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"Business Cycles, Asset Prices, and the Frictions of Capital and Labor"

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Business Cycles, Asset Prices, and the Frictions of Capital and Labor*

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Abstract

We propose a simple real business cycle model to explain two of the most important aspects of macroeconomics: business cycle facts and the asset pricing mechanism. Based on US and Japanese quarterly data, we estimate the model with capital and labor adjustment costs. Our analysis reveals that this simple model can explain the key business cycle facts, even without other frictions such as sticky prices, sticky wages, and search and matching frictions. Furthermore, this simple model also has explanatory power for whether a stock price will increase or decrease. However, this feature of the model is weaker for the Great Recession in the US economy.

JEL Classification: C32, E13, E32, E37

Keywords: Adjustment costs, DSGE model, Bayesian estimation, Stock price forecasting

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1 Introduction

This study explores a real business cycle model to explain two of the most important aspects of macroeconomics: business cycle facts and the asset pricing mechanism. The business cycle facts refer to the dynamics of various economic variables such as GDP, investment, employment, and wages, whereas the asset pricing mechanism is how the asset prices change according to these macroeconomic variables. We estimate the model with capital and labor adjustment costs using US and Japanese aggregate data and find that this simple model suits our purposes.

Specifically, we consider a real business cycle model as in Hansen (1985), with a general capital and labor adjustment cost function, and estimate this model using Bayesian estimation techniques. Such a methodology has several advantages. First, since the theoretical model is very simple, we can easily apply our model in varying circumstances. Second, unlike a maximum likelihood estimation, we can identify more structural parameters by combining the priors with the likelihood of the data. Third, rather than estimating a single-equation setting, we can exploit cross-equation restrictions that link agents' decision rules with the coefficients.

This study offers several contributions. First, our study is one of the few that measures factor adjustment costs in a general equilibrium setting. Second, to the best of our knowledge, this is the first application of this methodology to investigate the differences in factor adjustment costs between countries. Third, our study allows us to explain the business cycle facts successfully, in both the US and Japan, and obtain a new finding on stock price forecasting. That is, our real business cycle model cannot replicate the actual stock price data, but it can partially address whether the stock price will rise of fall. This characteristic of the model is remarkable, though does not apply for the period covering the Great Recession in the US economy.

There are two strands of literature associated with our study: research on measuring factor adjustment costs and that on quantitatively connecting asset pricing phenomena and macroeconomic activities. There is an extensive literature showing that adjusting capital or labor inputs is expensive. For example, Summers (1981) and Hayashi (1982) measure capital adjustment costs in the US by estimating the reduced form of a firm's investment function. Whited (1992) and Hubbard et al. (1995) investigate capital adjustment costs by estimating the structural form, such as the investment Euler equation. Shapiro (1986), Hall (2004), and Yashiv (2016) measure the factor adjustment costs for both capital and labor by estimating the investment and employment Euler equations.

There is also some research aiming to link stock returns to macroeconomic activities. Hansen and Singleton's (1982) pioneering study focuses on the optimal consumption rule of the household and develops a consumption-based asset pricing model. Cochrane (1991), on the other hand, focuses on the optimal investment rule of the firm and develops the production-based asset pricing model. Merz and Yashiv (2007) extend Cochrane's (1991) research to allow for joint adjustments of capital and labor. Finally, Mumtaz and Zanneti (2015) expand their model in a general equilibrium setting and allow for labor market frictions, as in Blanchard and Gali (2010).

Despite these studies, we are still interested in determining whether a real business cycle model with factor adjustment costs can explain the key business cycle facts and the actual fluctuations of a firm's market value. We are only beginning to understand these questions (see Cochrane, 2005). Finding answers requires testing this type of model in various areas, countries, periods, and so forth. Our study is among the first steps on this trial.

The rest of the paper is organized as follows. Section 2 provides the benchmark model and characterizes the equilibrium conditions. Section 3 explains the estimation strategies and describes the data characteristics in the US and Japan. Section 4 presents the estimation results, assesses the empirical fit of the model, and illustrates the dynamic properties of the model. Section 5 presents further considerations on stock price forecasting. Section 6 concludes.

2 Model

Our model is a simple and standard real business cycle model as in Hansen (1985), with the additional feature of capital and labor adjustment costs. We expand Merz and Yashiv's (2007) model in a general equilibrium setting. We briefly discuss the difference here.

Merz and Yashiv (2007) consider a representative firm that employs capital and labor inputs to produce output goods. They assume that adjustments in capital and labor require some costs for the firm. Since they focus on the production sector only, their model is a partial equilibrium model.

We extend their model by considering two additional sectors: the household and the government. The household determines the consumption and labor supply in each period and the government collects tax from the company and transfers it to the household. We describe the agents' technologies, preferences, and equilibrium conditions in detail below.

2.1 The Representative Firm

In each period, the representative firm uses k_t units of capital and n_t units of labor to produce y_t units of output goods according to the following technology:

$$y_t = f(a_t, k_t, n_t), \tag{1}$$

where f is the production function and a_t denotes productivity. Productivity follows the AR(1) process $a_t = \Gamma(a_{t-1}, \epsilon_{a,t})$, and $\epsilon_{a,t}$ is an i.i.d. shock.

The firm's profits are the difference between revenues net of factor adjustment costs and total labor compensation:

$$\pi_t = f(a_t, k_t, n_t) - g(i_t, k_t, h_t, n_t) - w_t n_t, \tag{2}$$

where π_t is the firm's real profits, w_t the real wage, i_t gross investment, h_t gross hiring, and g is an adjustment cost function. We derive this type of cost from such processes as recruiting, training, planning, installation, learning, and so on. (see Hamermesh and Pfann, 1996).

The firm's objective function is the present value of future dividends:

$$E_0 \sum_{t=0}^{\infty} \frac{\beta^t \lambda_t}{\lambda_0} d_t, \tag{3}$$

where d_t denotes the firm's real dividends, and $\beta^t \lambda_t / \lambda_0$ denotes the ratio of the marginal utility of consumption between period 0 and period t. The firm's real dividends are:

$$d_t = (1 - \tau_t)\pi_t - i_t, \tag{4}$$

where τ_t is the corporate income tax rate and follows the AR(1) process $\tau_t = \Gamma(\tau_{t-1}, \epsilon_{\tau,t})$, and $\epsilon_{\tau,t}$ is an i.i.d. shock.

The law of motion for capital and labor becomes the following:

$$k_{t+1} = (1 - \delta_t)k_t + i_t, \tag{5}$$

$$n_{t+1} = (1 - \psi_t)n_t + h_t, \tag{6}$$

where δ_t is the capital depreciation rate and ψ_t is the exogenous job separation rate, both of which follow the AR(1) process: $\delta_t = \Gamma(\delta_{t-1}, \epsilon_{\delta,t})$ and $\psi_t = \Gamma(\psi_{t-1}, \epsilon_{\psi,t})$. We assume that $\epsilon_{\delta,t}$ and $\epsilon_{\psi,t}$ are i.i.d.

The representative firm chooses the sequences of i_t and h_t to maximize its objective function (3) subject to the definition of d_t and the constraints (5) and (6). Letting q^k and q^n denote the Lagrange multipliers on the law of motion for capital and labor, we can derive the first-order necessary conditions:

$$q_t^k = E_t\beta_{t,t+1}\big[(1-\tau_{t+1})(f_{k,t+1}-g_{k,t+1})+(1-\delta_{t+1})q_{t+1}^k\big], \tag{7}$$
$$q_t^k = 1+(1-\tau_t)g_{i,t}, \tag{8}$$
$$q_t^n = E_t\beta_{t,t+1}\big[(1-\tau_{t+1})(f_{n,t+1}-g_{n,t+1}-w_{t+1})+(1-\psi_{t+1})q_{t+1}^n\big], \tag{9}$$
$$q_t^n = (1-\tau_t)g_{h,t}, \tag{10}$$

where E_t denotes the expectation operator depending on the information available in period t, $\beta_{t,t+1} = \beta\lambda_{t+1}/\lambda_t$ denotes the stochastic discount factor, f_x denotes the marginal product of increasing variable x, and g_x denotes the marginal adjustment cost of increasing variable x.

To observe this derivation more clearly, we can refer to Bond and Van Reenen (2007, pp.4429-4430) or Yashiv (2011, pp.8-10). Equations (7) and (8) state that the marginal cost of investment is equal to the expected marginal profit from this investment. Similarly, equations (9) and (10) state that the marginal cost of hiring is equal to the expected marginal profit from the hiring. According to this argument, we can interpret the Lagrange multipliers q^k and q^n as marginal q for capital and marginal q for labor (see Yashiv, 2016).

