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Investigating China's Monetary Policy Within a DSGE Framework: A Bayesian Likelihood Approach

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Abstract

This thesis aims to study the importance of a monetary policy rule within a New Keynesian Dynamic Stochastic General Equilibrium (NK-DSGE) framework estimated with Chinese data. Firstly, I develop the DSGE model and introduce price stickiness and four exogeneous shocks, namely shocks to total factor productivity, money demand, mark-ups and investment. I solve the DSGE model and derive the log-linearized system of 13 equations and 13 endogenous variables. Secondly, I collect quarterly data for China from 1996Q1 to 2019Q4 provided by the Federal Reserve Bank of Atlanta for four observable variables: output, investment, inflation and the nominal interest rate. Thirdly, I fix values for some parameters and assign prior distributions for the parameters to be estimated. Finally, I apply the Bayesian likelihood-based approach to estimate the NK-DSGE model and present the mean value and 90% interval of the posterior estimates. Furthermore, I present the variance decomposition for observables and perform counterfactual analysis to compare the impulse responses of the four observables following a monetary policy shock under different coefficient settings of the monetary policy rule. The estimation results suggest that both money and the nominal interest rate are important indicators for shaping the central bank's policy.

Keywords: monetary policy rule, DSGE model, interest rate rule, Bayesian Estimation

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List of Abbreviations and Acronyms

NK-DSGE: New Keynesian Dynamic Stochastic General Equilibrium

WWII: World War II

PBoC: People's Bank of China

NPC: National People's Congress

GDP: Gross Domestic Product

CPI: Consumer Price Index

OMOs: Open Market Operations

STR model: Smooth Transition Regression model

MS model: Markov switching model

CEIC: China Economic Information Center

HPD intervals: Highest Posterior Density intervals

TFP: Total Factor Productivity

I. Introduction

The New Keynesian dynamic stochastic general equilibrium (NK-DSGE) framework incorporated with a simple monetary policy rule has become increasingly popular in macroeconomic studies and monetary policy analysis for China. Following the work of Li and Liu (2017), this paper seeks to estimate a hybrid monetary policy rule within a small-scale NK-DSGE model that helps describe the Chinese economy built on 3 sectors (the household, the firms and the government). By using Bayesian likelihood estimation methods, the empirical results suggests that money plays an important role in the monetary policy of China. In addition, counterfactual analysis shows that the nominal interest rate and other endogenous variables do not respond much to the monetary policy shock if the central bank of China is very sensitive to the money growth rate.

The rule-based NK-DSGE models have become a standard framework for monetary policy analysis ever since the seminal work of Taylor (1993, 1999). The Taylor-type interest rate rule has been proven to be a good way to characterize monetary policy for advanced economies such as the U.S. and Europe in the post-WWII period. In almost the same period, New Keynesian Dynamic Stochastic General Equilibrium (NK-DSGE) models, which incorporate monopolistic competition and nominal rigidities, have become the standard framework for monetary policy analysis and economic forecasting. Within the NK-DSGE framework, simple rules such as the Taylor-type interest rate rule or a money growth rule are used to describe monetary policy behaviour. Both types of rules help the central bank adjust its intermediate targets, namely the nominal interest rate or money growth rate, in response to economic shocks and changes in economic conditions.

However, it is unclear whether such a rule-based NK-DSGE framework can be well-applied to macroeconomics analysis or forecasts for developing countries. China, as the largest developing country, is still in transition from a "central planned economy" to a fully "market-oriented economy". The monetary policy in China has its own unique features even compared to the counterparts of other developing countries. The following demonstrates these features from three aspects: final targets, intermediate targets and monetary policy instruments.

Firstly, according to the Law of People's Bank of China (PBoC) passed by the National People's Congress (NPC) in 1995, the central bank aims to maintain price stability and thereby promote economic growth. However, that PBoC seems to have more goals than just price stability and economic growth. According to the speech made by governor Zhou (Michel Camdessus Central Banking Lecture at International Monetary Fund 2016), other ultimate goals may include maximizing employment and achieving a balance-of-payments equilibrium. Among the multiple final targets, promoting economic growth has been prioritized as the foremost objective of the PBoC (Chen, et al., 2016).

Secondly, there has been ongoing debate on whether the growth rate of the money aggregate is still acceptable as an intermediate target. Since 1994, PBoC started to release the quarterly money supply data at three levels---M0, M1, and M2. After the abolishment of the credit plan in 1998, the money growth rate M2 was generally accepted as the intermediate target for the monetary policy of PBoC (Geiger, 2006). However, the unstable velocity of money during the past several decades led some to question whether the growth rate of the money aggregate or interest rates were the suitable target of the PBoC (Zhang, 2009).

Thirdly, while most central banks in advanced economies focus on single and indirect instrument tools such as short-term nominal interest rates, PBoC tends to employ both indirect tools and direct policy instruments. In addition to indirect tools, e.g., open market operations (OMOs) and a minimum reserve requirement, which are widely used by monetary authorities in advanced economies, PBoC uses direct tools such as window guidance and direct investment. Adopted in 1998, window guidance gives PBoC much more authority on determining commercial banks' lending decisions, especially the four state-owned banks. The employment of both direct and indirect policy instruments has made the interest rate monetary policy transmission blurred, thereby the monetary policy transmission channel is ineffective (Geiger, 2006).

Moreover, PBoC has a long history of controlling the interest rate. The bank deposit rates were regulated by the PBoC through the imposition of a deposit rate ceiling. The gradual interest rate liberalization has taken about 20 years until October 2017, when commercial banks were finally allowed to decide the deposit and loan interest rates without the guidance from PBoC (Rathnayake, et al., 2022).

Given that China's monetary policy is institutionally different at least in the above-mentioned ways, it may be that the canonical NK-DSGE framework used for advanced economies fits Chinese data differently.

A standard New Keynesian Dynamic Stochastic General Equilibrium model uses a real business cycle (RBC) model as its backbone and adds monopolistic competition and price stickiness, that is, a form of nominal rigidity that allows the economist or policy maker to better understand the impact of nominal shocks to the real economy (Sims, 2017). Although the basic RBC framework solves for the dynamic equilibrium of a representative household and a representative firm under perfect competition, money plays no role in this model, so that it provides little implication of the real effects of changes to nominal values. Cooley & Hansen's (1989) model manages to introduce money into the "cash-in-advance" household budget constraint. However, empirical studies suggest inconsistencies between the data and the model (i.e., money neutrality) in the short run. By incorporating both monopolistic competition and nominal rigidities, New Keynesian DSGE models break money neutrality in the short run and provide a more realistic description of the real effects of monetary shocks and the monetary policy transmission.

Within the DSGE framework, monetary policy usually takes the form of three different types of rules, namely a quantity-based rule, price-based rule or hybrid rule. Quantity-based rules, rooted in the Fisher quantity theory of money, assume that the velocity of money is relatively stable in the short run. The quantity-based rule describes the relationship between the money growth rate and other explanatory variables, namely inflation and the output gap. Price-based rules, based on Taylor's (1993) interest rule, capture the relationship between the short-term interest rate and other explanatory variables, namely inflation and the output gap. Since there is no consensus on which type of simple rule is the best and most appropriate rule to characterize China's monetary policy within a DSGE framework, some have explored a hybrid monetary policy that contains both the nominal interest rate and money growth rate as policy targets (e.g., Li and Liu, 2017).

This paper makes several contributions to the existing literature in the following ways. First, the paper establishes a small-scale NK-DSGE model and uses the Bayesian likelihood estimation method to estimate the parameters of the model with Chinese data. Second, it helps to establish the consensus on using the single linear policy rule as an abstraction for the complexity of monetary policy within the DSGE framework. Third, the counterfactual analysis also shows that different stances of the central bank of China would have large impact on the real economy. Moreover, the estimation results also suggest that the conventional Taylor rule that does not include money would not be an appropriate rule when considering a DSGE model for monetary policy in China, as it is not favored by the data.

The paper is structured as follows. Chapter 2 reviews the two different types of monetary policy rules and past research about the characterization of a monetary policy rule for China. Chapter 3 presents the DSGE model and presents the log-linearized equations. Chapter 4 describes the data and the Bayesian likelihood estimation method and priors. Chapter 5 reports the posterior estimation results and presents the counterfactual analysis. Chapter 6 concludes.

II. Literature Review

As mentioned above, China's monetary policy seems to be more complex compared to those of advanced economies for two reasons: multiple policy targets and an ineffective monetary policy transmission channel (Zhang, 2009). Due to the unique features of China's monetary authority, there has been an ongoing debate on which type of simple rule characterizes China's monetary policy better in the context of a DSGE framework. This chapter reviews the relevant literature concerned with the discussion towards different types of policy rules and illustrates the key research that utilized those policy rules within a DSGE model.

The discussion towards the comparison of monetary policy rules starts from the seminal work of Taylor (1993). The famous Taylor rule proposes a simple equation to capture the central bank's nominal interest rate decision. According to the policy rule, the central bank sets the nominal interest rate in response to inflation deviations from its target, as well as the output gap. Later, a normative Taylor rule was supported by many works, and has shown excellent empirical performance (Judd and Rudebusch, 1998).

The parsimony of the equation has also made Taylor-type rules the most common formulation for monetary policy within DSGE models or SVAR models for empirical research. However, Curdia, et al. (2012) point out that empirical DSGE studies pay little attention to the specification of the monetary policy rule. In their paper, they undertake a systematic comparison of interest rate rules within two popular New Keynesian

DSGE models by using Bayesian estimation methods. Using U.S. data, they find that the details of the specification of an interest rate rule (that is, the specific variables considered in the rule) can have a significant impact on the fit of a model.

In addition to Taylor-type rules, a McCallum rule has also made contributions to monetary-policy characterization. McCallum (1988, 2003) proposed a rule for determining the monetary base as the linear combination of nominal GDP, real GDP and money velocity. The McCallum rule sets the money base of the next quarter as the intermediate target of monetary authorities and GDP growth as the ultimate target. The rule determines monetary authorities should manipulate the supply of money to keep economic growth on a sustainable path in the long-run.

Among the literature that involves the characterization of China's monetary policy, there are various views and methods employed. Liu and Zhang (2007) use graphical analysis to compare the fit of the McCallum rule with actual numbers for M2 money supply of PBoC. Koivu et al. (2008) examine the McCallum rule over the period from 1994 to 2006 and find that the McCallum rule can be a useful tool for analysing China's monetary policy stance and gives information for the price and inflation forecast. Chen, et al. (2016) find that M2 growth responds positively to GDP growth when it is above the target (the normal state), but when actual GDP growth is below the target (the shortfall state), M2 growth takes an unusually aggressive response to stem the shortfall and conclude that China's monetary stance could be pro-growth.

The foundation of the estimation using the McCallum rule could be twofold: Firstly, PBoC has set the target value for money supply growth (M1 and M2) since 1996 (PBoC's official website). Secondly, compared to other advanced economics, the nominal interest rate was not liberalized in the past decades and the interest rate liberation has only recently been achieved in China. Due to the imperfect monetary transmission mechanism, some researchers believe that the quantity rule would be much more suitable than interest rate rules in the context of China (e.g., Burdekin and Siklos,2005).

