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Do Investment-Specific Technological Changes Matter for Business Fluctuations? Evidence from Japan*

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Abstract

The observed decline in the relative price of investment goods in Japan suggests the existence of investment-specific technological (IST) changes. This paper examines whether IST changes are a major source of business fluctuations in Japan, by estimating a dynamic stochastic general equilibrium model with Bayesian methods. We show that IST changes are less important than neutral technological changes in explaining output fluctuations. We also demonstrate that investment fluctuations are mainly driven by shocks to investment adjustment costs. Such shocks represent variations of costs involved in changing investment spending, such as financial intermediation costs. We then find that the estimated investment adjustment cost shocks correlate strongly with the diffusion index of firms' financial position in the Tankan (Short-term Economic Survey of Enterprises in Japan). We thus argue that the large decline in investment growth in the early 1990s is due to an increase in investment adjustment costs stemming from firms' tight financial constraint after the collapse of Japan's asset price bubble.

Keywords: Business fluctuation; Investment-specific technology; Investment adjustment cost shock; Financial intermediation cost; Firms' financial constraint

JEL Classification: E22; E31; E32

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1 Introduction

What is the main source of business fluctuations? The conventional view in the business cycle literature is that technological changes play a major role in explaining aggregate fluctuations. In particular, the importance of sector-specific technological changes has been emphasized. For instance, Canova et al. (1994) point out that co-trending relationships assumed in business cycle models are often rejected by data. More specifically, Greenwood et al. (1997, 2000) and Fisher (2006) focus on the relative price movement of investment goods to consumption goods, and demonstrate the crucial importance of investment-specific technological (IST) changes in the U.S. business fluctuations using calibrated dynamic stochastic general equilibrium (DSGE) models and estimated structural vector autoregression (SVAR) models. Motivated by these authors' results, recent studies by Ireland and Schuh (2008) and Justiniano et al. (2009) estimate DSGE models to reexamine whether IST changes are critical in explaining the U.S. business cycles.¹ However, Ireland and Schuh find that consumption-specific technological changes are more important than the IST changes. Also, Justiniano et al. show that investment efficiency shocks proposed by Greenwood et al. (1988) are the main driving force of U.S. aggregate fluctuations rather than the IST changes.

In this paper, we address the question of whether IST changes are a major source of business fluctuations in Japan, by estimating a DSGE model with Bayesian methods.² In recent studies, Christiano and Fujiwara (2006) suggest that the observed decline in the relative price of investment goods to consumption goods in Japan (see Figure 1) implies the necessity for IST changes in DSGE models of Japan's economy. Braun and Shioji (2007) incorporate IST changes into Hayashi and Prescott (2002)'s neoclassical growth model for Japan, and show that the introduction of IST changes improves overall fit of the calibrated model to data. Braun and Shioji also estimate a SVAR model in which sign restrictions are derived from implications

¹Edge et al. (2008) develop a more rigorous multi-sector model.

²For Bayesian estimation of DSGE models of Japan's economy, see Iiboshi et al. (2006), Hirose (2008), Sugo and Ueda (2008), Ichiue et al. (2008), and Fujiwara et al. (2008). These studies, except the last one, estimate DSGE models for stationary variables using detrended data as in line with Christiano et al. (2005), Smets and Wouters (2003), and Levin et al. (2006). This approach differs from that of the present paper, since our DSGE model incorporates stochastic trends both in neutral technology and in IST so that we can explicitly examine whether the boom and bust cycle during the late 1980s and the early 1990s in Japan is driven by changes in the trends or by nonpermanent shocks.

that are common to DSGE models with IST changes, and conclude that the IST changes are at least as important as neutral technological changes in Japan's business cycles.

We take a different approach from Braun and Shioji. Specifically, we use a Bayesian likelihood approach to estimate a fully specified DSGE model with IST changes and investment adjustment cost shocks. Such cost shocks have been used in recent business cycle studies since Smets and Wouters (2003), and represent variations of costs involved in changing investment spending, such as financial intermediation costs analyzed by Carlstrom and Fuerst (1997).³

The present paper has three main findings. First, we find that IST changes are less important than neutral technological changes in explaining output fluctuations in Japan. By investigating historical and variance decompositions of output growth, we show that the IST changes play a minor role or sometimes an offsetting role in the output fluctuations. This result is in stark contrast with that of Braun and Shioji (2007) mentioned above.

