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Estimating a DSGE Model for Japan: Evaluating and Modifying a CEE/SW/LOWW Model

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Estimating a DSGE Model for Japan: Evaluating and Modifying a CEE/SW/LOWW Model*

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Abstract

We estimate a medium-scale DSGE model of the Japanese economy following Christiano, Eichenbaum and Evans (2005), Smets and Wouters (2003) and Levin et al. (2005). By using actual capital utilization data and modifying the formulation of utilization following Greenwood, Hercowitz and Huffmann (1988), this paper succeeds in incorporating a negative correlation between capital utilization and rental costs to explain actual capital utilization rates. We find hump-shaped and persistent behavior of inflation rates in response to a monetary policy shock, which CEE cast doubt upon.

JEL Classification: E22, E32, E52
Keywords: DSGE model, monetary policy, capital utilization, Japan

1 Introduction

This paper constructs a medium-scale dynamic stochastic general equilibrium (hereafter DSGE) model by modifying the formulation of capital utilization following Greenwood, Hercowitz and Huffmann (1988), and estimates the model using Japanese data, including that on actual capital utilization.

There are similar empirical studies which estimate the medium-scale DSGE model developed by Christiano, Eichenbaum and Evans (2005) (hereafter CEE). Smets and Wouters (2003) (hereafter SW) is the first attempt to estimate a CEE's model using Bayesian techniques. They apply the model to the Euro economy, and argue that the estimated parameters are more or less consistent with microeconometric findings and that their medium-scale DSGE model explains the actual economy almost as well as VAR. Their results were later confirmed by Onatski and Williams (2004) (hereafter OW). Levin, Onatski, Williams and Williams (2005) (hereafter LOWW) estimate a similar model for the U.S. economy. As for applications to the Japanese economy, Iiboshi, Nishiyama and Watanabe (2006) (hereafter INW) have already estimated the model using Japanese data.

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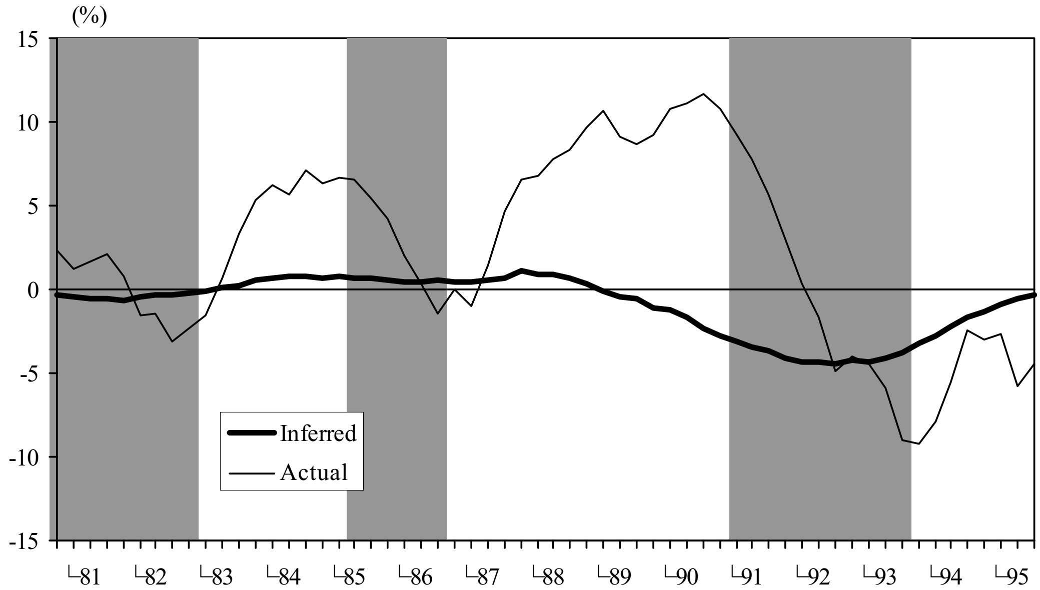

Figure 1: Actual and inferred capital utilization rates. Shaded areas represent recessions.

Although these studies seem to succeed in explaining the actual economy very well, we find that there are still unresolved problems relating to capital utilization rates which previous studies did not focus on. In SW and others, this variable is treated as unobservable, and inferred using the Kalman filter. Figure 1 shows the inferred movement of capital utilization rates obtained using Japanese data. Since there are available statistics on capital utilization rates, although these are limited to manufacturing firms in Japan, a comparison is instructive. We find that the two utilization rates are very different in terms of their movements and their amplitude.

Since we have data on capital utilization rates, it is quite natural to make use of this when estimating the model. This then generates another problem. The CEE/SW/LOWW model states that capital rental costs should positively affect capital utilization rates. This is because their model assumes that it is beneficial for capital lenders to increase capital utilization rates when capital rental costs are high. However, as is shown in Figure 2, these two variables are in fact negatively correlated. Such a negative correlation is perfectly intuitive, and can be explained as follows. While capital rental costs are positively determined by the marginal product of effective capital, the latter depends negatively on the capital utilization rate, so a negative correlation will be observed.

The main contribution of this paper is to incorporate this negative correlation between capital utilization and rental rates for capital into a medium-scale DSGE model. To this end, we follow Greenwood et al. (1988). We assume that the adjustment costs of capital utilization take the form not of additional expenditure on goods but of an accelerating speed of capital depreciation. This assumption makes utilization rates depend not only upon rental costs positively but also upon the value of capital negatively. On the one hand, higher rental costs lead to greater capital utilization because households can receive higher revenues by increasing capital utilization and by renting more effective capital to firms. On the other hand, a higher value of capital discourages capital utilization because, by making future capital more valuable, it deters households from utilizing their capital and so accelerating its speed of depreciation.

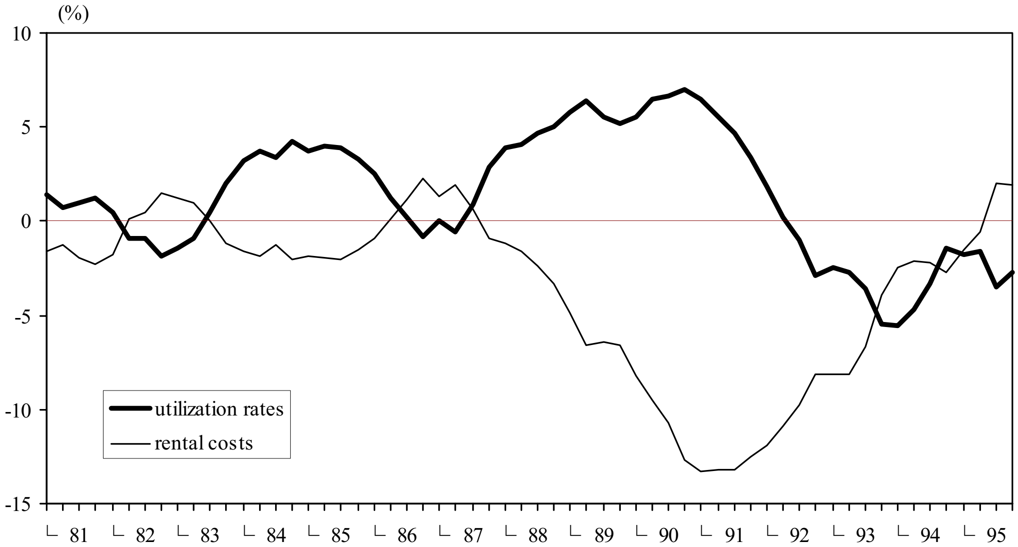

Figure 2: Utilization rates and rental costs

By applying this assumption to our highly persistent DSGE model, we succeed in incorporating the negative correlation between rental costs and utilization rates. We improve the goodness of fit; our model explains the behavior of utilization rates in most parts of the sample periods. Furthermore, we confirm that our model yields the inertial behavior of inflation in response to monetary policy shocks, as observed in previous econometric studies (e.g. Kim (1999), Shioji (2000)). This result contrasts with the argument offered by CEE. To explain the hump-shaped and persistent inflation behavior in response to a contractionary monetary policy shock, CEE advocate treating capital utilization costs not as capital depreciation but as additional spending on goods. This paper makes it clear that although CEE's assertion is qualitatively true, the difference in the assumption about capital utilization has no quantitative impact when we consider the overall impulse response of utilization rates and inflation to a monetary policy shock.

The rest of the paper is organized as follows. Section 2 presents the benchmark model following CEE/SW/LOWW. In Section 3, we present estimation results: estimated parameters and the movement of capital utilization rates. We also investigate business cycles in Japan. Section 4 compares our model with those of CEE/SW/LOWW from the viewpoint of the effect of monetary policy shocks. Section 5 concludes the paper.

2 Model

This section introduces the DSGE model used for our estimation. This model largely follows those of CEE/SW/LOWW. In addition to sound micro-foundations, it incorporates several distinct features in order to match the actual economy, in particular, staggered wage and price setting with partial indexation, the adjustment costs of capital investment, habit formation in consumption, variable capital utilization, and smoothed monetary policy.

2.1 Model Setup

Household Preferences A household h maximizes the present value of its present and future utility:

$$\Xi_t(h) = E_t \sum_{j=0}^{\infty} \beta_{t+j}^{j} V_{t+j}(h), \tag{2.1}$$

where a subjective discount factor is given by $\beta_{t+j}^{j} = \prod_{s=0}^{j} \beta_{t+s}$, and $\beta_t = \beta Z_t^b$. Stochastic variation in preferences is represented by Z_t^b whose mean is one. Furthermore, we assume that the logarithm of this disturbance obeys an AR(1) process. The utility function V_t is separable between consumption and leisure as

$$V_t = \frac{(C_t(h) - \theta C_{t-1}(h))^{1-\sigma}}{1-\sigma} - \frac{Z_t^L (L_t(h))^{1+\chi}}{1+\chi}, \tag{2.2}$$

where the first term represents the consumption habit, which generates more persistence in the economy[1]. The parameters σ, θ, and χ respectively denote the inverse of the intertemporal elasticity of substitution of consumption, the extent of the consumption habit ($0 \leq \theta < 1$), and the inverse of the elasticity of hours worked with respect to real wages. $C_t(h)$ and $L_t(h)$ represent aggregated consumption and labor supply. Z_t^L is a stochastic variation in labor supply disutility, which follows an AR(1) process.

Household h's budget constraint is given by

$$\begin{aligned} & \frac{B_{t-1}(h)}{P_t} + W_t(h)L_t(h) + R_t^k U_t(h) K_{t-1}(h) + \Pi_t(h) \\ \geq \; & C_t(h) + I_t(h) + b_t \frac{B_t(h)}{P_t}. \end{aligned} \tag{2.3}$$

The left and right hand sides of the equation show household h's income and expenditure, respectively. The variable $B_t(h)$ denotes h's bond holdings, and b_t is the bond price. P_t and $W_t(h)$ respectively stand for the aggregate price index and the real wage which household h receives. R_t^k is the return on capital and $U_t(h)$ is the capital utilization rate. $\Pi_t(h)$ denotes the transfer of firms' profits to household h. $K_t(h)$ and $I_t(h)$ denote household h's capital stock and capital investment.

