The Canon Institute for Global Studies

CIGS Working Paper Series No. 22-001E

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2022.02

General Incorporated Foundation
The Canon Institute for Global Studies
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Phone: +81-3-6213-0550 https://cigs.canon/

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*We are grateful to Keiichiro Kobayashi and seminar participants at CEF 2019 and Hosei University for their helpful comments. Of course, the remaining errors are ours. This work is financially supported by the Zengin Foundation for Studies on Economics and Finance in 2018 and the Research Institute for Socionetwork Strategies of Kansai University in 2020.

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Abstract

The literature has empirically shown that the labor wedge worsens during recessions. Taking this statement into consideration, this study poses two questions: First, what is the main driving force of the labor wedge, and second, is the main driver of the labor wedge the same as that of business cycles? In this study, we employ a commonly used medium-scale dynamic stochastic general equilibrium model with nominal and real frictions to analyze which structural shocks drive the fluctuation of the labor wedge and of business cycles. The model is estimated using Japanese data. Our estimation strategy is a particularly novel approach. In standard Bayesian estimation, the prior distribution of the parameters for the standard deviations of the structural shocks is the inverse gamma distribution, which does not support zero value and assumes the existence of structural shocks. By contrast, we employ a more flexible prior distribution of the parameters for the standard deviations of structural shocks and measurement errors to allow for the non-existence of structural shocks. Under the standard prior distribution, the estimation results imply that the labor wedge is mainly driven by preference and transitory technology shocks, whereas the investment adjustment cost shock is the most important for the business cycle fluctuations. However, under our relaxed prior distribution, which allows for the non-existence of structural shocks, the estimation results imply that both the labor wedge and business cycles are mainly driven by permanent technology and investment adjustment cost shocks.

Keywords: Labor wedge; DSGE model; structural shocks; measurement error; prior distribution

JEL codes: E32; E37

1 Introduction

It is well-known and empirically confirmed that the labor wedge, defined as the gap between the marginal rate of substitution and the marginal productivity of labor, worsens during recessions, as was the cause during the 1930s Great Depression and 2007–2009 Great Recession. Indeed, researchers have deeply investigated the labor wedge as an important variable to understand business cycle fluctuations.

The main research questions of this study are as follows. (i) What is the main driving force of the labor wedge in a commonly used medium-scale dynamic stochastic general equilibrium (DSGE) economy? (ii) Is the main driver of the labor wedge the same as that of business cycles?[1] Recent literature on the medium-scale DSGE model shows that such a model can account for the salient aspects of business cycle fluctuations. In the literature, the labor wedge is often treated as an exogenous variable, and there exist few studies on the source of the fluctuations of the labor wedge as an endogenous variable.[2] If the labor wedge is an important variable to understand business cycles, then the main driving force of the labor wedge should be the same as that of business cycles. Thus, using Japanese data, we analyze which structural shocks drive the fluctuation of the labor wedge and business cycles using a commonly used medium-scale DSGE model, which has many nominal and real frictions as well as structural shocks.

One of special features of this study is the estimation strategy. In the standard Bayesian estimation of DSGE models, the prior distribution of the parameters for the standard deviations of the shocks is the inverse gamma distribution. This does not support zero value, and, therefore, the existence of structural shocks is assumed. Imposing

[1]We especially focus on output as the most important element in the business cycle.

[2]Some of these studies include Cheremukhin and Restrepo-Echavarria (2014) and Chahrour, Chugh, Shapiro, and Lariau (2016), who investigate the source of the labor wedge in a DSGE model with search and matching in the labor market. Our model, by contrast, is a commonly used medium-scale DSGE model à la Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007).

a non-existent structural shock can have a serious consequence on inference, in that the estimated driving source of the business cycles and the labor wedge might be unreliable. To overcome this limitation, we employ a more flexible prior distribution of the parameters for the standard deviations of shocks and measurement errors to allow for the non-existence of shocks and measurement errors. Following Ferroni, Grassi, and Leon-Ledesma (2015, 2019), we employ a normal distribution.

Under the standard prior distribution of the parameters for the standard deviations of structural shocks, our estimation results imply that the labor wedge is mainly driven by preference and transitory technology shocks, whereas the investment adjustment cost shock is the most important for business cycle fluctuations. Meanwhile, under our relaxed prior distribution, which allows for the non-existence of shocks, the estimation results show that both the labor wedge and the business cycles are mainly driven by permanent technology and investment adjustment cost shocks.

As a result, if we employ an inverse gamma distribution—which is standard in the literature, but imposes the existence of structural shocks—then the investigation of the source of the labor wedge fluctuation might not be promising to understand business cycles. This is because the source of the labor wedge is different from that of business cycles. However, by using our more relaxed prior—the normal distribution—to allow for the non-existence of structural shocks, the investigation of the labor wedge would be more promising for understanding business cycles, that is, both the labor wedge and business cycles are driven by the same structural shocks.

Related literature: Chari, Kehoe, and McGrattan (2002, 2007); Kobayashi and Inaba (2006); Shimer (2009); Ohanian (2010); and Otsu (2011) are among some of the researchers who emphasize the importance of the labor wedge in business cycles. Specifically, Chari, Kehoe, and McGrattan's (2002, 2007) business cycle accounting method shows that the labor wedge is important for the Great Depression and the 1982 Reagan recession in the United States.[3] Kobayashi and Inaba (2006) find that the labor wedge is helpful to account for Japan's lost decade during the 1990s and the 1920s recession. Shimer (2009) and Ohanian (2010) find that the labor wedge worsens during recession. In particular, Ohanian (2010) focuses on the Great Recession of the United States. Otsu (2011) investigates the dynamics of the labor wedge of Japanese economy from 1980 to 2007.

In their investigation of the main driving force of labor wedge fluctuations, Hall (2009); Shimer (2009); Pescatori and Tasci (2011); Cheremukhin and Restrepo-Echavarria (2014); and Chahrour, Chugh, Shapiro, and Lariau (2016) emphasize the role of matching frictions in the labor market. Duras (2017) finds that matching frictions in the goods market, in addition to the labor market, help to account for fluctuations of the labor wedge. Karabarbounis (2014a) empirically finds that fluctuations of the labor wedge mainly reflect fluctuations of the gap between the real wage and the marginal rate of substitution. He emphasizes the importance of modeling the household side of the labor market. Karabarbounis (2014b) proposes that home production in the utility function accounts for the international findings of the labor wedge. Zhang (2018) finds that the collateral constraints of entrepreneurs is helpful to account for the variation in the labor wedge during a credit crunch. Gallen (2018) investigates the source of the labor wedge by considering both self-employed and employed workers.

Our medium-scale DSGE model does not include matching frictions, home production, and collateral constraints, while these frictions are investigated by existing works on the labor wedge. Instead, our model includes habit persistence and sticky wage, thus generating a gap between the marginal rate of substitution and the real wage. Note, however, that our set-up does not contradict the Karabarbounis's (2014a) empirical finding that the household side is important for the labor wedge.

[3] On the other hand, Cho and Doblas-Madrid (2013) and Gunji (2013) claim that the role of the labor wedge is limited in certain situations.

Numerous studies have thus far investigated the sources of business cycle fluctuations. In particular, King and Rebelo (1999) and Hayashi and Prescott (2002) emphasize the conventional importance of technology shock. Even recent works by Kaihatsu and Kurozumi (2014a, 2014b) find that technology shocks are the main driving force of business cycles both in the United States as well as Japan. Meanwhile, Justiniano, Primiceri, and Tambalotti (2010, 2011) and Hirose and Kurozumi (2012) emphasize the importance of the investment adjustment cost shock in business cycles. In our estimate, we find the (permanent) technology and investment adjustment cost shocks as important for business cycles, consistent with prior findings.

Our estimation method is based on the work of Ferroni, Grassi, and Leon-Ledesma (2015, 2019), who propose an estimation method allowing for the non-existence of structural shocks. They find that government spending, price markup, and wage markup shocks in the United States do not generate significant dynamics using the model of Smets and Wouters (2007).

The remainder of the paper is organized as follows. Section 2 introduces the model. Section 3 shows the data and the estimation strategy of the model. Section 4 explains the main results. Finally, Section 5 presents the conclusion.

