_{w,t}}} dj \right)^{\frac{\varphi_{w,t}}{\varphi_{w,t}-1}} \tag{15}$$

where $\varphi_{w,t}$ measures the time-varying price elasticity of demand for different types of labour. It acts as a wage markup shock in the labour market. The wage markup shock is assumed to be IID.

The staggered wage is introduced in the manner proposed by Erceg et al. (2000). Households are price setters in the labour market. In other words, wages are taken as given by the intermediate-good firms. Given the nominal wage $W_{j,t}$, the representative intermediate-good firm j minimizes its cost and yields the demand for labor $N_{j,t}$:

$$N_{j,t} = (\frac{W_{j,t}}{W_t})^{-\varphi_{w,t}} N_t \tag{16}$$

where W_t is an aggregate wage index:

$$W_t = \left(\int_0^1 W_{j,t}^{1-\varphi_{w,t}} dj \right)^{1/1-\varphi_{w,t}} \tag{17}$$

Following Calvo (1983), in each time period only a random fraction $1 - \theta_w$ of households have the opportunities to reset their wages. This friction is independent across households and time. In addition, the model assumes that households who cannot reset their wages simply index to lagged inflation as in Christiano *et al.* (2005) and Smets and Wouters (2007). Therefore, the wage index $W_{j,t}$ is given by:

$$W_{j,t}^{1-\varphi_{w,t}} = \theta_w[(\frac{P_{t-1}}{P_{t-2}})^{\gamma_w} W_{j,t-1}]^{1-\varphi_{w,t}} + (1-\theta_w)(W_{j,t}^*)^{1-\varphi_{w,t}}, \qquad 0 \le \theta_w \le 1, \quad 0 \le \gamma_w \le 1 \tag{18}$$

where γ_w is the degree of wage indexation, and $W_{j,t}^*$ represents the nominal wage level chosen by those households who can reset their wages at time period t.

The intermediate-good firms face the same restriction to set their prices. In each time period, the probability of being able to reset prices is $1 - \theta_p$, and firms who cannot reset their prices also index to lagged inflation. The price index $P_{j,t}$ is given by:

$$P_{j,t}^{1-\varphi_{p,t}} = \theta_p[(\frac{P_{t-1}}{P_{t-2}})^{\gamma_p} P_{j,t-1}]^{1-\varphi_{p,t}} + (1-\theta_p)(P_{j,t}^*)^{1-\varphi_{p,t}}, \qquad 0 \le \theta_p \le 1, \quad 0 \le \gamma_p \le 1 \tag{19}$$

The linearized first-order conditions are given by:

$$\begin{aligned}
mc_t &= \alpha r_{k,t} + (1-\alpha) w_t - \xi_{z,t} && (20)\\
w_t &= \frac{1}{1+\beta}\{w_{t-1} + \beta E_t w_{t+1} + \gamma_w \pi_{t-1} - (1+\beta\gamma_w)\pi_t + \beta E_t \pi_{t+1} \\
&\quad - \frac{(1-\beta\theta_w)(1-\theta_w)}{(1+\varphi_w \eta_n)\theta_w}[w_t - \eta_n n_t - \frac{\eta_c}{1-h}(c_t - h c_{t-1})]\} + \epsilon_{w,t} && (21)\\
\pi_t &= \frac{1}{1+\beta\gamma_p}[\gamma_p \pi_{t-1} + \beta E_t \pi_{t+1} + \frac{(1-\beta\theta_p)(1-\theta_p)}{\theta_p} mc_t] + \epsilon_{p,t} && (22)
\end{aligned}$$

Equation (20) implies that the real marginal cost is a function of the real rental rate of capital and the real wage, since capital and labour are being used in the intermediate-good production.

The real wage equation (21) states that, under staggered wage contracts, the usual intratemporal condition of real wages under fully flexible wages, that is that the real wage equals the marginal rate of substitution of consumption for labour, no longer holds. The representative household now takes into account not only the past and the expected future real wages, but also the past, current, and the expected future inflation rates. The representative household sets her real wage higher than the marginal rate of substitution, since she knows there is a possibility that she may not be able to reset her wage in the future. It is worth noting that the real wage equation here contains both backward-looking and forward-looking components of the real wage and inflation rate, to induce inertia in inflation through the marginal cost channel [8]. Therefore, it is not surprising that it is the staggered wage, not staggered price, which plays an important role in generating the observed inertia in inflation in response to a monetary policy shock (Huang and Liu, 2002, and Christiano *et al.*, 2005).

The New Keynesian Phillips curve (22) implies that inflation depends on the past and the expected future inflation. It also shows that the price indexation parameter γ_p governs the persistence in the response of inflation to a given shock. If $\gamma_p = 0$, equation (22) becomes a purely forward looking Phillips curve. Finally, it shows that inflation is a function of the current marginal cost and both γ_p and θp govern the contribution of marginal cost to the persistence of response of inflation. Here, we follow Gali and Gertler's (1999) argument that, as the theory suggests, real marginal cost is a significant and quantitatively important determinant of inflation instead of an ad hoc output cap.