Capital Utilization and Accumulation While CEE/SW/LOWW assume that the adjustment costs of capital utilization take the form of additional goods spending[2], our paper follows Greenwood et al. (1988) and assumes that high capital utilization leads to faster capital depreciation. In particular, we assume that capital depreciation rates depend on capital utilization rates:

$$\delta(U_t(h)) = \delta \Psi(Z_t^U U_t(h)). \tag{2.4}$$

A higher capital utilization rate leads to faster capital depreciation:

$$\Psi(X) = 1 + \mu \frac{X^{1+\psi^{-1}} - 1}{1+\psi^{-1}}. \tag{2.5}$$

[1] Following LOWW, we assume "internal habit persistence," in which the lagged value of individual consumption serves as the reference value for each individual household.

[2] See Appendix A.2.

The parameter ψ is the inverse of the elasticity of capital utilization costs[3]. Z_t^U is a stochastic variation in the adjustment costs of capital utilization, which follows an AR(1) process[4]. In steady state, the utilization rate is one, which implies that the capital depreciation rate is equal to δ.

Capital is used for producing goods, and cannot be accumulated or disposed of instantaneously because of adjustment costs. Capital $K_t(h)$ evolves as follows:

$$K_t(h) = \{1 - \delta(U_t(h))\}K_{t-1}(h) + \left\{1 - \zeta^{-1}\left(\frac{Z_t^I I_t(h)}{I_{t-1}(h)} - 1\right)^2\right\} I_t(h). \tag{2.6}$$

Z_t^I is a stochastic variation in the adjustment costs of investment, which follows an AR(1) process. $1/\zeta$ represents the magnitude of investment adjustment costs.

Production and Prices

Final Goods Sector The final goods sector is perfectly competitive. The final good Y is produced by bundling the differentiated intermediate goods $Y(j)$:

$$Y_t = \left[\int_0^1 (Y_t(j))^{\frac{1}{1+\lambda_{p,t}}} dj\right]^{1+\lambda_{p,t}}. \tag{2.7}$$

We assume that the price markup $\lambda_{p,t}$ is subject to an i.i.d. disturbance. This equation implies that the aggregate price index is given by

$$P_t = \left[\int_0^1 (P_t(j))^{-\frac{1}{\lambda_{p,t}}} dj\right]^{-\lambda_{p,t}}. \tag{2.8}$$

Intermediate Goods Producers Intermediate goods are differentiated, and their producers face monopolistic competition. Production technology exhibits increasing returns to scale because of fixed costs Φ :

$$Y_t(j) = A_t(\widetilde{K_t}(j))^{\alpha} L_t(j)^{1-\alpha} - \Phi. \tag{2.9}$$

Productivity is given by $A_t = Z_t^A A$, where Z_t^A obeys an AR(1) process. $\widetilde{K_t}$ denotes the effective capital stock embedding capital utilization, and the parameter α is the capital share.

We assume that there is Calvo-type price stickiness. Not all producers can optimize their prices in every period, and the probability that they cannot reset their prices is ξ_p $(0 < \xi_p < 1)$. The average duration that prices are not optimized for thus becomes $1/(1-\xi_p)$. We also assume, however, that even the firms which cannot revise their prices optimally can change their prices to some degree by means of indexation to the past inflation rate. The degree is given by parameter γ_p $(0 \leq \gamma_p < 1)$. This assumption yields the persistence of the inflation rate as well as of the price level.

The firms' cost-minimization condition is given by

$$\frac{W_t L_t}{R_t^k U_t K_{t-1}} = \frac{1-\alpha}{\alpha}. \tag{2.10}$$

[3] We share the same functional form, $\Psi(X)$ as SW and LOWW, but the meaning of the parameter ψ differs.

[4] Unlike SW and LOWW, we use actual data on capital utilization rates for estimation. To this end, we introduce an adjustment cost shock affecting capital utilization. In common with other shocks, this shock comes from the structure of the model.

Labor Supply and Wages This paper models wage stickiness in a similar way to price stickiness. We assume that households supply their differentiated labor in a monopolistically competitive manner as in Erceg, Henderson, and Levin (2000). We define the elasticity of substitution between different types of labor as $\lambda_{w,t}$, which is subject to an i.i.d. disturbance. Household h can optimize its wage with a constant probability $1-\xi_w$ $(0<\xi_w<1)$, and even the households who cannot reset their wages optimally can adjust their wages by indexing them to the past inflation rate. The degree is given by γ_w $(0 \leq \gamma_w < 1)$.

Market Clearing Condition The goods market is cleared according to

$$Y_t = C_t + G_t + I_t, \tag{2.11}$$

where G_t stands for external demand such as government expenditure. Its logarithmic variation follows an AR(1) process.

Monetary Policy Rule According to our monetary policy rule, the short-term nominal interest rate depends not only on the past inflation rate and output gap but also on their size of change. Furthermore, there is a smoothing effect in that a lagged nominal interest rate also affects the current nominal interest rate. Denoting *nominal* interest rates as r_t, we write the monetary policy rule as

$$\begin{aligned} r_t &= r_i r_{t-1} + (1-r_i)\overline{\pi}_t + r_\pi(\pi_{t-1} - \overline{\pi}_t) + r_y(y_{t-1} - y^*_{t-1}) \\ &\quad + r_{\Delta\pi}(\pi_t - \pi_{t-1}) + r_{\Delta y}((y_t - y^*_t) - (y_{t-1} - y^*_{t-1})) + \eta^r_t. \end{aligned} \tag{2.12}$$

π_t, y_t, and y^*_t represent the inflation rate, output, and natural output[5], respectively[6]. $\overline{\pi}_t$ and η^r_t are monetary policy shocks, that is, shocks to the target inflation rate and the interest rate, respectively. We assume that, while the interest rate shock is i.i.d., the target inflation rate follows an AR(1) process.

2.2 Log-Linearized Model

2.2.1 Real Economy

From the above setup, we can derive a log-linearized form. We write logarithmic deviations from steady states with lower-case letters, except that r_t and π_t represent deviations in levels. As for persistent shocks Z^x_t, $x = \{a, b, g, i, l, u\}$, we denote their logarithmic deviations as ϵ^x_t. Temporary i.i.d. shocks are denoted as η^z_t, $z = \{p, q, r, w\}$ or υ^x_t, $x = \{a, b, g, i, l, u\}$.

Households' habit-dependent consumption is written as

$$\begin{aligned} c_t &= E_t \frac{1}{1+\theta+\beta\theta^2} \left\{ \theta c_{t-1} + (1+\beta\theta^2+\beta\theta)c_{t+1} - \beta\theta c_{t+2} \right. \\ &\quad \left. - \frac{1-\theta}{\sigma}\left((1-\beta\theta)(r_t - \pi_{t+1}) - \epsilon^b_t + (1+\beta\theta)\epsilon^b_{t+1} - \beta\theta\epsilon^b_{t+2}\right) \right\}. \end{aligned} \tag{2.13}$$

[5] As will be discussed later, natural output is defined as the level of output that would prevail under flexible prices and wages in the absence of the three "cost push" shocks, namely, the price markup shock, the wage markup shock, and the external finance premium shock.

[6] This policy rule is slightly modified from SW and LOWW where not only $\overline{\pi}_t$ but also $\overline{\pi}_t + r_\pi(\pi_{t-1} - \overline{\pi}_t) + r_y(y_{t-1} - y^*_{t-1})$ is multiplied by $1 - r_i$. Our modification enables $r_i \geq 1$ as well as $r_i < 1$ to satisfy a Blanchard-Kahn condition for plausible parameter values of r_π and r_y.

The value of capital is written as

$$q_t = -(r_t - E_t\pi_{t+1}) + \frac{1}{1-\delta+\overline{R^k}}\left\{(1-\delta)E_t q_{t+1} + \overline{R^k}E_t r^k_{t+1}\right\} + \eta^q_t. \quad (2.14)$$

$\overline{R^k}$ stands for the equilibrium real rate of return on capital. The present value of capital is equal to the present discounted value of capital and rental revenues in the next period minus the opportunity cost. η^q_t is something like an "external finance premium" shock, which represents a stochastic variation in the expected rate of return on physical capital.

Investment becomes[7]

$$i_t = \frac{1}{1+\beta}E_t\left(i_{t-1} + \beta i_{t+1} + \zeta q_t + \beta\epsilon^i_{t+1} - \epsilon^i_t\right). \quad (2.15)$$

Capital accumulation is given by

$$k_t = (1-\delta)k_{t-1} + \delta i_t - \overline{R^k}(u_t + \epsilon^u_t). \quad (2.16)$$

The higher the capital utilization rate, the faster capital is depreciated. Thus, less capital is accumulated.

Capital utilization is described as

$$u_t = \psi(r^k_t - q_t - \epsilon^u_t) - \epsilon^u_t. \quad (2.17)$$

A higher rental cost leads to greater capital utilization because households can receive higher revenues by increasing capital utilization and by renting more effective capital to firms. On the other hand, a higher q discourages capital utilization. The intuition behind this is simple. A higher q makes future capital more valuable, but greater capital utilization accelerates the speed of capital depreciation. This, in turn, discourages capital utilization.

Labor demand is given by

$$l_t = -w_t + r^k_t + u_t + k_{t-1}. \quad (2.18)$$

The market clearing condition is

$$y_t = c_y c_t + g_y\epsilon^g_t + \delta k_y i_t, \quad (2.19)$$

where c_y and g_y represent the shares of consumption and external demand relative to output.

The firm's production function is

$$y_t = \phi\left[\epsilon^a_t + \alpha(u_t + k_{t-1}) + (1-\alpha)l_t\right]. \quad (2.20)$$

Real wages are

$$\begin{aligned} w_t \;=\; & \frac{1}{1+\beta}E_t\{\beta w_{t+1} + w_{t-1} + \beta\pi_{t+1} - (1+\beta\gamma_w)\pi_t + \gamma_w\pi_{t-1} \\ & - \frac{\lambda_w(1-\beta\xi_w)(1-\xi_w)}{(\lambda_w+(1+\lambda_w)\chi)\xi_w}\left(w_t - \chi l_t - \epsilon^l_t + \frac{\beta\theta}{1-\beta\theta}(\epsilon^b_t - \epsilon^b_{t+1}) - \eta^w_t\right. \\ & \left.\left. - \frac{\sigma}{(1-\theta)(1-\beta\theta)}((1+\beta\theta^2)c_t - \theta c_{t-1} - \beta\theta c_{t+1})\right)\right\}, \end{aligned} \quad (2.21)$$

where η^w_t is a wage markup shock.