At the end of the 1990s, the PBoC started to liberalize the lending and deposit interest rate of commercial banks. The gradual interest rate liberalization drove empirical researchers to care more about the nominal interest rate. A general notion is that PBoC has been undergoing a gradual transition from a quantity-based policy rule to a price-based policy rule. Moreover, China's velocity of money (M2) seems to be unsteady and has increased remarkably since the early 1990s (Zhang 2009). Analysis only based on a money growth rule would not be appropriate for the current policy stance of PBoC. Zhang (2009) makes a comparison of different monetary policy rules between a price rule (interest rate rule) and quantity rule (money growth rule) in the framework of a DSGE model and concludes that the price rule would be more suitable than the quantity rule because the linkage between money supply and inflation is weak.

Researchers have also investigated a hybrid monetary policy framework that involves both the nominal interest rate and money growth as dual policy targets. Li and Liu (2017) explore the hybrid rule within the DSGE framework. The hybrid rule includes responses to gaps between inflation, output growth and money growth from their respective targets. By applying Bayesian estimation methods, their research shows that money has been more closely targeted than the nominal interest rate and a conventional Taylor-type interest rate rule is not the most appropriate to characterize China's monetary policy.

Apart from a linear monetary policy function, some researchers propose a non-linear policy rule. A recent finding reveals that there has been an increase in the adoption of nonlinear policy rules, because central banks tend to have asymmetric preferences in their loss functions (Castro 2008). Non-linearity of the policy rule has also been discussed in the context of China. For instance, Ma (2016) evaluates and analyzes the non-linearity of China's monetary policy rule within the DSGE framework. Apart from the three-factor augmented Taylor-type rule, namely gaps of output, inflation and real exchange rate, he describes the monetary policy rule as a transition function given by a quadratic logistic STR (smooth transition regression) model. Using Bayesian estimation methods, he concludes that a non-linear monetary policy rule can be more suitable than a traditional linear policy rule to achieve economic stability. Moreover, other researchers such as Chen (2009), and Zheng, et al. (2012) investigate the non-linearity of the monetary policy rule via the Markov switching (MS) model.

Overall, the previous studies suggest that neither conventional Taylor-rules nor McCallum rules have done a great job in characterizing China's monetary policy function. While I acknowledge the prior empirical work on a non-linear monetary policy rule, I still focus on the linear monetary policy rule for two reasons: Firstly, the complexity of a non-linear monetary policy rule makes the estimation much more sophisticated and beyond the scope of this study. Secondly, the existing literature only gives empirical evidence for such type of policy rule and little theoretical background (such as normative analysis) to support its use.

As mentioned before, the choice of the monetary policy rule could have different empirical results and policy implications. In this paper, I follow the work of Li and Liu (2017) and estimate an expanded hybrid rule where I assume that the central bank of China adjusts the linear combination of the dual policy targets, namely inflation and the money growth rate, to achieve its policy goals. Relative to Li and Liu (2017), I estimate the model with different observables and over a more recent sample period, as well as consider a slightly different model specification.

III. New Keynesian DSGE model

This chapter presents a standard New Keynesian DSGE model with several features standard in the estimation literature, e.g., Smets and Wouters (2007). The model consists of a representative household who supplies labor and capital to firms. The production is divided into two sectors: the final good producer and the intermediate good producer. The final good's market is perfectly competitive, while the intermediate good's market is monopolistically competitive. The model includes price rigidities, habit formation, variable capital utilization and capital adjustment costs. Unlike the sophisticated model built by Smets and Wouters (2007), I assume that the nominal wage is flexible and the exogenous total factor productivity technology shock follows an AR (1) process instead of a balanced steady-state growth path.

3.1. Household problem

The representative household maximizes the following utility function:

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t \left\{ [\ln(C_t - h\overline{C_{t-1}}) + V_t \ln\left(\frac{M_t}{P_t}\right)] - \frac{\psi}{1+\gamma} N_t^{1+\gamma} \right\} \qquad (1)$$

where $\beta \in (0,1)$ is the stochastic discount factor, and V_t is the money demand shock, which follows the AR (1) process:

$$\ln V_t = \rho_v \ln V_{t-1} + \varepsilon_t^v \qquad (2)$$

where $\rho_v \in (0,1)$, $\varepsilon_t^v \sim iid\ N(0, \delta_v^2)$.

In addition, C_t denotes individual household consumption, $\overline{C_{t-1}}$ denotes the aggregate consumption of the previous period, which is exogenous to the household, and $h \in (0,1)$ controls external habit formation. M_t denotes nominal cash, P_t denotes the aggregate price level and N_t denotes the hours worked.

The representative household's budget constraint is given by:

$$C_t + I_t + \frac{B_t}{P_t} + \frac{M_t}{P_t} \leq \frac{M_{t-1}}{P_t} + \frac{R_{t-1}B_{t-1}}{P_t} + \frac{T_t}{P_t} + \frac{D_t}{P_t} + \frac{W_t}{P_t}N_t + \frac{Q_t}{P_t}K_t \tag{3}$$

In the period t, the household starts with capital stock K_t, money stock M_{t-1} and one-period government bonds B_{t-1},which give the household a gross nominal return R_{t-1}. The household receives a lump sum T_t from the government and returns from the bonds. During the period, the household supplies labor to intermediate firms for the nominal wage W_t and rents capital at the nominal rate Q_t to these firms. The household also receives dividends (profits) D_t from these firms. The household spends on consumption C_t, investment I_t and the acquisition of government bonds B_t and cash balances M_t.

The law of motion for capital is given by

$$K_{t+1} = \mu_t \left[1 - \frac{\phi}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right] I_t + (1-\delta)K_t \tag{4}$$

I use the adjustment cost specification based on Christiano, et al. (2005), as they show it matches well moments of investment. μ_t is an investment-specific technology shock and it follows the AR (1) process:

$$\ln \mu_t = (1-\rho_\mu)\ln \mu + \rho_\mu \ln \mu_{t-1} + \varepsilon_t^\mu \tag{5}$$

where $\rho_\mu \in (0,1), \varepsilon_t^\mu \sim iid\ N(0, \delta_\mu^2)$, μ is the steady state value of μ_t.

The representative household maximizes the lifetime utility subject to the two constraints, namely the budget constraint (3) and capital accumulation law (4). The Lagrange equation associated with this problem is

$$\mathcal{L} = E_0 \sum_{t=0}^{\infty} \beta_t \Big\{ [\ln(C_t - h\overline{C_{t-1}}) + V_t \ln\left(\frac{M_t}{P_t}\right) - \frac{\psi}{1+\gamma} N_t^{1+\gamma}] + \lambda_t \Big(\frac{M_{t-1}}{P_t} + \frac{R_{t-1}B_{t-1}}{P_t} + \frac{\Gamma_t}{P_t} + \frac{D_t}{P_t} + \frac{W_t}{P_t} N_t + \frac{Q_t}{P_t} K_t - C_t - I_t - \frac{B_t}{P_t} - \frac{M_t}{P_t}\Big) + \chi_t \left(\mu_t \left[1 - \frac{\phi}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right] I_t + (1-\delta)K_t - K_{t+1}\right) \Big\} \tag{6}$$

The first-order conditions associated with the household's problem are:

$$\frac{\partial \mathcal{L}}{\partial C_t}: \ \frac{1}{C_t - h\overline{C_{t-1}}} - \lambda_t = 0 \tag{7}$$

$$\frac{\partial \mathcal{L}}{\partial N_t}: (-\psi N_t^{\gamma}) + \lambda_t \frac{W_t}{P_t} = 0 \tag{8}$$

$$\frac{\partial \mathcal{L}}{\partial M_t}: \left[v_t \left(\frac{P_t}{M_t}\right)\left(\frac{1}{P_t}\right) - \lambda_t \frac{1}{P_t}\right] + \beta E_t \left(\frac{\lambda_{t+1}}{P_{t+1}}\right) = 0 \tag{9}$$

$$\frac{\partial \mathcal{L}}{\partial K_{t+1}}: (-\chi_t) + \beta E_t \left[\lambda_{t+1} \frac{Q_{t+1}}{P_{t+1}} + \chi_{t+1}(1-\delta)\right] = 0 \tag{10}$$

$$\frac{\partial \mathcal{L}}{\partial I_t}: \left\{(-\lambda_t) + \chi_t \mu_t \left(\left[1 - \frac{\phi}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right] + \left[-\phi\left(\frac{I_t}{I_{t-1}} - 1\right)\frac{I_t}{I_{t-1}}\right]\right)\right\} - \beta \chi_{t+1} E_t \mu_{t+1} \left[\phi\left(\frac{I_{t+1}}{I_t} - 1\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right] = 0 \tag{11}$$

$$\frac{\partial \mathcal{L}}{\partial B_t}: \left(-\frac{\lambda_t}{P_t}\right) + \beta E_t \left(\frac{\lambda_{t+1}}{P_{t+1}}\right) R_t = 0 \tag{12}$$

Rearranging terms, I obtain the following equations:

$$\lambda_t = \left(\frac{1}{C_t - h\overline{C_{t-1}}}\right) \tag{13}$$

$$\lambda_t = (\psi N_t^{\gamma})\left(\frac{W_t}{P_t}\right)^{-1} \tag{14}$$

$$\lambda_t = v_t\left(\frac{M_t}{P_t}\right)^{-1} + \beta E_t \lambda_{t+1}\left(\frac{P_t}{P_{t+1}}\right) \tag{15}$$

$$\chi_t = \beta(1-\delta)E_t \chi_{t+1} + \beta E_t \lambda_{t+1} \frac{Q_{t+1}}{P_{t+1}} \tag{16}$$

$$\lambda_t = \chi_t \mu_t \left[1 - \frac{\phi}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 - \phi\left(\frac{I_t}{I_{t-1}} - 1\right)\frac{I_t}{I_{t-1}}\right] - \beta E_t \chi_{t+1} \mu_{t+1} \left[\phi\left(\frac{I_{t+1}}{I_t} - 1\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right] \tag{17}$$

$$1 = \beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t}\right)\left(\frac{P_t}{P_{t+1}}\right) R_t \tag{18}$$

3.2. Production

The production is split into two sectors: the final good producer and the intermediate good producer. The final good market is perfectly competitive, where the final good producer achieves zero profit in equilibrium. The final good producer aggregates intermediate goods from the intermediate good market according to a CES technology. To introduce price stickiness, I assume that the intermediate good's market is monopolistically competitive. The intermediate good producers have a certain degree of pricing power, but they are not freely able to adjust their price in each period. The details are explained in the following paragraphs.