Second, we find that investment fluctuations in Japan are mainly driven by the investment adjustment cost shocks rather than IST changes. Our historical and variance decompositions of investment growth demonstrate that the investment adjustment cost shocks are the main driving force of investment fluctuations and also play a major role in output fluctuations.

Last, we find that the estimated series of investment adjustment cost shocks correlate strongly with the diffusion index of firms' financial position in the *Tankan* (Short-term Economic Survey of Enterprises in Japan).⁴ This suggests that the estimated shocks can be considered as a measure for firms' financial constraint regarding investment spending. We thus argue that the large decline in investment growth in the early 1990s is due to an increase in investment adjustment costs stemming from firms' tight financial constraint after the collapse of Japan's asset price bubble. This view is in stark contrast with that of Hayashi and Prescott (2002), who point out that the dysfunction of Japan's banking system during the 1990s did not constrain firms' financing for investment.

³The investment adjustment cost shock considered in this paper and the investment efficiency shock studied by Greenwood et al. (1988) and Justiniano et al. (2009, 2010) capture a similar wedge in equilibrium conditions for investment spending. The efficiency shock is a technology shock that affects the transformation of investment goods into productive capital. We have confirmed that our findings do not alter even when we employ investment efficiency shocks in our model.

⁴Justiniano et al. (2009) obtain a similar result that there is correlation between their estimated investment efficiency shocks and a spread between yields of the lowest and the highest rated categories of investment grade securities investigated by Levin et al. (2004).

The remainder of the paper proceeds as follows. Section 2 describes a DSGE model with IST changes and investment adjustment cost shocks. Section 3 illustrates data and estimation strategy. Section 4 presents estimation results. Finally, Section 5 concludes.

2 The model

We develop a DSGE model along the lines of recent business cycle studies such as Christiano et al. (2005), Smets and Wouters (2003), and Levin et al. (2006). We consider balanced growth as in Erceg et al. (2006) and Smets and Wouters (2007) and incorporate IST changes as in Justiniano et al. (2009). We also allow for stochastic trends in neutral technological changes and in IST changes, since there seems to be at least one break in Japan's GDP growth around 1991 as Sugo and Ueda (2008) indicate. Further, we suppose monopolistic competition in the investment-good sector so that the associated price markup generates a wedge between the IST level and the relative price of investment goods to consumption goods.

In the model economy there are four types of firms, a continuum of households, and a central bank. We describe each in turn.

2.1 Firms

We first begin with firms' behavior. There are a representative capital-service-providing firm, a continuum of investment-good-producing firms $f_i \in [0, 1]$, a representative consumption-good-producing firm, and a continuum of intermediate-good-producing firms $f_c \in [0, 1]$.

2.1.1 Capital-service firm

At the beginning of period, the capital-service firm owns the entire stock of capital K_{t-1} . This firm rents utilization-adjusted capital $u_t K_{t-1}$ to intermediate-good firms at the real price R_t^k . The firm then chooses the capital utilization rate u_t and investment spending I_t so as to maximize profit

$$E_t \sum_{j=0}^{\infty} \beta^j \frac{\Lambda_{t+j}}{\Lambda_t} \left(R_{t+j}^k u_{t+j} K_{t+j-1} - \frac{P_{t+j}^i}{P_{t+j}} I_{t+j} \right)$$

subject to the capital accumulation equation

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

Here, $\beta^j \Lambda_{t+j}/\Lambda_t$ shows the stochastic discount factor between period t and period $t+j$, $\beta \in (0, 1)$ is the subjective discount factor, Λ_t denotes households' marginal utility of consumption, P_t^i is the aggregate price of investment goods, and P_t is the price of consumption goods. Following Greenwood et al. (1988), our model supposes that a higher utilization rate of capital leads to a higher depreciation rate of capital. Hence, the depreciation rate function $\delta(\cdot)$ has properties of $\delta' > 0$, $\delta'' > 0$, $\delta(u) = \delta \in (0, 1)$, and $\mu = \delta'(u)/\delta''(u) > 0$, where u is the steady-state capital utilization rate. The term $S(\cdot)$ represents costs involved in changing investment spending, such as financial intermediation costs analyzed by Carlstrom and Fuerst (1997), and this function takes the quadratic form of $S(x) = (x-1)^2/(2\zeta)$, where ζ is a positive constant. The variable z_t^i is a shock added to the investment adjustment costs. The parameters $z^*, \psi > 1$ show the (gross) trend rates of balanced growth and IST changes given below.