2 The Model

2.1 The Model

Our model is a variant of the medium-scale DSGE model à la Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007). Here, we introduce habit persistence, adjustment costs of investment, and variable capital utilization, along with Calvo-type nominal price and wage rigidities with partial inflation indexations.

The central bank follows a Taylor-type nominal interest rate rule. There are many structural shocks: permanent and transitory technology, preference (a shock to the discount factor), labor supply (a shock to the weight of disutility from labor supply), investment adjustment cost, price markup, wage markup, government purchases, and monetary policy shocks.[4][5]

Final-good firms: The final-good firms are perfectly competitive, and they produce a homogeneous final-good Y_t using an intermediate-good $Y_t(f)$. The production function is given by

$$Y_t = \left[\int_0^1 Y_t(f)^{\frac{1}{1+\lambda_t^p}} df \right]^{1+\lambda_t^p}, \tag{1}$$

where λ_t^p is a time-varying parameter for elasticity of substitution among intermediate-good $\theta_t^p > 1$, which is defined by $\lambda_t^p = 1/(\theta_t^p - 1) > 0$.

Profit maximization implies the demand function of intermediate-good $Y_t(f)$:

$$Y_t(f) = \left[\frac{P_t(f)}{P_t} \right]^{-\frac{1+\lambda_t^p}{\lambda_t^p}} Y_t, \tag{2}$$

where P_t is the price of final-good Y_t and $P_t(f)$ is the price of intermediate-good $Y_t(f)$.

Intermediate-good firms: The intermediate-good firms are monopolistically competitive. The intermediate-good firm indexed by $f \in [0, 1]$ produces differentiated intermediate-good $Y_t(f)$ using labor input $\ell_t(f)$ and capital service $K_t^S(f)$. Then, the production function is given by

[4]In our model, the investment-specific technology shock is eliminated from the model of Hirose and Kurozumi (2012), and the transitory technology shock is introduced.

[5]As explained in Section 5, we redefine the wage shock as the linear combination of the labor supply and wage markup shocks because the labor supply and wage markup shocks cannot be identified in this model.

$$Y_t(f) = \exp(z_t^{zt})[K_t^S(f)]^{\alpha}[Z_t^P \ell_t(f)]^{1-\alpha} - \Phi Z_t^P, \tag{3}$$

where $\alpha \in (0,1)$ is the cost share of capital; Φ is the fixed cost of production; z_t^{zt} is the transitory technology shock; and Z_t^P is the permanent technology that evolves according to

$$\log Z_t^P = z^* + \log Z_{t-1}^P + z_t^{zp}, \tag{4}$$

where z^* is the steady-state growth rate of Z_t^P and z_t^{zp} is the permanent technology shock.

Both z_t^{zt} and z_t^{zp} follow the AR(1) process. The last term in the production function, ΦZ_t^P, is multiplied by Z_t^P to guarantee the existence of the balanced growth path. Then, the cost minimization of intermediate-good firms implies

$$R_t^k = mc_t \, \alpha \exp(z_t^{zt}) \left[\frac{Z_t^P \ell_t(f)}{K_t^S(f)} \right]^{1-\alpha}, \tag{5}$$

$$W_t = mc_t \, (1-\alpha) \exp(z_t^{zt}) Z_t^P \left[\frac{Z_t^P \ell_t(f)}{K_t^S(f)} \right]^{-\alpha}, \tag{6}$$

where mc_t is the real marginal cost, R_t^k is the rental rate of capital, and W_t is the real wage rate.

Next, we introduce the Calvo-type sticky prices. In every period, a fraction $\xi_p \in [0,1]$ of intermediate-good firms can reoptimize their prices. The other firms index their prices to the weighted average of past inflation (π_{t-1}) and the steady-state inflation (π^*): $\pi_{t-1}^{\gamma_p}(\pi^*)^{1-\gamma_p}$, where $\gamma_p \in [0,1]$ is the relative weight of the past inflation. The objective function of the intermediate-good firms that reoptimize their prices at period t is

$$E_t \sum_{j=0}^{\infty} \left(\beta \xi_p\right)^j \left(\frac{\Lambda_{t+j}}{\Lambda_t}\right) \left[\frac{P_t(f)}{P_{t+j}} \prod_{k=1}^{j} \left(\pi_{t+k-1}^{\gamma_p}(\pi^*)^{1-\gamma_p}\right) - mc_{t+j} \right] Y_{t+j}(j), \tag{7}$$

where Λ_t is the marginal utility of consumption of households and $\beta^j \frac{\Lambda_{t+j}}{\Lambda_t}$ is the stochastic discount factor. The demand function for $Y_{t+j}(f)$ is given by

$$Y_{t+j}(f) = \left[\frac{P_t(f)}{P_{t+j}} \prod_{k=1}^{j} \left(\pi_{t+k-1}^{\gamma_p} (\pi^*)^{1-\gamma_p} \right) \right]^{-\frac{1+\lambda_{t+j}^p}{\lambda_{t+j}^p}} Y_{t+j}. \tag{8}$$

The reoptimized price P_t^o is the same for all intermediate-good firms. The first-order condition for reoptimized price P_t^o is

$$1 = \frac{E_t \sum_{j=0}^{\infty} (\beta \xi_p)^j \frac{(1+\lambda_{t+j}^p) mc_{t+j} \Lambda_{t+j} Y_{t+j}}{\lambda_{t+j}^p} \left[\frac{P_t^0}{P_t} \prod_{k=1}^{j} \left(\frac{\pi_{t+k-1}}{\pi^*} \right)^{\gamma_p} \frac{\pi^*}{\pi_{t+k}} \right]^{-\frac{1+\lambda_{t+j}^p}{\lambda_{t+j}^p}}}{E_t \sum_{j=0}^{\infty} (\beta \xi_p)^j \frac{\Lambda_{t+j} Y_{t+j}}{\lambda_{t+j}^p} \left[\frac{P_t^0}{P_t} \prod_{k=1}^{j} \left(\frac{\pi_{t+k-1}}{\pi^*} \right)^{\gamma_p} \frac{\pi^*}{\pi_{t+k}} \right]^{-\frac{1}{\lambda_{t+j}^p}}}. \tag{9}$$

Households: The household indexed by $h \in [0, 1]$ consumes $C_t(h)$, invests $I_t(h)$, holds safe asset $B_t(h)$ and capital stock $K_t(h)$, and supplies differentiated labor service $\ell_t(h)$.

The utility function is then given by

$$E_0 \sum_{t=0}^{\infty} \beta^t \exp(z_t^b) \left[\frac{[C_t(h) - \theta C_{t-1}(h)]^{1-\sigma}}{1-\sigma} - \frac{Z_t^{1-\sigma} \exp(z_t^\ell) \ell_t(h)^{1+\chi}}{1+\chi} \right], \tag{10}$$

where $\beta \in (0, 1)$ denotes the discount factor; $\sigma > 0$ is the elasticity of intertemporal substitution; $\theta \in (0, 1)$ is the degree of habit persistence; $\chi > 0$ denotes the inverse of the labor supply elasticity; and z_t^b and z_t^ℓ are the structural shocks to discount factor (preference shock) and labor supply (labor supply shock), respectively. The technology term $Z_t^{1-\sigma}$ appears in the disutility of labor supply, as employed by Erceg, Guerrieri, and Gust (2006), to ensure the existence of a balanced growth path.

The budget constraint of the household is

$$C_t(h) + I_t(h) + \frac{B_t(h)}{P_t} = W_t(h)\ell_t(h) + R_t^k u_t(h) K_{t-1}(h) + \frac{R_{t-1}^n B_{t-1}(h)}{P_t} + T_t(h), \tag{11}$$

where P_t denotes the price level, $W_t(h)$ is the real wage rate, R_t^n is the nominal gross interest rate, R_t^k denotes the real rental rate of capital, $u_t(h)$ is the capital utilization rate, $K_{t-1}(h)$ is capital stock at the end of period $t-1$, and $T_t(h)$ denotes a transfer from the government and firms.