2.4 The monetary authority

The model is closed by assuming that the monetary authority follows an augmented Taylor-type interest rate rule as in Ireland (2003) and Andres *et al.* (2007). That is, the monetary authority adjusts its instrument, the nominal short-term interest rate, in response not only to the deviations of output, inflation, and the lagged interest rate from their steady-state levels, but also to the deviation of money growth rate:

$$i_t = \kappa_i i_{t-1} + (1 - \kappa_i)(\kappa_\varpi \varpi_t + \kappa_\pi \pi_t + \kappa_y y_t) + \xi_{i,t} \tag{23}$$

where ϖ_t represents the percentage deviation of money growth rate, $\varpi_t = m_t - m_{t-1} + \pi_t$. The monetary policy shock $\xi_{i,t}$ is assumed to follow an AR(1) process:

$$\xi_{i,t} = \rho_i \xi_{i,t-1} + \epsilon_{i,t}, \qquad 0 \leq \rho_i < 1, \qquad \epsilon_{i,t} \sim i.i.d.(0, \sigma_i^2) \tag{24}$$

3 Model Estimates

The model is estimated using Bayesian estimation techniques. The mode of the posterior distribution is estimated by maximizing the log posterior function combining the prior information. Bayesian estimation and evaluation techniques have become the industrial standard for empirical work with DSGE models due

[8] As shown in (20), marginal cost is an increasing function of real wage, and marginal cost appears in the inflation equation (22).

to the following two main advantages. First, it allows one to formalize the use of a prior information based on previous studies either at a micro or macro level. Second, it provides a framework for evaluating fundamentally misspecified models on the basis of the marginal likelihood of the model or the Bayes' factor [9].

We compare the estimated results from the sticky-wage model (the structural model described in the previous section) and the flexible-wage model. In the flexible-wage model, the only nominal rigidity is the Calvo-type sticky prices. In other words, wages are flexible and the indexation of price is dropped in the flexible-wage model. Other features are the same as those in the sticky-wage model.

Gavin and Kydland (1999) observe the changes in the cyclical behavior of nominal variables after 1979:03 when the Federal Reserve started implementing a policy to lower the inflation rate. It is believed that there was a regime shift in the Federal Reserve policy after Paul Volker's appointment as Chairman in August 1979 (Ireland, 2003). To accommodate the possible policy regime shift in 1979 and to analyze the sensitivity of the model estimates, we divide the full sample into two sub-samples, the first covering from 1959:01 to 1979:02 and the second covering from 1979:03 to 2008:02. Both the sticky-wage model and the flexible-wage model are estimated with the data from each sub-sample.

3.1 The data

The model is estimated using quarterly data on real output (GDP), real money balances, real wages, inflation, and a short-term nominal interest rate over the period of 1959:1-2008:2. All data were obtained from the Federal Reserve Bank of St. Louis FRED database.

Real money balances is derived by dividing M2 money stock by the GDP deflator. Both real money balances and real output are in per-capita terms derived by dividing the civilian non-institutional population, aged 16 and over. Inflation is measured by the changes in GDP deflator. Real wage is calculated by dividing nominal wage by GDP deflator, whereas the measure of the nominal wage is the "hourly compensation for the non-farm business sector". The short-term nominal interest rate is measured by the 3-month Treasury bill rate.

3.2 Prior distributions

The prior distribution of the parameters are shown in Table 1 columns 2-4. The Calvo parameters and friction coefficients of wage and price indexation are assumed to follow beta distribution, and the following prior means. The Calvo sticky wage parameter θ_w is assumed to be 0.75, which implies that wages are fixed on average for a year. Prices are fixed on average for two quarters, i.e. $\theta_p = 0.5$. The degree of wage indexation is set at 0.5, whereas the degree of price indexation is set at 0.55.

In the utility function, the prior on habit formation parameter h is set at 0.7 with a standard deviation of 0.05, which is consistent with the literature (eg. Boldrin *et al.*, 2001 and Rabanal, 2007). The coefficient of relative risk aversion η_c is assumed to follow gamma distribution with mean 2 and standard deviation

[9] For a detailed discussion on estimating DSGE models using Bayesian techniques, See Smets and Wouters (2003), and An and Schorfheide (2007).

0.1. We adopt a normal distribution for the inverse of the interest rate elasticity of real money demand with mean 2.5, which is close to 2.56 in Walsh (2003), and standard deviation 0.1.

The inverse of the elasticity of capital utilization cost ψ and the investment adjustment cost parameter ν are assumed to follow gamma distribution. The mean is set at 98 for ψ with standard deviation 14.14, and 2 for ν with standard deviation 0.4.

We assume the real shock is more persistent than the nominal shocks. The persistence of the AR(1) processes is assumed to follow beta distribution with mean 0.75 and standard deviation 0.1 for ρ_x and ρ_m, mean 0.55 and standard deviation 0.05 for ρ_i, and mean 0.95 and standard deviation 0.02 for ρ_z. Whereas the standard deviations of the shocks are inverse-gamma distributed with a mean of 0.1.

The parameters of the monetary policy rule are assumed to follow normal distribution with standard deviation 0.05, and a mean of 0.65, 0.5, 1.38, 0.18, with respect to κ_i, κ_ϖ, κ_π, κ_y. These values are assigned based on a standard Taylor rule, close to the values reported in Andres *et al.* (2007).

Four parameters are fixed prior to estimation. As pointed out by Ireland (2003), the inverse of elasticity of labor supply η_n cannot be estimated directly without the data on employment, and the depreciation rate δ cannot be estimated if capital stock is not included in the data set. η_n is set equal to 1.5 and δ is set equal to 0.025. In addition, the discount factor β is calibrated to be 0.99, and the capital income share $\alpha = 0.24$. Values assigned on the above parameters are consistent with those in the literature (eg. Smets and Wouters, 2007).

3.3 Parameter estimates

This section presents the parameters estimated by maximizing the posterior distribution. The posterior mode of the parameters and the corresponding standard errors for both the sticky-wage model and the flexible-wage model are reported in Table 1[10].

The parameter estimates for the sticky-wage model are reported in columns 5 and 6 in Table 1. For the parameters that characterize the degree of price and wage stickiness, the results indicate a slightly higher degree of stickiness in wage than that in price. More Precisely, the estimated degree of Calvo stickiness of wage of 0.66 implies an average three quarters duration of wage contracts. This finding is consistent with the one in Christiano *et al.* (2005). However, a slightly lower degree of Calvo stickiness of price 0.62 is obtained from the estimated sticky-wage model, implying an average two-and-a-half quarters duration of price contracts. This value is lower than that in Gali and Gertler (1999), who report a degree of price stickiness of 0.83, obtained from the single-equation estimation. As far as price and wage indexation are concerned, the degree of indexation for wage is relatively high (0.7) compared to the degree of indexation for price (0.08), which is negligible.