The first-order conditions for the profit maximization with respect to I_t , u_t , and K_t are given by

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

$$R_t^k = Q_t \delta'(u_t), \quad (3)$$

$$Q_t = E_t \beta \frac{\Lambda_{t+1}}{\Lambda_t} \left\{ R_{t+1}^k u_{t+1} + Q_{t+1} (1 - \delta(u_{t+1})) \right\}, \quad (4)$$

where Q_t shows the real price of capital.⁵

The investment spending I_t represents an aggregate of differentiated investment goods given by $I_t = (\int_0^1 I_t(f_i)^{(\theta_t^i-1)/\theta_t^i} df_i)^{\theta_t^i/(\theta_t^i-1)}$, where $\theta_t^i > 1$ denotes the elasticity of substitution between investment goods. The first-order condition for the cost-minimizing combination of investment goods yields the capital-service firm's demand for each investment good

$$I_t(f_i) = I_t \left(\frac{P_t^i(f_i)}{P_t^i} \right)^{-\theta_t^i}, \quad (5)$$

⁵When we use investment efficiency shocks z_t^e as in Justiniano et al. (2009, 2010), the capital accumulation equation becomes

$$K_t = (1 - \delta(u_t))K_{t-1} + \exp(z_t^e) \left\{ 1 - S\left(\frac{I_t}{z^*\psi I_{t-1}}\right) \right\} I_t.$$

Then, the first-order condition for investment spending I_t becomes

$$\frac{P_t^i}{P_t} = Q_t \exp(z_t^e) \left\{ 1 - S\left(\frac{I_t}{z^*\psi I_{t-1}}\right) - S'\left(\frac{I_t}{z^*\psi I_{t-1}}\right) \frac{I_t}{z^*\psi I_{t-1}} \right\} + E_t \beta \frac{\Lambda_{t+1}}{\Lambda_t} Q_{t+1} \exp(z_{t+1}^e) S'\left(\frac{I_{t+1}}{z^*\psi I_t}\right) \left(\frac{I_{t+1}}{I_t}\right)^2 \frac{1}{z^*\psi}.$$

where $P_t^i(f_i)$ is the price of investment good f_i . Then, the associated aggregate price P_t^i is given by

$$P_t^i = \left(\int_0^1 P_t^i(f_i)^{1-\theta_t^i} df_i \right)^{\frac{1}{1-\theta_t^i}}. \quad (6)$$

2.1.2 Investment-good firms

Each investment-good firm f_i uses the production technology which converts one unit of consumption goods into Ψ_t units of differentiated investment good f_i . Thus Ψ_t represents the level of IST. Our model assumes that this level follows the stochastic process

$$\log \Psi_t = \log \psi + \log \Psi_{t-1} + z_t^\psi, \quad (7)$$

where z_t^ψ is a shock to the rate of IST changes and is governed by a stationary first-order autoregressive process. The inverse of the IST level, $1/\Psi_t$, turns out to be real marginal cost of producing each investment good, and thus the marginal cost is identical among investment-good firms.

Facing the capital-service firm's demand (5), each investment-good firm sets the price of its product so as to maximize profit $(P_t^i(f_i)/P_t - 1/\Psi_t) I_t(f_i)$. The first-order condition for profit maximization yields the price of investment good f_i given by $P_t^i(f_i) = (1 + \lambda_t^i) P_t / \Psi_t$, where $\lambda_t^i \equiv 1/(\theta_t^i - 1) > 0$ is the investment-good price markup over nominal marginal cost P_t / Ψ_t . This equation shows that the price of each investment good is identical, and hence it follows from (5) that output of each investment good is identical. Then, (6) yields

$$P_t^i = \frac{P_t(1 + \lambda_t^i)}{\Psi_t} = P_t^i(f_i). \quad (8)$$

Also, combining this equation and (5) implies

$$I_t = I_t(f_i). \quad (9)$$

From (8), the (gross) rate of the relative price of investment goods to consumption goods is given by

$$r_t^i \equiv \frac{P_t^i/P_t}{P_{t-1}^i/P_{t-1}} = \frac{1 + \lambda_t^i}{1 + \lambda_{t-1}^i} \frac{\Psi_{t-1}}{\Psi_t}. \quad (10)$$

Notice that when the investment-good market is perfectly competitive as in Justiniano et al. (2009) and Braun and Shioji (2007), we have $\lambda_t^i = 0$ in each period t , and hence (8) leads to

$$\frac{P_t^i}{P_t} = \frac{1}{\Psi_t}.$$

That is, the inverse of the IST level must equal the relative price of investment goods. In contrast to this restrictive specification, our model assumes the monopolistically competitive investment-good market with the time-varying price markup. This markup gives rise to a wedge between IST changes and the rate of the relative price of investment goods, as shown in (10).