Finally, we come to the link between our model and the firm's market value. The firm's period t market value is the expected discounted pre-dividend market value in the following period:

$$s_t = E_t\beta_{t,t+1}(s_{t+1}+d_{t+1}), \tag{11}$$

where s_t is the firm's market value. As Merz and Yashiv (2007) show, we can decompose the firm's market value into the sum of the value from physical capital and the value from the stock of employment. Furthermore, we can replace this relationship with the following asset pricing equation under two conditions: the constant returns-to-scale property of the production function, f, and of the adjustment cost function, g.

$$s_t = k_{t+1}q_t^k + n_{t+1}q_t^n. \tag{12}$$

2.2 The Representative Household

The representative household maximizes the following expected utility function:

$$E_0\sum_{t=0}^{\infty}\beta^t\Big[\ln c_t - \chi_t n_t^{1+\phi}/(1+\phi)\Big], \tag{13}$$

where c_t denotes consumption, n_t denotes labor supply, β denotes the discount factor, ϕ denotes the inverse of the Frisch elasticity of labor supply, and χ_t is the degree of the disutility of labor. We assume that χ_t follows the AR(1) process $\chi_t = \Gamma(\chi_{t-1}, \epsilon_{\chi,t})$, and $\epsilon_{\chi,t}$ is an i.i.d. shock.

The budget constraint for the household is:

$$c_t + b_t = w_t n_t + d_t + (1 + r_t) b_{t-1} + T_t, \tag{14}$$

where b_t denotes the degree of bonds issued, r_t the real interest rate, and T_t the transfers from the government. The representative household receives labor compensation and cash flow payments from the company, and uses its income for consumption.

The household chooses the sequences of c_t and n_t to maximize its utility function (13) subject to its budget constraint (14). Letting λ denote the Lagrange multiplier on the budget constraint (14), we can derive the first-order necessary conditions[1]:

$$\lambda_t = 1/c_t, \tag{15}$$

$$w_t = \chi_t n_t^{\phi} / \lambda_t. \tag{16}$$

2.3 The Government

In our model, the government plays the limited role of collecting tax from the firm and transferring it to the household. Hence, the following condition holds:

$$T_t = \tau_t \pi_t. \tag{17}$$

2.4 Market Equilibrium

Substituting the firm's profit definition (2), the firm's real cash flow payments (4), and the government's income distribution (17) into the household's budget constraint (14) leads to the following aggregate resource constraint[2]:

$$y_t = c_t + i_t + g(i_t, k_t, h_t, n_t). \tag{18}$$

[1] Strictly speaking, the household decides the degree of bonds issued, b_t. We omit this to describe the model briefly.

[2] In this derivation, we apply the condition that b_t equals zero in the bond market equilibrium.

Finally, we specify the stochastic processes for the various exogenous shocks, which evolve according to the following:

$$\ln a_t = (1-\rho_a)\ln(a) + \rho_a \ln(a_{t-1}) + \epsilon_{a,t}, \quad (19)$$

$$\ln \chi_t = (1-\rho_\chi)\ln(\chi) + \rho_\chi \ln(\chi_{t-1}) + \epsilon_{\chi,t}, \quad (20)$$

$$\ln \tau_t = (1-\rho_\tau)\ln(\tau) + \rho_\tau \ln(\tau_{t-1}) + \epsilon_{\tau,t}, \quad (21)$$

$$\ln \delta_t = (1-\rho_\delta)\ln(\delta) + \rho_\delta \ln(\delta_{t-1}) + \epsilon_{\delta,t}, \quad (22)$$

$$\ln \psi_t = (1-\rho_\psi)\ln(\psi) + \rho_\psi \ln(\psi_{t-1}) + \epsilon_{\psi,t}, \quad (23)$$

where a, χ, τ, δ, and ψ are the steady state levels of technology, disutility of labor, corporate income tax rate, capital depreciation rate, and job separation rate, respectively. The parameters satisfy the condition that $0 < (\rho_a, \rho_\chi, \rho_\tau, \rho_\delta, \rho_\psi) < 1$, and the zero-mean, serially uncorrelated innovations $\epsilon_{a,t}, \epsilon_{\chi,t}, \epsilon_{\tau,t}, \epsilon_{\delta,t}, \epsilon_{\psi,t}$ are normally distributed with standard deviations $\sigma_a, \sigma_\chi, \sigma_\tau, \sigma_\delta, \sigma_\psi$, respectively.

We summarize our theoretical model such that it contains the 16 endogenous variables $\{y_t, c_t, k_t, i_t, n_t, h_t, w_t, s_t, q_t^k, q_t^n, \lambda_t, a_t, \chi_t, \tau_t, \delta_t, \psi_t\}$ with the 16 equilibrium conditions (1), (5)-(10), (12), (15)-(16), (18)-(23). Hence, we can solve the system. However, the equilibrium conditions do not have an analytical solution. We approximate the system by log-linearizing its equations around the steady state and solve the system using Sims' (2002) method. We construct a state-space representation that involves state-transition equations and observation equations, and derive the likelihood function using the Kalman filter (see Hamilton, 1994, Chapter13). We use this likelihood function in the next section.

3 Estimation

3.1 Parameterization

To quantify the system, we need to parameterize the relevant functions. For the production function, we use the standard Cobb-Douglas function:

$$f(a_t, k_t, n_t) = a_t k_t^{1-\alpha} n_t^{\alpha}, \quad 0 < \alpha < 1. \quad (24)$$

For the adjustment cost function, as in Merz and Yashiv (2007), we adopt the following generalized convex function:

$$g(\cdot) = \left[f_1 \frac{i_t}{k_t} + f_2 \frac{h_t}{n_t} + \frac{e_1}{\eta_1}\left(\frac{i_t}{k_t}\right)^{\eta_1} + \frac{e_2}{\eta_2}\left(\frac{h_t}{n_t}\right)^{\eta_2} + \frac{e_3}{\eta_3}\left(\frac{i_t}{k_t}\frac{h_t}{n_t}\right)^{\eta_3} \right] f(a_t, k_t, n_t). \quad (25)$$

This function is linearly homogeneous in its four arguments i, k, h, and n, which we need in order to derive the asset pricing condition (12).

The function supposes that the costs are proportional to output and that they increase with the investment and hiring levels. The specification also captures the idea that a disruption in the production process increases with the extent of factor adjustments relative to the size of the firm, where we measure firm size by its capital or labor stock. The last term in square brackets expresses the interaction of capital and labor adjustment costs. The parameters f_1, f_2, and e_1 through e_3 express scale, and η_1 through η_3 express the elasticity of adjustment costs with respect to the different arguments.

3.2 Estimation Methodology

We estimate the model in the previous section using Bayesian estimation techniques. Let Θ denote the parameter space of our DSGE model, and $Z^T = \{z_t\}_{t=1}^T$ the observed data. According to the Bayes' theorem, the posterior distribution of the parameter is: $P(\Theta \mid Z^T) \propto P(Z^T \mid \Theta)P(\Theta)$. The left hand side of this equation is the posterior distribution, while the right hand side is the product of the prior distribution and the likelihood of the data. In practice, it is difficult to derive the posterior distribution, so we use the following approximation method as an alternative (see Schorfheide, 2000, An and Schorfheide, 2007, and Herbst and Schorfheide, 2015).

First, we calculate the mode of the posterior distribution by maximizing the log posterior function, which combines the prior information with the likelihood of the data. Second, we employ the random walk Metropolis-Hastings algorithm to obtain a complete picture of the posterior distribution. We select the sample from a multivariate normal distribution and use 500,000 replications, neglecting the first 100,000 as burn-in. We control the scaling parameter to obtain the resulting acceptance rate, of around 0.234 (from that developed by Roberts et al. (1997)).[3] Once we obtain the approximated posterior distribution, we can use it to conduct a statistical inference of the parameters.

3.3 Data

Our estimation uses US and Japanese quarterly data for 1994:Q1-2014:Q4, during which the US economy experienced two NBER-dated recessions: the first from March 2001 to November 2001 and the second from December

[3]We set the scaling parameter at 0.35 in the US and 0.37 in Japan, which makes the acceptance rate of 0.24 applicable for both countries.

2007 to June 2009. On the other hand, the Japanese economy experienced four recessions according to the Economic and Social Research Institute in Cabinet Office in Japan (ESRI): from May 1997 to January 1998, from November 2000 to January 2002, from February 2008 to March 2009, and from March 2012 to November 2012. Hence, our long sample period covers many business cycles, including significant recessions and their aftermath.

In the US, we use NIPA data on GDP, labor share of income, capital, investment, BLS CPS data on employment, and on worker flows, and US Federal Reserve data on the quarterly investment series. For Japan, we use National Accounts data on GDP, labor share of income, capital, and investment, and Labor Force Survey data on employment and on worker flows. For both the US and Japan, we obtain data on stock prices and the corporate income tax rate from OECD Statistics. The Appendix contains a detailed explanation of the data sources and data construction.