The estimated productivity, money demand, and monetary policy processes are very persistent, whereas the investment shock is less persistent. The estimated standard deviations of the innovations to the invest-

[10] As some parameter estimates are similar to those in the literature, only estimates of those key parameters are discussed here. A comparison of the prior and posterior distributions of the estimated parameters for both sticky-wage and flexible-wage models (full-sample period) are reported in Figure 1 and 2.

ment shock and money demand shock are relatively large compared to those of the other shocks. Ireland (2003) also reports the same findings and points out that it helps the model explain the investment boom in the 1990s.

Finally, the parameter estimates of the monetary policy rule indicate that the Federal Reserve policy can be described as following an augmented Taylor rule. That is, the Federal Reserve adjusts the nominal interest rate in response not only to the deviations of output, inflation, and lagged interest rate, but also to the deviation of money growth. The moderately significant estimate of κ_ω (0.73) proves the idea of augmenting the money growth into the standard Taylor rule in describing the Federal Reserve's policy. The estimated response of the nominal interest rate to inflation rate is 1.17. The response to output is 0.17, which is very close to the value (0.15) obtained using maximum likelihood estimation in Andres *et al.* (2007). The parameter estimates of monetary policy rule indicate the significance of endogenous money in explaining the correlations between money growth, interest rates and output.

For comparison purpose, the flexible-wage model is estimated using the same priors and standard deviations as those in the sticky-wage model. The estimates are more or less consistent with those from the sticky-wage model[11], indicating the sticky-wage model described here is very robust. However, compared to the sticky-wage model, two points are worth noting in the flexible-wage model estimates. First, price becomes less sticky. The average duration of price contracts is about one-and-a-half quarters. Second, among others, the productivity shock exhibits the most persistence with an AR(1) parameter of 0.99. These two significant changes in the flexible-wage model estimates imply that with the absence of sticky wages and price indexation, postwar US data suggest a much more persistent productivity shock process and more flexible prices in the markets.

We report the parameter estimates for the two sub-samples of both the sticky-wage model and the flexible-wage model in Table 2 and 3. Overall, parameter estimates are consistent across the models and sub-sample periods. It is worth noting that the estimated monetary policy parameters are very stable across models and sub-sample periods, indicating that there was unlikely a regime shift in 1979, at least under the augmented Taylor rule here. It is also worth pointing out that, in both the sticky-wage model and flexible-wage model, the estimated ϵ_x and ϵ_m for the post-1979 sub-sample period are much larger than those for the pre-1979 sub-sample period, which confirms the observation of the investment boom in the 1990s.

4 Endogenous Money or Sticky Wages?

In this section, we answer the question whether endogenous money, sticky wages, or some combination of the two, are necessary features in a dynamic New Keynesian model in explaining the correlations between nominal and real variables in postwar US data.

The estimated sticky-wage model contains six shocks in total. In addition to the investment shock, the monetary policy shock, and the real technology shock as the one in the RBC literature, the stochastic dynamics of the model are also driven by the money demand shock, the price markup shock and wage markup

[11] Parameter estimates for the flexible-wage model are reported in the last two columns in Table 1.

shock. The only stochastic element of households' preferences, $\xi_{m,t}$ can be identified as a money demand shock. Other shocks only affect the real money demand indirectly (Kim, 2000). It is standard to include both price and wage markup shocks in the New Keynesian framework. Both the price and wage markup shocks are empirically important to capture price and wage dynamics. However, the price and wage markup shocks generate a trade-off problem as long as the monetary authority aims at stabilizing both inflation and the output gap (Smet and Wouters, 2007).

Introducing six shocks in the sticky-wage model allows us to estimate the sticky-wage model and the flexible-wage model using data on five variables as listed in the previous section. Since the estimation uses five variables, both models must include at least five shocks [12]. Kydland and Prescott (1982) argue that in the basic RBC framework, the U.S. business cycle fluctuations are purely driven by real technology shocks. This one-shock assumption makes the real business cycle model stochastically singular. Using a version of the King *et al.* (1988) model, Ingram *et al.* (1994) point out that it is impossible to derive the realizations of the productivity shocks using a singular model if the variance-covariance matrix of the observable variables is actually nonsingular. In order to overcome this singularity problem, one needs to elaborate the model by including at least as many shocks as there are endogenous variables in the model. This approach, in addition, can be served to identify sources of output variation.

Table 4 reports the independent contribution of each shock to the variance of the observable variables for both the sticky-wage and flexible-wage models for the full-sample period.

Looking first at the estimated results from the sticky-wage model, one important finding is that, except for the real wage, the contribution of the technology shock in explaining the variation of both nominal and real variables are negligible.

The variation in real variables is explained mainly by nominal shocks: the monetary policy shock, the money demand shock, and the wage markup shock in particular. The policy shock together with the wage markup shock account for the most variation in output, 63 percent and 26 percent respectively. The money demand shock and wage markup shock are equally important in explaining the variation in real balances, whereas a 15 percent contribution of the policy shock is also non-negligible. Not surprisingly, the wage markup shock together with the productivity shock are dominant factors in explaining the variation in the real wage.

The variation in nominal variables is explained mainly by nominal shocks as well. The wage markup shock explains a big part of the variation in inflation (68 percent); the price markup shock, the policy shock, and the productivity shock also explain a proportion of the variation in inflation, namely 13 percent, 9 percent, and 9 percent respectively. Similarly, the wage markup shock accounts for half of the variation in nominal interest rate. The rest of the variation in nominal interest rate are explained mainly by the money demand shock (24 percent) and the policy shock (18 percent).