3.2.1. Final Good Producer

The final output good is a CES aggregate of a continuum of intermediates:

$$y_t = (\int_0^1 y_t(j)^{\frac{\eta-1}{\eta}} dj)^{\frac{\eta}{\eta-1}} \tag{19}$$

Here $\eta > 1$ denotes the elasticity of substitution across varieties. After I solve the profit maximization problem, I get the demand curve:

$$y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\eta} y_t \tag{20}$$

By definition, I have the following aggregation equation:

$$P_t y_t = \int_0^1 P_{t(j)} y_{t(j)} = \int_0^1 P_{t(j)} \left(\frac{P_t(j)}{P_t}\right)^{-\eta} y_t = P_t^{\eta} y_t \int_0^1 P_{t(j)}^{1-\eta} \tag{21}$$

which gives me the relationship between the aggregate price and individual final good firm price:

$$P_t = \left[\int_0^1 P_t^{1-\eta}(j)dj\right]^{\frac{1}{1-\eta}} \tag{22}$$

3.2.2. Intermediate Good Producer

In the intermediate good sector, there is monopolistic competition among a continuum of firms on the unit interval. I assume that the production function follows a Cobb-Douglas function, and A_t is the exogenous total factor productivity. For simplification, I do not impose a wage rigidity on wage setting and assume a perfectly competitive labor market, so each firm faces a flexible and common wage. The production function of the jth firm is given by:

$$y_t(j) = A_t K_{t(j)}^{\alpha} N_{t(j)}^{1-\alpha} \quad 0 < \alpha < 1 \tag{23}$$

I assume that TFP follows the AR (1) process:

$$lnA_t = \rho_a lnA_{t-1} + \varepsilon_t^a \tag{24}$$

where $\rho_a \in (0,1), \varepsilon_t^a \sim iid\ N(0, \delta_a^2)$.

Each firm faces the demand curve given by equation (20). I assume price stickiness via a Calvo (1983) assumption: Firms are not freely able to adjust their price to the optimal price $\tilde{p}_t$. In each period, firms change their price with a constant probability equal to $(1-\theta)$, whereas firms stick to the previous price with a constant probability equal to θ. The dynamic problem of the intermediate good producer j is to maximize

$$E_t \sum_{s=t}^{\infty} (\beta\theta)^{s-t} \frac{\lambda_s}{\lambda_t} \left(\frac{\widetilde{P}_t \tilde{y}_s - minimum\ costs}{P_S} \right) \tag{25}$$

The total demand the producer j faces in period s ($s \geq t$) is $\tilde{y}_s = \left(\frac{\widetilde{p}_t}{P_s}\right)^{-\eta} y_s$.

To determine the optimal price $\tilde{p}_t$, I first find the minimum cost of the intermediate good producer:

$$min\ W_t N_{t(j)} + Q_t K_{t\,(j)} \tag{26}$$

$$\text{subject to } \; y_t(j) = A_t K_{t(j)}^{\alpha} N_{t(j)}^{1-\alpha} \tag{23}$$

Taking MC_t as the Lagrange multiplier, I can get the following equations from the FOCs:

$$W_t = (1-\alpha) MC_t \frac{y_{t(j)}}{N_{t(j)}} \tag{24}$$

$$Q_t = \alpha MC_t \frac{y_{t(j)}}{K_{t(j)}} \tag{25}$$

Combining equations (24) and (25), I obtain

$$W_t N_{t(j)} + Q_t K_{t\,(j)} = MC_t y_t(j) \tag{26}$$

where I can interpret MC_t as both the marginal and minimum cost of firm j. Together, the dynamic intertemporal profit maximization problem of firm j can be solved as the following:

$$Max\ \Pi_t = E_t \sum_{s=t}^{\infty} (\beta\theta)^{s-t} \frac{\lambda_s}{\lambda_t} \left(\frac{\widetilde{P}_t - MC_s}{P_s} \right) \left(\frac{\widetilde{p}_t}{P_t} \right)^{-\eta} y_s \tag{27}$$

subject to the demand for the firm's good. After calculating the derivative Π_t with respect to the optimal price $\widetilde{p}_t$, I get the following equation:

$$\widetilde{P}_t = \frac{\eta}{\eta - 1} \frac{E_t \sum_{s=t}^{\infty} (\beta\theta)^{s-t} \wedge_{t,s} MC_s \tilde{y}_s}{E_t \sum_{s=t}^{\infty} (\beta\theta)^{s-t} \wedge_{t,s} \tilde{y}_s} \tag{28}$$

where I define $\wedge_{t,s} = \frac{\lambda_s}{\lambda_t P_s}$. When prices are perfectly flexible $(\theta = 0)$, the optimal price $\widetilde{p}_t$ is the mark-up times the marginal cost at time t.

$$\widetilde{P}_t = \frac{\eta}{\eta - 1} MC_t \tag{29}$$

After log-linearizing equation (28), I introduce an additional shock into the equation. The shock has the same interpretation as an exogenous mark-up shock (that is, it can be fully derived from the assumption that the mark-up includes an exogenous, stochastic component). I assume this shock follows the AR (1) process:

$$lnup_t = \rho_{up} * lnup_{t-1} + \varepsilon_t^{up} \tag{30}$$

where $\rho_{up} \in (0,1), \varepsilon_t^{up} \sim iid\ N\left(0, \delta_{up}^2\right)$.

The proportion of firms that have chosen a new price at time s and have not changed yet at time t $(t \geq s)$ is equal to the probability that the price chosen at time s was still in effect at time t. The probability is equal to $(1-\varphi)\varphi^{t-s}$. So, the aggregate price level $P_t$would be

$$P_t = \left((1-\theta) \sum_{s=-\infty}^{t} \varphi^{t-s}\, \widetilde{p}_s{}^{1-\eta}\right)^{\frac{1}{1-\eta}} \tag{31}$$

which implies

$$P_t^{1-\eta} = \varphi P_{t-1}^{1-\eta} + (1-\varphi)\widetilde{P}_t{}^{1-\eta} \tag{32}$$

3.3. Government

I define the gross inflation rate as:

$$\pi_t = \frac{P_t}{P_{t-1}} \tag{33}$$

I assume that the government has the following consolidated budget constraint:

$$T_t = M_t - M_{t-1} + B_t - R_{t-1}B_{t-1} \tag{34}$$

The money growth equation is defined from the following identity:

$$m_t = \left(\frac{Mgr_t}{\pi_t}\right) * m_{t-1} \tag{35}$$

I define Mgr_t as nominal money growth rate, and $\left(\frac{Mgr_t}{\pi_t}\right)$ as real money growth rate. m_t is the real money balance.

Moreover, I assume that the central bank of China follows an expanded (log-linearized) Taylor-type monetary policy rule as the following,

$$\widehat{R_t} = \rho_r * \widehat{R_{t-1}} + (1-\rho_r) * (\rho_\pi \widehat{\pi_t} + \rho_y \widehat{y_t} + \rho_m * Mgr_t) + \varepsilon_{Rt} \tag{36}$$

where $\rho_r \in (0,1), \varepsilon_{Rt} \sim iid\ N(0, \delta_a^2)$.

The central bank of China will respond to three possible factors: inflation, output and the nominal money growth rate.

3.4. Aggregation and Equilibrium

Recall from the intermediate good producer, I have the following aggregation equations:

$$N_t = \int_0^1 N_t(j)dj \tag{37}$$

$$K_t = \int_0^1 K_t(j)dj \tag{38}$$

$$Y_t = \int_0^1 y_t(j)dj \tag{39}$$

Since all firms have the same capital/labor ratio, I have:

$$Y_t = \int_0^1 A_t K_{t(j)}^{\alpha} N_{t(j)}^{1-\alpha} dj = A_t {N_t}^{1-\alpha} {K_t}^{\alpha} \tag{40}$$

Recall from the household's problem, I have the following FOC equation:

$$C_t + I_t + \frac{B_t}{P_t} + \frac{M_t}{P_t} \leq \frac{M_{t-1}}{P_t} + \frac{R_{t-1}B_{t-1}}{P_t} + \frac{T_t}{P_t} + \frac{D_t}{P_t} + \frac{W_t}{P_t}N_t + \frac{Q_t}{P_t}K_t \tag{3}$$

By definition, I have:

$$D_t = \int_0^1 D_t(j)dj = \int_0^1 P_{t(j)}y_{t(j)} - W_t N_{t(j)} - Q_t K_{t(j)} dj = \int_0^1 P_{t(j)}y_{t(j)} - W_t N_t - Q_t K_t \tag{41}$$

Combining equation (33) and equation (40) into the FOC equation (3), I have

$$C_t + I_t = \frac{D_t}{P_t} + \frac{W_t}{P_t}N_t + \frac{Q_t}{P_t}K_t \tag{42}$$

$$C_t + I_t = \frac{\int_0^1 P_{t(j)}y_{t(j)} - W_t N_t - Q_t K_t}{P_t} + \frac{W_t N_t}{P_t} + \frac{Q_t K_t}{P_t} \tag{43}$$

$$C_t + I_t = \int_0^1 \frac{P_{t(j)}}{P_t} y_{t(j)} \tag{44}$$

Recall from final good producer problem, I have

$$y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\eta} y_t \tag{45}$$

$$P_t = \left[\int_0^1 P_t^{1-\eta}(j)dj\right]^{\frac{1}{1-\eta}} \tag{46}$$

Plugging these two equations into equation (43), it is easy to prove that $y_t = C_t + I_t$.

Recall that $Y_t = \int_0^1 y_t(j)dj = \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\eta} y_t dj = y_t \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\eta} dj$, I can also write the equation as

$$Y_t\left[\int_0^1\left(\frac{P_t(j)}{P_t}\right)^{-\eta}dj\right]^{-1}=C_t+I_t \tag{47}$$

3.5. Log-linearized System

The equilibrium conditions of the model are log-linearized around the steady state of the real variables. Firstly, I need to rewrite the FOC equations in real terms. For better clarification, I always use the lower-case letter to express variables in real terms and the capital letter to express variables in nominal terms. For example, I use w_t instead of $\frac{W_t}{P_t}$ to express the real wage.