We use this data to construct variables associated with our model: output y, gross investment rate i/k, gross hiring rate h/n, corporate income tax rate τ, labor share of income wn/y, and the firm's market value s. We first take the logarithm of these variables, and then detrend the non-stationary series for $y, i/k, \tau, wn/y, s$ using a one-sided HP filter with a smoothing parameter of 1,600 and demean the remaining stationary series, h/n. These procedures are necessary to fit the data to the log-linearized formulation of the model and are useful to compare variables with different units (e.g., dollar, yen, %). When detrending the data, we use a one-sided HP filter to substitute for the well-known two-sided. Since our model solution takes the form of a backward-looking state-space system, i.e. the solution today depends on current and past states and shocks, the backward-looking one-sided HP filter is the better option (see Stock and Watson, 1999).

Table 1 reports the original sample statistics. Comparing these statistics between US and Japan yields several findings. First, both countries have similar means and standard deviations of the gross investment rate (i/k), with values of around 0.02 and 0.002, respectively. Second, the gross hiring rate shows distinct features. The mean is 0.124 in the US, while in Japan it is 0.038, which partially reflects the institutional difference that the Japanese economy has long-term employment and low turnover rates (see Waldman, 2012). Third, the value for the labor share of income (wn/y) is larger in Japan than in the US. The mean of this variable is around 0.6 in the US, while it is around 0.7 in Japan. Finally, the standard deviation in stock prices (s) shows a slightly larger value in Japan.

We finally discuss the dynamics of our data series in Figure 1, which depicts the dynamics of the post-filtered data series for our model variables.

Table 1: Descriptive sample statistics (Pre-conversion, 1994-2014)

a. the US (n=84)

Variable	y	i/k	h/n	τ	wn/y	s
Mean	1670[a]	0.027	0.124	0.393	0.610	99.64[c]
Standard deviation	240.7	0.002	0.004	0.001	0.027	25.17

b. Japan (n=84)

Variable	y	i/k	h/n	τ	wn/y	s
Mean	122993[b]	0.024	0.038	0.419	0.706	137.3[c]
Standard deviation	6262	0.002	0.003	0.043	0.023	29.69

[a] In billions of chained 2009 US dollars.

[b] In billions of chained 2005 Japanese yen.

[c] In index (the base year 2010 = 100).

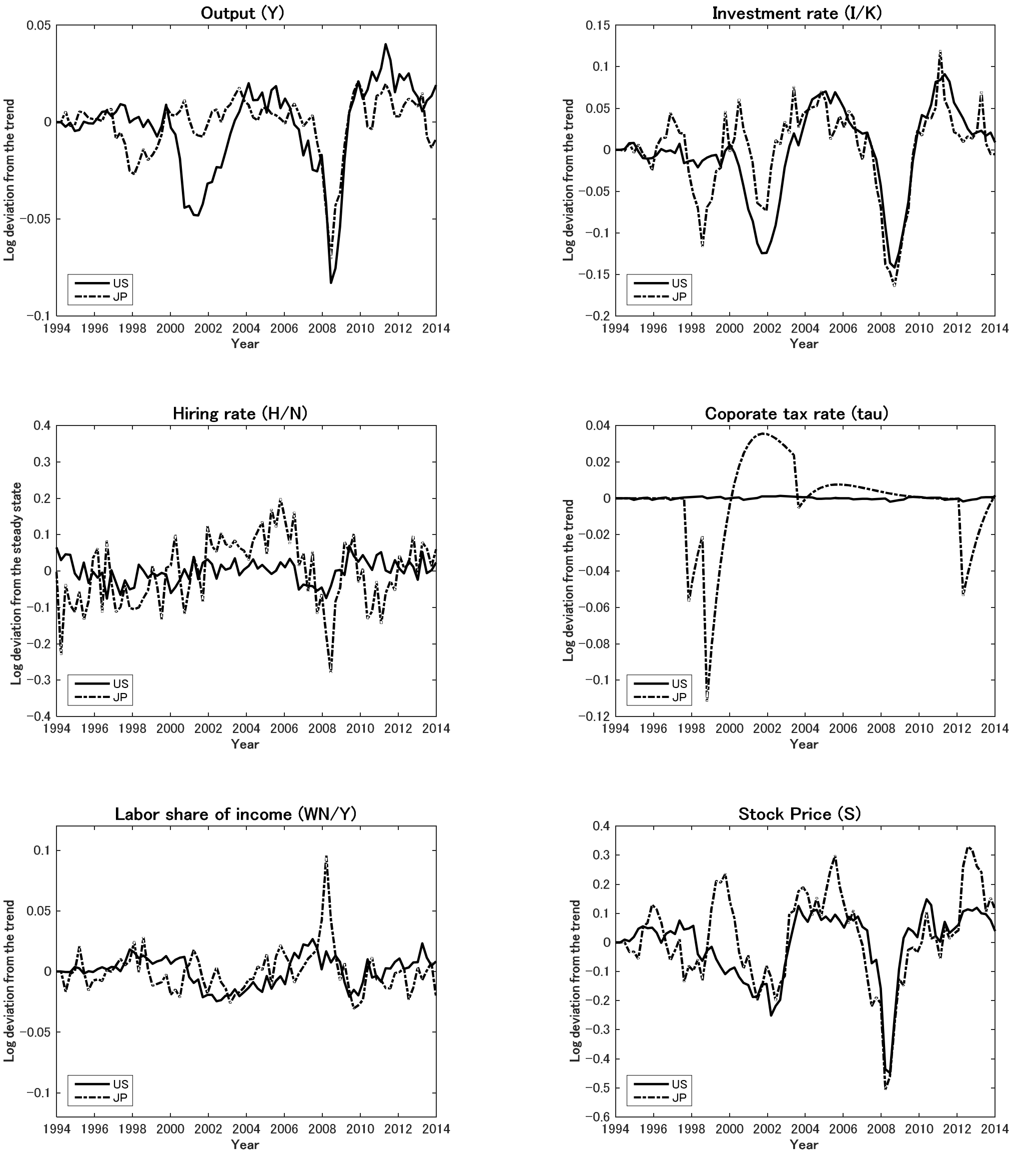
We plot the value of the log deviation from the trend or from the steady state for each variable: $y, i/k, h/n, \tau, wn/y$, and s. The figure shows that the output (y) largely declines at the same time as the NBER- or ESRI-dated recessions. Second, the gross investment rate (i/k) shows similar dynamics to the output, while the gross hiring rate (h/n) shows a weaker relationship in the US. The variable τ shows very stable movements in the US, while it fluctuates intensely in Japan. Finally, from the bottom panel, the Japanese stock prices have higher volatility than those in the US.

3.4 Prior distributions

Tables 2 and 3 describe the prior distributions, means, and standard deviations of our model. Table 2 reports the priors of the structural parameters of the household's preference, production function, and the adjustment cost function. Table 3 reports the priors on the shock parameters such as the steady state values, persistence, and standard deviation of shocks. We set these priors following Mumtaz and Zanetti (2015) and provide a brief review below.

The priors for the structural parameters, except for those of the adjustment cost function, are relatively tight in order to match important stylized facts. In particular, the labor share of the production function, α,

Figure 1: Dynamics of key variables (Post-filtered, 1994-2014)



Notes: This figure plots the dynamics of the post-filtered data series ($y, i/k, h/n, \tau, wn/y$, and s). Each panel shows the value of the log deviation from the trend or from the steady state value. For detrending the data, a one-sided HP filter with a smoothing parameter of 1,600 is used.

Table 2: Prior distribution of structural parameters (the US and Japan)

Parameter	Distribution	Mean	S.D.
Taste and technological parameters			
α	Normal	0.66	0.05
β	Normal	0.989	0.001
ϕ	Normal	1	0.01
Adjustment cost function parameters			
Linear adjustment costs			
f_1	Normal	0	1.5
f_2	Normal	0	1.5
Convex adjustment costs			
e_1	Normal	0	3
e_2	Normal	0	3
e_3	Normal	0	3
Elasticity of adjustment costs			
η_1	Gamma	2	0.2
η_2	Gamma	2	0.2
η_3	Gamma	2	0.2

Notes: The table shows the prior density, mean, and standard deviation of the model's structural parameters. All parameters have the same priors in both the US and Japan.