Turning to the flexible-wage model, the conclusion diverges. The productivity shock accounts for most of the variation in real variables, whereas the variation in nominal variables is explained mainly by nominal

[12] There are five shocks in the flexible-wage model. The wage markup shock is shut down.

shocks. In the flexible-wage model, half of the variation in output are explained by the productivity shock, and the rest is explained mainly by the policy shock (25 percent) and the investment shock (9 percent). Besides the productivity shock, the contribution of money demand shock to the variation of real balances is non-negligible (18 percent). Not surprisingly, with flexible wages, the variation in real wage is solely explained by the productivity shock.

As far as nominal variables are concerned, the policy shock contributes the most (76 percent) in explaining the variation in inflation. Intuitively, in the sticky-wage model, both the estimated degree of Calvo stickiness of wage θ_w and the degree of wage indexation γ_w are relatively high. Since inflation depends partially on marginal cost and marginal cost depends partially on the real wage, the variation in inflation is explained mainly by the wage markup shock. However, in the flexible-wage model, the assumption of flexible wages together with the absence of a wage markup shock weakens the contribution of marginal cost to the response of inflation. The policy shock contributes the most to the response of inflation via the Fisher equation $i_t = r_t + E_t\pi_{t+1}$.

The variance decompositions for the two sub-sample periods are reported in Table 5 and 6. The results are consistent with those from the full-sample period estimation. Two observations are worth noting here. First, the contribution of the investment shock to the variation in output is increased in the post-1979 sub-sample period across models, which confirms the finding in the previous section. Second, the contribution of price markup shock is negligible across models and sub-sample periods. It suggests that sticky prices by itself is incapable of explaining the correlation between nominal and real variables in postwar US data.

In short, both the estimated sticky-wage model and flexible-wage model suggest that variation in nominal variables in postwar US business cycle is explained mainly by nominal shocks. As far as real variables are concerned, the conclusion diverges. The estimated sticky-wage model shows that nominal shocks dominate in explaining the variation in real variables. However, the fluctuations in real variables are mainly driven by the productivity shock in the flexible-wage model.

Finally, it is worth noting, as McCallum (2001) pointed out, in this type of theoretical models, the systematic component of monetary policy (coefficients) also plays an important role in explaining the variation in key macroeconomic variables[13]. As one can see from previous section that the estimated monetary policy coefficients are very consistent across the models and sub-sample periods, which implies that postwar US monetary policy can be described as the augmented Taylor rule suggested here. Thus, both endogenous money and sticky wages account for the fluctuations in postwar US business cycle.

5 Conclusions

The wage markup shock plays a prominent role in explaining the variation of both nominal and real variables in the stick-wage model. In contrast with the finding in Smets and Wouters (2007), where the contribution of wage markup shock to the variation in output is very low, the wage markup shock accounts for 26 percent of

[13] See Ireland (2003).

the variation in output. Among other shocks, the wage markup shock dominates in explaining the variation in inflation.

On the other hand, real variables cannot be determined independently of monetary policy. The policy shock accounts for 63 percent of the variation in output in the sticky-wage model, and 25 percent in the flexible-wage model , indicating that monetary policy is non-neutral.

In summary, the findings here imply that both endogenous money and sticky wages are necessary features in a dynamic New Keynesian model in explaining the variation in key macroeconomic variables, both nominal and real.

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Table 1 Prior and posterior distributions (full-sample period)

	Prior distribution			Estimated posteprior mode			
				Sticky-wage model		Flexible-wage model	
Parameter	type	mean	std dev.	mean	std dev.	mean	std dev.
θ_p	beta	0.5	0.1	0.6222	0.0203	0.4139	0.0202
θ_w	beta	0.75	0.05	0.6543	0.068	—	—
γ_p	beta	0.55	0.15	0.0791	0.0296	—	—
γ_w	beta	0.5	0.2	0.7074	0.0622	—	—
η_m	norm	2.5	0.1	2.6524	0.0995	2.7195	0.0972
h	beta	0.7	0.05	0.8471	0.0256	0.8782	0.025
η_c	gamma	2	0.1	2.0357	0.1003	2.0507	0.1008
ψ	gamma	98	14.14	93.8545	13.8308	99.2903	14.4911
ν	gamma	2	0.4	2.0024	0.3151	4.3591	0.5283
ρ_x	beta	0.75	0.1	0.3128	0.0582	0.2842	0.06
ρ_m	beta	0.75	0.1	0.8623	0.018	0.6306	0.0185
ρ_i	beta	0.55	0.05	0.7228	0.0259	0.6305	0.0185
ρ_z	beta	0.95	0.02	0.7306	0.0396	0.9979	0.0014
κ_i	norm	0.65	0.05	0.3247	0.0306	0.1275	0.03
κ_ϖ	norm	0.5	0.05	0.7373	0.0437	0.6979	0.0415
κ_π	norm	1.38	0.05	1.167	0.0523	1.2492	0.0575
κ_y	norm	0.18	0.02	0.1753	0.0204	0.158	0.0207
ϵ_i	inv gamma	0.1	Inf	0.0145	0.001	0.0189	0.0013
ϵ_m	inv gamma	0.1	Inf	0.1265	0.0064	0.1629	0.0093
ϵ_z	inv gamma	0.1	Inf	0.0104	0.0009	0.0179	0.001
ϵ_x	inv gamma	0.1	Inf	0.0792	0.0058	0.0795	0.0045
ϵ_p	inv gamma	0.1	Inf	0.0076	0.0004	0.0135	0.0011
ϵ_w	inv gamma	0.1	Inf	0.0116	0.0006	—	—

Table 2 Posterior distributions (sticky-wage model)