[7] This equation corrects a slight error in LOWW regarding the investment adjustment cost shock.

Inflation dynamics are described by

$$\pi_t = \frac{1}{1+\beta\gamma_p}\{\beta E_t\pi_{t+1} + \gamma_p\pi_{t-1} + \frac{(1-\beta\xi_p)(1-\xi_p)}{\xi_p}(w_t + \alpha(l_t - u_t - k_{t-1}) - \epsilon_t^a + \eta_t^p)\Big\}, \tag{2.22}$$

where η_t^p is a price markup shock.

The monetary policy rule is

$$r_t = r_i r_{t-1} + (1-r_i)\overline{\pi}_t + r_\pi(\pi_{t-1} - \overline{\pi}_t) + r_y(y_{t-1} - y_{t-1}^*) + r_{\Delta\pi}(\pi_t - \pi_{t-1}) + r_{\Delta y}((y_t - y_t^*) - (y_{t-1} - y_{t-1}^*)) + \eta_t^r. \tag{2.23}$$

This model includes 11 persistent and temporary shocks. The persistent shocks are

$$\epsilon_t^x = \rho_x\epsilon_{t-1}^x + \nu_t^x \tag{2.24}$$

$$\overline{\pi}_t = \rho_\pi\overline{\pi}_{t-1} + \nu_t^\pi, \tag{2.25}$$

where $x = \{a, b, g, i, l, u\}$.

ν_t^x, η_t^p, η_t^q, η_t^r,and η_t^w are i.i.d. shocks with mean zero and variance σ_x^2, σ_p^2, σ_q^2, σ_r^2, and σ_w^2.

2.2.2 Frictionless Economy

We formulate the monetary policy rule so that policy responds to an output gap measured as the deviation of actual output from natural output. In order to justify this formulation, we need to answer the following two questions.

The first question regards what constitutes natural output. It is conventional to define natural output as the level of output that would occur in a frictionless economy. Following SW/LOWW, this paper further assumes that, in a frictionless economy, prices and wages are perfectly flexible, and there are no cost push shocks (i.e. no price markup shock η_t^p, wage markup shock η_t^w, or external finance premium shock η_t^q). Therefore, in our frictionless economy, there will be ten equations involving ten variables, $\{c_t^*, i_t^*, y_t^*, w_t^*, l_t^*, u_t^*, q_t^*, r_t^*, r_t^{k*}, k_t^*\}$, where the asterisk superscript denotes the frictionless economy value of the variable.

The next question is why central banks should seek to stabilize this output gap. Without nominal rigidities and cost push shocks, the economy could immediately converge to its desirable level. However, their presence prevents automatic price adjustment in each market, which results in inefficient resource allocation. Therefore, from a social welfare perspective, the difference between actual and natural output, that is, the output gap, should not be allowed to become large, and this is why central banks respond to the output gap. It is here worth noting that the frictionless economy is assumed to have real rigidities (such as habit formation) as well as real shocks (such as households' preference shock) because economic fluctuations caused by real disturbances represent an economy's fundamental variations and do not result in inefficient resource allocation. Central banks thus should not try to control real disturbances.

Note that this output gap is very different from the widely-used gap defined as the deviation of demand from supply capacity. Since many economists including central bankers pay great attention to this latter gap, it may seem more reasonable to make use of this formulation. For the purposes of the current paper, however, in which we focus on normative perspectives for central banks, our formulation is the more appropriate.

The full model consists of Eq. (2.13)-(2.25) as well as log-linearized equations describing the frictionless-economy values.

3 Model Estimation

3.1 Preliminary Setting

When we estimate the model for the Japanese economy, we fix certain parameters following Fujiwara et al. (2005) who calibrate the model to match the data. For the parameters not given by Fujiwara et al. (2005), we follow LOWW. We set the capital share $\alpha = 0.37$, the discount rate $\beta = 0.995$, the steady-state capital depreciation rate $\delta = 0.06$, the output share of consumption $c_y = 0.6$, the output share of government expenditure $g_y = 0.2$, price and wage markup $\lambda_p = \lambda_w = 0.2$, and the real rate of return on capital $\overline{R^k} = 1/\beta - (1 - \delta)$.

We estimate the model using quarterly Japanese data over the period from 1981:1Q to 1995:4Q. The data set consists of eight variables: real GDP, real consumption, real investment, hours worked, real wages, the capital utilization rate, the inflation rate and the overnight call rate. Appendix A.1 gives further details about the data. A notable difference from much of the previous literature is that we use actual data on capital utilization rates. This is mainly because, as was shown in Figure 1, the utilization rates which are inferred in their methods are inconsistent with those actually observed. Since we have relatively reliable actual data series on capital utilization rates, we explicitly treat this as an observable variable. However, to be fair, we must admit the available data represents the utilization rates of only manufacturing firms.

All the variables are detrended or demeaned over the period from 1981:1Q to 2006:2Q, although we estimate the model over the period from 1981:1Q to 1995:4Q. This end period marks the point when the overnight call rate fell to 0.5%. We choose this period because we suppose that, around then, people became aware of the zero lower bound on nominal interest rates. The starting period is chosen because it marks the point since which inflation rates have been stable and low. This paper detrends four real variables (GDP, consumption, investment and real wages) allowing for kinked linear trends. All the other variables are simply demeaned[8,9]. The timings of trend breaks in the real variables are assumed to be in 1991:2Q and 2001:1Q a priori[10]. The underlying idea behind this is that there were structural changes at these points: the former corresponds to approximately when the asset price bubble burst and the economy entered a long-lasting depression; and the latter corresponds to approximately when there was a significant shift from full-time employment to part-time[11]. We admit that our choices of kinks are rather ad-hoc. It would be better for us to use a statistical test to check whether these structural changes are robust. Nevertheless, it is worth noting that, even if we assume only one kink in 1991:2Q, parameter estimates hardly change.

[8] In SW and LOWW, most of variables are linearly detrended with no kink. INW detrend data using the Hodrick-Prescott filter.

[9] Another point of detrending is that we use independent different trends for the real variables. Although this method is widely accepted, there has been a criticism against an inconsistency with the balanced growth path of these variables. One possible remedy may be to introduce investment-specific technology (Greenwood, Hercowitz and Krussel (1997, 2000)). Doing so allows for a different trend with respect to investment and output. However, even such a remedy is not fully satisfactory, because this does not allow for other important trends such as a structural change in the labor share. For this reason, we simply detrend data with independent trends.

[10] Both of these trend breaks are points when the Japanese economy entered recessions according to official determinations of the beginnings of these recessions.

[11] There is some evidence to suggest a structural change in the labor market around 2001. Kuroda and Yamamoto (2005) argue that the downward rigidity of wages disappeared from 1998 on. With the amendment of the Worker Dispatching Law in 1999 and 2004, dispatched workers were allowed to work in a wider range of industries. Looking at the trends before and after the latter break, we see an increase in the slopes of all the variables except for real wages. These changes imply that a reduction in wages induced an economic recovery, and that the economic recovery did not cause an increase in wages.

3.2 Methods

Our estimation methodology is similar to that of SW and LOWW[12,13]. We use Dynare which is a convenient tool for conducting Bayesian estimation. The Dynare toolbox derives the reduced-form representation of the DSGE model and automatically provides stability and eigenvalue analysis. In addition, it enables us to conduct Bayesian estimation. The details of the prior distributions used in this paper are given in Table 2. For the choice of the prior distributions, we mostly follow the previous literature, SW and LOWW[14]. As for the utilization adjustment cost parameter ψ, because we model capital utilization differently, we cannot use the same prior distribution. However, in both of the models, the effect of capital rental costs on utilization rates is the same: ψ. We therefore use a slightly wider (but broadly similar) prior distribution for ψ with a mean of one and a standard deviation of one. For the persistence of capital utilization shock, ρ_u, we impose the same persistence as for the other shocks. For the standard deviation of capital utilization shock, σ_u, we choose the value using a rough grid-search so that it maximizes the value of the likelihood function. Given the prior distributions, Dynare calculates the posterior distributions using a Metropolis-Hastings Markov chain Monte Carlo (MCMC) algorithm. We sample two separate chains for 500,000 periods each, discarding the first 250,000 periods. Using potential scale reduction statistics developed by Brooks and Gelman (1998), we confirm that convergence for all the parameters is achieved.

3.3 Results: Estimated Parameters

Figures 8 to 11 show the prior and posterior distributions of the parameters, and Table 3 reports the posterior means and 90% confidence intervals for the parameters. Several important parameters are worth comment[15].

Regarding inflation dynamics, the Calvo price-setting parameter ξ_p is 0.88, which implies that the average contract duration of price setting is about eight quarters. This duration is longer than that obtained in micro-based estimation (Bils and Klenow (2004), Dhyne et al. (2005), Saita et al. (2006))[16]. The Calvo wage-setting parameter ξ_w is 0.52, which suggests

[12] In estimating the model, we omit the shock η_t^q. This is because this shock (unlike the others) is not derived from the structure of the model. We note that omitting the shock hardly changes our results.

[13] Following SW/LOWW, we normalize the stochastic shocks in the estimation procedure. This implies that in the case of the consumption preference, government spending, investment, and the two markup shocks, the estimated standard deviation does not correspond to the standard deviation of the corresponding shocks in Eq. (2.13) to (2.23).

[14] All the variances of the shocks are assumed to be distributed according to an inverted Gamma distribution with a degree of freedom equal to one. For the parameter on fixed costs, we impose a narrow prior distribution referring to Basu (1996), Basu and Fernald (1997) and LOWW.

[15] Although both estimations are based on the Japanese economy, we find some differences with the estimation results in INW. The reasons are as follows. As is discussed above, INW do not use actual data on capital utilization. The model of capital utilization is different from ours: it is the same as that of CEE/SW/LOWW. Second, the method of detrending the data is also different. INW use the Hodrick-Prescott (HP) filter for all the variables. However, using the HP filter is subject to criticism, because of arbitrariness and because there is a danger of underestimating the cyclical movement (e.g. see McCallum (2000)). Furthermore, detrending both nominal interest rates and inflation rates is problematic because it implies that they continue to increase or decrease in the future. Thirdly, INW use the GDP deflator instead of the CPI to provide data on inflation rates. Fourthly, they do not take account of the effect of *jitan*, a statutory decrease in hours worked in the late 1980s and the early 1990s. *Jitan* affects the structural paths of hours worked and real wages, so it is important to carefully detrend these data. For these reasons, we must be careful in comparing our results with INW even though both are applied to the Japanese economy.