Table 3: Prior distribution of shock parameters (the US and Japan)

Parameter	Distribution	Mean	S.D.
Steady state values			
a	Normal	1	0.01
χ	Normal	1	0.01
δ	Normal	0.020	0.005
ψ_{us}	Normal	0.123	0.005
ψ_{jp}	Normal	0.038	0.005
τ_{us}	Normal	0.39	0.001
τ_{jp}	Normal	0.42	0.001
Persistence of shocks			
ρ_a	Beta	0.6	0.2
ρ_χ	Beta	0.6	0.2
ρ_τ	Beta	0.6	0.2
ρ_δ	Beta	0.6	0.2
ρ_ψ	Beta	0.6	0.2
Standard deviation of shocks			
σ_a	Inv. gamma	0.08	0.1
σ_χ	Inv. gamma	0.08	0.1
σ_τ	Inv. gamma	0.08	0.1
σ_δ	Inv. gamma	0.08	0.1
σ_ψ	Inv. gamma	0.08	0.1
Standard deviation of measurement errors			
σ_y	Inv. gamma	0.08	0.1
σ_i	Inv. gamma	0.08	0.1
σ_h	Inv. gamma	0.08	0.1
σ_{tax}	Inv. gamma	0.08	0.1
σ_w	Inv. gamma	0.08	0.1
σ_s	Inv. gamma	0.08	0.1

Notes: The table shows the prior density, mean, and standard deviation of the model's shock parameters. All parameters, except for ψ and τ, have the same priors in both the US and Japan.

is normally distributed with a prior mean of 0.66, a value common in the literature, and a standard error of 0.05. Similarly, the discount factor, β, is normally distributed with a prior mean of 0.989 that generates an annual real interest rate of 4% as in the data, and a standard error equal to 0.001. The inverse of the Frisch elasticity of substitution in labor supply, ϕ, is normally distributed with a prior mean of 1, which is in line with micro and macro evidence as in Card (1994) and King and Rebelo (1999), and a standard error equal to 0.01.

In contrast, the priors for the parameters of the adjustment cost function allow for a wide range of values. The linear parameters, f_1 and f_2, are normally distributed with a prior mean of 0 and a prior standard deviation of 1.5. The priors of the scale parameters, e_1, e_2, and e_3, are normally distributed with a mean of 0 and a standard error of 3. Finally, the priors of the elasticity parameters, η_1, η_2, and η_3, are gamma distributed with a prior mean of 2 and a standard error of 0.2.

Secondly, Table 3 reports the priors of the shock parameters. In particular, we assume that the steady state values for technological progress, a, and the disutility of labor, χ, are normally distributed with prior means of 1 and standard errors of 0.01. We also assume that the steady state capital depreciation rate, δ, job separation rate, ψ, and corporate income tax rate, τ, are normally distributed with prior means set to match the data characteristics, and with small standard errors. We harmonize the priors on the autoregressive components and standard errors of the stochastic processes across different shocks. The persistence parameters $\rho_a, \rho_\chi, \rho_\delta, \rho_\psi$, and ρ_τ are beta distributed, with a prior mean of 0.6 and a standard deviation of 0.2. The standard errors of the innovations $\sigma_a, \sigma_\chi, \sigma_\delta, \sigma_\psi$, and σ_τ follow an inverse gamma distribution with a prior mean of 0.08 and a standard deviation of 0.1.

In the estimation, we allow each observation equation[4] to be enriched with a measurement error, which is normally distributed with standard errors, $\sigma_y, \sigma_i, \sigma_h, \sigma_{tax}, \sigma_w$, and σ_s. In general, there are some reasons to assume the presence of measurement errors in the observation equations (see Pfeifer, 2015, pp.61-65). First, some time series, such as wages, are noisy and poorly measured (see Justiniano et al., 2011). Second, adding the measurement errors helps account for model misspecification when the data violates cross-equation restrictions (see Del Negro and Schorfheide, 2009; Sargent, 1989).

[4]The solution to the DSGE model takes the form of a state-space representation that involves state-transition equations and observation equations, which link the model variables and the data.

Third, adding measurement errors is a useful means to circumvent the identification problem (see Schmitt-Grohé and Uribe, 2012). We assume that the measurement errors follow the same priors as those of the innovations.

Once we determine the prior distributions (Tables 2 and 3), we can easily find the posterior mode by combining the likelihood of the data with the priors. We obtain this value using numerical optimization in the Matlab function, fmincon. Then, as in Section 3.2, we use the random walk Metropolis-Hastings algorithm to obtain the approximated posterior distribution. We confirm that the sequence of this random draw provides strong evidence of convergence by using the Metropolis-Hastings diagnosis tests proposed by Brooks and Gelman (1998).

4 Estimation Results

In this section, we report the results of our model estimation, assess the fit of the model, and compare the results with the literature. We also show the dynamic properties of our model by referring to the impulse response functions and the forecast error variance decompositions.

4.1 Posterior estimates and model fit

Table 4 reports the values of posterior means and standard deviations for the model's structural parameters and Table 5 summarizes these results for shock parameters. We start by discussing the results for the structural parameter estimates.

The posterior mean of the technological parameter, α, is equal to 0.614 in the US and 0.634 in Japan. The larger value for Japan is consistent with the fact that the Japanese labor share of income is larger than in the US (see Table 1).[5] The posterior means of the taste parameters, β and ϕ, are around 0.989 and 1.000 for the US and Japan, respectively, which is in line with the stylized facts.

We next examine the estimates of the adjustment cost function. The posterior means of the linear components, f_1 and f_2, are 1.746 and 0.232 for the US and 2.776 and 0.135 for Japan. The convex components of the adjustment cost function, e_1 and e_2, are 1.423 and 4.184 for the US and 1.500 and 3.207 for Japan. Finally, the posterior means of the interaction term, e_3, are small and equal to -0.029 in the US and 0.044 in Japan. The results indicate that the linear term plays a key role in the capital adjustment costs,

[5] In the steady state of our model, this parameter is equal to the labor share of income.

Table 4: Posterior distribution of structural parameters (the US and Japan)

Parameter	the US		JP	
	Mean	S.D.	Mean	S.D.
Taste and technological parameters				
α	0.614	(0.046)	0.634	(0.047)
β	0.990	(0.001)	0.989	(0.001)
ϕ	0.999	(0.010)	1.000	(0.010)
Adjustment cost function parameter				
Linear adjustment costs				
f_1	1.746	(0.925)	2.776	(0.869)
f_2	0.232	(0.338)	0.135	(0.351)
Convex adjustment costs				
e_1	1.423	(3.130)	1.500	(3.079)
e_2	4.184	(1.526)	3.207	(1.571)
e_3	−0.029	(2.967)	0.044	(2.986)
Elasticity of adjustment costs				
η_1	1.971	(0.210)	1.970	(0.210)
η_2	1.949	(0.182)	1.960	(0.179)
η_3	1.999	(0.199)	1.998	(0.200)

Notes: Each entry shows the posterior mean with the standard error in brackets. To approximate the posterior distribution, we use a random walk Metropolis-Hastings algorithm (500,000 replications, discarding the first 100,000 as burn-in).

Table 5: Posterior distribution of shock parameters (the US and Japan)

Parameter	the US		JP	
	Mean	S.D.	Mean	S.D.
Steady state values				
a	1.0002	(0.010)	0.9999	(0.010)
χ	1.0000	(0.010)	0.9999	(0.010)
δ	0.023	(0.004)	0.025	(0.004)
ψ	0.122	(0.005)	0.038	(0.005)
τ	0.390	(0.001)	0.420	(0.001)
Persistence of shocks				
ρ_a	0.986	(0.012)	0.863	(0.079)
ρ_χ	0.421	(0.159)	0.586	(0.161)
ρ_δ	0.532	(0.154)	0.561	(0.152)
ρ_ψ	0.497	(0.159)	0.825	(0.088)
ρ_τ	0.326	(0.135)	0.811	(0.071)
Standard deviation of shocks				
σ_a	0.013	(0.001)	0.013	(0.001)
σ_χ	0.014	(0.001)	0.015	(0.002)
σ_δ	0.061	(0.025)	0.076	(0.034)
σ_ψ	0.026	(0.005)	0.044	(0.011)
σ_τ	0.013	(0.001)	0.016	(0.002)
Standard deviation of measurement errors				
σ_y	0.013	(0.001)	0.013	(0.001)
σ_i	0.015	(0.002)	0.020	(0.003)
σ_h	0.024	(0.003)	0.049	(0.008)
σ_{tax}	0.013	(0.001)	0.015	(0.002)
σ_w	0.014	(0.001)	0.015	(0.002)
σ_s	0.113	(0.009)	0.155	(0.012)
Marginal log-likelihood	1058		903	

Notes: Each entry shows the posterior mean estimate with the standard error in brackets. To approximate the posterior distribution, we use a random walk Metropolis-Hastings algorithm (500,000 replications, discarding the first 100,000 as burn-in).

whereas the convex term plays an important role in the labor adjustment costs.