	Estimated posteprior mode			
	Pre-1979		Post-1979	
Parameter	mean	std dev.	mean	std dev.
Parameter	mean	std dev.	mean	std dev.
θ_p	0.4412	0.0525	0.684	0.0287
θ_w	0.7833	0.0476	0.812	0.0366
γ_p	0.7643	0.0963	0.2097	0.0709
γ_w	0.8897	0.081	0.7675	0.0549
η_m	2.5951	0.0993	2.5844	0.0996
h	0.8294	0.0332	0.8443	0.027
η_c	2.0273	0.1001	2.0348	0.1003
ψ	95.584	13.9843	96.9642	13.9454
ν	2.9645	0.4095	2.7464	0.4246
ρ_x	0.558	0.0818	0.4698	0.0727
ρ_m	0.8124	0.0336	0.8047	0.0297
ρ_i	0.4674	0.0423	0.559	0.0424
ρ_z	0.9369	0.0372	0.8286	0.0357
κ_i	0.4886	0.0407	0.4149	0.0371
κ_ϖ	0.5828	0.0463	0.6355	0.0446
κ_π	1.2497	0.05	1.2189	0.05
κ_y	0.2035	0.0192	0.1889	0.0191
ϵ_i	0.0211	0.0019	0.0183	0.0014
ϵ_m	0.1293	0.0099	0.1749	0.0115
ϵ_z	0.0156	0.0023	0.0149	0.0017
ϵ_x	0.0735	0.0116	0.1485	0.013
ϵ_p	0.0132	0.0011	0.0099	0.0007
ϵ_w	0.013	0.001	0.0134	0.0009

Table 3 Posterior distributions (flexible-wage model)

	Estimated posteprior mode				
	Pre-1979			Post-1979	
Parameter	mean	std dev.		mean	std dev.
θ_p	0.5194	0.0357		0.4927	0.03
θ_w	—	—	—	—	—
γ_p	—	—	—	—	—
γ_w	—	—	—	—	—
η_m	2.6295	0.0976		2.6422	0.098
h	0.7758	0.0433		0.8377	0.0489
η_c	2.0517	0.0999		2.064	0.1005
ψ	103.5271	13.4129		106.7247	13.4854
ν	3.381	0.422		3.7052	0.4752
ρ_x	0.4179	0.0736		0.394	0.0549
ρ_m	0.6741	0.0358		0.5897	0.033
ρ_i	0.5569	0.0335		0.5959	0.0337
ρ_z	0.9964	0.001		0.9979	0.0014
κ_i	0.2981	0.0365		0.1726	0.0342
κ_ϖ	0.6242	0.0453		0.6807	0.0433
κ_π	1.3742	0.0518		1.3282	0.0561
κ_y	0.16	0.0201		0.146	0.0205
ϵ_i	0.0262	0.0023		0.0244	0.0019
ϵ_m	0.1302	0.0115		0.2009	0.0151
ϵ_z	0.0398	0.0037		0.0302	0.0026
ϵ_x	0.1172	0.0109		0.1522	0.0125
ϵ_p	0.0219	0.0024		0.0178	0.0017

Table 4 Variance Decompositions (full-sample period)

	Sticky-wage model						Flexible-wage model				
	ϵ_z	ϵ_x	ϵ_m	ϵ_i	ϵ_p	ϵ_w	ϵ_z	ϵ_x	ϵ_m	ϵ_i	ϵ_p
y	3.02	3.01	4.35	62.96	0.6	26.07	58.26	8.74	6.12	24.91	1.97
m	3.6	0.46	39.7	14.56	1.83	39.86	70.61	1.21	17.77	8.11	2.3
w	12.9	0.03	0.38	3.08	8.46	75.15	99.78	0	0.05	0.12	0.05
pie	9.33	0	1.14	8.77	12.98	67.78	5.88	0.75	7.52	76.26	9.58
i	4.69	0.53	24.11	17.86	2.36	50.45	20.03	1.86	60.99	13.44	3.68

Note: numbers are in percentage.

Table 5 Variance Decompositions (sticky-wage model)

	Pre-1979						Post-1979					
	ϵ_z	ϵ_x	ϵ_m	ϵ_i	ϵ_p	ϵ_w	ϵ_z	ϵ_x	ϵ_m	ϵ_i	ϵ_p	ϵ_w
y	13.33	5.56	1.84	51.55	2.34	25.38	8.52	10.86	5.1	41.29	2.26	31.98
m	11.63	0.73	15.18	26.23	3.28	42.94	4.52	0.98	23.71	14.18	2.06	54.54
w	40.28	0.03	0.04	0.46	11.06	48.14	18.16	0.05	0.09	0.28	9.18	72.24
pie	21.64	0	0.09	0.64	19.5	58.14	10.58	0	0.1	0.18	13.77	75.36
i	13.56	0.74	5.97	29.14	3.78	46.81	5.65	1.08	11.25	16.8	2.52	62.7