The capital stock evolves as follows:

$$K_t(h) = [1 - \delta(u_t(h))]K_{t-1}(h) + \left[1 - S\left(\frac{I_t(h)}{I_{t-1}(h)} \frac{\exp(z_t^i)}{z^*}\right)\right] I_t(h), \tag{12}$$

where z_t^i is the investment adjustment cost shock. In this specification, the cost of high capital utilization is a high depreciation rate of capital, as in Greenwood, Hercowitz, and Huffman (1988), that is, $\delta'(\cdot) > 0$, $\delta''(\cdot) > 0$, and $\delta'(u^*)/\delta''(u^*) = \mu$, where u^* is the steady-state capital utilization rate. The functional form of the adjustment costs of investment is given by

$$S(x) = \frac{1}{\zeta}\left(x - 1\right)^2, \tag{13}$$

where $1/\zeta > 0$ is the degree of adjustment cost of investment.

Because of the existence of complete insurance markets, the decisions of $C_t(h)$, $B_t(h)$, $u_t(h)$, $K_t(h)$, and $I_t(h)$ are the same for all households; then, the first-order conditions are given by

$$\Lambda_t = \exp(z_t^b)\,[C_t - \theta C_{t-1}]^{-\sigma} - \beta\theta E_t\left(\exp(z_{t+1}^b)\,[C_{t+1} - \theta C_t]\right), \tag{14}$$

$$\Lambda_t = \beta E_t\left[\Lambda_{t+1} \cdot \frac{R_t^n}{\pi_{t+1}}\right], \tag{15}$$

$$R_t^k = Q_t\,\delta'(u_t), \tag{16}$$

$$\begin{aligned} 1 = Q_t&\left[1 - S\left(\frac{I_t}{I_{t-1}} \frac{\exp(z_t^i)}{z^*}\right) - S'\left(\frac{I_t}{I_{t-1}} \frac{\exp(z_t^i)}{z^*}\right) \frac{I_t}{I_{t-1}} \frac{\exp(z_t^i)}{z^*}\right] \\ &+ \beta E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t} Q_{t+1}\, S'\left(\frac{I_{t+1}}{I_t} \frac{\exp(z_{t+1}^i)}{z^*}\right)\left(\frac{I_{t+1}}{I_t}\right)^2 \frac{\exp(z_{t+1}^i)}{z^*}\right], \end{aligned} \tag{17}$$

$$Q_t = \beta E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}\left\{R_{t+1}^k u_{t+1} + Q_{t+1}\left(1 - \delta(u_{t+1})\right)\right\}\right], \tag{18}$$

where Λ_t is the marginal utility of consumption, $\pi_{t+1} = P_{t+1}/P_t$ is the gross price inflation rate, and Q_t is the real price of capital, which is defined as the ratio of the Lagrange multiplier of the evolution of capital to the marginal utility Λ_t.

Wage setting: The household supplies its differentiated labor service $\ell_t(h)$ to the intermediate-good firms. Then, the labor market is monopolistically competitive. The intermediate-good firm f aggregates its labor inputs $\ell_t(f,h)$ according to the following technology:

$$\ell_t(f) = \left[\int_0^1 \ell_t(f,h)^{\frac{1}{1+\lambda_t^w}} dh\right]^{1+\lambda_t^w}, \tag{19}$$

where λ_t^w is a time-varying parameter for the elasticity of substitution between labor supplies $\theta_t^w > 1$, which is defined by $\lambda_t^w = 1/(\theta_t^w - 1) > 0$. The cost minimization of the intermediate-good firm and the aggregation over intermediate-good firms imply the following demand function of labor $\ell_t(h)$:

$$\ell_t(h) = \left[\frac{W_t(h)}{W_t}\right]^{-\frac{1+\lambda_t^w}{\lambda_t^w}} \ell_t. \tag{20}$$

We now introduce the Calvo-type sticky wages as in Erceg, Henderson, and Levin (2000). In every period, a fraction $\xi_w \in [0,1]$ of households can reoptimize their wages. The other households index their wages to both the gross steady-state balanced growth rate (z^*) and the weighted average of past inflation and the steady-state inflation, $\pi_{t-1}^{\gamma_w}(\pi^*)^{1-\gamma_w}$, where $\gamma_w \in [0,1]$ is the relative weight of the past inflation. The objective function is

$$E_t \sum_{j=0}^{\infty} (\beta\xi_w)^j \left[\Lambda_{t+j}\ell_{t+j}(h)\left(\frac{P_t W_t(h)}{P_{t+j}}\right)\prod_{k=1}^{j}\left(z^*\pi_{t+k-1}^{\gamma_w}(\pi^*)^{1-\gamma_w}\right) - \frac{Z_{t+j}^{1-\sigma}\exp(z_{t+j}^{\ell})\ell_{t+j}(h)^{1+\chi}}{1+\chi}\right], \tag{21}$$

and the labor demand function is given by

$$\ell_{t+j}(h) = \left[\frac{P_t W_t(h)}{P_{t+j}W_{t+j}}\prod_{k=1}^{j}\left(z^*\pi_{t+k-1}^{\gamma_w}(\pi^*)^{1-\gamma_w}\right)\right]^{-\frac{1+\lambda_t^w}{\lambda_t^w}} \ell_{t+j}. \tag{22}$$

The reoptimized wage W_t^o is the same for all households. The first-order condition for reoptimized wage W_t^o is

$$1 = \frac{E_t \sum_{j=0}^{\infty} (\beta\xi_w)^j \frac{(1+\lambda_{t+j}^w)\exp(z_{t+j}^b)\exp(z_{t+j}^\ell) Z_{t+j}^{1-\sigma}}{\lambda_{t+j}^w} \left(\ell_{t+j} \left[\frac{W_t^o (z^*)^j}{W_{t+j}} \prod_{k=1}^{j} \left(\frac{\pi_{t+k-1}}{\pi^*} \right)^{\gamma_w} \frac{\pi^*}{\pi_{t+k}} \right]^{-\frac{1+\lambda_{t+j}^w}{\lambda_{t+j}^w}} \right)^{1+\chi}}{E_t \sum_{j=0}^{\infty} (\beta\xi_w)^j \frac{\Lambda_{t+j} W_{t+j}}{\lambda_{t+j}^w} \ell_{t+j} \left[\frac{W_t^o (z^*)^j}{W_t} \prod_{k=1}^{j} \left(\frac{\pi_{t+k-1}}{\pi^*} \right)^{\gamma_w} \frac{\pi^*}{\pi_{t+k}} \right]^{-\frac{1}{\lambda_{t+j}^w}}}. \tag{23}$$

Central bank: The central bank follows a Taylor-type nominal interest rate rule. That is,

$$\log R_t^n = \phi_r \log R_{t-1}^n + (1-\phi_r) \left[\log \bar{R}^n + \phi_\pi \frac{1}{4} \sum_{j=0}^{3} \log \frac{\pi_{t-j}}{\pi^*} + \phi_y \log \frac{Y_t}{Y_t^P} \right] + z_t^r, \tag{24}$$

where π^* is the steady-state inflation rate, Y_t^P is the potential output, and z_t^r is the monetary policy shock. Parameter $\phi_r \in [0, 1)$ represents the degree of interest rate smoothing, and $\phi_\pi > 1$ and $\phi_y \geq 0$ are the monetary policy responses to inflation and output, respectively. Then, the potential output Y_t^P is defined by

$$Y_t^P = [u^* k^* Z_{t-1}^P]^\alpha [Z_t^P \ell^*]^{1-\alpha} - \Phi Z_t^P, \tag{25}$$

where u^* is the steady-state of capital utilization, k^* is the steady-state detrended capital stock (K_t/Z_t^P), and ℓ^* is the steady-state hours worked. This specification of the potential output is similar to the estimates of Hara et al. (2006). In this specification, only the permanent (technology) shock is considered as a driving force of potential output. This setup is similar to the estimates of Fueki et al. (2016).