Secondly, I need to determine the steady state of the system. For future reference, I express the steady state variables with a line on top. For example, I express the steady state of the short-term interest rate R as $\bar{R}$. The system of the steady state is the following:

$$\delta\bar{K}=\bar{\mu}\bar{I} \tag{48}$$

$$\bar{\lambda}=\frac{1}{(1-h)\bar{C}} \tag{49}$$

$$\bar{\lambda}=\psi\bar{N}^{\gamma}\frac{1}{\bar{\omega}} \tag{50}$$

$$\bar{R}=\frac{1}{\beta} \tag{51}$$

$$1=\frac{1}{\bar{m}\bar{\lambda}}+\frac{1}{\bar{R}} \tag{52}$$

$$[1-\beta(1-\delta)]\bar{\chi}=\beta\bar{\lambda}\bar{q} \tag{53}$$

$$\bar{\lambda}=\bar{\chi}\bar{\mu} \tag{54}$$

$$\bar{\pi}=\beta\bar{R} \tag{55}$$

$$\bar{y}=\bar{A}\bar{K}^{\alpha}\bar{N}^{1-\alpha} \tag{56}$$

$$\bar{w}=(1-\alpha)\overline{mc}\frac{\bar{y}}{\bar{N}} \tag{57}$$

$$\bar{q}=\alpha\overline{mc}\frac{\bar{y}}{\bar{K}} \tag{58}$$

$$\bar{y}=\bar{C}+\bar{I} \tag{59}$$

$$\overline{mc}=\frac{\eta}{\eta-1} \tag{60}$$

Finally, I derive the log-linearized equations around the steady state. By using the first-order Taylor expansion, I derive the 13 log-linearized equations in terms of 13 endogenous variables. For reference, I express the log-linearized variables as hat variables. The last equation in the following system is the equation for monetary policy. Note that an exogenous shock has been added to equation (71), representing an exogenous shock to the mark-up.

$$\widehat{K_{t+1}} = \delta \widehat{I_t} + (1-\delta)\widehat{K_t} \tag{61}$$

$$\widehat{\lambda_t} = -\frac{1}{1-h}\widehat{C_t} + \frac{h}{1-h}\widehat{C_{t-1}} \tag{62}$$

$$\widehat{\lambda_t} + \widehat{w_t} = \gamma \widehat{N_t} + \widehat{u_t^d} \tag{63}$$

$$\widehat{R_t} = \frac{1-\beta}{\beta}\widehat{v_t} - \frac{1-\beta}{\beta}\widehat{\lambda_t} - \frac{1-\beta}{\beta}\widehat{m_t} \tag{64}$$

$$\widehat{\chi_t} = \beta(1-\delta)E_t\widehat{\chi_{t+1}} + [1-\beta(1-\delta)]E_t\left(\widehat{\lambda_{t+1}} + \widehat{q_{t+1}}\right) \tag{65}$$

$$\widehat{\lambda_t} = \widehat{\chi_t} + \widehat{\mu_t} - (1-\beta)\phi\widehat{I_t} + \phi\widehat{I_{t-1}} - \beta\phi E_t\widehat{I_{t+1}} \tag{66}$$

$$E_t\widehat{\lambda_{t+1}} = \widehat{\lambda_t} + E_t\widehat{\pi_{t+1}} - \widehat{R_t} \tag{67}$$

$$\widehat{y_t} = \widehat{A_t} + \alpha\widehat{K_t} + (1-\alpha)\widehat{N_t} \tag{68}$$

$$\widehat{w_t} = \widehat{mc_t} + \widehat{y_t} - \widehat{N_t} \tag{69}$$

$$\widehat{q_t} = \widehat{mc_t} + \widehat{y_t} - \widehat{K_t} \tag{70}$$

$$\widehat{\pi_t} = \beta E_t\widehat{\pi_{t+1}} + \frac{(1-\theta)(1-\theta\beta)}{\theta}\widehat{mc_t} + \widehat{up_t} \tag{71}$$

$$\widehat{I_t} = \left(\frac{\bar{y}}{\delta\bar{K}}\right)\widehat{y_t} - \left(\frac{\bar{c}}{\delta\bar{K}}\right)\widehat{c_t} \tag{72}$$

$$\widehat{R_t} = \rho_r * \widehat{R_{t-1}} + (1-\rho_r) * (\rho_\pi\widehat{\pi_t} + \rho_y\widehat{y_t} + \rho_m * Mgr_t) + \varepsilon_{Rt} \tag{36}$$

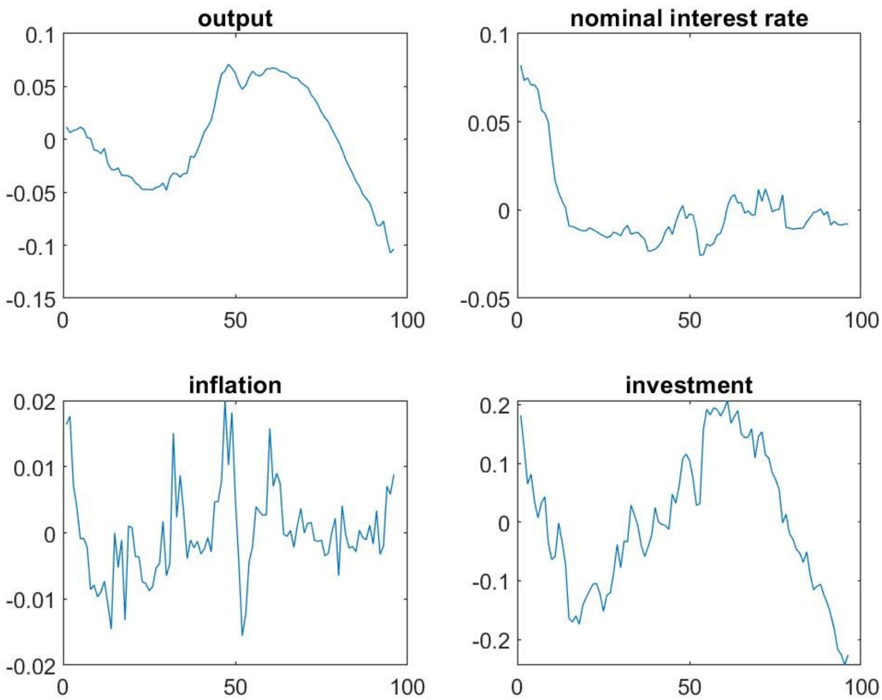
IV. Data and Prior Setting

In this chapter, I estimate the model with China's quarterly data using the Bayesian likelihood approach. First, I introduce the four observables and provide the data sources that I use. Second, I briefly explain the Bayesian estimation method. Third, I set the prior mean and distribution for parameters and briefly explain the values chosen for the prior setting.

4.1. Data

The time span for the baseline estimation is 1996Q1 to 2019Q4. There are 4 observable variables, which are real GDP, real investment, the nominal interest rate and inflation rate. Firstly, I collect the quarterly data from the dataset provided by Federal Reserve Bank of Atlanta, where most of the data were originally collected from CEIC (China Economic Information Center) and the Wind Info database (China's version of Bloomberg). Due to the availability of the data, I can only find quarterly short-term interest rates since 1996Q1. For the nominal interest rate, I use the 7-day repo rate, which echoes other authors who used the 7-day repo rate to study China's monetary policy (e.g., Chen, et al. 2016). For inflation, I use CPI index as the measure of inflation because most of the relevant studies use CPI as the price index for inflation (e.g., Zhang and Murasawa 2011, Li and Liu 2017). Moreover, I believe that CPI is a better measurement than GDP deflator to reflect the cost of living because the GDP deflator measures the prices of all goods and services produced, whereas the CPI measures the prices of a fixed basket of the goods and services bought by consumers. I use the GDP deflator to convert nominal GDP to real GDP and nominal investment into real investment (nominal investment is defined as gross fixed capital formation). This is also consistent with the empirical literature using Chinese data (e.g., Li and Liu 2017).

<u>Figure 1 Stationary Time Series Data of Four Observables from 1996Q1 to 2019Q4</u>



Secondly, I take the log and demean real GDP and real investment. I linearly detrend the data for these two observable variables to have stationary time series.

Finally, I demean the nominal interest rate. As for inflation, I calculate the growth rate and demean the data. The final time series used for the estimation are presented in Figure 1.

4.2. Methodology

The model presented in the previous chapter is estimated with Bayesian estimation methods using the four key macroeconomic quarterly time series as observable variables. Since I have already made several preparations for the data in the last chapter, the corresponding measurement equations for the model is simply:

$$gdp\_data = y \tag{73}$$

$$inf\_data = pi \tag{74}$$

$$inv\_data = inv \tag{75}$$

$$r\_data = r \tag{76}$$

The data for observable variables exactly correspond to the endogenous variables of the NK-DSGE model.

According to the Bayes' theorem, the posterior density is defined as the following equation:

$$P(\theta|D) = \frac{\mathcal{L}(D|\theta) * P(\theta)}{\int \mathcal{L}(D|\theta) * P(\theta) d\theta} \tag{77}$$

where θ and D denote the whole set of model parameters and the observed data, respectively. $\mathcal{L}$ denotes the likelihood function. $P(\theta|D)$ and $P(\theta)$ are the posterior and prior distributions, respectively. The likelihood function is approximated using the Kalman filter. The estimation procedure uses the Metropolis-Hastings algorithm to construct the posterior chain, which is initiated at the posterior mode. To find the posterior mode, I initiated parameters at their prior means and used Dynare to search the parameter space and find the parameter values that maximize the posterior likelihood.

The prior distribution represents the existing knowledge of the parameters before estimation. The posterior distribution represents a revised version of prior distribution after the observed data was considered. An unreliable prior (for instance, very strict and inconsistent with the data) can lead to highly biased model estimates. The following part will explain the choice of the priors and posterior estimation in details.

4.3. Priors

To get a better understanding of the parameters to be estimated, I construct priors by separating the NK-DSGE model parameters into three sets following the same separation method used by Del Negro and

Schorfheide (2008). The first set consists of the parameters that define the steady states. The second set consists of the parameters that are tied to endogenous propagation inside the NK-DSGE model, for example, the elasticity of the labor supply. The parameters of the monetary policy rule are also included in the second set. The third set of parameters include the AR(1) coefficients and standard deviations of the exogenous shocks.

Firstly, I fix the values of some parameters because those parameters are difficult to identify. Their values are chosen to be consistent with the literature for China's economy, as shown in Table 1. The discount factor β is usually calibrated within the literature of DSGE model estimation for China. For instance, 0.985 in Liu (2008), 0.98 in Zhang (2009), and 0.984 in Ma (2011). In this paper, I set it at 0.99 to produce an annual steady-state interest rate of 4%. The capital share in the production function is fixed at 0.4, which echoes past paper's studying China's economy. The value is higher than the counterpart of advanced economies. Moreover, I set the depreciation factor and mark-up at 0.035 and 10, respectively, following the work of Li and Liu (2017). The value for the elasticity of substitution implies a steady-state net mark-up of approximately 11%.

Table 1 Fixed Parameter Values

Parameters	Name	Fixed Value
β	stochastic discount factor	0.99
α	output elasticity of capital	0.4
δ	depreciation factor	0.035
η	mark-up	10
ψ	coefficient for labor in utility	1
$\bar{\pi}$	inflation	1
$\bar{A}$	total factor productivity	1
$\overline{\varepsilon^{up}}$	Mark-up shock	1
$\bar{V}$	money demand shock	1
$\bar{\mu}$	investment shock	1

Secondly, I set the prior distributions, including their functional forms, means and standard deviations, for the parameters to be estimated by Bayesian methods. The priors are set consistently with most of the estimation literature for China's economy.