Next, we look at the parameter estimates of the shock processes. In the US, the productivity shock ϵ_a is the most persistent, with an AR(1) coefficient of 0.986. This estimate is consistent with a wide range prior findings (Ireland, 2004, Smets and Wouters, 2007, and Zanetti, 2008). Similarly, this parameter is the most persistent in Japan with a coefficient of 0.863. The posterior means of the volatilities of shock processes show that shocks to the capital depreciation rate and job separation rate are more volatile, whereas the other shocks show very low volatility. This finding is similar to that of Mumtaz and Zanetti (2015). The standard deviation of technology shock is of special interest. The estimate of σ_a of 0.013 for both countries has the same order of magnitude as the calibrated value in Kydland and Prescott (1982).

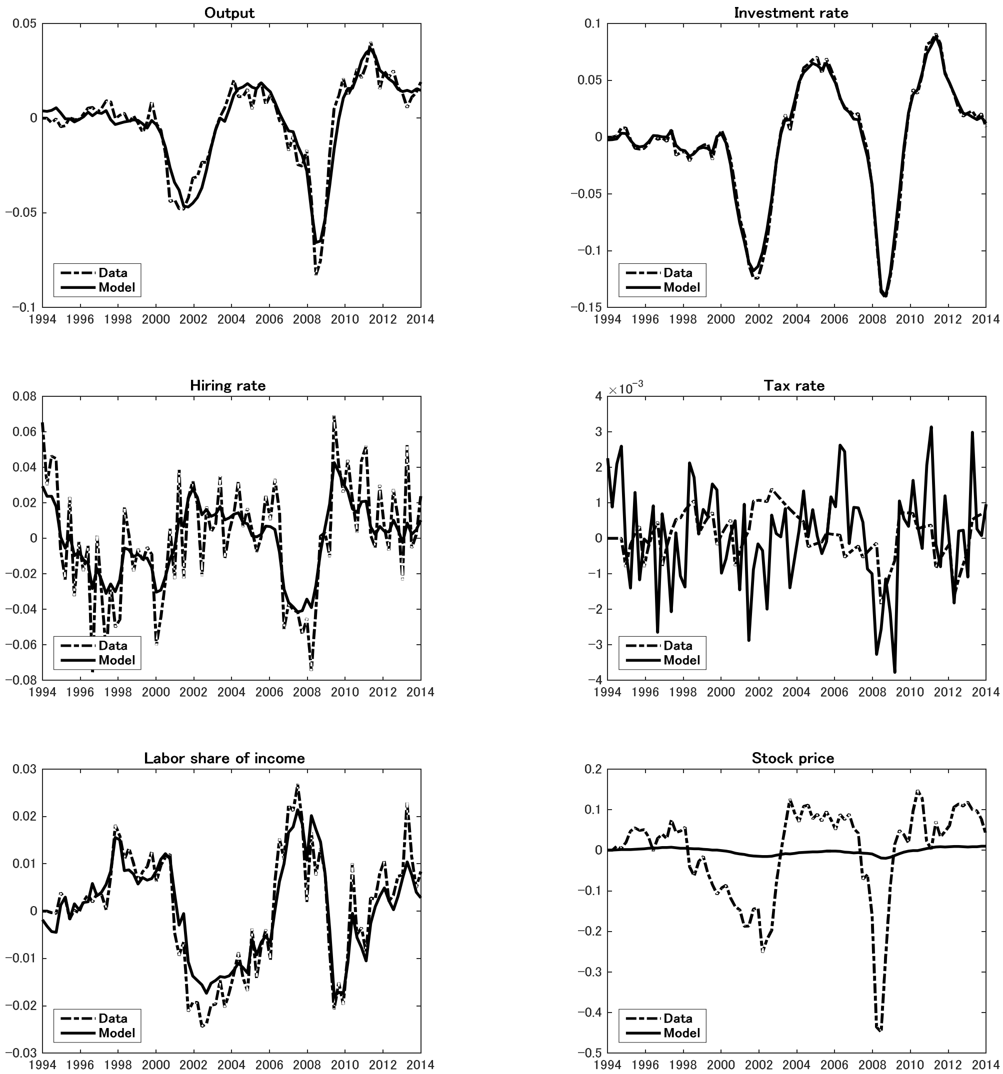
Finally, we confirm the fit of our theoretical model. We can recover the estimates of the individual shocks using the Kalman smoothing algorithm to obtain the estimated time series path of the model's endogenous variables. Figures 2 and 3 describe these results, which show that the data series and the smoothed series of the model without measurement errors are very close, except for the stock price data, where the realized measurement error is substantial. Hence, we can conclude that except for the firm's market value, our model successfully explains the key business cycle facts. This fulfills the first goal stated in the introduction. We conduct a further analysis of the stock price in a later section.

4.2 Total and marginal adjustment costs

We next summarize our results for the adjustment cost function in more detail. As shown in Section 4.1, the linear term plays a key role in the capital adjustment cost mechanism, whereas the convex term plays an important role in the labor adjustment cost mechanism. We can calculate the ratios g/y, $g_i/(y/k)$, and $g_h/(y/n)$ using the point estimates in Tables 4 and 5. The ratio of total adjustment cost to output levels, g/y, is approximately 7-10% in the US and 5-7% in Japan. Furthermore, the marginal cost of investment in terms of average output per unit of capital, $g_i/(y/k)$, is 1.78 in the US and 2.81 in Japan, while the marginal cost of hiring in terms of average output per worker, $g_h/(y/n)$, is 0.80 in the US and 0.27 in Japan.

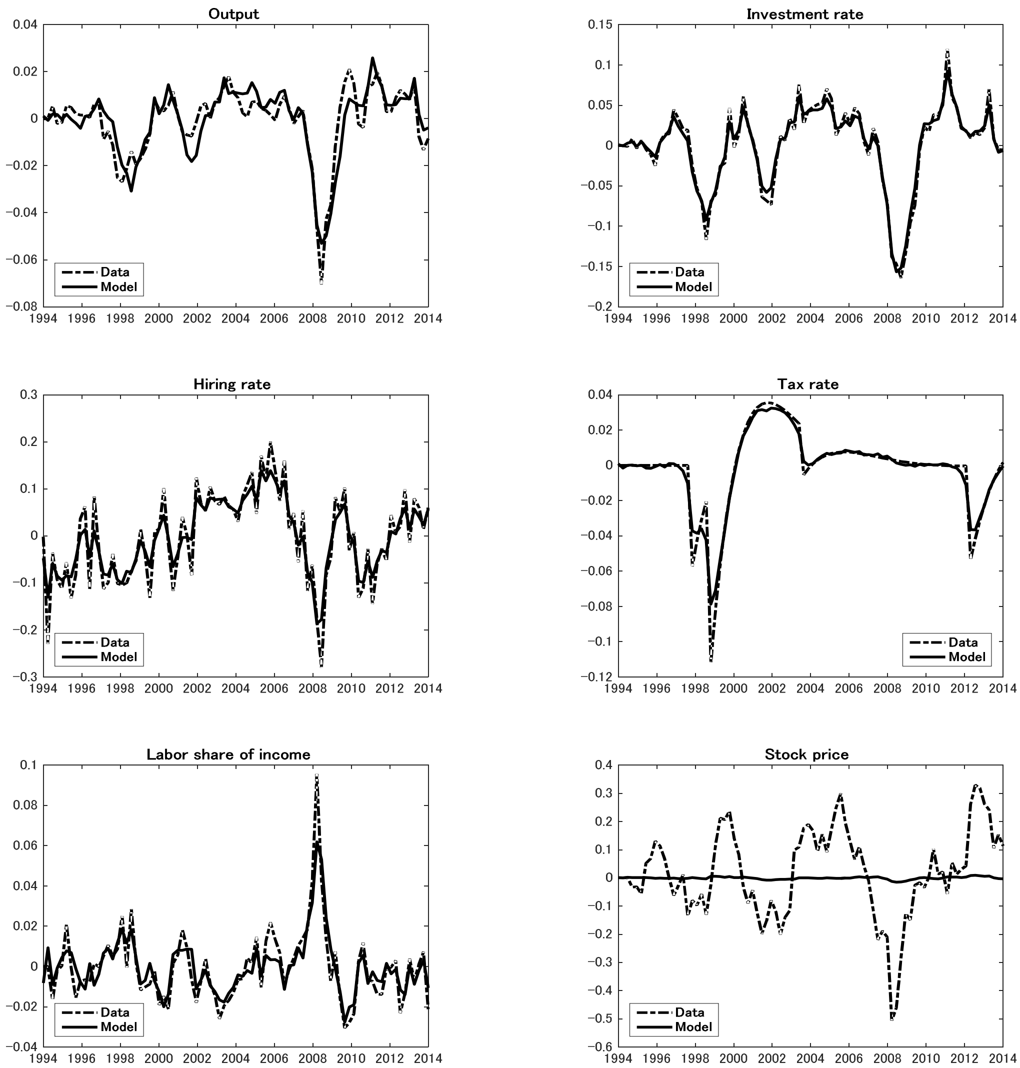
These results illustrate the following. First, our estimate of total adjustment costs fits into the middle adjustment cost group, which is within the range of estimates between 0% in Hall (2004) and 15-100% in Summers

Figure 2: Simulated vs actual data (the US)



Notes: The solid line depicts the dynamics of the smoothed series of the model's endogenous variables without measurement errors; the dotted line depicts the dynamics of the data series.