Aggregations and market clearing conditions: Because the decisions on $u_t(h)$, $I_t(h)$, and $K_t(h)$ are the same for all households, the evolution of the capital stock (12) is given by

$$K_t = [1 - \delta(u_t)] K_{t-1} + \left[1 - S \left(\frac{I_t}{I_{t-1}} \frac{\exp(z_t^i)}{z^*} \right) \right] I_t. \tag{26}$$

and the capital market-clearing conditions are given by

$$u_t K_{t-1} = \int_0^1 K_t^S(f) df. \tag{27}$$

Combining the cost-minimization conditions of intermediate-good firms (5) and (6) and aggregation over intermediate-good firms yields

$$\frac{1-\alpha}{\alpha} = \frac{W_t \ell_t}{R_t^k u_t K_{t-1}}. \tag{28}$$

The real marginal cost is then given by

$$mc_t = \frac{1}{\exp(z_t^{zt})} \left(\frac{W_t}{(1-\alpha) Z_t^P} \right)^{1-\alpha} \left(\frac{R_t^k}{\alpha} \right)^{\alpha}. \tag{29}$$

Aggregating the production function (3) over intermediate-good firms yields

$$Y_t s_t = \exp(z_t^{zt}) \left[u_t K_{t-1} \right]^{\alpha} \left[Z_t^P \ell_t \right]^{1-\alpha} - \Phi Z_t^P, \tag{30}$$

where $s_t = \int_0^1 \left[P_t(f)/P_t \right]^{-(1+\lambda_t^p)/\lambda_t^p} df$ is the price dispersion of the intermediate-good price. This price dispersion can be ignored in the linearized system around the steady state, where the steady-state value is one.

Finally, the resource constraint is

$$C_t + I_t + g^* Z_t^P \exp(z_t^g) = Y_t, \tag{31}$$

where g^* is the steady-state ratio of government purchases to output and z_t^g is a government shock.

Labor wedge: Following Shimer (2009), we define the labor wedge as follows:

$$(\text{Labor wedge}) = \frac{1}{1-\alpha} \left[\frac{C_t}{Y_t} \right] \ell_t^{\frac{1+\chi}{\chi}}. \tag{32}$$

This specification is based on the period utility $\log(C_t(h)) - \frac{\ell_t(h)^{1+\chi}}{1+\chi}$ and the Cobb–Douglas production function. This labor wedge is not the gap between the marginal rate of substitution and the marginal product of labor of our model. Because this labor wedge is consistent with that of Shimer (2009), it is possible to investigate the source of the labor wedge fluctuation that is empirically observed.

Log-linearized equilibrium conditions and exogenous structural shocks The endogenous variables, except for marginal utility Λ_t, are detrended by the technology level Z_t as $x_t = X_t/Z_t$. The marginal utility Λ_t is detrended as $\lambda_t = \Lambda_t/Z_t^{-\sigma}$. The equilibrium conditions are log-linearized around a steady state. The log-linearized equilibrium system is described in Appendix.

There are eight (independent) exogenous shocks in the model. They follow the AR(1) process:

$$\text{permanent technology:} \quad z_t^{zp} = \rho_{zp} z_{t-1}^{zp} + \sigma_{zp}\varepsilon_t^{zp} \tag{33}$$

$$\text{transitory technology:} \quad z_t^{zt} = \rho_{zt} z_{t-1}^{zt} + \sigma_{zt}\varepsilon_t^{zt} \tag{34}$$

$$\text{preference:} \quad z_t^{b} = \rho_{b} z_{t-1}^{b} + \sigma_{b}\varepsilon_t^{b} \tag{35}$$

$$\text{government purchases:} \quad z_t^{g} = \rho_{g} z_{t-1}^{g} + \sigma_{g}\varepsilon_t^{g} \tag{36}$$

$$\text{investment adjustment cost:} \quad z_t^{i} = \rho_{i} z_{t-1}^{i} + \sigma_{i}\varepsilon_t^{i} \tag{37}$$

$$\text{price markup:} \quad z_t^{p} = \rho_{p} z_{t-1}^{p} + \sigma_{p}\varepsilon_t^{p} \tag{38}$$

$$\text{wage:} \quad z_t^{w} = \rho_{w} z_{t-1}^{w} + \sigma_{w}\varepsilon_t^{w} \tag{39}$$

$$\text{monetary policy:} \quad z_t^{r} = \rho_{r} z_{t-1}^{r} + \sigma_{r}\varepsilon_t^{r}. \tag{40}$$

where $\sigma_x \varepsilon_t^x$ is a structural shock to z_t^x for $x = zp$, zt, b, g, i, p, w, and r;and ε_t^x is independently and identically distributed (i.i.d.), with a mean of zero and standard deviation of one.[6]

[6]The price markup shock z_t^p is defined by

$$z_t^p = \frac{(1-\xi_p)(1-\beta\xi_p(z^*)^{1-\sigma})}{\xi_p}\tilde{\lambda}_t^p.$$

The wage shock z_t^w is defined by

$$z_t^w = \frac{1-\xi_w}{\xi_w} \times \frac{(1-\beta\xi_w(z^*)^{1-\sigma})\lambda^w}{\lambda^w + \xi(1+\lambda^w)}\left(\tilde{\lambda}_t^w + z_t^\ell\right).$$

3 Data and Estimation Strategy

We use seven quarterly Japanese series as observable variables: real GDP per capita Y_t, real consumption per capita C_t, real investment per capita I_t, real wage W_t, hours worked ℓ_t, consumer price index P_t, and overnight call rate R_t^n. As in Hirose and Kurozumi (2012), the sample period is from 1981:Q1 to 1998:Q4. The model does not take into account the non-linearity of monetary policy. The end of the sample period is then set to exclude the zero nominal interest policy of the Bank of Japan.

Except for I_t and ℓ_t, the other series follow Hirose and Kurozumi (2012). Following Kobayashi and Inaba (2006), I_t is defined as per capita gross fixed capital formation by the private sector, which comprises private residential investment, private non-residential investment, and change in private inventories; it is taken from the Economic and Social Research Institute, Cabinet Office of Japan, *the System of National Accounts*. Following Hayashi and Prescott (2002) and Kobayashi and Inaba (2006), ℓ_t is constructed by

$$\ell_t = \frac{\text{Averaged hours worked per employed person} \times \text{Employed person}}{\text{Labor force}}.$$

The data for the average hours worked per employed person are obtained from the Ministry of Health, Labour and Welfare, *Monthly Labor Survey*. The employed persons and labor force data are obtained from the Ministry of Internal Affairs and Communications, *Labour Force Survey*. Because our study focuses on the labor wedge, this definition of ℓ_t is commonly used for calculating the labor wedge (see Shimer, 2009).[7]

In the log-linearized equilibrium system, the wage markup shock λ_t^w and the labor supply shocks z_t^ℓ cannot be identified. Then, the wage shock z_t^w is defined as the linear combination of the (log-linearized) wage markup shock $\tilde{\lambda}_t^w$, where λ^w is the steady-state value of λ_t^w and labor supply shock z_t^ℓ. See Appendix for details.

[7]Considering housing and durable consumer goods is important in macroeconomics, In this paper, following Hayashi and Prescott (2002) and Kobayashi and Inaba (2006), we employ the current data construction method, but do not focus on these elements.

The observation equation is

$$\begin{bmatrix} 100\Delta\log Y_t \\ 100\Delta\log C_t \\ 100\Delta\log I_t \\ 100\Delta\log W_t \\ 100\log \ell_t \\ 100\Delta\log P_t \\ 100\Delta\log R_t^n \end{bmatrix} = \begin{bmatrix} z^* \\ z^* \\ z^* \\ z^* \\ \ell^* \\ \pi^* \\ r^* + \pi^* \end{bmatrix} + \begin{bmatrix} \tilde{y}_t - \tilde{y}_{t-1} + z_t^{zp} \\ \tilde{c}_t - \tilde{c}_{t-1} + z_t^{zp} \\ \tilde{i}_t - \tilde{i}_{t-1} + z_t^{zp} \\ \tilde{w}_t - \tilde{w}_{t-1} + z_t^{zp} \\ \tilde{\ell}_t \\ \tilde{\pi}_t \\ \tilde{R}_t^n \end{bmatrix} + \begin{bmatrix} \sigma_y^{me} me_t^y \\ \sigma_c^{me} me_t^c \\ \sigma_i^{me} me_t^i \\ \sigma_w^{me} me_t^w \\ \sigma_\ell^{me} me_t^\ell \\ \sigma_\pi^{me} me_t^\pi \\ \sigma_{rn}^{me} me_t^{rn} \end{bmatrix} \tag{41}$$

where $\sigma_j^{me} me_t^j$ is the measurement error of variable $j = y, c, i, w, \ell, \pi$, and rn. me_t^j is an i.i.d. shock in which the mean is zero and the standard deviation is one. The measurement errors are necessary to allow for the non-existence of structural shocks in the estimation. Generally, the number of exogenous shocks must be equal to or greater than the number of observations. Otherwise, it becomes a case of stochastic singularity, and the model cannot be estimated. There are seven observations and eight (independent) structural shocks in this model. To allow for the non-existence of two or more structural shocks, we need additional exogenous shocks: measurement errors to avoid stochastic singularity.[8]

The growth rate of the labor wedge is calculated by the following observations:

$$100\Delta\log \text{Labor Wedge}_t = 100\Delta\log C_t - 100\Delta\log Y_t + (1+\chi)\Delta\log \ell_t. \tag{42}$$

Most of the model parameters are estimated, while the following aspects are fixed: The steady-state depreciation rate of capital stock is set to $\delta(u^*) = 0.06/4$; the cost share of capital in the production function is set to $\alpha = 0.37$; and the steady-state wage markup is set to $\lambda^w = 0.20$. These three parameter values are taken from Sugo and Ueda (2008). Finally, the steady-state ratio of government purchases to output is set to $g^* = 0.30$, which is at the data mean.