Table 2 Endogenous Propagation Parameters

Parameters	Distribution	Name	Mean	Standard deviation
h	Beta	habit formation	0.5	0.15
ϕ	Normal	coefficient for investment adjustment	4.0	1.5
θ	Beta	probability of firms that can't change their price	0.75	0.1
γ	Gamma	elasticity of labor supply	1.0	0.5
ρ_r	Beta	interest rate smoothing coefficient	0.5	0.2
ρ_π	Gamma	inflation reaction coefficient	1.5	0.5
ρ_y	Gamma	output reaction coefficient	0.5	0.2
ρ_m	Normal	money growth rate reaction coefficient	0.5	0.5

In the second group of endogenous propagation parameters, I set the habit parameter as a Beta distribution with a mean of 0.5 and a standard deviation of 0.15, following previous work using China's data (Li and Liu, 2017). Note that most papers using U.S. dataset the habit parameter to a mean of 0.7 and a standard deviation of 0.2, which is slightly higher than the habit prior set in this paper. The coefficient for investment adjustment costs is assumed to follow the normal distribution with a mean of 4.0 and a standard deviation of 1.5, following the work of Smets and Wouters (2007). This distribution has also been used for China's data (Li and Liu, 2017). Since there is no consensus for the Calvo-pricing parameter, I set θ following a Beta distribution with a mean of 0.75 and a standard deviation of 0.1, as in Li and Liu (2017). I assume γ follows a Gamma distribution with a mean of 1 and a standard deviation of 0.5. The past studies seem to reach a consensus for a mean value of 1 for the elasticity of the labor supply. Since there is no consensus for the standard deviation, I follow the work of Li and Liu (2017) and set it to 0.5.

In addition, the priors for parameters describing the monetary policy rule are set based on the previous studies of China's monetary policy. In this case, I follow the work of Ma (2016) and set the parameters as follows: the interest rate smoothing coefficient is assumed to follow a Beta distribution with a mean of 0.5 and a standard deviation of 0.2; the interest rate reaction on output gap $\boldsymbol{\rho_y}$ is assumed to follow a Gamma distribution with a mean of 0.5 and a standard deviation of 0.2; the interest rate reaction on inflation gap $\boldsymbol{\rho_\pi}$ is assumed to follow a Gamma distribution with a mean of 1.5 and a standard deviation of 0.5; the money growth rate reaction coefficient $\boldsymbol{\rho_m}$ is assumed to follow a Normal distribution with a mean of 0.5 and a standard deviation of 0.5.

Table 3 Exogenous Propagation Parameters

Parameters	Distribution	Name	Mean	Standard deviation
ρ_a	Beta	Total Factor productivity	0.5	0.2
ρ_p	Beta	Mark-up shock	0.5	0.2
ρ_v	Beta	Money demand shock	0.5	0.2
ρ_μ	Beta	Investment shock	0.5	0.2
σ_{up}	Inverse Gamma	Error tern for Mark-up shock	0.1	2
σ_v	Inverse Gamma	Error term for Money demand shock	0.1	2
σ_μ	Inverse Gamma	Error term for Investment shock	0.1	2
σ_g	Inverse Gamma	Error term for output shock	0.1	2
σ_{Rt}	Inverse Gamma	Error term for monetary policy shock	0.1	2

In the third group of exogenous propagation parameters, I set the priors as is standard in the literature. All the error terms for exogenous AR (1) processes are assumed to follow the inverse Gamma distribution with a mean of 1 and a standard deviation of 2.

In summary, to be consistent with China's data, it is reasonable and discreet to follow the priors of the past DSGE estimation literature. Although there may be no consensus on the distribution and the mean value of some parameters and the setting may reflect the authors' personal introspection on the likely location of the parameters of their model, most of the parameters' setting are within the range of estimates found in the literature.

V. Posterior Estimation Analysis

5.1. Posterior Estimation

In table (4), I report the posterior means and 90% HPD (highest posterior density) intervals of the parameters for the estimation obtained by the Metropolis-Hastings algorithm based on 10,000,000 draws for the parameters. I adjust the tuning parameter so that the acceptance rate of the draws is 36%, in line with the range suggested by Herbst and Schorfheide (2016). From the parameter posterior distribution graphs included in the appendix A, the difference between the prior distribution and the posterior distribution is nonnegligible, implying that the quarterly dataset of China has been very informative to the estimation.

The mean value of habit persistence is 0.9834, which is much higher than the habit estimate of 0.36 obtained by Li and Liu (2017). This could result from the lack of real consumption data or the slightly different model specification. As for θ that determines the nominal price rigidity, the posterior mean is 0.7504, which is well within the range of calibrated values in the literature, e.g., 0.84 in Zhang (2009).

Regarding the parameters in the monetary policy rules, I find that the mean value for the nominal interest rate smoothing coefficient is only 0.14, which implies a low degree of interest rate policy smoothing. The mean value of the reaction coefficient towards the money growth rate is 2.58, implying that money does play an important role in the monetary policy behavior. The response of the central bank to inflation, 0.93, is stronger than the response to the output gap, 0.23, which echoes the fact that PBoC sets price stability as its prime policy target (Law of People's Bank of China, 1995).

Table 4 Posterior Estimates of Model Parameters: from 1996Q1 to 2019Q4

Parameters	Name	Mean	5 percent	95 percent
h	habit formation	0.9834	0.9781	0.9887
ϕ	coefficient for investment adjustment	10.0413	7.4133	12.7022
θ	probability of firms that can't change their price	0.7504	0.5928	0.9121
γ	coefficient for labor in the utility	0.3207	0.1000	0.5259
ρ_r	interest rate smoothing coefficient	0.1416	0.0252	0.2529
ρ_π	inflation reaction coefficient	0.9334	0.4277	1.4223
ρ_m	money growth rate reaction coefficient	2.5821	2.0641	3.0979
ρ_y	output reaction coefficient	0.2357	0.1087	0.3480
ρ_a	Total Factor productivity coefficient	0.1478	0.0255	0.2634
ρ_v	coefficient of Money demand shock	0.9617	0.9325	0.9889
ρ_μ	Coefficient of investment shock	0.9108	0.8055	0.9910
ρ_p	Coefficient of mark-up shock	0.0432	0.0100	0.0762
ε_t^a	Technology shock	0.0197	0.0151	0.0242
ε_t^v	money demand shock	0.0115	0.0099	0.0130
ε_t^μ	investment shock	0.0132	0.0109	0.0156
ε_t^r	Monetary policy shock	0.0213	0.0162	0.0263
ε_t^{up}	Mark-up shock	0.0091	0.0079	0.0102

For the estimates of the shock processes, the investment-specific technology shock and the money demand shock turn out to be very persistent. The coefficient of the mark-up shock is only 0.0432, indicating the shock is virtually i.i.d. The technology shock's persistence likely exhibits multi-peaks in the likelihood function, as I estimated a value of 0.97 when I initialized the estimation at a different starting point. While beyond the scope of this thesis, this suggests that it would be useful to use a more robust estimation method that searches the entire parameter space to account for multiple peaks (see for instance the method of Chib and Ramamurthy, 2010).

5.2. Variance decomposition

I calculate variance decompositions based on the posterior mean estimates. The table (5) gives the information about the percentage of the movement in a variable due to its own shock versus shocks to other variables over a 5-year horizon.

Table 5 Variance Decompositions

	ε_t^a	ε_t^v	ε_t^μ	ε_t^r	ε_t^{up}
Investment	0.55	0.19	86.29	1.16	11.81
Output	1.05	0.29	75.53	2.06	21.07
Inflation	3.93	0.24	0.86	1.73	93.24
Interest rate	0.47	45.28	43.70	0.94	9.61

The investment shock accounts for most of the variation in investment and output. It explains 86.29% of the variation in investment and 75.53% of the variation in output. The mark-up shock explains 93.24% of the variation in inflation. Both the money demand shock and the investment shock explain the variation of the nominal interest rate. The money demand shock explains 45.28% of the nominal interest variation and the investment shock explains 43.70% of nominal interest variation.

Neither the exogenous technology shock nor the monetary policy shock plays a significant role in the variation of the four observable variables. However, this does not imply that monetary policy is not important, because there is still an endogenous reaction of monetary policy following other shocks via the estimated policy rule.

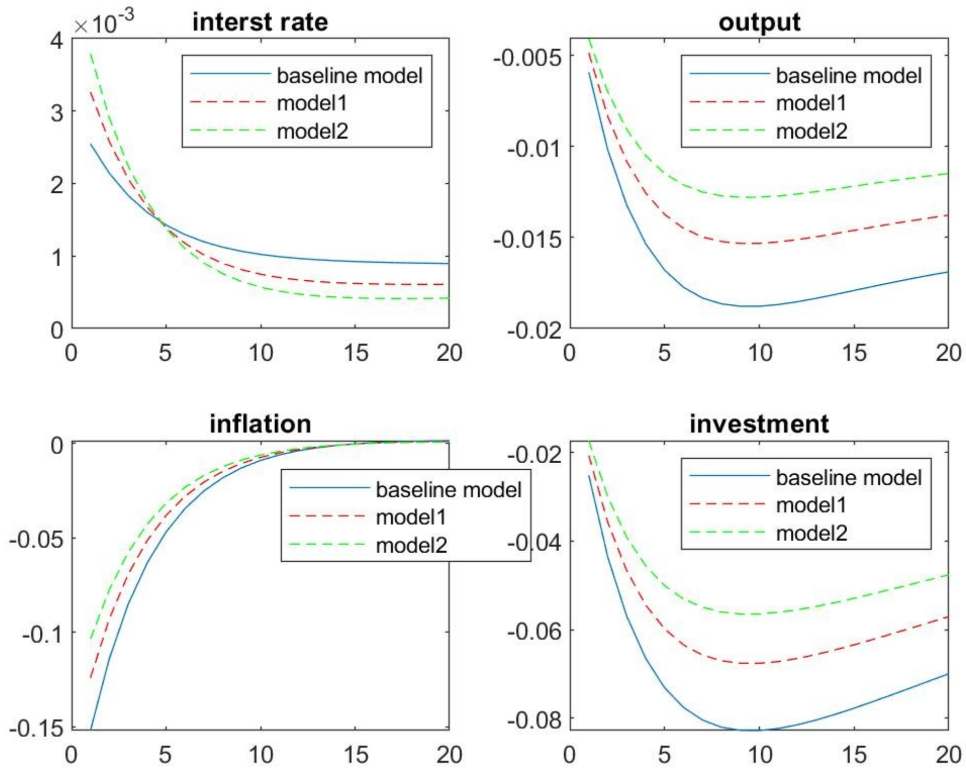
5.3. Counterfactual Analysis

I now examine the effect of monetary policy in the estimated model, as well as following some counterfactual assumptions on the parameter values in the monetary policy rule.

The solid blue line represents the impulse response of the four observable variables to a two standard deviation monetary policy shock based on the posterior mean estimates. In the baseline model, I have the inflation reaction coefficient as 0.93. For a counterfactual analysis, I increase the coefficient to 1.93 for model 1 and 3.0 for model 2. The dotted line represents the impulse response to a monetary policy shock in those two models with different inflation coefficient values.

In general, an increase in the nominal interest rate encourages households to save more in bonds, which lowers demand for consumption and in turn, output. The increase in the nominal interest rate also decreases investment, which further decreases output. With less demand, firms that can adjust their prices will lower the price level, and inflation decreases.

<u>Figure 2 Impulse Response under Different Inflation Coefficients</u>



From Figure 2, the monetary policy shock has a more persistent impact on the interest rate as the central bank reacts more aggressively to the increase of inflation. However, output decreases more if the central bank reacts less to the increase of inflation. The investment shows a "hump-shape" pattern towards the monetary policy shock: gradually decreasing before bottoming out around two years after the shock. The impulse response of investment appears weaker if the central bank is more sensitive to the increase of inflation. Note that the monetary policy shock has less impact on output and investment if the central bank reacts more to inflation.