Figure 3: Simulated vs actual data (Japan)



Notes: The solid line depicts the dynamics of the smoothed series of the model's endogenous variables without measurement errors and the dotted line depicts the dynamics of the data series.

(1981), and not much greater than in Merz and Yashiv (2007) and Mumtaz and Zanetti (2015).[6] Second, our estimate of marginal costs for the US is close to that in Merz and Yashiv (2007), who report values of 1.31 for the investment and 1.48 for the hiring. Finally, comparing the adjustment costs between countries reveals that the US has higher total adjustment costs than Japan and that the ratio of capital adjustment costs to labor adjustment costs is higher in Japan than in the US.

4.3 Impulse response functions and variance decompositions

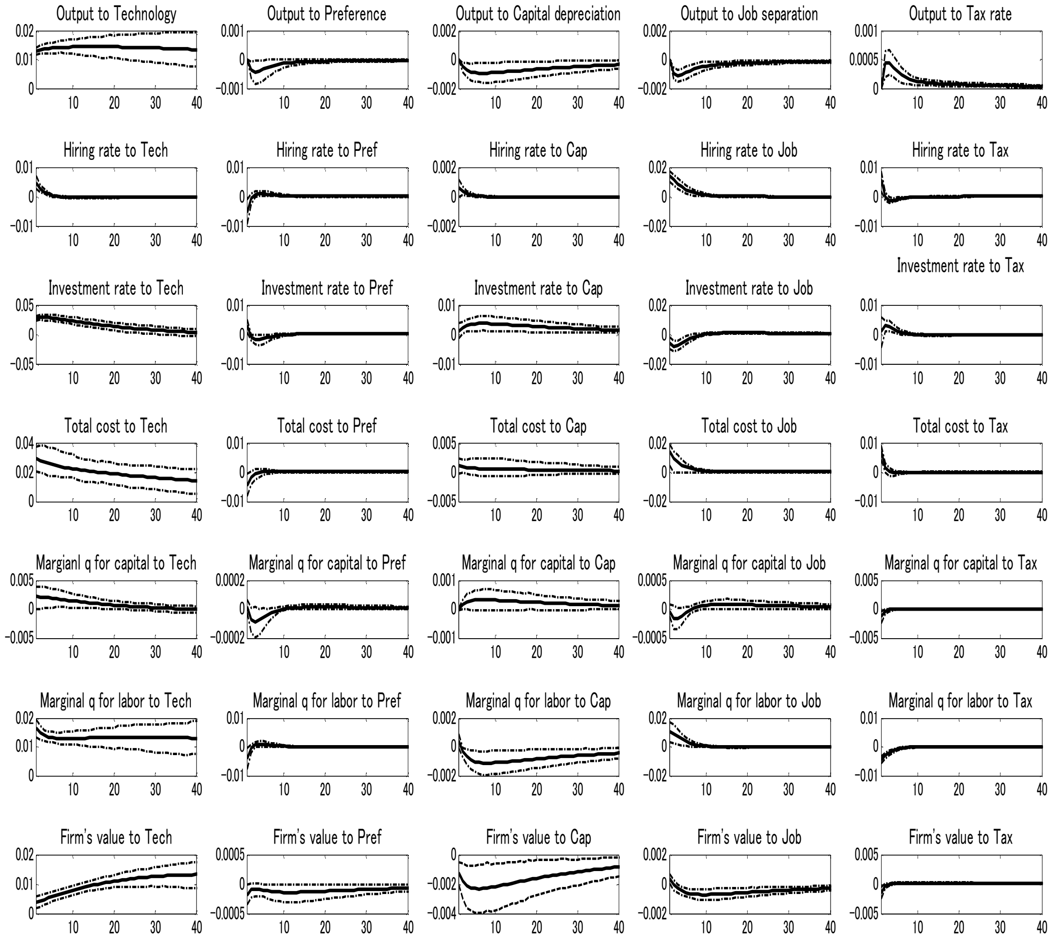
Figures 4 and 5 depict the impulse response functions of some key endogenous variables to one standard deviation in the shocks of exogenous innovations. The solid line reports the mean responses and the dashed lines report the lower and upper bound of a 90% HPD interval. The figures reveal some interesting results from our model.

In both the US and Japan, each of the shocks to the preference, capital deprecation rate, and job separation rate decreases the output levels. This depends on the fact that these shocks reduce either or both of the capital or labor. Second, all shocks, except for the preference, increase the total adjustment costs for the firm because they increase the investment or employment levels temporarily. We can understand this mechanism by considering the effects of these shocks on the marginal product of capital (and labor) or on the marginal rate of substitution between consumption and leisure. Third, the movements in the firm's market value reflect the dynamics of marginal q for capital and marginal q for labor faithfully. For example, in response to technological shocks, both q series increase, triggering similar movements in the firm's market value.

To evaluate the extent to which each shock explains the movements of the endogenous variables, Tables 6 and 7 report the forecast error variance decomposition results in the US and Japan, respectively. As in Section 4.1, the productivity shock has the highest persistence in both countries, which implies that for longer horizons, this shock will explain most of the forecast errors. The data in the tables indicates that this is correct. The tables also show that, in both countries, shocks to the capital depreciation rate explain the measurable fractions (about $10\% - 20\%$) of the short-run fluctuations of the firm's market value. Furthermore, shocks to the preference and job

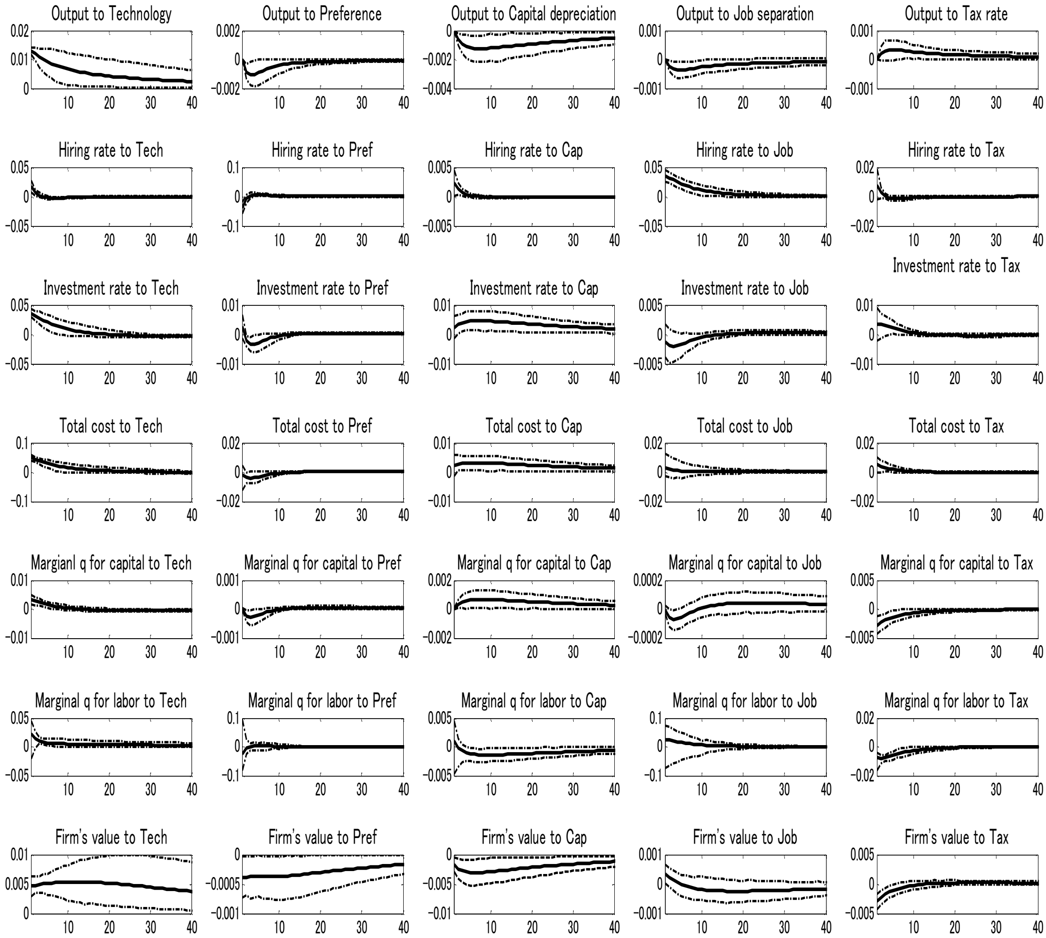
[6] Hall (2004) uses annual data for two-digit industry groups from 1949 to 2000 in the US. Summers (1981) uses annual data for all the non-financial US corporations from 1932 to 1978. Merz and Yashiv (2007) use quarterly data for the US corporate sectors from 1964 to 2002.