[8] In Section 4, the case of no measurement errors is also considered to interpret the main results.

Bayesian estimation is employed by using Dynare following Ferroni, Grassi, and Leon-Ledesma (2015). The prior distributions of the parameters are presented in Tables 1 and 2. For the structural parameters σ, θ, χ, $1/\zeta$, μ, Φ, γ_w, ξ_p, γ_p, ξ_p, ϕ_r, ϕ_π, and ϕ_y, the prior distributions are the same as those in Hirose and Kurozumi (2012). For the steady-state price markup λ^p, the mean and standard deviation of the prior distribution are taken from Justiniano, Primiceri, and Tambalotti (2011); however, but the gamma distribution is employed to fit the theory. For the steady-state growth rate z^*, labor supply ℓ^*, inflation π^*, and real interest r^*, the means of prior distribution are set at the sample mean. For the persistence parameters of structural shocks, the prior distribution is the beta distribution with a mean of 0.5 and a standard deviation of 0.2.

The key setting of our estimation strategy is on the parameters of standard deviations of structural shocks σ_x and those for measurement errors σ_j^{me}. We consider two types of prior distributions: one, the inverse gamma distribution, which is standard in the literature, with a mean of 0.5 and a standard deviation of infinity; and two, normal distribution.

For the parameter of standard deviations of structural shocks σ_x, the mean is 0.1 and the standard deviation is 10.[9] For the parameter of standard deviations of measurement errors σ_j^{me}, the mean is $\sigma_j^{data}/10$ and the standard deviation is σ_j^{data}, where σ_j^{data} is the standard deviation of observations.[10] Because the inverse gamma distribution does not support zero values, it assumes the existence of structural shocks and measurement errors. The normal distribution supports zero value, and then, allows for the non-existence

[9] If the prior distribution is normal, the values of σ_x and σ_j^{me} can be negative. This is not a problem because σ_x and σ_j^{me} themselves are not the standard deviations of structural shocks and measurement errors. The structural shocks and the measurement errors in our model are formulated as $\sigma_x \varepsilon_t^x$ and $\sigma_j^{me} me_t^j$, as explained in the equations (33)–(41). ε_t^x and me_t^j are i.i.d., with a mean of zero and a standard deviation of one. Then, the absolute values of σ_x and σ_j^{me} denote the standard deviations of structural shocks and measurement errors.

[10] Even if we set the standard deviation of the prior distribution to $\sigma_j^{data}/2$, our main claim does not change.

of structural shocks. We call the case of inverse gamma distribution as the *IG w/o MEs* setting, and the case of normal distribution as the *NN* setting.

[Tables 1 and 2]

Following standard Bayesian likelihood approaches, we use the Kalman filter to evaluate the likelihood function of the log-linearized equilibrium system and the Metropolis–Hastings algorithm to generate draws from the posterior distribution of the deep parameters. For the ensuing analysis, 1 million draws are generated; their first half is discarded. The target acceptance rate is approximately 30%.

4 Empirical Results

Posterior Estimates: The posterior estimates are presented in Tables 3 and 4. The IG w/o MEs setting is the case in which the inverse gamma distribution is employed as the prior distribution of the parameters for the standard deviation of structural shocks σ_x. The IG w/o MEs setting is standard in the Bayesian estimation of DSGE models; however, it imposes the existence of structural shocks. In the NN setting, the normal distribution is employed as the prior distribution of the parameters for the standard deviations of structural shocks σ_x and measurement errors σ_j^{me}. It allows for the non-existence of both structural shocks and measurement errors. It is the case in which we are most interested.

[Tables 3 and 4]

In Table 3, most estimates are similar in two prior distributions. Table 4 implies that, in the case of the NN setting, some structural shocks (transitory technology, preference, government spending, price markup, and wage shocks) might not exist in the sense in which the zero value lies inside the 90% credible intervals of the parameters for the standard deviations. The posterior mean is also close to zero for these parameters except for σ_b (preference shock).

Our result is similar to the findings of Ferroni, Grassi, and Leon-Ledesma (2015, 2019), that the posterior means of the parameters for the standard deviations of the government spending, price markup, and wage markup shocks are close to zero in the US economy using the model of Smets and Wouters (2007). Our result is also related to that of Justiniano, Primiceri, and Tambalotti (2013), who find that the variation of the wage markup shock becomes minor if measurement errors are included in the observation equations.[11] As discussed by Justiniano, Primiceri, and Tambalotti (2013), if there is no wage markup shock, then there is no trade-off between inflation and output stabilization. Indeed, Chari, Kehoe, and McGrattan (2009) doubt the existence of a wage markup shock as a fundamental structural shock. Our estimate implies that the wage shock (including wage markup shock) might not exist as per their conjecture. However, the labor wedge is driven by other structural shocks in our model.

Driving sources of business cycles and the labor wedge: Table 5 shows the variance decomposition of the output growth ($100\Delta \log Y_t$) and the labor wedge (100 $\Delta \log$ labor wedge). As in Tables 3 and 4, the IG w/o MEs setting shows a case in which the inverse gamma distribution is employed as the prior distribution of standard deviation of structural shocks σ_x, and the NN setting is the case in which the normal distribution is employed as the prior distribution of standard deviation of structural shocks σ_x and measurement errors σ_j^{me}.

[Table 5]

In the case of the IG w/o MEs setting, the main driving force of output fluctuation

[11] Justiniano, Primiceri, and Tambalotti (2013) employ inverse gamma distribution as a prior distribution of the parameters for the standard deviations of shocks, in contrast to this study, which employs normal distribution to allow for the non-existence of shocks.

is the investment adjustment cost shock. The preference, government, and permanent technology shocks are also important. The importance of the investment adjustment cost shock is consistent with the findings made by Justiniano, Primiceri, and Tambalotti (2010, 2011) and Hirose and Kurozumi (2012). However, the main driving force of the labor wedge is the preference and transitory technology shocks. The driving force of the labor wedge is then different from that of output fluctuation. According to this result, the investigation of the labor wedge is not promising to understand business cycle fluctuations.

In the case of the NN setting, the main driving force of both output fluctuation and the labor wedge is the permanent technology shock. This finding is consistent with that of Kaihatsu and Kurozumi (2014a, 2014b), who find that technology shock is the main driving force of business cycles, both in the United States and Japan. The investment adjustment cost shock is also important for these two variables, as in the result of the IG w/o MEs setting. According to this estimate, output and the labor wedge are mainly driven by the same structural shocks. In this study, the NN setting is considered a better prior distribution because it allows for the non-existence of structural shocks. Therefore, the investigation of the labor wedge fluctuations is promising to understand business cycles.

Why does the permanent technology shock become the driving source of both output and labor wedge fluctuations in the NN setting? Table 4 shows that the posterior means of σ_b and σ_{zt} in the NN setting are much smaller than those in the IG w/o MEs setting, and the zero value lies inside the 90% credible intervals. This is possible because the NN setting allows for the non-existence of structural shocks. In addition, the posterior mean of σ_{zp} in the NN setting is more than twice as large as that in the IG w/o MEs setting. In other words, the difference in the results can be interpreted as a result of the smaller variation in the preference and temporary technology shocks and the larger variation in the permanent technology shock.