[16] It is widely known that macro-based estimation tends to report a higher probability that prices remain unchanged than micro-based estimation. This longer duration may reflect the underlying specification of the real

that the average contract duration for wages is about two quarters. This wage flexibility looks a little too high considering that our wage data do not include bonuses which are normally paid twice a year and that, in what is known as *base-up* or *shunto*, salary is normally reviewed every April. Nevertheless, this result is consistent with Yoshikawa (1992), which argues that Japanese wages are far more flexible than Europe and the U.S.

As for other structural parameters, the parameter for the intertemporal substitution of consumption, $1/\sigma$, is about 0.8. This value lies between 0.5 and 1, which is widely seen in estimation and calibration in macroeconomic models. The parameter for labor supply substitution, $1/\chi$, is about 0.5, which is close to those of SW and LOWW. The parameter for investment adjustment costs, $1/\zeta$, is about 6, which is larger than that of LOWW, 2, but very close to that of SW, 7. The parameter for the consumption habit persistence, θ, is about 0.1, which is very small compared to those in SW/LOWW/INW[17]. Finally, the parameter for capital utilization adjustment costs, ψ, is about 2. Since our model differs from those of SW/LOWW/INW in the setup of capital utilization, direct comparison might be misleading, but our value is lower than that of SW, higher than that of LOWW, and one order higher than that of INW[18].

Regarding monetary policy parameters, the coefficient on lagged interest rates in the monetary policy rule, r_i, is 0.84. This implies that monetary policy has a very high inertia[19]. The coefficients on both the output gap and its change are positive and significant, and larger than those in SW and LOWW. The persistence parameter, ρ_π, is estimated as 0.97. This implies that the time for the target inflation to converge half the way to equilibrium is roughly six years.

3.4 Movement of Capital Utilization Rates

Figure 3 compares the movement of estimated and actual utilization rates. This figure looks much better than Figure 1 which was based on the CEE/SW/LOWW model. We find that our model explains the sizable decline in utilization rates in the early 1990s and their recovery in 1994-5 well. As Eq. (2.17) suggests our model does not require a strictly positive correlation between capital rental costs and utilization rates (the empirical relationship between these is shown in Figure 2). This helps to improve the goodness of fit. We admit, however, that the goodness of fit in the early 1980s is not so good. We will discuss possible reasons and remedies for this in our conclusion.

marginal costs. SW point out that while individual households' marginal costs of supplying labor are upward-sloping, the marginal cost curve in the intermediate goods sector is the same for all firms. For a given elasticity of prices to real marginal cost, this will tend to bias upward the estimate of Calvo price stickiness. Firm-specific investment, for example, may well help decrease the estimate of ξ_p (Woodford 2003). Another reason is related to the inflation indexation parameter γ_p estimated as high as $\gamma_p = 0.8$. Through indexation, firms can adjust their prices in a rather flexible manner although their price setting is still not optimal. Micro-based estimation seems to include such non-optimal indexation when estiamting the frequency of price revision. The third reason is that this paper uses the CPI. Final goods prices recorded in the CPI tend to be more sticky than those for intermediate and investment goods. Koga and Nishizaki (2005) compare the results obtained using the GDP deflator with those obtained using the CPI, and find higher price flexibility when they use the GDP deflator.

[17] Such a discrepancy may be due to our and LOWW's assumption of "internal habit preference" as opposed to SW and INW's "external habit preference." In fact, the value estimated by LOWW is 0.3, and is the closest to ours.

[18] However, this value is far lower than that calibrated in CEE, which is 100.

[19] A high inertia of monetary policy is observed in previous literature on Japan, too. For instance, Oda and Nagahata (2005) report 0.8, and INW report 0.7 although their specifications are different from ours in their definitions of output gaps, sample periods, and in that they do not include terms for target inflation, the change in inflation, or the change in the output gap.

Figure 3: Actual and estimated utilization rates. Shaded areas represent recessions.

3.5 Driving Force behind Japanese Business Cycles

In this subsection we investigate the following question: What is the driving force behind the Japanese business cycles[20]?

Figure 4 depicts the impulse responses of endogenous variables to productivity shocks for the ten years following each of the shocks (Other impulse responses will be shown later). The horizontal axis represents time on a quarterly scale, and the vertical axis represents percentage deviations from equilibrium[21]. The magnitude of each shock is one standard error. Due to the parameter uncertainty surrounding the posterior distribution of parameters, impulse responses fall within a certain confidence interval. The lines in the figures represent 10% gradations in the confidence level.

When there is a positive productivity shock, hours worked and inflation rates decrease. The logic runs as follows. An increase in productivity means that less work is required to produce the same amount of goods, so hours worked decrease. The productivity shock also increases the marginal product of labor, in turn decreasing real marginal costs. Thus, inflation rates decrease. Such responses are very important in considering whether the productivity shock is the main driving force behind economic fluctuations. If so, an economic expansion should see a decrease in both hours worked and inflation rates. However, this is not observed in reality. Therefore, we might better argue that economic fluctuations are affected mainly by other shocks such as

[20] Kim (1999) finds that the relative contribution of monetary policy shocks to output fluctuations is moderate even though they have a significant effect on output in Japan. Miyao (2002) calculates the historical decomposition of real output and concludes that real disturbances account for most of the output movements for the pre- and post-bubble period in Japan, while other factors such as stock price shocks mattered during the bubble period. However, it should be noted that these studies are based on a structural VAR approach; the number of identified disturbances is limited; and identification is highly dependent on assumptions about the properties of disturbances. Our paper, on the other hand, can identify as many as ten structural disturbances by using a model with micro foundations.

[21] Inflation and interest rates are not annual but quarterly.

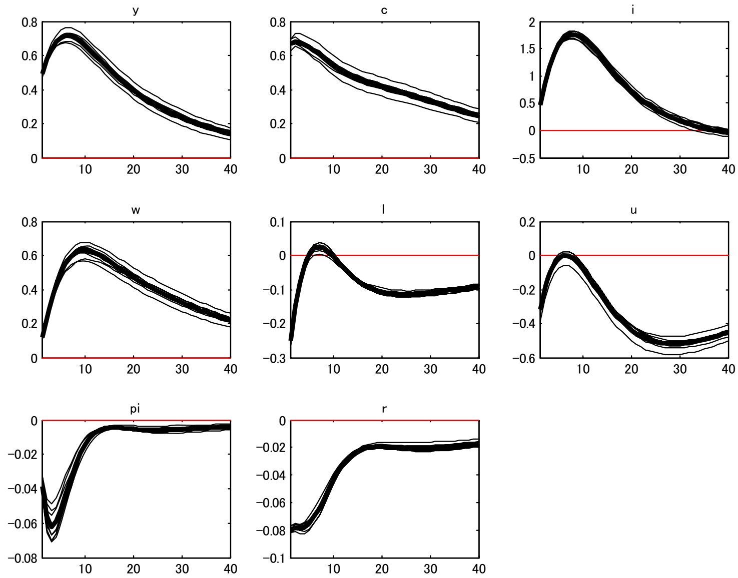

Figure 4: Impulse responses to a productivity shock

demand or nominal shocks (see Gali (1999)).

Tables 4 and 5 provide a variance decomposition demonstrating the contribution of each shock to the forecast error variance of the endogenous variables at horizons of 1, 4, 10, and 30 quarters.

We find that a productivity shock has a not insignificant impact, but the effect of monetary policy shocks is far smaller[22]. Regarding hours worked, the contribution of demand shocks, in particular an investment adjustment cost shock and an external demand shock, looks considerable while that of preference shocks is very small[23]. In $T = 1$ and 4, the investment adjustment cost shock causes significant variations in investment and output. These results imply that, over a short horizon, the increase in output and hours worked usually observed in economic booms is caused mainly by the investment adjustment cost shock rather than a productivity innovation or a change in households' preferences[24]. In the medium-term, however, the productivity shock is the dominant driving force.

4 Effect of Monetary Policy Shocks

CEE seek to understand the inertial behavior of inflation in response to monetary policy shocks, as observed in the U.S. By using a structural VAR approach, Kim (1999) and Shioji (2000) also find a similar phenomenon in Japan. To explain the hump-shaped and persistent inflation

[22] This calculates only the contribution of monetary policy *shocks* as a deviation from a specific policy reaction function, so this result does not mean that monetary policy itself has limited impact.

[23] Some people regard preference and labor disutility shocks as demand shocks because they enter households' utility and affect consumption. In contrast, we follow the treatment in SW, and interpret preference, investment adjustment cost, and external demand shocks as demand shocks.

[24] Focusing on the determinants of the nominal side of the economy, that is, nominal interest rates and inflation, we find that variations are mainly driven by target inflation shocks. In addition, productivity shocks and price markup shocks also have significant impacts on inflation.

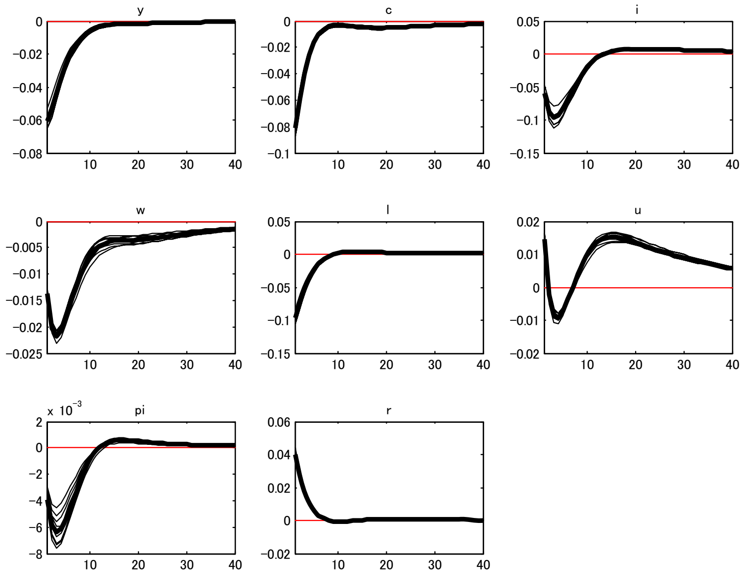

Figure 5: Impulse responses to an interest rate shock

behavior in response to a contractionary monetary policy shock, CEE advocate treating capital utilization costs not as capital depreciation but as additional spending on goods. Their assumption plays a role in ensuring that capital utilization rates fall in response to a contractionary monetary policy shock, generating a modest fall in the rental cost of capital. They also point out that if the cost of capital utilization is modeled as a faster capital depreciation rate, then a contractionary monetary policy shock raises capital utilization rates.

CEE's point can be confirmed in Figure 5, which shows the impulse response of utilization rates to a tightening monetary policy shock. In our model, the short-run policy tightening given by η^r increases utilization rates on impact, while it decreases the utilization rates in CEE/SW/LOWW. Notice that in SW, policy tightening decreases the rental cost of capital, r_t^k, and decreases capital utilization. In addition to this effect, in our model, policy tightening also decreases the value of capital, q_t, since real interest rates increase. As can be seen from Eq. (2.17), this effect encourages capital utilization because households do not need to pay much attention to the depreciation of capital. Which effect dominates depends on the deep parameters of the model. Figure 5 shows that, on impact, the utilization rate increases since the latter effect dominates the former.