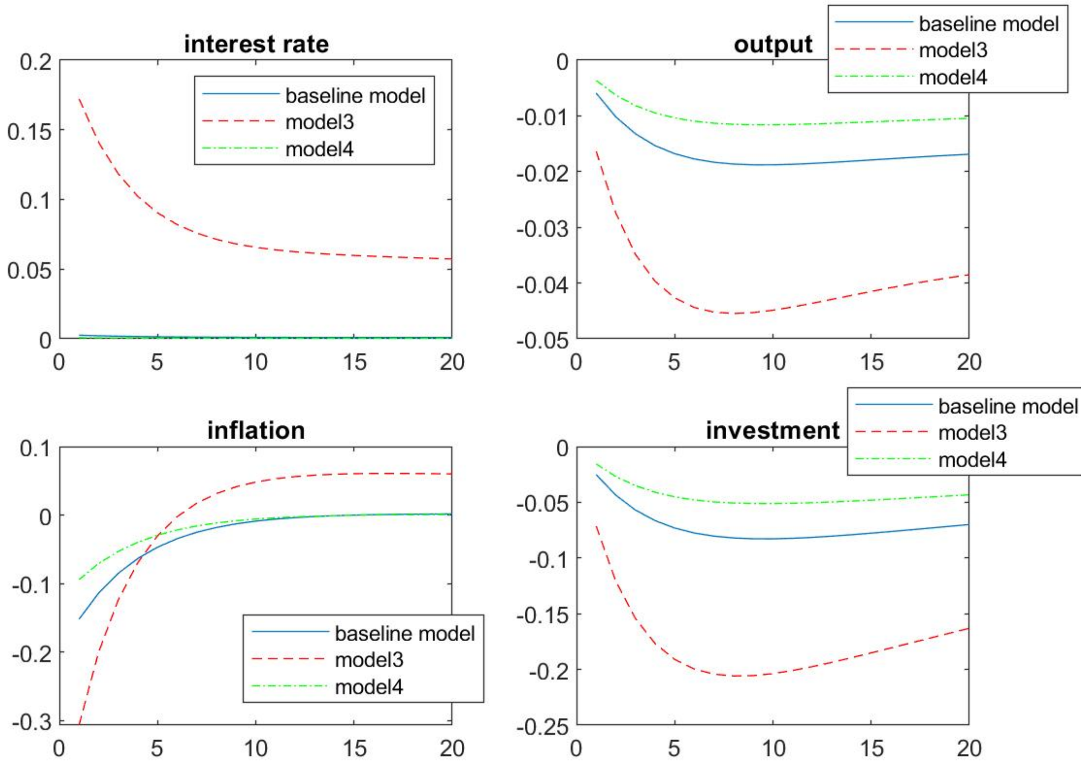
To get a plausible economic interpretation for the results, I also examine the monetary policy shock to other endogenous variables in the DSGE model. (See appendix for more details). With different reaction coefficients of inflation, other variables, namely consumption, the real wage, time of labor supply and real money balance, show similar reaction patterns to the monetary policy shock. This finding indicates that the difference in the impulse responses of output and investment towards the same monetary policy shock is mainly due to different levels of the nominal interest rate. For the baseline model where the central bank reacts less aggressively to inflation, the nominal interest rate is higher over time than the other two models. The increase of the nominal interest rate decreases investment, which accounts for the decrease in output since output and investment share the same dynamics. The increase of the nominal interest rate will also motivate the household to save more on the bonds and consume less.

Secondly, as the main interest is the role of money in the central bank's behaviour, I change the value of the money growth coefficient for the other two models. For the baseline model, money growth reaction coefficient is 2.58. However, I decrease the money growth coefficient to 0.1 to see how the four observables will react if the central bank reacts much less to the nominal money growth rate. In contrast, in model 4, I increase the coefficient to 5.0, indicating that the central bank is extremely sensitive to the increase of nominal money growth.

Figure 3 shows that the interest rate will decrease over the following 20 periods if the central bank does not react much to the nominal money growth rate. However, the interest rate will not react to the monetary policy shock for both the baseline model and the model with a high reaction to money growth. The impulse response of output shows a "hump-shape" pattern for the low reaction to money growth model. However, the impulse response of output towards the monetary policy shock is much weaker for the baseline model and the model with a high reaction to money growth. The monetary policy shock will have a more profound and persistent impact on inflation if the central bank reacts little to nominal money growth. As the coefficient on the money growth coefficient increases, investment is less likely to respond to the monetary policy shock.

Note that the four observable variables do not react much to the monetary policy shock for the baseline model and the high reaction to money growth model.

Figure 3 Impulse Response under Different Money Growth Coefficients



The nominal interest rate does not respond much to the monetary policy shock within the baseline model and the model with a high reaction to money growth. This is because the increase of the nominal interest rate from the exogenous shock is offset by the decrease of the nominal interest rate due to less supply of money. The increase of the nominal interest rate will encourage the household to save more and consume less. With less demand for money, the central bank will lower the level of the money supply. However, since the central bank is so sensitive to the money growth rate, the central bank will adjust the nominal interest rate to a lower level to maintain the same rate of money growth. The fall in the nominal interest rate adjusted by the central bank offsets the rise in the nominal interest rate caused by the exogenous monetary policy shock. Thus, overall, the nominal interest rate does not respond much to the monetary policy shock. Since there is not much of a change in the nominal interest rate, other variables such as output, investment and inflation show a weaker response to the monetary policy shock within the baseline model and the model with a high reaction to money growth.

VI. Conclusion

In conclusion, the empirical analysis shows that money plays an important role in monetary policy when the NK-DSGE model is built to capture the main features of the Chinese economy. Based on the posterior mean values of the monetary policy rule, money could be an important indicator for the central bank policy. This feature is supported by the long-lasting tradition of PBoC's quantity control.

Moreover, the posterior means of the interest smoothing coefficient is quite small while the posterior mean of nominal money growth rate is quite high. This finding echoes Li and Liu's (2017) analysis. Their empirical analysis suggests that once money is targeted by the PBoC, the absence of the nominal interest rate from the policy rule does not matter much for the policy analysis.

The counterfactual analysis indicates that PBoC is currently sufficiently sensitive to the nominal money growth. This is because an increase of quantity control does not impact output or inflation's response to the monetary policy shock much since the baseline model and the model with a higher reaction to money growth display similar responses. Output and investment will respond stronger to the monetary policy shock if the central bank reacts less to inflation or the money growth rate.

Overall, the empirical analysis bears important implications to the policymakers in China. The empirical analysis shows that the current monetary policy stance is still a quantity-based rule, since the central bank responds much more sensitively to money growth than the nominal interest rate. In addition, policymakers should be aware of the fact that the response of investment and output following a monetary policy shock will not be "humped-shaped" because the nominal interest rate will not respond much to the monetary policy shock under such a high reaction to the money growth rate. However, this paper has some certain limitations. First, a more robust estimation procedure could be useful as the posterior might have multiple modes. Second, this paper leaves out the data of real consumption and a preference shock because of the identification problem caused by the aggregate resource constraint (equation (72)). The inclusion of real consumption data might favor different parameter estimation results. Third, the paper does not cover the discussion towards the possibility of nonlinear monetary policy reaction functions. The research towards this type of monetary policy rule can be interesting and I leave that to future research.

VII. References

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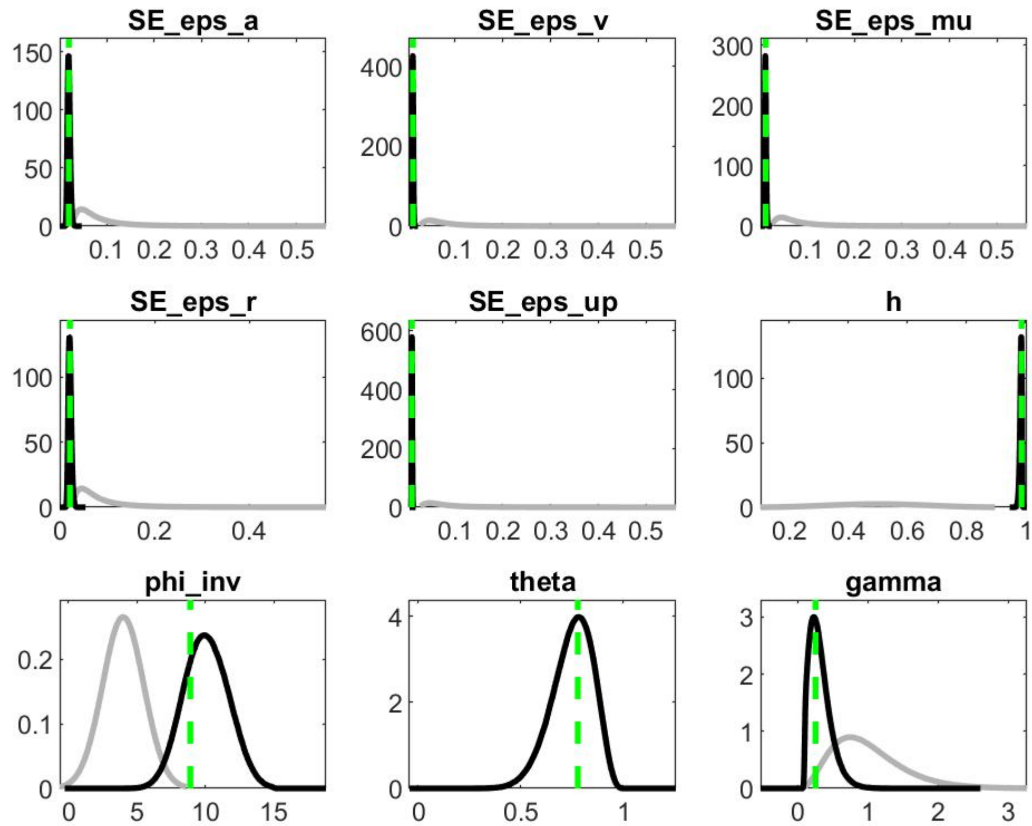
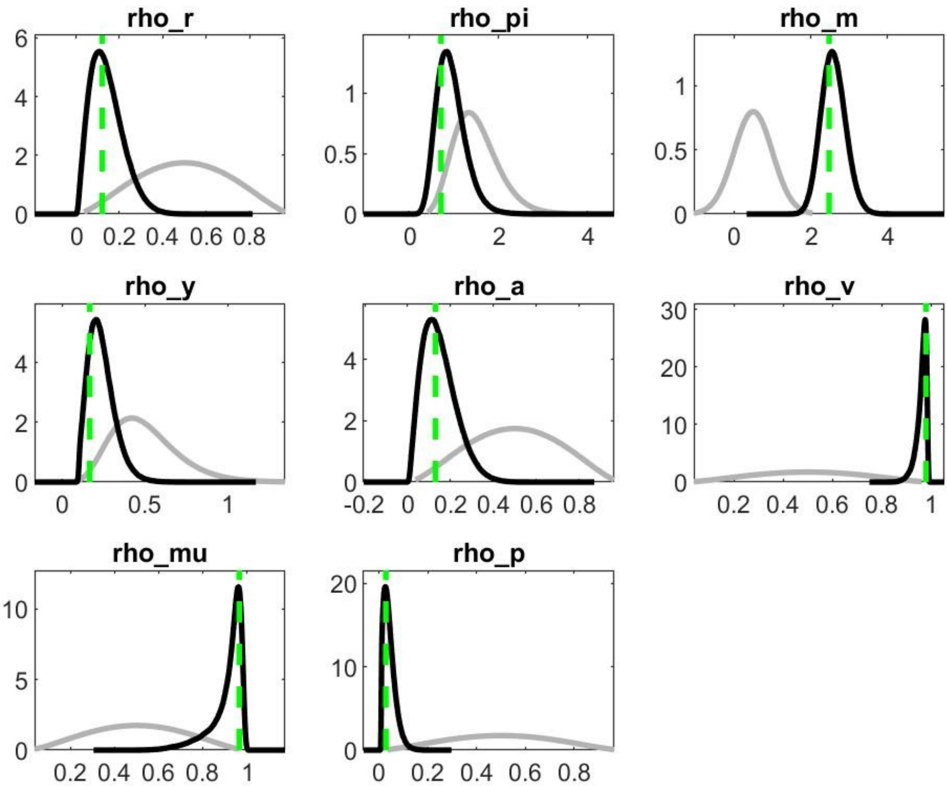
VIII. Appendix

Appendix A

This appendix presents posterior estimation results. Figure 1 displays posterior distribution of the parameters using the quarterly Chinese data from 1996Q1 to 2019Q4.