Then, by what mechanism do the variation in these shocks change? We think that the keys are the log-linearized version of the aggregate production function (30), given by

$$\tilde{y}_t = (1+\phi)\left\{z_t^{zt} + (1-\alpha)\tilde{\ell}_t + \alpha(\tilde{u}_t + \tilde{k}_{t-1} - z_t^{zp})\right\},$$

and the log-linearized version of the marginal utility of consumption (14), given by

$$\begin{aligned}\left(1-\frac{\theta}{z^*}\right)\left(1-\frac{\beta\theta}{(z^*)^\sigma}\right)\tilde{\lambda}_t = -\sigma\left\{\tilde{c}_t - \frac{\theta}{z^*}(\tilde{c}_{t-1} - z_t^{zp})\right\} + \left(1-\frac{\theta}{z^*}\right)z_t^b \\ + \frac{\beta\theta}{(z^*)^\sigma}\left[\sigma\left\{E_t\tilde{c}_{t+1} + E_t z_{t+1}^{zp} - \frac{\theta}{z^*}\tilde{c}_t\right\} - \left(1-\frac{\theta}{z^*}\right)E_t z_{t+1}^b\right].\end{aligned}$$

Then, through the aggregate production function, the variation of the temporary technology shock z_t^{zt} is replaced by the variation of the permanent technology shock z_t^{zp}. In addition, as the variation of permanent technology shock becomes larger, the variation of preference shock z_t^b becomes smaller through the marginal utility of consumption.

Roles of prior distribution and measurement errors: We also find that the main driving force of both output fluctuation and the labor wedge is the same in the case of the NN setting, whereas the driving force of the labor wedge is different from that of output fluctuation in the case of the IG w/o MEs setting. There are two differences between the IG w/o MEs setting and the NN setting: prior distribution and the measurement errors. Which among the two, then, is important for this result?

To focus on this point, two alternative cases are considered. One is the *N w/o MEs* setting wherein normal distribution is employed as the prior distribution of the parameters for the standard deviation of structural shocks σ_x and no measurement errors are included. This can be seen as a case in which the prior distribution is changed from the IG w/o MEs setting. The other is the *IGIG* setting wherein the inverse gamma distribution is employed as the prior distribution of the parameters for the standard deviations of structural shocks σ_x and measurement errors σ_j^{me}. Here, measurement errors are added to the IG w/o MEs setting.

Table 6 shows the variance decomposition of the output growth ($100\Delta \log Y_t$) and the labor wedge (100 Δ log labor wedge) in the cases of the N w/o MEs setting and the IGIG setting.

[Table 6]

In the case of the N w/o MEs setting, the main driving force of output fluctuation is the investment adjustment cost shock, as in the IG w/o MEs setting. The fraction accounted for by the investment adjustment cost shock is much larger than the result in the IG w/o MEs setting, and the roles of the preference, government, and permanent technology shocks are limited. The main driving force of the labor wedge is the preference and transitory technology shocks. Then, the main driving force of the labor wedge fluctuation is different from that of output fluctuation. Therefore, the change in the prior distribution alone is not enough to overturn the implication of the IG w/o MEs setting.

In the case of the IGIG setting, the main driving force of output fluctuation is the investment adjustment cost, as in the N w/o MEs setting and the IG w/o MEs setting. The fraction accounted for by the preference and investment adjustment cost shocks is almost same as in the N w/o MEs, and the fraction accounted for by the permanent technology shock is almost same as in the IG w/o MEs setting. The labor wedge fluctuations are mainly driven by the preference, investment adjustment cost, and transitory technology shocks. Then, the main driving force of the labor wedge fluctuation is different from that of output fluctuation. Therefore, measurement error alone is not enough to overturn the implication of the IG w/o MEs setting.

Finally, the combination of the change in the prior distribution and the inclusion of the measurement errors is important to obtain the main finding in the case of the NN setting: that the driving source of the output fluctuation and the labor wedge is the same.

NN setting is the best fit setting in our estimations. Table 7 shows the marginal log likelihoods in four estimations: (1) IG w/o MEs setting, (2) NN setting, (3) N w/o MEs setting, and (4) IGIG setting. We find that the N w/o MEs setting is not better than the

IG w/o MEs setting. Then, the change in prior distribution itself does not improve the estimation result. By contrast, the IGIG setting is better than the IG w/o MEs setting in Table 7. Then, the inclusion of measurement errors improves the estimation result. However, the marginal log likelihood in the case of the NN setting obtained in Table 7 is better than the cases of the N w/o MEs setting and the IGIG setting. Therefore, the combination of the change in prior distribution and the inclusion of measurement errors is the best setting in these estimations.

[Table 7]

5 Concluding Remarks

The labor wedge has been investigated by various researchers as an important variable to understand business cycle fluctuations. In this study, we estimated the main sources of the labor wedge and business cycle in the Japanese economy using a canonical medium-scale DSGE model with many nominal and real frictions and structural shocks. We employed a more flexible prior distribution of the parameters for the standard deviations of structural shocks and measurement errors to allow for the non-existence of structural shocks. However, in standard Bayesian estimation, the standard prior distribution of the parameters for the standard deviations of the shocks is an inverse gamma distribution, which does not support a zero value.

Our estimation results imply that the labor wedge is mainly driven by preference and transitory technology shocks, whereas the business cycle is mainly driven by the investment adjustment cost shock. Meanwhile, under our relaxed prior distribution, which allows for the non-existence of structural shocks, the estimation results show that both the labor wedge and business cycles are mainly driven by the permanent technology and investment adjustment cost shocks. Our results also imply that the investigation of the labor wedge is promising to understand business cycles because both the labor wedge and business cycles are driven by the same structural shocks. Indeed, the labor market policies would be important for macroeconomic stability.

However, a limitation of this paper is that our medium-scale DSGE model does not include matching frictions, home production, and collateral constraint. While these frictions are investigated by existing works on the labor wedge, as a first step, we consider the canonical medium-scale DSGE model without such frictions in our examination. One of our future tasks would be to investigate the driving sources of business cycles and the labor wedge in a DSGE model with such frictions.

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Appendix: Log-Linearized Equilibrium Conditions

The variable with tilde $\tilde{x}_t$ is defined as the log deviation of x_t from its steady-state value x^*:

$$\tilde{x}_t = \log(x_t) - \log(x^*).$$

The log-linearized equilibrium system of our medium-scale DSGE economy is described as follows:

The marginal utility of consumption (14) is

$$\begin{aligned}\left(1-\frac{\theta}{z^*}\right)\left(1-\frac{\beta\theta}{(z^*)^\sigma}\right)\tilde{\lambda}_t = &-\sigma\left\{\tilde{c}_t - \frac{\theta}{z^*}(\tilde{c}_{t-1} - z_t^{zp})\right\} + \left(1-\frac{\theta}{z^*}\right)z_t^b \\ &+ \frac{\beta\theta}{(z^*)^\sigma}\left[\sigma\left\{E_t\tilde{c}_{t+1} + E_t z_{t+1}^{zp} - \frac{\theta}{z^*}\tilde{c}_t\right\} - \left(1-\frac{\theta}{z^*}\right)E_t z_{t+1}^b\right].\end{aligned}$$

The Euler equation for nominal bond (15) is

$$\tilde{\lambda}_t = E_t\tilde{\lambda}_{t+1} - \sigma E_t z_{t+1}^{zp} + \tilde{R}_t^n - E_t\tilde{\pi}_{t+1}.$$

The capital utilization (16) is

$$\tilde{u}_t = \mu(\tilde{R}_t^k - \tilde{q}_t).$$

The Euler equation for investment (17) is

$$\frac{1}{\zeta}\left\{\tilde{i}_t - \tilde{i}_{t-1} + z_t^{zp} + z_t^i\right\} = \tilde{q}_t + \frac{\beta(z^*)^{1-\sigma}}{\zeta}\left\{E_t\tilde{i}_{t+1} - \tilde{i}_t + E_t z_{t+1}^{zp} + E_t z_{t+1}^i\right\}.$$

The Euler equation for capital (18) is

$$\tilde{q}_t = E_t\tilde{\lambda}_{t+1} - \lambda_t - \sigma E_t z^{zp}_{t+1} + \frac{\beta}{(z^*)^\sigma}\left\{R^k E_t \tilde{R}^k_{t+1} + (1-\delta)E_t\tilde{q}_{t+1}\right\}.$$