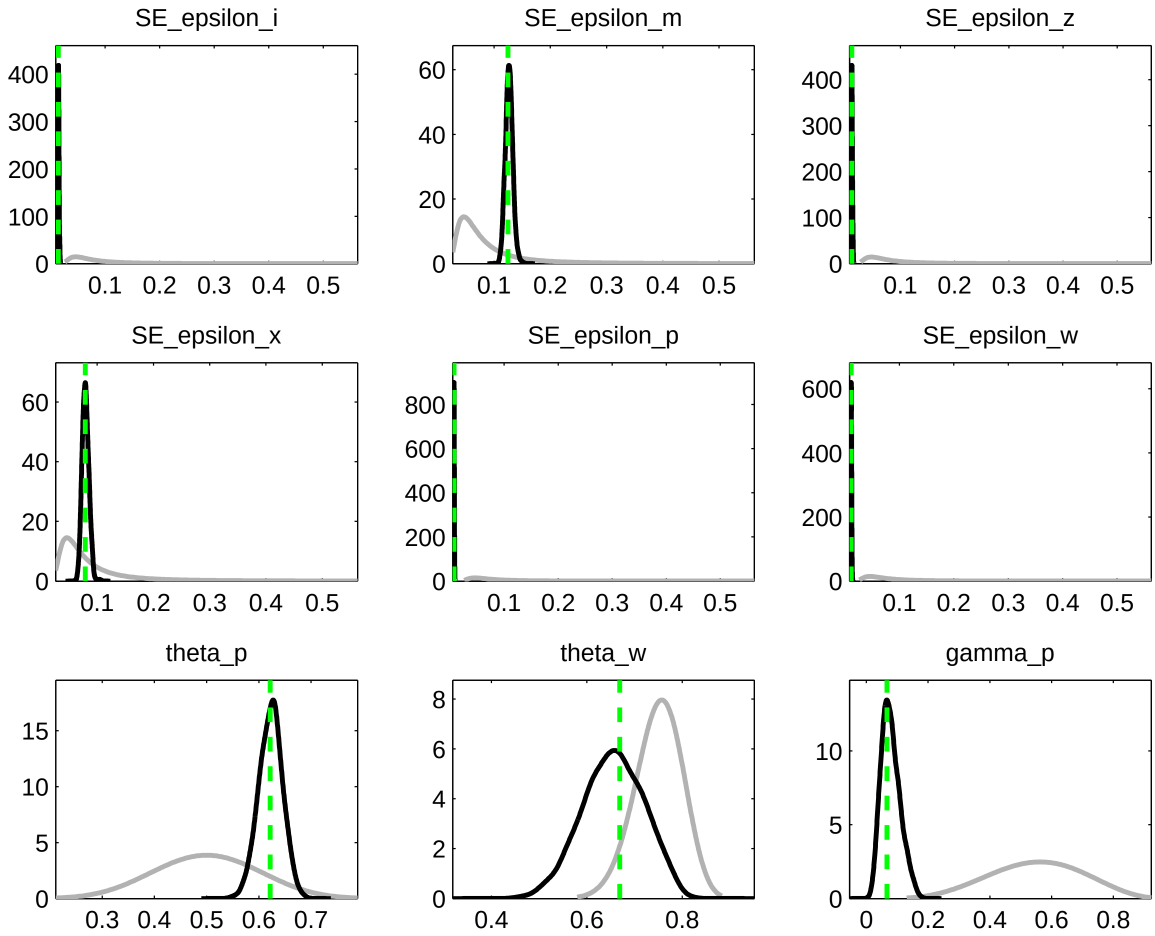
Note: numbers are in percentage.

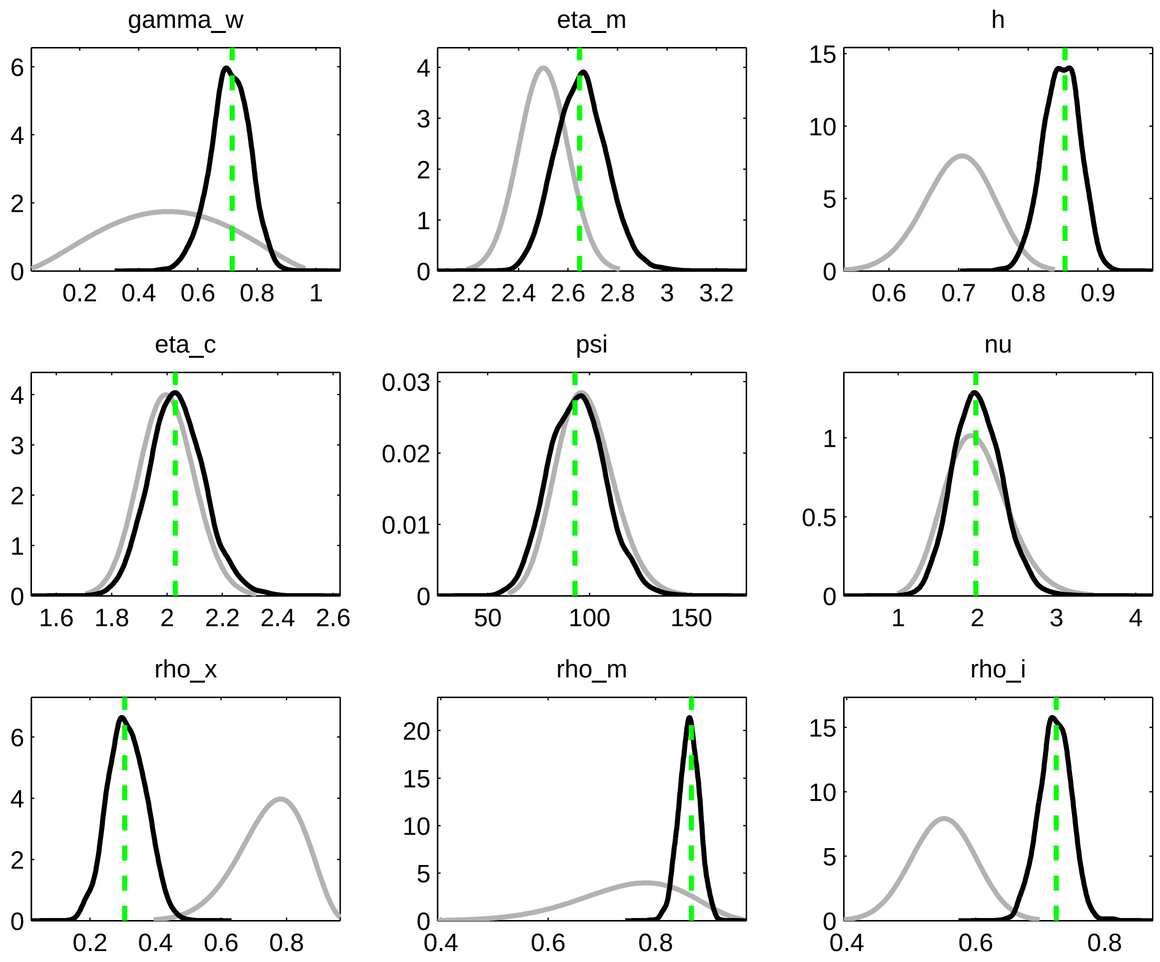
Table 6 Variance Decompositions (flexible-wage model)