Appendix A Figure 1 Posterior Distribution of the Estimates: From 1996Q1 to 2019Q4



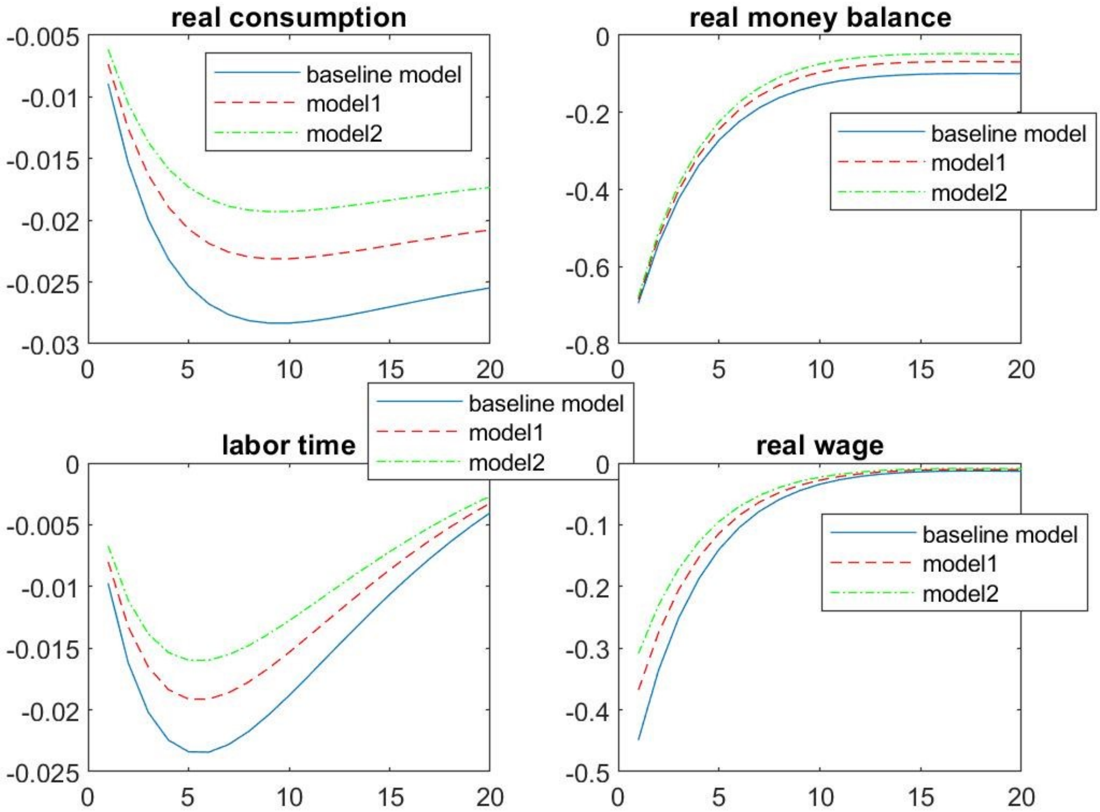


Note: The Figure 1 presents the posterior distribution of the parameters using the quarterly Chinese data set from 1996Q1 to 2019Q4. The grey line represents the prior distribution. The black line represents the posterior distribution. The green vertical line indicates the mean value of the posterior distribution of the estimates. The figure implies the informative data set.

Appendix B Counterfactual Analysis

This appendix presents the figure of the counterfactual analysis. Figure 1 displays the counterfactual analysis of the other four endogenous variables (real wage, real consumption, real money balance and labor time) following a monetary policy shock.

Appendix B Figure 1 the impulse responses following a monetary policy shock

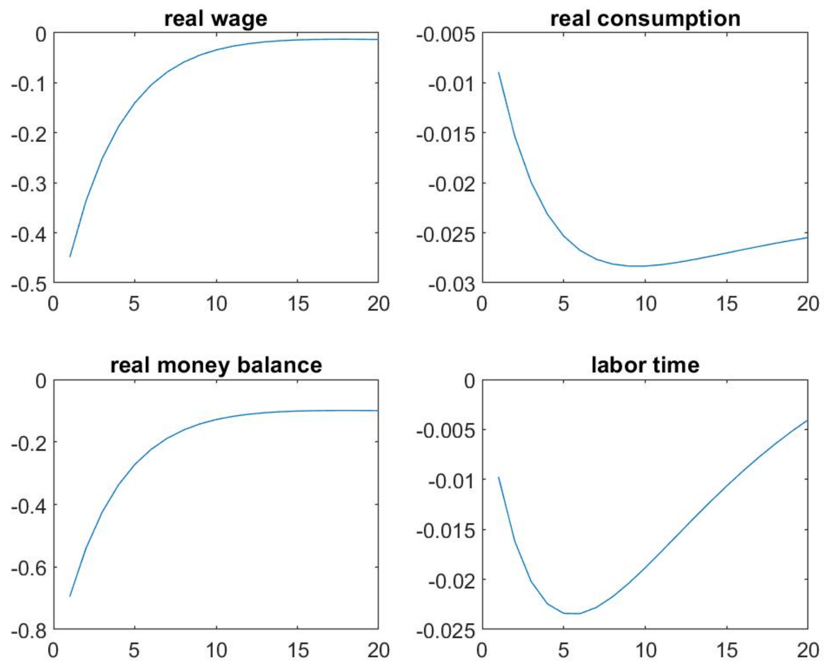


Note: Figure 1 shows the impulse responses of the other four endogenous variables (real wage, real consumption, real money balance and labor time) following a monetary policy shock in the different models. The solid blue line represents the baseline model. (ρ_π=0.93). The dashed red line represents model 1(ρ_π=1.93) and the dotted-dashed green line represents model 2. (ρ_π=3.0) Just as mentioned in the paper, the impulse responses of the other 4 endogenous variables share similar patterns towards the monetary policy shock.

Appendix C Figures of Impulse Responses

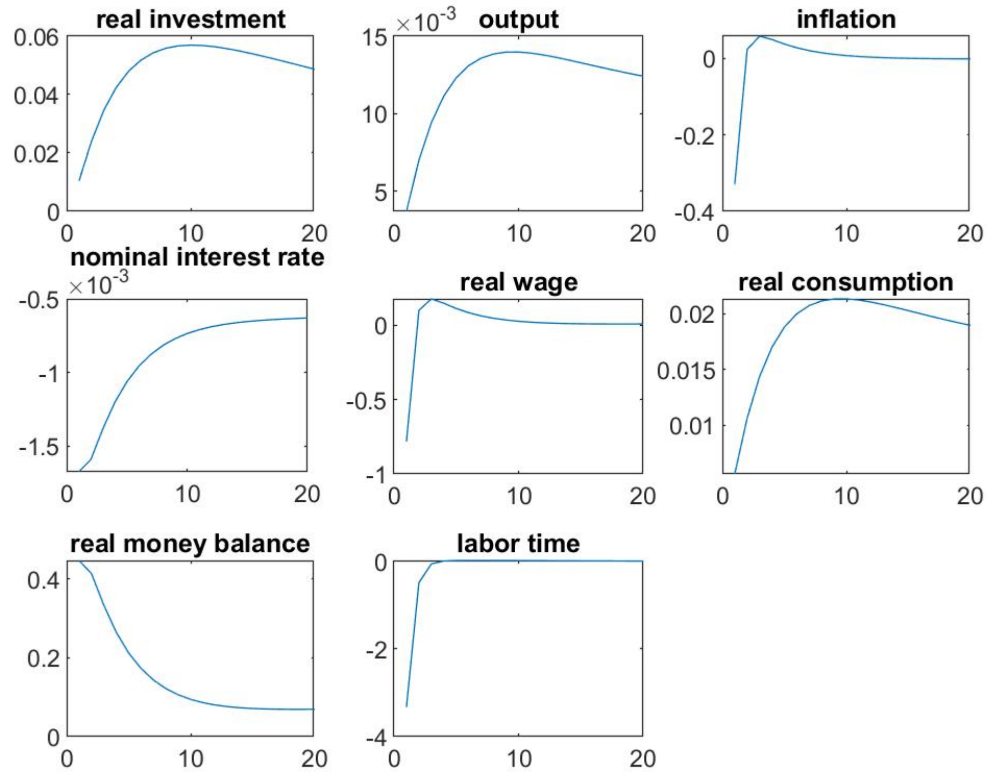
This appendix presents the figures of the impulse responses for all shocks in the model. Figure 1 shows the impulse responses of the other four endogenous variables (real wage, real consumption, real money balance and labor time) following a monetary policy shock. The rest display the impulse responses of 8 endogenous variables following the other four exogenous shocks (TFP shock, investment shock, mark-up shock and money demand shock).