The New Keynesian Phillips curve (9) is

$$\tilde{\pi}_t - \gamma_p\tilde{\pi}_{t-1} = \beta(z^*)^{1-\sigma}(E_t\tilde{\pi}_{t+1} - \gamma_p\tilde{\pi}_t) + \frac{(1-\xi_p)(1-\beta\xi_p z^{1-\sigma})}{\xi_p}\widetilde{mc}_t + z^p_t.$$

where z^p_t is the price markup shock defined by

$$z^p_t = \frac{(1-\xi_p)(1-\beta\xi_p(z^*)^{1-\sigma})}{\xi_p}\tilde{\lambda}^p_t.$$

The New Keynesian wage Phillips curve (23) is

$$\begin{aligned}
&\tilde{w}_t - \tilde{w}_{t-1} + \tilde{\pi}_t - \gamma_w\tilde{\pi}_{t-1} + z^{zp}_t \\
&= \beta z^{1-\sigma}(E_t\tilde{w}_{t+1} - \tilde{w}_t + E_t\tilde{\pi}_{t+1} - \gamma_w\tilde{w}_t + E_t z^{zp}_{t+1}) \\
&+ \frac{1-\xi_w}{\xi_w}\frac{(1-\beta\xi_w(z^*)^{1-\sigma})\lambda^w}{\lambda^w + \chi(1+\lambda^w)}\left(\chi\tilde{\ell}_t - \tilde{\lambda}_t - \tilde{w}_t + z^b_t\right) + z^w_t,
\end{aligned}$$

where z^w_t is the wage shock defined by

$$z^w_t = \frac{1-\xi_w}{\xi_w} \times \frac{(1-\beta\xi_w(z^*)^{1-\sigma})\lambda^w}{\lambda^w + \xi(1+\lambda^w)}\left(\tilde{\lambda}^w_t + z^\ell_t\right).$$

In the log-linearized equilibrium system, the wage markup shock λ^w_t and the labor supply shocks z^ℓ_t cannot be identified. Then, the wage shock z^w_t is defined as the linear combination of the (log-linearized) wage markup shock $\tilde{\lambda}^w_t$, where λ^w is the steady-state value of λ^w_t and labor supply shock z^ℓ_t.

The monetary policy rule (24) is

$$\tilde{R}^n_t = \phi_r\tilde{R}^n_{t-1} + (1-\phi_r)\left\{\phi_\pi\left(\frac{1}{4}\sum_{j=0}^{3}\tilde{\pi}_{t-j}\right) + \phi_y(\tilde{y}_t - \tilde{y}^P_t)\right\} + z^r_t.$$

The potential output (25) is

$$\tilde{y}^P_t = -\alpha(1+\phi)z^{zp}_t,$$

where $\phi = \Phi/y^*$, and y^* is the steady-state value of detrended output Y_t/Z_t^P. The evolution of aggregate capital (26) is

$$\tilde{k}_t = \frac{1-\delta}{z^*}(\tilde{k}_{t-1} - z_t^{zp}) - \frac{\bar{R}^k}{z^*}\tilde{u}_t + \left(1 - \frac{1-\delta}{z^*}\right)\tilde{i}_t.$$

The cost-minimization conditions (28) and (29) are

$$\tilde{u}_t + \tilde{k}_{t-1} - \tilde{\ell}_t - z_t^{zp} = \tilde{w}_t - \tilde{R}_t^k,$$
$$\widetilde{mc}_t = (1-\alpha)\tilde{w}_t + \alpha\tilde{R}_t^k - z_t^{zt}.$$

The aggregate production function (30) is

$$\tilde{y}_t = (1+\phi)\left\{z_t^{zt} + (1-\alpha)\tilde{\ell}_t + \alpha(\tilde{u}_t + \tilde{k}_{t-1} - z_t^{zp})\right\}.$$

The resource constraint (31) is

$$\tilde{y}_t = \frac{c^*}{y^*}\tilde{c}_t + \frac{i^*}{y^*}\tilde{i}_t + \frac{g^*}{y^*}z_t^g.$$

The evolutions of the exogenous structural shocks are given by the equations from (33) to (40).

Table 1: Prior Distribution (1/2)

	Parameter	Distribution	Mean	SD
σ	Relative risk aversion	Gamma	1.0000	0.3750
θ	Habit persistence	Beta	0.7000	0.1500
χ	Inverse of Frisch elasticity of labor supply	Gamma	2.0000	0.7500
$1/\zeta$	Inverse of adj. cost of investment	Gamma	4.0000	1.5000
μ	Inverse of elasticity of utilization adj. cost	Gamma	1.0000	1.0000
Φ	Fixed cost in production function	Gamma	0.0750	0.0125
γ_w	Wage indexation	Beta	0.5000	0.2500
ξ_w	Wage stickiness	Beta	0.3750	0.1000
γ_p	Price indexation	Beta	0.5000	0.2500
ξ_p	Price stickiness	Beta	0.3750	0.1000
λ^p	Steady-state price markup	Gamma	0.1500	0.0500
z^*	Steady-state output growth	Gamma	0.353	0.0500
ℓ^*	Steady-state hours worked	Normal	0.0000	0.0500
π^*	Steady-state inflation	Gamma	0.341	0.0500
r^*	Steady-state real interest rate	Gamma	1.088	0.0500
ϕ_r	Interest rate smoothing	Beta	0.8000	0.1000
ϕ_π	Monetary policy response to inflation	Gamma	1.7000	0.1000
ϕ_y	Monetary policy response to output	Gamma	0.125	0.0500

Table 2: Prior Distribution (2/2)

	Parameter	(1) IG w/o MEs setting			(2) NN setting		
			Mean	SD		Mean	SD
ρ_{zp}	Persistence of permanent technology shock	Beta	0.5	0.2	Beta	0.5	0.2
ρ_{zt}	Persistence of transitory technology shock	Beta	0.5	0.2	Beta	0.5	0.2
ρ_b	Persistence of preference shock	Beta	0.5	0.2	Beta	0.5	0.2
ρ_i	Persistence of investment adj. cost shock	Beta	0.5	0.2	Beta	0.5	0.2
ρ_g	Persistence of government shock	Beta	0.5	0.2	Beta	0.5	0.2
ρ_w	Persistence of wage shock	Beta	0.5	0.2	Beta	0.5	0.2
ρ_p	Persistence of price markup shock	Beta	0.5	0.2	Beta	0.5	0.2
ρ_r	Persistence of monetary policy shock	Beta	0.5	0.2	Beta	0.5	0.2
σ_{zp}	SD of permanent technology shock	IG	0.5	Inf	Normal	0.1	10
σ_{zt}	SD of transitory technology shock	IG	0.5	Inf	Normal	0.1	10
σ_b	SD of preference shock	IG	0.5	Inf	Normal	0.1	10
σ_i	SD of investment adj. cost shock	IG	0.5	Inf	Normal	0.1	10
σ_g	SD of government shock	IG	0.5	Inf	Normal	0.1	10
σ_w	SD of wage shock	IG	0.5	Inf	Normal	0.1	10
σ_p	SD of price markup shock	IG	0.5	Inf	Normal	0.1	10
σ_r	SD of monetary policy shock	IG	0.5	Inf	Normal	0.1	10
σ_y^{me}	SD of ME of GDP	NA	NA	NA	Normal	$\sigma_y^{data}/10$	σ_y^{data}
σ_c^{me}	SD of ME of consumption	NA	NA	NA	Normal	$\sigma_c^{data}/10$	σ_c^{data}
σ_i^{me}	SD of ME of investment	NA	NA	NA	Normal	$\sigma_i^{data}/10$	σ_i^{data}
σ_w^{me}	SD of ME of wage	NA	NA	NA	Normal	$\sigma_w^{data}/10$	σ_w^{data}
σ_ℓ^{me}	SD of ME of hours worked	NA	NA	NA	Normal	$\sigma_\ell^{data}/10$	σ_ℓ^{data}
σ_π^{me}	SD of ME of inflation	NA	NA	NA	Normal	$\sigma_\pi^{data}/10$	σ_π^{data}
σ_{rn}^{me}	SD of ME of call rate	NA	NA	NA	Normal	$\sigma_{rn}^{data}/10$	σ_{rn}^{data}

Notes: IG denotes the inverse gamma distribution. ME denotes measurement error. σ_x^{data} is the standard deviation of actual data for $x = y$, c, i, w, ℓ, π, and rn.