Figure 4: Impulse response functions (the US)



Notes: Each panel shows the percentage point response in one of the model's endogenous variables to a one standard deviation shock in one of the model's exogenous shocks. The solid line reports the mean responses and the dashed lines report the lower and upper bound of a 90% HPD interval. Periods along the horizontal axes correspond to quarter years.

Figure 5: Impulse response functions (Japan)



Notes: Each panel shows the percentage point response in one of the model's endogenous variables to a one standard deviation shock in one of the model's exogenous shocks. The solid line reports the mean responses and the dashed lines report the lower and upper bound of a 90% HPD interval. Periods along the horizontal axes correspond to quarter years.

Table 6: Forecast error variance decomposition (the US)

Quarters ahead	Tech	Pref	Cap	Job	Tax
Output					
1	100.00	0.00	0.00	0.00	0.00
4	99.16	0.05	0.21	0.51	0.07
10	99.29	0.03	0.31	0.33	0.04
100	99.81	0.00	0.12	0.06	0.01
Firm's market value					
1	78.43	0.20	9.23	0.74	11.41
4	83.08	0.05	14.24	0.48	2.15
10	89.10	0.02	9.54	0.78	0.56
100	99.09	0.00	0.79	0.09	0.02
Total adjustment costs					
1	84.26	1.19	0.13	11.07	3.35
4	93.40	0.40	0.09	5.03	1.08
10	96.80	0.19	0.06	2.43	0.51
100	98.94	0.06	0.03	0.80	0.17
Marginal Q for capital					
1	73.37	0.00	0.00	0.01	26.63
4	89.46	0.07	0.74	0.35	9.39
10	93.16	0.04	1.61	0.23	4.96
100	93.99	0.03	2.62	0.36	3.00
Marginal Q for labor					
1	69.19	2.77	0.04	22.69	5.31
4	76.69	1.09	0.15	18.96	3.10
10	86.76	0.62	0.38	10.59	1.66
100	97.67	0.10	0.18	1.77	0.28

Notes: Where Tech is the technological shock, Pref is the preference shock, Cap is the capital depreciation rate shock, Job is the job separation rate shock, and Tax is the corporate income tax rate shock.

Table 7: Forecast error variance decomposition (Japan)

Quarters ahead	Tech	Pref	Cap	Job	Tax
Output					
1	100.00	0.00	0.00	0.00	0.00
4	98.95	0.45	0.47	0.07	0.05
10	98.02	0.44	1.29	0.13	0.12
100	96.38	0.37	2.88	0.17	0.20
Firm's market value					
1	65.03	0.39	9.16	0.36	25.07
4	68.71	0.28	18.03	0.13	12.85
10	72.95	0.25	21.11	0.10	5.59
100	77.86	0.21	19.27	0.24	2.42
Total adjustment costs					
1	98.01	0.29	0.27	0.48	0.95
4	97.67	0.56	0.50	0.31	0.96
10	97.42	0.49	0.94	0.26	0.89
100	96.29	0.48	2.07	0.28	0.88
Marginal Q for capital					
1	57.14	0.00	0.00	0.00	42.86
4	58.05	0.32	1.34	0.03	40.27
10	54.97	0.32	4.65	0.04	40.02
100	57.66	0.30	10.06	0.12	31.86
Marginal Q for labor					
1	40.45	26.44	0.13	26.47	6.51
4	36.54	13.63	0.15	39.18	10.51
10	34.15	11.82	0.51	42.21	11.32
100	36.90	10.91	1.40	40.12	10.66

Notes: Where Tech is the technological shock, Pref is the preference shock, Cap is the capital depreciation rate shock, Job is the job separation rate shock, and Tax is the corporate income tax rate shock.

separation rate explain a certain amount of the short-run fluctuations in the marginal cost of hiring (this is around 20% in the US and around 50% in Japan).

5 Stock Price Forecasting

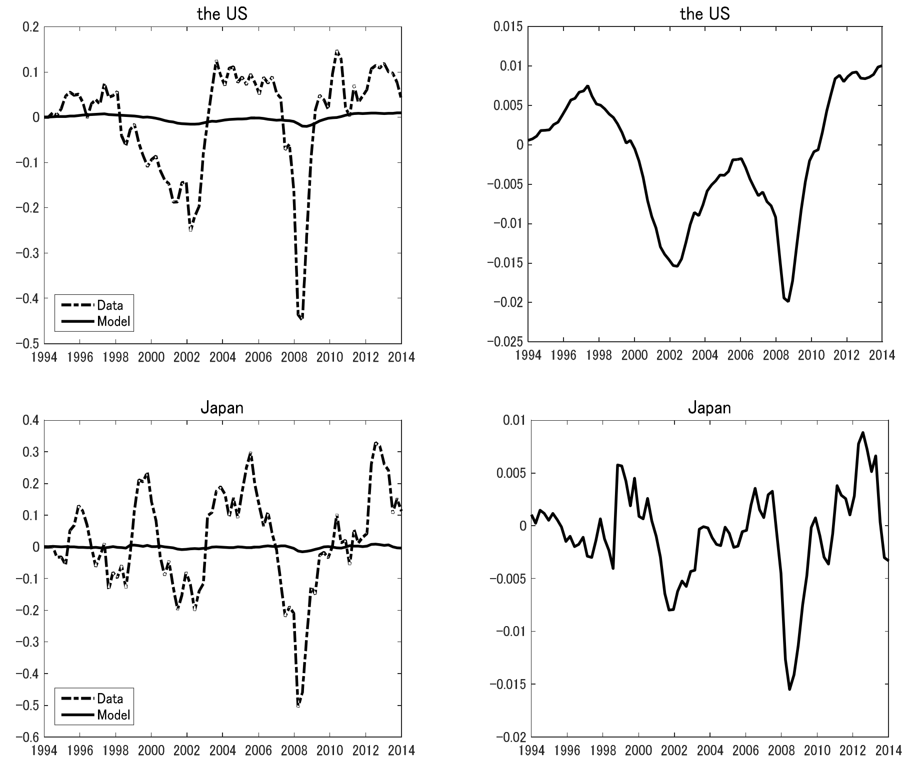
The results in the previous section show that our simple real business cycle model cannot replicate the dynamics of the actual stock price data. Specifically, the standard deviation of the firm's actual market value is 0.118 in the US and 0.158 in Japan, while the standard deviation of the simulated series is 0.008 in the US and 0.004 in Japan, with a difference of more than 10 times in the US and more than 30 times in Japan.

Interestingly, Shiller (1981) finds the same phenomenon with a different method (see Figures 1 and 2 on page 422). He calculates the present discounted value of the actual subsequent real dividends based on the efficient asset markets model, and finds that under various settings, this model cannot replicate the large volatility of stock price indexes in the data. He attributes the failure of the model to the irrational human actions known as "animal spirits." This raises the question of whether we can learn anything from the simulated path of our estimated real business cycle model.

We address this question by observing our model's failure in more detail. Figure 6 depicts our simulated series more clearly. In the right panel, we plot only the dynamics of the simulated series. Unlike the panel on the left, we find that this simulated series can show similar movements as in the data. For both countries, we calculate the correlation between the actual and simulated series and find that this value is 0.63 in the US and 0.66 in Japan. Hence, although our real business cycle model cannot replicate the actual stock price data, it may have a measurable explanatory power for whether the stock price increases or decreases.

To check the robustness of this finding, we split the sample periods, re-estimate the model, and calculate the correlation between the actual and simulated market values of the firm. We choose sample periods that do not contain the Great Recession of 2007-2009. If we use the sample to 2006, the correlation between the actual and simulated asset values is 0.78 in the US and 0.65 in Japan. With the sample to 2004, this value becomes 0.83 in the US and 0.73 in Japan. Finally, if we use the sample to 2002 (similar to that of Merz and Yashiv (2007)), the correlation becomes 0.94 in the US and 0.68 in Japan. Hence, the correlation between the actual and simulated series is significantly large, regardless of the sample period, and this value

Figure 6: Simulated vs actual firm's market value



Notes: The left panel shows the actual (dotted line) and simulated (solid line) firm market value from applying a Kalman smoothing algorithm. The right panel shows only the simulated firm market value. The sample period is from 1994:Q1 to 2014:Q4.

becomes relatively larger in the US when we exclude the Great Recession of 2007-2009.