Appendix C Figure 1 Impulse Responses of other Variables following a Monetary Policy Shock



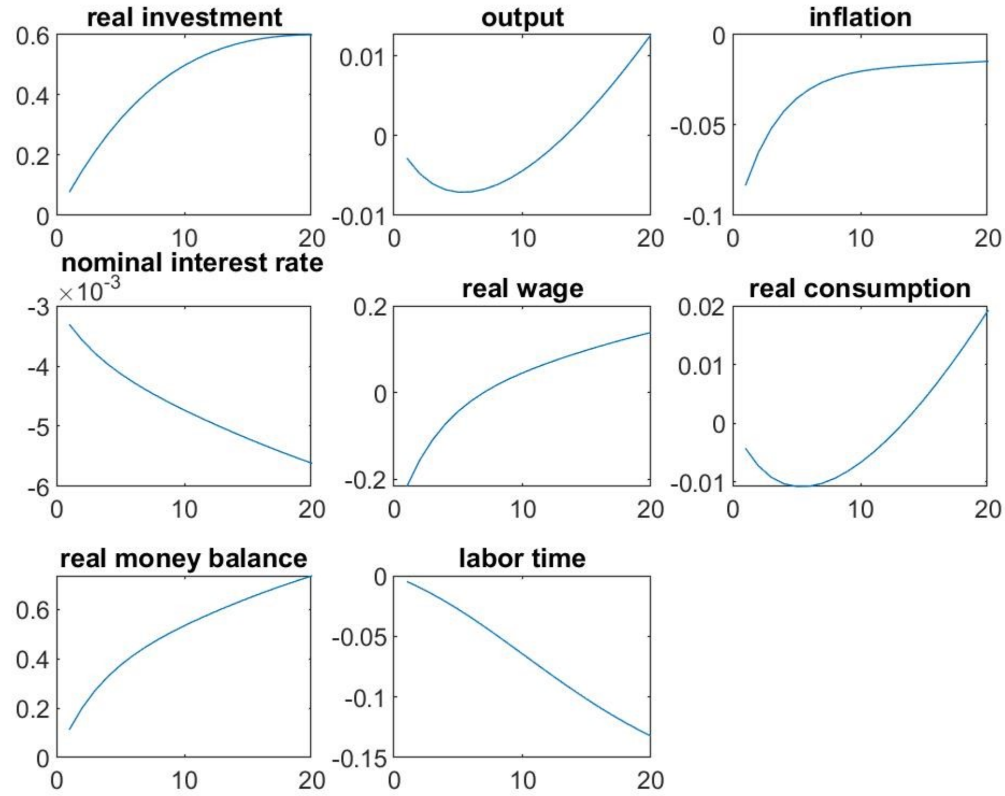
Note: Figure 1 shows the impulse responses of the other four endogenous variables (real wage, real consumption, real money balance and labor time) following a monetary policy shock in 20 periods for the baseline model. (Recall that the baseline model is the model with posterior mean estimates) The x-axis denotes the period. The y-axis denotes the movement of the variable.

Appendix C Figure 2 Impulse Responses of Variables following a Total Factor productivity Shock



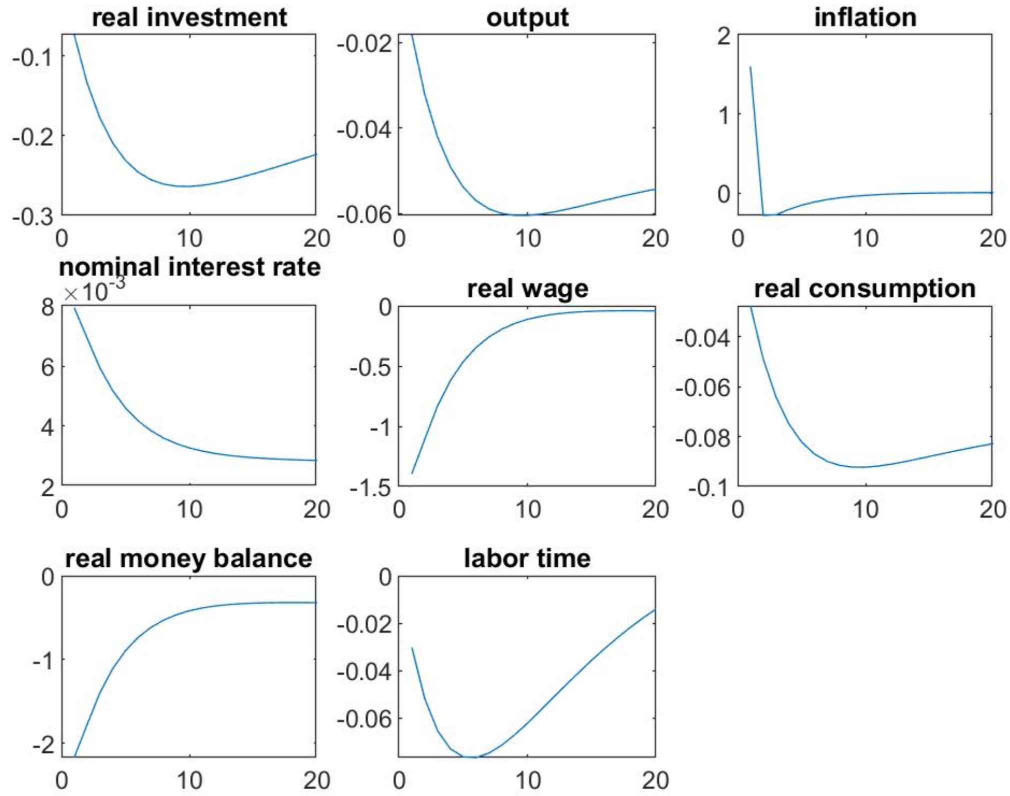
Note: Figure 2 shows the impulse responses of the endogenous variables following a shock to total factor productivity in 20 periods for the baseline model. The x-axis denotes the period. The y-axis denotes the movement of the variable. Results are at the posterior mean values.

Appendix C Figure 3 Impulse Responses of Variables following an Investment Shock



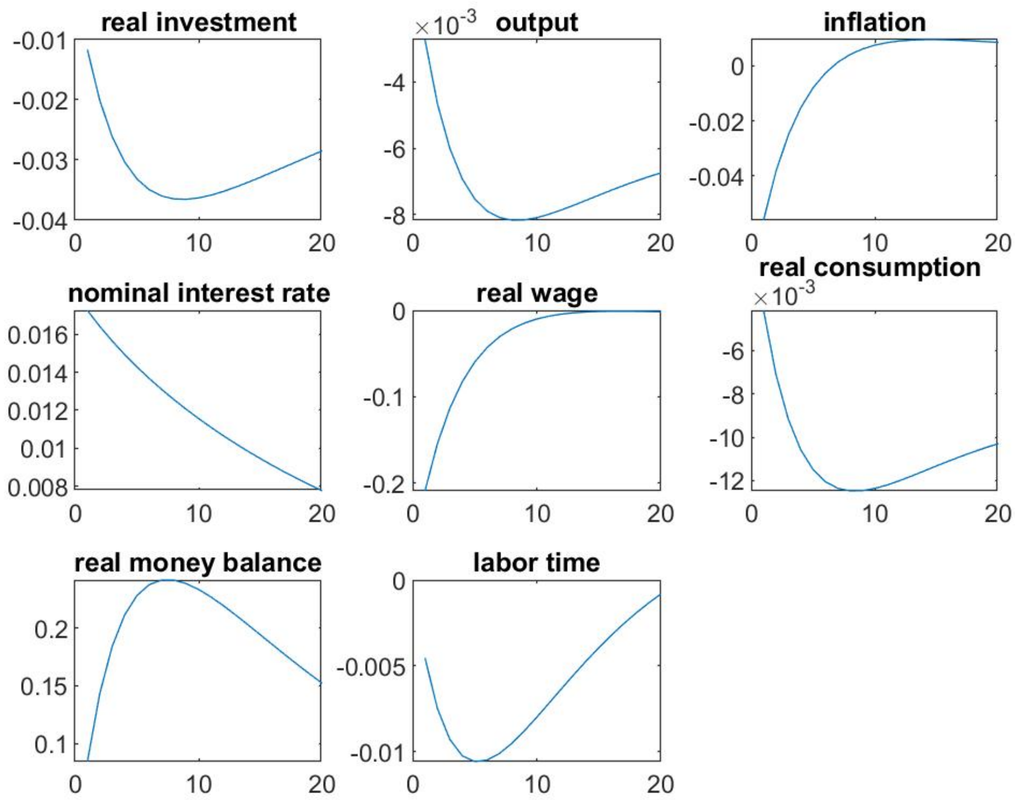
Note: Figure 3 shows the impulse responses of the endogenous variables following an investment shock in 20 periods for the baseline model. The x-axis denotes the period. The y-axis denotes the movement of the variable. Results are based on posterior mean estimates.

Appendix C Figure 4 Impulse Responses of Variables following a Mark-up Shock



Note: Figure 4 shows the impulse responses of the endogenous variables following a mark-up shock in 20 periods for the baseline model. The x-axis denotes the period. The y-axis denotes the movement of the variable. Results are based on posterior mean estimates.

Appendix C Figure 5 Impulse Responses of Variables following a Money Demand Shock



Note: Figure 5 shows the impulse responses of the endogenous variables following a money demand shock in 20 periods for the baseline model. The x-axis denotes the period. The y-axis denotes the movement of the variable. Results are based on posterior mean estimates.

Appendix D List of Variables and Parameters

This appendix summarizes the notation and code names for variables, parameters, and Lagrange multipliers in the NK-DSGE Model.

Appendix D Table 1 Endogenous Variables

Notation	Name	Code Name
K_t	Capital	k
I_t	Investment	inv
C_t	Consumption	c
w_t	Real wage	w
N_t	Hours of Labor	n
R_t	Short Term Interest Rate	R
m_t	Real Money Balance	m
q_t	Rate of Capital rent to the firms	q
π_t	Inflation	pi
mc_t	Marginal cost	mc
y_t	Output	y
Mgr_t	Money growth rate	Mgr

Appendix D Table 2 Exogenous Shocks Process

Notation	Name	Code Name	Process
A_t	Total Factor productivity shock	A	$lnA_{t+1} = \rho_a lnA_t + \epsilon_{t+1}$
up_t	Mark up shock	up	$lnup_t = \rho_{up} * lnup_{t-1} + \varepsilon_t^{up}$
V_t	money demand shock	v	$\ln V_t = \rho_v \ln V_{t-1} + \varepsilon_t^v$
μ_t	investment shock	mu	$\ln \mu_t = \rho_\mu \ln \mu_{t-1} + \varepsilon_t^\mu$
ε_{Rt}	Monetary policy shock	eps_r	$\varepsilon_{Rt} \sim iid\ N(0, \delta_a^2)$

Appendix D Table 3 Parameters

Notation	Name	code name
β	stochastic discount factor	beta
η	mark-up	eta
δ	depreciation factor	delta
ϕ	coefficient for investment adjustment	phi_inv
h	habit formation	h
α	output elasticity of capital	alpha
θ	probability of firms that can't change their price	theta
ρ_r	interest rate smoothing coefficient	rho_r
ρ_π	inflation reaction coefficient	rho_pi
ρ_y	output reaction coefficient	rho_y
ρ_m	money growth rate reaction coefficient	rho_m
κ	coefficient for Philips Curve $\kappa = \frac{(1-\theta)(1-\theta\beta)}{\theta}$	kappa
γ	coefficient for labor in the utility	gamma
ψ	labor preference	psi
ρ_a	Total Factor productivity coefficient	rho_a
ρ_v	coefficient of money demand shock	rho_v
ρ_μ	Coefficient of investment shock	rho_mu
ρ_p	Coefficient of mark-up shock	rho_p

Appendix D Table 4 Multipliers

Notation	Name	code name
λ_t	multiplier for budget constraint	lambda
χ_t	multiplier for capital accumulation	chi