The capital utilization rate, however, quickly drops and becomes negative for a period. This makes the decline in real marginal costs mild, which helps yield the hump-shaped behavior of inflation in response to a contractionary monetary policy shock. The implication of CEE's argument is that, with our model following Greenwood et al. (1988), Q should be the dominant factor affecting utilization rates, rather than rental costs, so that policy tightening would generate an increase in capital utilization for a certain period. However, this argument is largely subject to parameter values, in particular the value of the investment adjustment costs parameter. Figure 6 demonstrates the impulse responses of four variables to the same policy shock for three different values of investment adjustment costs parameter. If the adjustment cost is small, i.e. $\zeta^{-1} = 0.01$, then capital can become volatile, and the deviation of Q from its equilibrium value becomes negligible. The effect of rental costs dominates that of Q, which makes

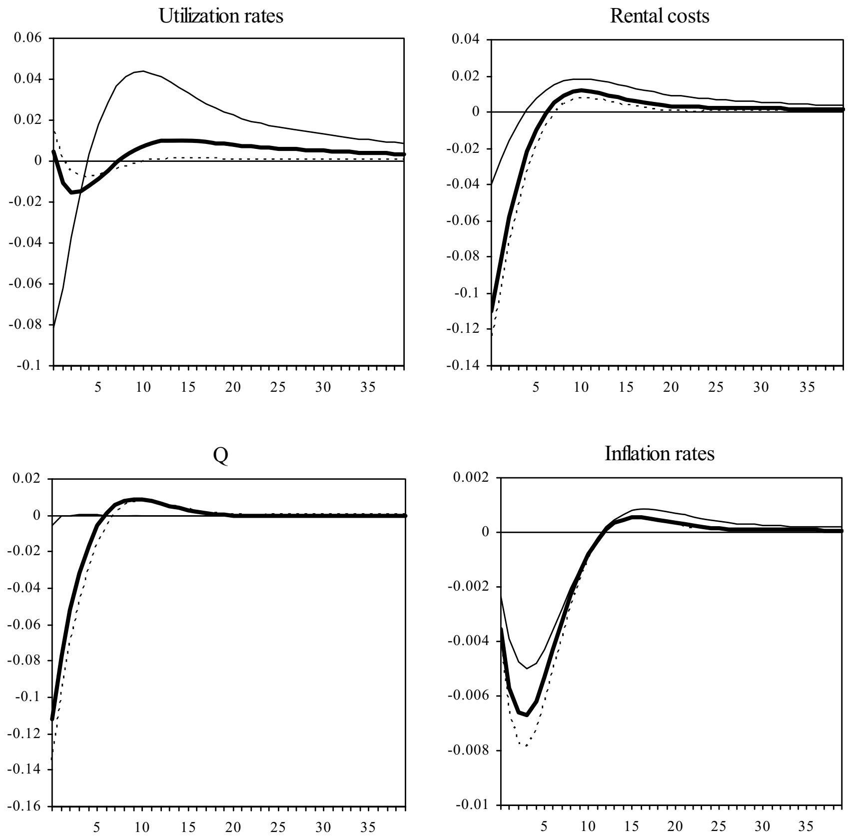

Figure 6: Impulse responses to an interest rate shock for different values of the investment adjustment costs parameter. Solid thick lines represent the baseline case. Solid thin and broken lines represent the case of $\zeta^{-1} = 0.01$ and $\zeta^{-1} = 100$ respectively.

the response close to that in the CEE model. On the other hand, if adjustment costs are large, i.e. $\zeta^{-1} = 100$, then it becomes important for households to take account of the future capital stock and thus the value of Q. This amplifies the effect of Q on capital utilization rates. Hence, policy tightening causes utilization rates to rise on impact, and this positive effect on utilization rates is still evident in later periods long after the shock (i.e. in line with CEE's argument). Yet even with such a high value of adjustment costs, capital utilization rates still turn negative a couple of quarters after the policy shock. Qualitatively, what CEE point out is true, but quantitatively, it does not seem to be a serious matter when we consider the overall impulse response of utilization rates and inflation to a monetary policy shock.

Moreover, the point raised by CEE becomes even less convincing when we check the impulse responses to a target inflation shock. As Figure 7 demonstrates, a positive policy shock $\overline{\pi}$, or policy accommodation, increases utilization rates even on impact[25]. Such an effect is perfectly in line with the CEE model. Moreover, according to variance decomposition, the effect of the target inflation shock is much larger than that of the i.i.d. interest rate shock, so it looks more sensible to focus on the effect of the target inflation shock.

[25] Despite the accommodating policy, nominal interest rates increase. This is because the medium-run equilibrium level of nominal interest rates rises in proportion to the rise in medium-term target inflation. Real interest rates fall, however, which increases consumption and investment.

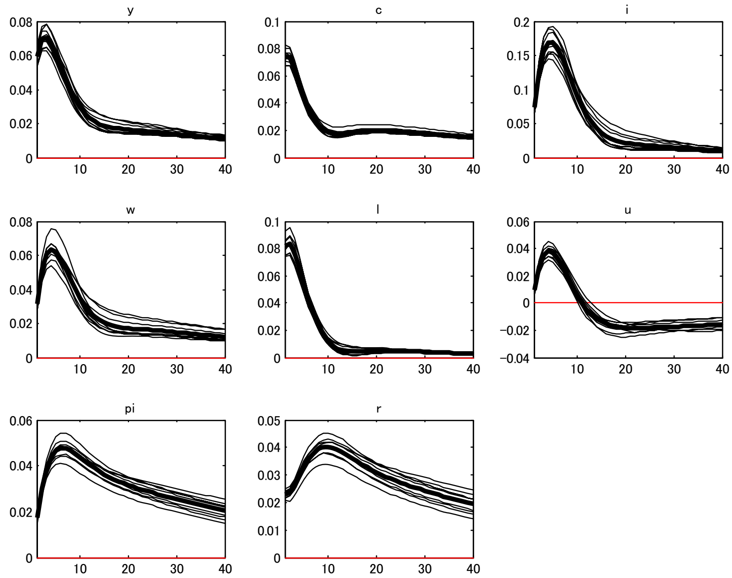

Figure 7: Impulse responses to a target inflation shock

The above reasons explain why inflation exhibits a hump-shaped and persistent response to both monetary policy shocks. While we admit that the model's success in recreating this response also owes something to inflation indexation, we still feel very confident in using the model of Greenwood et al. in preference to that of CEE/SW/LOWW.

5 Concluding Remarks

This paper formulates a medium-scale DSGE model and applies it to the Japanese economy. It employs estimation using Bayesian techniques, and obtains plausible results for structural and policy parameters, impulse responses, variance decomposition, and the movement of capital utilization rates.

If we apply the same method as SW and LOWW, we encounter problems – in particular the inconsistency between the movement of implied and actual capital utilization rates. This paper has thus made two main modifications. Firstly, we use actual capital utilization rate data for estimation. Secondly, we modify the CEE/SW/LOWW model with respect to capital utilization rates following Greenwood et al. (1988). In short, we assume that the cost of capital utilization is not to cause additional expenditure on goods but to accelerate capital depreciation. This enables us to incorporate a negative correlation between the capital utilization rate and the rental cost of capital and to make the movement of estimated capital utilization rates fall almost in line with the observed data.

A remaining task, however, is to improve the goodness of fit of the estimation[26]. As was mentioned in Section 3.4, estimated capital utilization rates do not quite coincide with those observed. As a possible reason for this, we suspect that, in our model, the adjustment of wages

[26] The other anomalies we have found in this study are (1) high pro-cyclicality of productivity growth rates, (2) unexplained movement of the output gap in some periods, (3) a lack of strength in the relationship between real marginal costs and inflation rates.

and labor is far slower than that of capital. This makes rental costs, or the relative productivity of capital over labor, highly dependent upon effective capital. This may make rental costs seem negatively correlated with utilization rates.

One way of dealing with this would be to incorporate the movement of wages and labor into the model, such as by introducing a model of effective labor. If wages and labor were more volatile and procyclical, then productivity growth would become less pro-cyclical. This could be achieved, for example, by incorporating labor hoarding or overhead labor[27]. Another and more promising remedy is to incorporate unemployment. Widely-accepted DSGE models are based on the model of full-employment, and ignore the existence of involuntary labor slack. This is truly an important factor which we should not overlook. Some economists have attempted the difficult task of combining unemployment with Real Business Cycle or New-Keynesian models[28]. Incorporating real side costs as opposed to monetary frictions will certainly open up our understanding of the macroeconomy and help us to construct better models.

Finally, up to now, we have not discussed the issue of optimal monetary policy. Appendix A.3 attempts to make a first step in this direction by investigating how social welfare is characterized in our medium-scale DSGE model. We expect that this investigation will help us to identify the most appropriate variables for central banks to stabilize.

A Appendix

A.1 Data Description

This appendix explains our dataset. Our data range from 1981:1Q to 2006:2Q. But for our baseline estimation, the data range from 1981:1Q to 1995:4Q. We use eight variables: real GDP, real consumption, real investment, hours worked, real wages, the capital utilization rate, the inflation rate and the overnight call rate. Their sources are summarized in Table 1. All the variables are detrended or demeaned (see Section 3.1 for detailed discussion), and represented as log deviations in percent. Except for the call rate, all the variables are seasonally adjusted. Inflation and call rates are given on a quarterly basis.

Regarding hours worked and real wages, we adjust for the effect of *jitan*, a decrease in the number of statutory workdays per week. However, we must admit that it is impossible to perfectly adjust for this effect because we cannot accurately tell how much and when *jitan* influenced hours worked. There were two periods when *jitan* was gradually introduced, 1988:1Q to 1993:4Q and 1997:2Q to 1998:4Q, while the extent of *jitan* varied across firms. We therefore take an approximation by assuming that hours worked per workday remained unchanged in spite of *jitan*. Thanks to this assumption, we may use the series of 'total hours worked' divided by 'workdays' as hours worked. Both data series are available. Furthermore, we assume that monthly salary remained unaffected by *jitan*. Then, we use the series 'monthly salary' divided by hours worked and by the price index (CPI) as real wages. Another point to make concerning hours worked is that we do not include the number of workers. We do this following LOWW. This treatment is further justified by Braun et al. (2006), who point out that, compared with the U.S., Japan's business cycles are largely caused by the fluctuations of hours worked.

Capital utilization rates are available only for manufacturing firms. Meanwhile, manufacturing firms account only for twenty percent of GDP, and non-manufacturing firms may adjust capital utilization rates to a lesser extent than manufacturing firms. Hence, simply using

[27] See Rotemberg and Woodford (1999) for related discussion. Such a modification can be done rather easily, but according to our trial, the degree of effective labor is estimated to be unrealistically high.