Table 3: Posterior Estimates (1/2)

	(1) IG w/o MEs setting no Measurement Errors (Prior on σ_x: Inverse Gamma)		(2) NN setting with Measurement Errors (Prior on σ_x and σ_j^{me}: Normal)	
	Mean	90% credible interval	Mean	90% credible interval
σ	1.8176	[0.2985 , 3.3961]	2.3811	[1.6397 , 3.1031]
θ	0.6795	[0.2730 , 0.9815]	0.3660	[0.1837 , 0.5416]
χ	2.1229	[1.2790 , 3.0523]	1.3495	[0.6600 , 2.0457]
$1/\zeta$	6.8186	[3.3844 , 10.0621]	4.1703	[1.8334 , 6.3872]
μ	2.1878	[0.4406 , 3.8635]	0.0705	[0.0000 , 0.1595]
Φ	0.0776	[0.0559 , 0.0969]	0.0739	[0.0543 , 0.0936]
γ_w	0.5891	[0.2273 , 0.9791]	0.4347	[0.0248 , 0.8217]
ξ_w	0.5965	[0.5131 , 0.6786]	0.4664	[0.3246 , 0.6080]
γ_p	0.4481	[0.1126 , 0.7982]	0.4034	[0.0174 , 0.7739]
ξ_p	0.705	[0.6407 , 0.7655]	0.5307	[0.3590 , 0.7103]
λ^p	0.3066	[0.1882 , 0.4234]	0.1494	[0.0687 , 0.2252]
z^*	0.3222	[0.2530 , 0.3900]	0.4777	[0.3907 , 0.5701]
ℓ^*	-0.0005	[-0.0828 , 0.0820]	-0.0022	[-0.0857 , 0.0803]
π^*	0.3586	[0.2725 , 0.4461]	0.3427	[0.2588 , 0.4236]
r^*	1.0655	[0.9863 , 1.1400]	1.0119	[0.9367 , 1.0871]
ϕ_r	0.6897	[0.5943 , 0.7849]	0.6090	[0.5058 , 0.7182]
ϕ_π	1.7645	[1.6089 , 1.9194]	1.7154	[1.5632 , 1.8679]
ϕ_y	0.1064	[0.0426 , 0.1932]	0.1163	[0.0616 , 0.1697]

Table 4: Posterior Estimates (2/2)

	(1) IG w/o MEs setting no Measurement Errors (Prior on σ_x: Inverse Gamma)		(2) NN setting with Measurement Errors (Prior on σ_x and σ_j^{me}: Normal)	
	Mean	90% credible interval	Mean	90% credible interval
ρ_{zp}	0.5532	[0.2259 , 0.8721]	0.3854	[0.1779 , 0.5799]
ρ_{zt}	0.9613	[0.9361 , 0.9864]	0.4739	[0.1031 , 0.8281]
ρ_b	0.3091	[0.0191 , 0.6505]	0.6274	[0.2774 , 0.9948]
ρ_i	0.5005	[0.2382 , 0.7497]	0.8813	[0.8147 , 0.9506]
ρ_g	0.7292	[0.3163 , 0.9946]	0.4719	[0.0822 , 0.8315]
ρ_w	0.1049	[0.0138 , 0.1976]	0.7633	[0.3516 , 0.9892]
ρ_p	0.9462	[0.9078 , 0.9853]	0.4963	[0.1661 , 0.8395]
ρ_r	0.539	[0.3479 , 0.7348]	0.4162	[0.2233 , 0.6027]
σ_{zp}	0.5216	[0.1752 , 0.8636]	1.1108	[0.8277 , 1.5184]
σ_{zt}	0.8466	[0.7051 , 0.9857]	0.0056	[-0.2459 , 0.2548]
σ_b	9.3614	[0.1110 , 20.7598]	-0.1434	[-1.8223 , 1.6020]
σ_i	5.3242	[3.6466 , 7.0190]	7.1110	[2.9951 , 11.2634]
σ_g	1.5095	[1.0323 , 1.9465]	0.0388	[-0.9004 , 0.9858]
σ_w	0.9992	[0.8245 , 1.1594]	0.0369	[-0.2661 , 0.3446]
σ_p	0.1569	[0.0937 , 0.2253]	-0.0025	[-0.2026 , 0.1987]
σ_r	0.1192	[0.1006 , 0.1368]	0.0939	[0.0714 , 0.1169]
σ_y^{me}	NA	NA	0.1213	[-0.5871 , 0.6286]
σ_c^{me}	NA	NA	0.0463	[-0.6649 , 0.6937]
σ_i^{me}	NA	NA	2.7165	[2.2638 , 3.1748]
σ_g^{me}	NA	NA	0.8827	[0.7491 , 1.0164]
σ_ℓ^{me}	NA	NA	-0.0972	[-0.4815 , 0.4505]
σ_π^{me}	NA	NA	0.0109	[-0.1614 , 0.1673]
σ_{rn}^{me}	NA	NA	0.0007	[-0.0459 , 0.0463]

Table 5: Variance Decompositions (1):Baseline

	(1) IG w/o MEs setting no Measurement Errors (Prior on σ_x: Inverse Gamma)		(2) NN setting with Measurement Errors (Prior on σ_x and σ_j^{me}: Normal)	
	$100\Delta \log Y_t$	$100\Delta \log \text{Labor Wedge}_t$	$100\Delta \log Y_t$	$100\Delta \log \text{Labor Wedge}_t$
z^b	28.46	50.47	0.02	0.38
z^i	35.03	5.81	12.55	19.59
z^g	9.56	4.57	0.01	0.08
z^w	0.78	7.70	0.08	0.95
z^p	5.06	5.31	0.00	0.00
z^r	0.19	2.79	0.24	4.53
z^{zp}	12.44	0.73	85.80	62.40
z^{zt}	8.47	22.62	0.00	0.05
me^y	NA	NA	1.30	1.46
me^c	NA	NA	0.00	0.21
me^i	NA	NA	0.00	0.00
me^ℓ	NA	NA	0.00	10.35
me^w	NA	NA	0.00	0.00
me^π	NA	NA	0.00	0.00
me^{rn}	NA	NA	0.00	0.00

Note: Infinity-horizon forecast error variance decompositions are performed.

Table 6: Variance Decompositions (2): Alternative Estimations

	(3) N w/o MEs setting no Measurement Errors (Prior on σ_x: Normal)		(4) IGIG setting with Measurement Errors (Prior on σ_x and σ_j^{me}: Inverse Gamma)	
	$100\Delta\log Y_t$	$100\Delta\log \text{Labor Wedge}_t$	$100\Delta\log Y_t$	$100\Delta\log \text{Labor Wedge}_t$
z^b	13.74	23.95	13.59	27.58
z^i	66.21	15.06	68.54	19.92
z^g	9.85	6.71	2.09	1.54
z^w	0.32	8.78	0.95	6.34
z^p	3.73	3.14	0.03	0.15
z^r	0.19	3.89	0.08	2.72
z^{zp}	0.06	0.01	12.67	0.34
z^{zt}	5.90	38.87	0.03	23.98
me^y	NA	NA	2.03	0.27
me^c	NA	NA	0.00	0.06
me^i	NA	NA	0.00	0.00
me^ℓ	NA	NA	0.00	17.09
me^w	NA	NA	0.00	0.00
me^π	NA	NA	0.00	0.00
me^{rn}	NA	NA	0.00	0.00

Note: Infinity-horizon forecast error variance decompositions are performed.

Table 7: Marginal Log Likelihoods

(1) IG w/o MEs setting no Measurement Errors (Prior on σ_x: Inverse Gamma)	(2) NN setting with Measurement Errors (Prior on σ_x and σ_j^{me}: Normal)
-570.705	-549.151

(3) N w/o MEs setting no Measurement Errors (Prior on σ_x: Normal)	(4) IGIG setting with Measurement Errors (Prior on σ_x and σ_j^{me}: Inverse Gamma)
-570.916	-557.397