	Pre-1979					Post-1979				
	ϵ_z	ϵ_x	ϵ_m	ϵ_i	ϵ_p	ϵ_z	ϵ_x	ϵ_m	ϵ_i	ϵ_p
y	66.79	10.93	1.02	18.26	3	68.14	16.48	1.66	12.19	1.54
m	94.32	0.68	2.83	0.53	1.65	85.7	2.33	8.21	1.78	1.98
w	99.69	0	0.01	0.21	0.08	99.81	0.01	0.03	0.11	0.04
pie	14.22	0.69	1.54	64.46	19.08	11.13	1.95	5.06	66.86	15
i	62.64	3.66	20.66	3.35	9.7	31.29	6.04	52.13	5.13	5.42

Note: numbers are in percentage.

Figure 1: Prior and posterior distributions of the estimated parameters (sticky-wage model)

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0.2 0.4 0.6 0.8 1
eta_m
0 1 2 3 4
2.2 2.4 2.6 2.8 3 3.2
h
0 5 10 15
0.6 0.7 0.8 0.9
eta_c
0 1 2 3 4
1.6 1.8 2 2.2 2.4 2.6
psi
0 0.01 0.02 0.03
50 100 150
nu
0 0.5 1
1 2 3 4
rho_x
0 2 4 6
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rho_m
0 5 10 15 20
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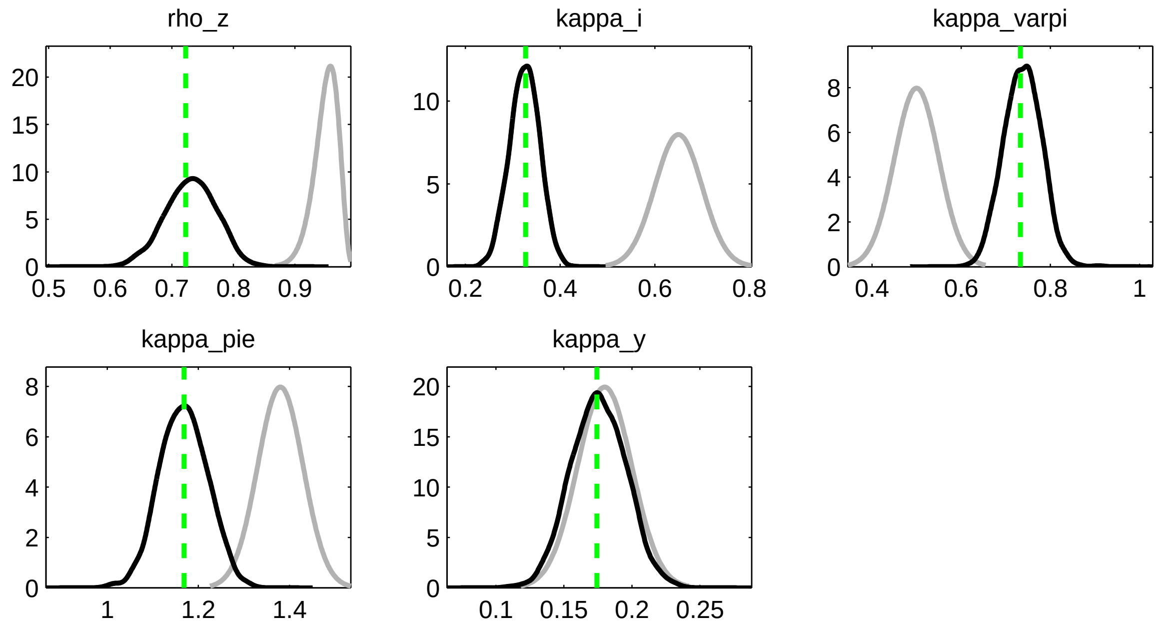
rho_i
0 5 10 15
0.4 0.6 0.8