[28] For example, see Merz (1995), Walsh (2005), and Blanchard and Gali (2006).

released statistics may result in over-estimating the effect of capital utilization. This paper therefore makes the following admittedly ad hoc adjustment: we multiply our data series by 0.6, on the assumption that half of non-manufacturing firms have the same utilization rates as manufacturing firms and that the other firms keep utilization rates constant[29].

A.2 Model in CEE/SW/LOWW

In contrast to the treatment in this paper, the adjustment cost of capital utilization in CEE/SW/LOWW is assumed to be incurred by households. Note also that the functional form for the adjustment costs of capital utilization is given by

$$\Psi(Z_t^U U_t(h)) = \mu \frac{\{Z_t^U U_t(h)\}^{1+\psi^{-1}} - 1}{1+\psi^{-1}}.$$

The household budget constraint is given by

$$\begin{aligned} & \frac{B_{t-1}(h)}{P_t} + W_t(h)L_t(h) + R_t^k U_t(h) K_{t-1}(h) + \Pi_t(h) \\ \geq \; & \Psi(Z_t^U U_t(h))K_{t-1} + C_t(h) + I_t(h) + b_t \frac{B_t(h)}{P_t}. \end{aligned} \tag{A.1}$$

The first term on the right hand side is a new term representing additional demand for goods due to capital utilization. The market clearing condition is transformed into

$$Y_t = C_t + G_t + I_t + \Psi(Z_t^U U_t(h))K_{t-1}. \tag{A.2}$$

The depreciation rate of capital becomes constant as

$$\delta(U_t(h)) = \delta. \tag{A.3}$$

With this setup, we can obtain the following log-linearized equations:

$$k_t = (1-\delta)k_{t-1} + \delta i_t \tag{A.4}$$
$$u_t = \psi r_t^k - \epsilon_t^u \tag{A.5}$$
$$y_t = c_y c_t + g_y \epsilon_t^g + \delta k_y i_t + \overline{R^k} k_y (u_t + \epsilon_t^u), \tag{A.6}$$

while the other equations are the same as before. For the following discussion, we also write down the labor demand function:

$$l_t = -w_t + r_t^k + u_t + k_{t-1}. \tag{A.7}$$

Let us firstly present results when we estimate the above CEE/SW/LOWW model of capital utilization rates without using actual data for the capital utilization rates. In doing so, we omit the capital utilization adjustment cost shock, ϵ_t^u, from the above equations. Table 6 shows the posterior distribution of parameters estimated from 1981:1Q to 1995:4Q by sampling two separate chains for 300,000 periods. There are very few differences from those of our baseline

[29] Actually, there is an alternative approach that involves using Hara et al. (2006). They calculate the utilization rates of both manufacturing and non-manufacturing firms from some other statistics. However, we adopt the approach described here because we want to use raw data as much as possible. Moreover, estimating our model using the alternative approach hardly changes our result.

model, but we find a big decrease in the parameter for capital utilization adjustment costs, ψ. Of course, we have to note that the definition of the parameter is different between the two models but that the impact of rental costs on capital utilization rates in both is given by this same parameter ψ.

Another distinct contrast from our method is the movement of inferred utilization rates. As was shown in Figure 1, inferred utilization rates look hugely different from actual ones. Of course, we do not take the utilization rate data at face value because our statistics are limited only to manufacturing firms. However, the inferred utilization rates move far less strongly than actual ones.

Motivated by dissatisfaction with the above result, the next attempt is to use actual capital utilization rate data while maintaining the framework of the CEE/SW/LOWW model. Since we add one observed variable, we include and estimate the capital utilization adjustment cost shock.

In doing so, we notice that the model cannot be well estimated. Simply stated, this is because estimated rental costs are highly negatively correlated with capital utilization rates (see Figure 2) while, in the CEE model, they should be positively correlated. In order to understand this in detail, let us examine what happens in this model. The equation governing the motion of capital has no shock component, so after setting its initial value, the movement of capital is completely determined by the movement of actual investment. Therefore, in Eq. (A.7), rental costs become virtually the only unobserved or unknown variable, and are determined from this equation. Observed wages and hours worked are stable, and any substantial variability in this equation comes from variation in utilization rates. Rental costs thus have an almost negative correlation with utilization rates as was shown in Figure 2. To put it differently, rental costs describe the relative profitability of using capital as opposed to using labor, and this value becomes smaller as capital is more utilized. However, this negative correlation between utilization rates and rental costs contradicts Eq. (A.5) which requires a positive correlation[30]. This explains why the model cannot be well estimated once we incorporate the data on capital utilization rates.

On the other hand, in our model, Eq. (A.5) is altered to Eq. (2.17). Since there is an additional term, the value of capital Q, the model no longer requires strong positive correlation between utilization rates and rental costs.

A.3 Social Welfare Analysis

This appendix aims to analyze social welfare. This study is important because one of the objectives of central banks is considered to be to maximize social welfare. In the presence of frictions such as sticky prices and wages, when shocks arise the economy cannot immediately and costlessly return to desirable states, and households' utility declines. This appendix calculates the social welfare costs of business cycles from our model and considers what kind of factors strongly affect these welfare costs. Such a study is expected to provide a useful guideline as to which variables central bankers should stabilize. In a simple New-Keynesian model with purely forward-looking IS and Phillips curves, it is known that the social welfare loss function can be written as

$$L = \pi^2 + \lambda(y - y^*)^2,$$

where the second term represents the output gap[31]. However, this function needs to be modified in more realistic models. For instance, if we consider sticky wages, then the loss function comes

[30] This contradiction is squeezed into the utilization adjustment cost shock, which results in extremely strong comovement with actual utilization rates.

[31] See Woodford (2003).

to depend on wages. If inflation itself has persistence, then the loss function comes to depend on the past inflation rate. Since our model is not small, it is very difficult for us to analytically derive a social loss function. To begin with, we thus calculate not the loss function but the value of social welfare losses numerically[32].

A.3.1 Social Welfare Losses due to Business Cycles

According to numerical calculation, with central banks following a policy reaction function from 1981 to 1995, social welfare losses due to business cycles amount to approximately a one percent reduction in steady-sate consumption. This value is far larger than the 0.05% which Lucas (2003) derives from using a consumption equation with U.S. data. However, our value is about half of that obtained by LOWW, 2.6%, who use almost the same model as ours. This discrepancy is because, in Japan, both wage stickiness and the standard deviation of wage markup shocks are estimated to be lower. Lower stickiness of wages is consistent with Yoshikawa (1992), but considering some of the problems surrounding the labor market formalization, it would be sensible to maintain some reservations about these results[33].

A.3.2 Deriving a Welfare Loss Function

It is true that it is extremely difficult to analytically derive a welfare loss function in medium-scale DSGE models, but in order to conduct monetary policy, it is still very important to see which variables central banks should stabilize. In order to grasp some intuitions about this, we devise a method of calculating an approximate welfare loss function as follows[34].

Define a vector of structural shocks as e. These shocks have a variance of

$$\Sigma = E(ee'), \tag{A.8}$$

and are independent of each other, that is, $E(e_i e_j) = 0$ for $i \neq j$. Provided that households maximize their utility and that there is no efficiency loss in steady state, these shocks have a second order effect on utility U:

$$U = e'Me. \tag{A.9}$$

M is a matrix of coefficients representing the extent to which utility is affected by the shocks[35]. We also define

$$y = Ae. \tag{A.10}$$

where y is a vector of "target variables", for example including inflation, wage inflation, and an output gap. Matrix A represents the extent to which y is affected by the shocks.

[32] To this end, we modify the code used by LOWW and use Dynare.

[33] See our concluding remarks.

[34] There exist previous attempts in the literature to derive a loss function in a similar model. Onatski and Williams (2004) derives an analytical form of a loss function with ten independent variables $S_t = (Y_t, K_t, K_{t-1}, u_t, G_t, \epsilon_t^i, I_{t-1}, \epsilon_t^a, \epsilon_t^b \epsilon_t^l)$ in addition current and lagged inflation and wages, and reports that the loss function may be approximated as

$$\pi_t^2 + 0.21K_t^2 - 0.51\pi_t\pi_{t-1} + 0.24(w_t + \pi_t)(w_t - w_{t-1}).$$

In short, the loss function depends not only on inflation rates but also on wages and lagged capital stocks.

However, it seems that their analysis has a serious problem. This is because the vector S_t contains a number of variables which affect current inflation and wages. For instance, the productivity shock, ϵ_t^a, has a negative influence on the current inflation rate, so it is not appropriate to include this shock.

[35] With the help of Dynare, if we assume a specific form of monetary policy reaction function, this matrix can be numerically obtained by second order approximation.

Here, let us assume that y has fewer elements than the vector of shocks e. This means that we cannot accurately write utility U with respect to y. In the case of our model, which has ten structural shocks, we cannot accurately write utility as a function of inflation, wage inflation and the output gap. However, if we know the variance of the shocks (Eq. (A.8)) from estimation or prior knowledge, by using Eq. (A.10) and observing y, we can infer what kind of shocks occur. Then from Eq. (A.9), we can infer the utility U. Regarding the optimal method to infer U, we obtain the following proposition.

Proposition 1 *With respect to y, utility U is optimally approximated as*

$$U \sim y'Py \tag{A.11}$$
$$P = (A\Sigma A')^{-1}A\Sigma M\Sigma A'(A\Sigma A')^{-1}. \tag{A.12}$$

Proof. *Find a matrix P so that*

$$\arg\min E[U - y'Py]^2.$$

Expanding this leads to

$$\begin{aligned} E[U - y'Py]^2 &= E[e'Me - y'Py]^2 \\ &= E[e'Mee'Me + y'Pyy'Py - 2e'Mey'Py] \\ &= Ee'[Mee'M + A'PAee'A'PA - 2Mee'A'PA]e \\ &= [M_{jk}\Sigma_{kk}M_{kj} + A_{ij}P_{ik}A_{kl}\Sigma_{ll}A_{ml}P_{mn}A_{nj} - 2M_{ji}\Sigma_{ii}A_{ki}P_{kl}A_{lj}]\Sigma_{jj}, \end{aligned}$$

because $E(e_ie_j) = 0$ *for* $i \neq j$. *Differentiating this with respect to* P_{uv} *yields*

$$\begin{aligned} 0 &= [A_{uj}A_{vl}\Sigma_{ll}A_{ml}P_{mn}A_{nj} - M_{ji}\Sigma_{ii}A_{ui}A_{vj}]\Sigma_{jj} \\ &= A_{uj}\Sigma_{jj}A_{nj}P_{nm}A_{ml}\Sigma_{ll}A_{vl} - A_{ui}\Sigma_{ii}M_{ij}\Sigma_{jj}A_{vj} \end{aligned}$$

because P and M are obviously symmetric. This can be simplified as

$$0 = A\Sigma A'PA\Sigma A' - A\Sigma M\Sigma A'.$$

Thus we can obtain

$$P = (A\Sigma A')^{-1}A\Sigma M\Sigma A'(A\Sigma A')^{-1}.$$

■

Applying this proposition, we obtain the loss function approximated as[36,37]

$$\pi^2 + 1.9\pi_w^2 + 1.8(y - y^*)^2 - 0.1\pi\pi_w + 0.6\pi(y - y^*) + 0.2\pi_w(y - y^*). \tag{A.13}$$

Compared with the coefficient on inflation, those on wage inflation and the output gap become almost twice as large. In other words, social welfare depends more on wage inflation and the output gap than on inflation. This result is consistent with LOWW, who propose a monetary policy rule reacting not to inflation but to wage inflation, based on numerical calculation of social welfare.