Why does our model have such a large explanatory power for how the stock price changes according to macroeconomic activities? We consider this question by estimating a plain, real business cycle model without capital and labor adjustment costs. From equations (8), (10), and (12), we find that without these frictions, the volatility of the firm's market value becomes equal to that of the capital stock. This experiment shows that the correlation between the firm's actual and simulated market value becomes 0.30 in the US and -0.19 in Japan, with considerably less explanatory power in the model. We can thus conclude that the capital and labor adjustment costs play a key role in connecting asset pricing phenomena to macroeconomic activities.

6 Conclusion

This study estimates a simple real business cycle model using a Bayesian estimation method with US and Japanese aggregate data. We find that the real business cycle model with capital and labor adjustment costs can explain the key business cycles facts (GDP, investment, hiring, wages). Furthermore, this simple real business cycle model can also partially address whether the stock price will increase or decrease.

Since our model does not contain several frictions like sticky prices, sticky wages, and search and matching frictions which is common in the recent literature, we can easily use this model in varying contexts. This is the first benefit of our study. Second, our new finding that the real business cycle model has a measurable explanatory power for whether the stock price rises or falls sheds new light on the connection between asset pricing phenomena and macroeconomic activities. Of course, monetary shocks and monetary frictions are considered by many to be an essential ingredient for the asset pricing mechanism. However, without these frictions, we can explain how the stock price changes according to macroeconomic variables.

Our study does have limitations. The explanatory power of our model may be weaker during a significant economic recession. Since our model does not describe the bubble in the economy, we cannot identify why our real business cycle model fails to explain the dynamics of asset prices in these periods. This will become a task for future research. Second, some critics point out that the model in this paper is useful for forecasting, but the adjustment cost function in the article has an ambiguous meaning. This indication is incompatible with the purpose of our study, though is certainly important. To address this issue, we must analyze more concrete settings in our model.

Appendix

This appendix provides information about the dataset used in this study. Our data mainly come from the National Accounts of US and Japan. The following subsections describe the construction of the variables for both countries.

a. the US

GDP(y) and labor share of income (wn/y)

Real GDP in the US pertains to the non-financial corporate business sector. The data originate from BEA NIPA accounts, Table 1.14, line 41 (gross value added of non-financial corporate business, in billions of chained (2009) dollars, seasonally adjusted). For the labor share of income, we use employee compensation in the NFCB sector (NIPA Table 1.14, line 20) divided by the total sector output (NIPA Table 1.14, line 17).

Gross investment rate (i/k)

The goal here is to construct a quarterly series of real investment flow i_t and the real capital stock k_t. We adopt the method in Yashiv (2011) and Yashiv (2016). The process is as follows:

- Construct end-of-year fixed-cost net stock of private non-residential fixed assets in the NFCB sector, K_t. We do this by using the quantity index for net stock of fixed assets in the NFCB sector (FAA Table 4.2, line 37, BEA). The base year for this index is 2009. Therefore, we obtain the fixed-cost estimate by multiplying this series by the current-cost net stock of fixed assets in the NFCB sector in 2009 (FAA Table 4.1, line 37).

- Construct annual fixed-cost depreciation of private non-residential fixed assets in the NFCB sector, D_t. Here, we follow the same procedure as in the previous paragraph with respect to depreciation series. The chain-type quantity index for depreciation originates from FAA Table

4.5, line 37. The current-cost depreciation estimates appear in FAA Table 4.4, line 37.

- Calculate the annual fixed-cost investment flow, I_t:

$$I_t = K_t - K_{t-1} + D_t$$

- Calculate the annual depreciation rate, δ_a:

$$\delta_a = \frac{I_t - (K_t - K_{t-1})}{K_{t-1} + I_t/2}$$

- Calculate the quarterly depreciation rate for each year, δ_{qt}:

$$\delta_{qt} + (1-\delta_{qt})\delta_{qt} + (1-\delta_{qt})^2\delta_{qt} + (1-\delta_{qt})^3\delta_{qt} = \delta_{at}, \quad \text{for each year } t$$

- Take the seasonally adjusted quarterly investment in private nonresidential fixed assets by NFCB sector from the Flow of Funds accounts, atabs files, series FA105013005.

- Deflate it using the investment price index. We calculate the latter as consumption of fixed capital in domestic the NFCB sector in current dollars (NIPA Table 1.14, line 18) divided by consumption of fixed capital in domestic the NFCB sector in chained 2009 dollars (NIPA Table 1.14, line 42). This process yields the implicit price deflator for depreciation in the NFCB sector, which is conceptually the same as the investment price index.

- Simulate the quarterly real capital stock series k_t, starting from k_0 (k_0 is actually the fixed-cost net stock of fixed assets at the end of 1970; this value comes from series K_t), using the quarterly depreciation series δ_{qt} and investment series i_t above:

$$k_{t+1} = k_t(1-\delta_{qt}) + i_t$$

Gross hiring rate (h/n)

To calculate the gross hiring rate, we use Labor Force Statistics from the US Current Population Survey. We first calculate the employment stock series (n) using the quarterly average of the original seasonally adjusted total employment series (LNS12000000). Then, we build the flows between E (employment), U (unemployment), and N (not-in-the-labor-force) using labor flow data from the US Labor Force Statistics (LNS17100000, LNS17200000, LNS17400000, and LNS17800000). Finally, we calculate the quarterly gross hiring rate and the quarterly job separation rate:

$$h/n = \frac{NE + UE}{E}$$
$$\psi = \frac{EN + EU}{E}$$

Stock prices (s) and corporate income tax rates (τ)

We take the index of US stock prices from the OECD Monthly Monetary and Financial Statistics data set, which is a subset of the Main Economic Indicators database. This stock price index covers all listed companies on the New York Stock Exchange. We deflate this index with a GDP deflator. We take data for the corporate income tax rate from the OECD Tax Database. We use the combined corporate income tax rate, which is the sum of the central and sub-central corporate income tax rates.

b. Japan

GDP(y) and labor share of income (wn/y)

We take GDP from Japan's National Accounts from the Cabinet Office. We measure the gross value added in billions of chained (2005) yen, without seasonal adjustment. We use X12-ARIMA to introduce seasonal adjustment. For the labor share of income, we use the employee compensation divided by the total national income. Both data series are taken from Japan's National Accounts data, and measured with nominal values (billions of yen, seasonally adjusted).

Gross investment rate (i/k)

First, we calculate the quarterly investment series i_t from the Quarterly Estimates of Gross Capital Stock of Private Enterprises (published by Japan's Cabinet Office). This data reports the quarterly gross investment series at constant prices by industry (base year = 2005). We take the values for the NFCB sector, measured in millions of 2005 yen.

To construct the quarterly real capital stock series k_t, we use the perpetual inventory method, as in the US. First, we take the end-of-year fixed-cost net stock of tangible fixed assets in the NFCB sector, K_t, from the appendix table of the National Accounts. The values cover 1980 to 2009, measured in billions of yen at constant prices (base year = 2000). We use the investment price deflator to change the base year from 2000 to 2005 to match with the other data.

We simulate the quarterly real capital stock series k_t starting from k_0 (k_0 is actually the fixed-cost net stock of fixed assets at the end of 1993 from the series K_t), using the quarterly depreciation series 0.020 which we adopt from Ogawa et al. (1996), and investment series i_t above:

$$k_{t+1} = k_t(1 - 0.020) + i_t$$

Finally, we divide the gross investment series i_t by the value of real capital stock series k_t and change the data into seasonally adjusted values.

Gross hiring rate (h/n)

To construct the stock of employment series n, we use Labor Force Survey data from the Ministry of Internal Affairs and Communications of Japan. We use seasonally adjusted quarterly data from this database's historical data. Then, we take the job separation rate data from Japan's Survey on Employment Trends compiled by the Ministry of Health, Labour and Welfare. Because the separation rate reported here is the annual rate, we interpolate them to obtain quarterly data. Finally, we obtain the gross hiring flows (h_t) as follows:

$$h_t = n_t - (1 - \psi_t)n_{t-1}$$

Stock prices (s) and corporate income tax rates (τ)

We take the index of the Japanese stock prices from the OECD Monthly Monetary and Financial Statistics. This stock price index covers large companies on the Tokyo Stock Exchange. We deflate this index with a GDP deflator. We take data for the Japanese corporate income tax rate from the OECD Tax Database as in the US.

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