rho_z
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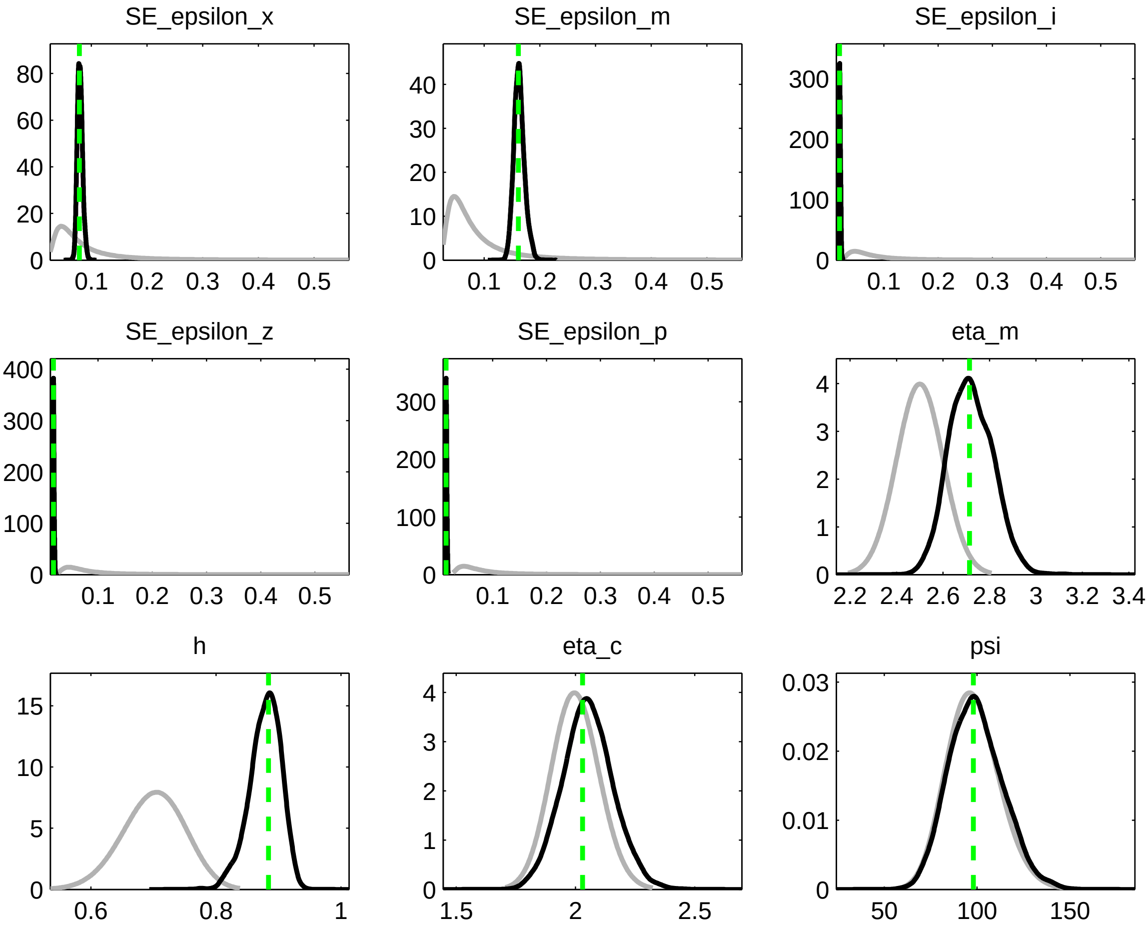
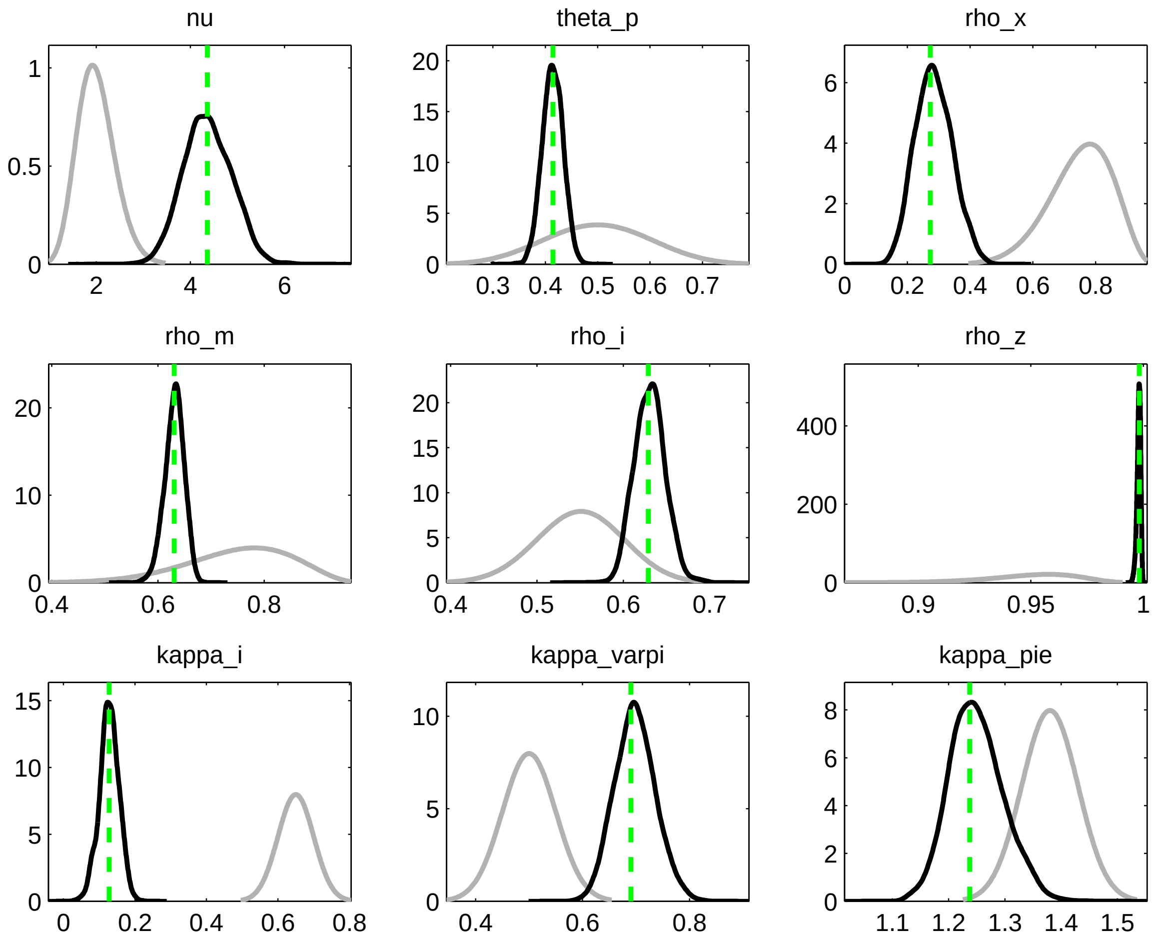
0.5 0.6 0.7 0.8 0.9
kappa_i
0 5 10
0.2 0.4 0.6 0.8
kappa_varpi
0 2 4 6 8
0.4 0.6 0.8 1
kappa_pie
0 2 4 6 8
1 1.2 1.4
kappa_y
0 5 10 15 20
0.1 0.15 0.2 0.25

Figure 2: Prior and posterior distributions of the estimated parameters (flexible-wage model)




nu
theta_p
rho_x
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kappa_varpi
kappa_pie