[36] In order to calculate M and A, we use an estimated policy reaction function from 1981 to 1995. The same estimation provides Σ. It is important to be aware that a different policy rule may yield a different result.

[37] Notice that this calculation takes account only of the impact of current shocks on welfare. By assuming that the economy was in steady state before, we neglect the impacts of predetermined variables such as capital on welfare.

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Table 1: Data sources

Variables	Sources
Real GDP	Cabinet Office "National Accounts"
Real consumption	Cabinet Office "National Accounts"
Real investment	Cabinet Office "National Accounts"
Hours worked	Ministry of Health, Labour and Welfare "Monthly Labor Survey"
Real wages	Ministry of Health, Labour and Welfare "Monthly Labor Survey" Ministry of Internal Affairs and Communications "Consumer Price Index"
Capital utilization rates	Ministry of Economy, Trade and Industry "Indices of Industrial Production"
Inflation rates (excluding fresh food)	Ministry of Internal Affairs and Communications "Consumer Price Index"
Overnight call rates	Bank of Japan

Table 2: Prior distribution of parameters

Parameters	Descriptions	Distribution	Mean	S.D.
Structural parameters				
θ	consumption habit	beta	0.7	0.15
σ	inverse of the elasticity of substitution	normal	1	0.375
χ	inverse of the elasticity of work	normal	2	0.75
$1/\zeta$	investment adjustment costs	normal	4	1.5
ψ	inverse of the elasticity of capital utilization costs	normal	1	1
$\phi - 1$	fixed-cost share	gamma	0.075	0.0125
ξ_p	probability of no price revision	beta	0.375	0.1
ξ_w	probability of no wage revision	beta	0.375	0.1
γ_p	price indexation	beta	0.5	0.25
γ_w	wage indexation	beta	0.5	0.25
Policy parameters				
r_i	lagged interest rate	normal	1	0.15
r_π	inflation	normal	0.5	0.2
r_y	output gap	normal	0.01	0.1
$r_{\Delta\pi}$	change in inflation	normal	0.1	0.1
$r_{\Delta y}$	change in output gap	normal	0.1	0.5
S.D. of shocks				
σ_a	productivity shock	inv. gamma	1	inf
σ_π	target inflation shock	inv. gamma	0.1	inf
σ_b	preference shock	inv. gamma	0.1	inf
σ_g	external demand shock	inv. gamma	0.4	inf
σ_l	labor supply disutility shock	inv. gamma	2	inf
σ_i	investment adjustment cost shock	inv. gamma	1	inf
σ_u	utilization adjustment cost shock	inv. gamma	0.5	inf
σ_r	interest rate shock	inv. gamma	0.1	inf
σ_q	external finance premium shock	-	-	-
σ_p	price markup shock	inv. gamma	0.2	inf
σ_w	wage markup shock	inv. gamma	0.2	inf
Persistence of shocks				
ρ_a	productivity shock	beta	0.85	0.1
ρ_π	target inflation shock	beta	0.85	0.1
ρ_b	preference shock	beta	0.85	0.1
ρ_g	government spending shock	beta	0.85	0.1
ρ_l	labor supply disutility shock	beta	0.85	0.1
ρ_i	investment adjustment cost shock	beta	0.85	0.1
ρ_u	utilization adjustment cost shock	beta	0.85	0.1

Table 3: Posterior distribution of parameters

Parameters	SW (2003) mean	OW (2004) mean	LOWW (2005) mean	INW (2006) mean	This paper mean	This paper 90 % interval
Structural parameters						
θ	0.592	0.4	0.294	0.641	0.102	0.042 - 0.164
σ	1.391	2.178	2.045	2.041	1.249	0.960 - 1.522
χ	2.503	3	1.405	2.427	2.149	1.764 - 2.532
$1/\zeta$	6.962	6.579	1.822	8.338	6.319	4.297 - 8.266
ψ	4.975	2.8	0.198	0.182	2.370	1.398 - 3.336
$\phi - 1$	0.417	0.8	0.082	0.581	0.084	0.061 - 0.106
ξ_p	0.905	0.93	0.824	0.65	0.875	0.8844 - 0.914
ξ_w	0.742	0.704	0.807	0.367	0.516	0.428 - 0.599
γ_p	0.477	0.323	0.116	0.613	0.862	0.740 - 0.995
γ_w	0.728	0	0.0773	0.578	0.246	0.011 - 0.458
Policy parameters						
r_i	0.956	0.962	0.832	0.682	0.842	0.725 - 0.957
r_π	0.074	0.152	0.460	0.505	0.606	0.481 - 0.729
r_y	0.004	0.004	0.000	0.017	0.110	0.046 - 0.170
$r_{\Delta\pi}$	0.151	0.14	0.285	-	0.250	0.133 - 0.366
$r_{\Delta y}$	0.158	0.159	0.481	-	0.647	0.445 - 0.864
S.D. of shocks						
σ_a	0.639	0.343	0.594	11	0.843	0.717 - 0.970
σ_π	0.033	1	0.107	-	0.062	0.032 - 0.091
σ_b	0.407	0.24	0.121	7.7	0.102	0.063 - 0.138
σ_g	0.335	0.354	0.285	4.3	0.403	0.344 - 0.462
σ_l	3.818	2.351	2.322	7.4	1.538	1.073 - 2.085
σ_i	0.113	0.059	1.035	4.6	1.413	1.134 - 1.681
σ_u	-	-	-	-	0.646	0.522 - 0.766
σ_r	0.089	0	0	1.1	0.066	0.025 - 0.110
σ_q	0.613	7	3.678	11.4	-	- - -
σ_p	0.165	0.172	0.205	24.5	0.151	0.123 - 0.179
σ_w	0.297	0.246	0.299	7.9	0.212	0.174 - 0.249
Persistence of shocks						
ρ_a	0.811	0.957	0.961	0.851	0.949	0.926 - 0.976
ρ_π	0.855	0.582	0.994	-	0.974	0.952 - 0.998
ρ_b	0.838	0.876	0.944	0.368	0.892	0.827 - 0.957
ρ_g	0.943	0.972	0.942	0.792	0.960	0.931 - 0.990
ρ_l	0.881	0.974	0.980	0.462	0.563	0.379 - 0.727
ρ_i	0.913	0.943	0.731	0.871	0.350	0.247 - 0.455
ρ_u	-	-	-	-	0.901	0.850 - 0.958

Table 4: Variance decomposition

Nominal interest rate

	$T=1$	$T=4$	$T=10$	$T=30$
ν_a	26.6	23.4	31.1	31.1
ν_b	26.1	19.1	18.5	8.3
ν_i	5.9	24.3	9.1	9.6
ν_g	0.9	0.6	1.7	3.4
ν_u	6.4	6.2	8.1	0.6
ν_l	26.9	1.4	0.0	0.0
η_p	0.1	19.5	0.1	0.4
η_w	0.0	0.3	0.7	0.1
η_r	3.9	0.4	0.0	0.0
ν_π	3.3	4.7	30.7	46.5

Inflation rate

	$T=1$	$T=4$	$T=10$	$T=30$
ν_a	1.8	32.9	2.8	3.7
ν_b	0.0	1.2	2.0	0.6
ν_i	0.0	0.0	0.0	0.8
ν_g	0.0	0.2	0.2	0.3
ν_u	0.2	4.0	0.2	0.0
ν_l	0.0	0.0	0.0	0.0
η_p	97.1	27.7	16.9	0.1
η_w	0.2	3.8	0.1	0.0
η_r	0.0	0.6	0.1	0.0
ν_π	0.5	29.6	77.6	94.4

Real wages

	$T=1$	$T=4$	$T=10$	$T=30$
ν_a	12.9	52.3	85.8	90.1
ν_b	2.0	1.7	0.1	4.0
ν_i	3.6	9.5	7.7	4.4
ν_g	0.0	0.0	0.1	1.0
ν_u	0.6	2.4	2.8	0.3
ν_l	0.8	0.2	0.0	0.0
η_p	28.4	29.8	3.3	0.1
η_w	50.4	2.3	0.0	0.0
η_r	0.2	0.1	0.0	0.0
ν_π	1.2	1.6	0.2	0.1

Hours worked

	$T=1$	$T=4$	$T=10$	$T=30$
ν_a	16.5	0.3	0.2	48.7
ν_b	4.7	0.1	24.6	6.2
ν_i	41.9	57.3	4.6	17.3
ν_g	16.2	12.6	65.6	27.0
ν_u	3.6	0.6	0.5	0.4
ν_l	8.0	1.9	0.8	0.0
η_p	1.2	21.7	0.1	0.2
η_w	2.4	2.0	3.2	0.1
η_r	2.3	0.5	0.0	0.0
ν_π	3.3	3.1	0.5	0.1

Note:

ν_a	productivity shock
ν_b	preference shock
ν_i	investment adjustment cost shock
ν_g	external demand shock
ν_u	utilization adjustment cost shock
ν_l	labor supply disutility shock
η_p	price markup shock
η_w	wage markup shock
η_r	interest rate shock
ν_π	target inflation shock

Table 5: Variance decomposition (continued)

Consumption

	$T = 1$	$T = 4$	$T = 10$	$T = 30$
ν_a	62.5	72.1	84.0	78.2
ν_b	19.9	9.8	0.6	5.4
ν_i	2.4	0.3	3.5	8.4
ν_g	5.7	6.3	8.2	7.4
ν_u	5.9	5.6	3.4	0.3
ν_l	1.5	0.2	0.0	0.0
η_p	0.8	5.0	0.0	0.1
η_w	0.0	0.1	0.1	0.0
η_r	0.5	0.1	0.0	0.0
ν_π	0.9	0.6	0.0	0.1

Investment

	$T = 1$	$T = 4$	$T = 10$	$T = 30$
ν_a	1.6	13.1	65.3	69.9
ν_b	0.6	3.8	12.5	1.6
ν_i	97.4	80.6	19.1	27.7
ν_g	0.0	0.1	0.5	0.2
ν_u	0.0	0.1	0.6	0.0
ν_l	0.0	0.1	0.1	0.1
η_p	0.3	2.0	1.6	0.4
η_w	0.0	0.0	0.1	0.1
η_r	0.0	0.0	0.0	0.0
ν_π	0.0	0.2	0.2	0.0

Output

	$T = 1$	$T = 4$	$T = 10$	$T = 30$
ν_a	43.7	56.6	84.0	94.9
ν_b	7.0	0.3	1.7	2.9
ν_i	36.7	32.1	10.3	1.5
ν_g	6.2	2.2	1.1	0.4
ν_u	3.3	2.7	2.1	0.3
ν_l	1.0	0.2	0.1	0.0
η_p	1.0	5.2	0.5	0.0
η_w	0.0	0.1	0.1	0.0
η_r	0.4	0.1	0.0	0.0
ν_π	0.7	0.6	0.1	0.1

Table 6: Comparison of two models of capital utilization

Parameters	Our model mean	Alternative model (same as CEE/SW/LOWW) mean	90 % interval		
Structural parameters					
θ	0.102	0.087	0.033	-	0.141
σ	1.249	1.240	0.947	-	1.555
χ	2.149	2.144	1.770	-	2.531
$1/\zeta$	6.319	4.732	2.529	-	6.983
ψ	2.370	0.863	0.176	-	1.599
$\phi - 1$	0.084	0.088	0.064	-	0.110
ξ_p	0.875	0.875	0.843	-	0.912
ξ_w	0.516	0.568	0.473	-	0.659
γ_p	0.862	0.908	0.817	-	0.998
γ_w	0.246	0.237	0.012	-	0.443
Policy parameters					
r_i	0.842	0.889	0.775	-	1.008
r_π	0.606	0.515	0.376	-	0.649
r_y	0.110	0.115	0.056	-	0.185
$r_{\Delta\pi}$	0.250	0.196	0.079	-	0.308
$r_{\Delta y}$	0.647	0.471	0.230	-	0.713
S.D. of shocks					
σ_a	0.843	0.741	0.626	-	0.847
σ_π	0.062	0.067	0.032	-	0.098
σ_b	0.102	0.101	0.063	-	0.138
σ_g	0.403	0.407	0.346	-	0.465
σ_l	1.538	1.261	0.612	-	1.748
σ_i	1.413	1.331	1.074	-	1.596
σ_u	0.646	-	-	-	-
σ_r	0.066	0.085	0.031	-	0.147
σ_q	-	-	-	-	-
σ_p	0.151	0.152	0.122	-	0.180
σ_w	0.212	0.205	0.170	-	0.240
Persistence of shocks					
ρ_a	0.949	0.975	0.955	-	0.995
ρ_π	0.974	0.976	0.955	-	0.997
ρ_b	0.892	0.894	0.821	-	0.969
ρ_g	0.960	0.957	0.924	-	0.987
ρ_l	0.563	0.689	0.503	-	0.910
ρ_i	0.350	0.445	0.315	-	0.566
ρ_u	0.901	-	-	-	-

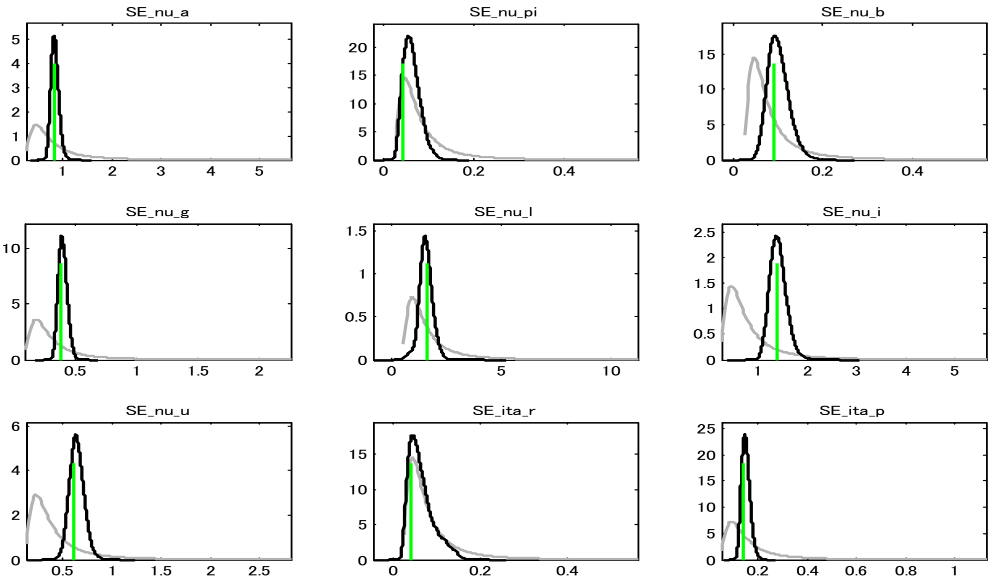

Figure 8: Prior and posterior distributions. Thick and thin curves indicate the posterior and prior distribution of parameters respectively. Vertical lines represent their mode obtained by a maximum likelihood method.

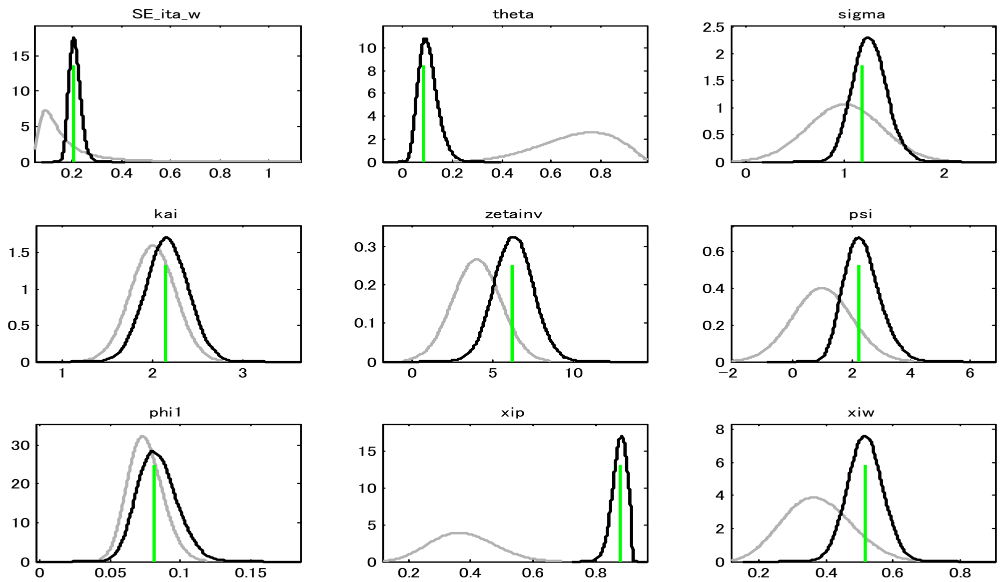

Figure 9: Prior and posterior distributions (continued)

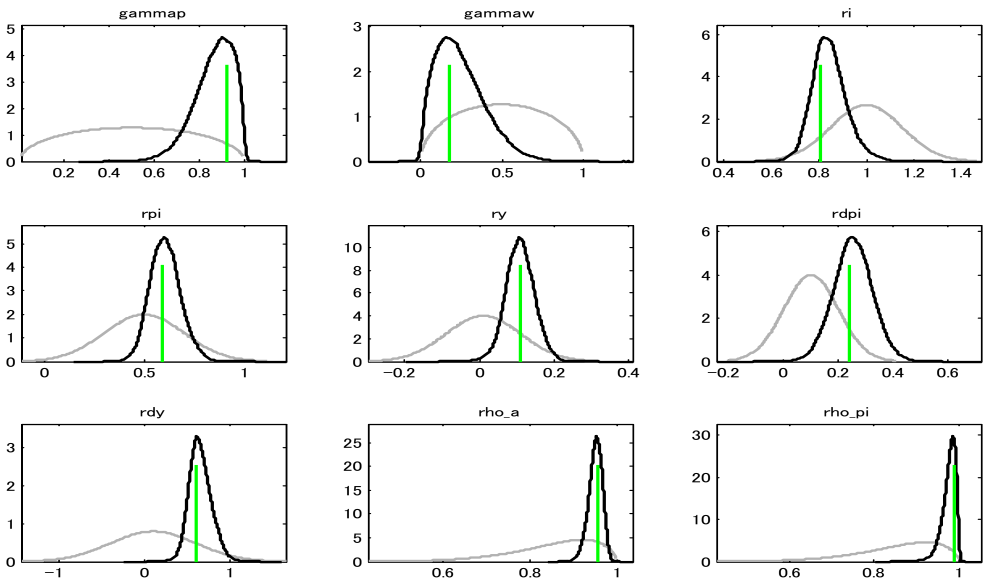

Figure 10: Prior and posterior distributions (continued)

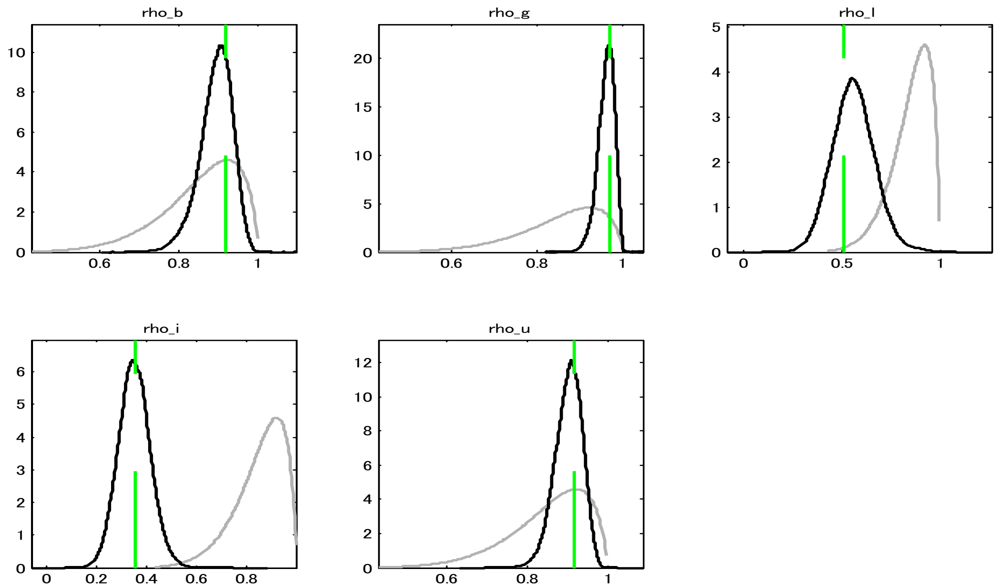

Figure 11: Prior and posterior distributions (continued)