2.1.3 Consumption-good firm

The consumption-good firm produces output Y_t by choosing a combination of intermediate inputs $\{Y_t(f_c)\}$ so as to maximize profit $P_t Y_t - \int_0^1 P_t(f_c) Y_t(f_c) df_c$ subject to the production technology $Y_t = (\int_0^1 Y_t(f_c)^{(\theta_t^p - 1)/\theta_t^p} df_c)^{\theta_t^p / (\theta_t^p - 1)}$, where $P_t(f_c)$ is the price of intermediate good f_c and $\theta_t^p > 1$ measures the elasticity of substitution between intermediate goods.

The first-order condition for profit maximization yields the consumption-good firm's demand for each intermediate good given by $Y_t(f_c) = Y_t (P_t(f_c)/P_t)^{-\theta_t^p}$, while perfect competition in the consumption-good market leads to its price P_t given by

$$P_t = \left(\int_0^1 P_t(f_c)^{1-\theta_t^p} df_c \right)^{\frac{1}{1-\theta_t^p}}. \quad (11)$$

The market clearing condition for consumption goods is

$$Y_t = C_t + \int_0^1 \frac{I_t(f_i)}{\Psi_t} df_i + g Z_t^* \exp(\tilde{z}_t^g) = C_t + \frac{I_t}{\Psi_t} + g Z_t^* \exp(\tilde{z}_t^g), \quad (12)$$

where the second equality follows from (9).

2.1.4 Intermediate-good firms

Each intermediate-good firm f_c produces output $Y_t(f_c)$ by choosing a cost-minimizing pair of capital and labor services $\{u_t K_{t-1}(f_c), l_t(f_c)\}$, given their real rental prices (R_t^k, W_t) and the production function

$$Y_t(f_c) = (Z_t l_t(f_c))^{1-\alpha} (u_t K_{t-1}(f_c))^\alpha - \phi Z_t^*. \quad (13)$$

Here, Z_t represents the level of neutral technology, and this level is assumed to follow the stochastic process

$$\log Z_t = \log z + \log Z_{t-1} + z_t^z, \quad (14)$$

where $z > 1$ shows the (gross) trend rate of neutral technological changes and z_t^z represents a shock to the rate of the changes and is governed by a stationary first-order autoregressive

process. Each firm's labor input $l_t(f_c) = (\int_0^1 l_t(f_c, h)^{(\theta_t^w - 1)/\theta_t^w} dh)^{\theta_t^w / (\theta_t^w - 1)}$ is an aggregate of differentiated labor services with the substitution elasticity $\theta_t^w > 1$, and the corresponding aggregate wage is given by

$$W_t = \left(\int_0^1 W_t(h)^{1 - \theta_t^w} dh \right)^{\frac{1}{1 - \theta_t^w}}. \quad (15)$$

The parameter $\alpha \in (0, 1)$ measures the capital elasticity of output. The last term in the production function (13), $-\phi Z_t^*$, is a fixed cost of producing intermediate goods, ϕ is a positive constant, and Z_t^* is the composite technology level given by $Z_t^* = Z_t(\Psi_t)^\alpha / (1 - \alpha)$, which is derived from the Cobb-Douglas form of the production function (13). Then, the logarithm of the composite technological changes, $\log(Z_t^*/Z_{t-1}^*)$, turns out to be the (gross) rate of balanced growth, and the associated trend rate is given by $z^* = z\psi^{\alpha/(1-\alpha)}$.

Combining cost-minimizing conditions with respect to capital and labor services shows that real marginal cost is identical among intermediate-good firms and is given by

$$mc_t = \left(\frac{W_t}{(1 - \alpha)Z_t} \right)^{1 - \alpha} \left(\frac{R_t^k}{\alpha} \right)^\alpha. \quad (16)$$

Also, combining the cost-minimizing conditions and aggregating the resulting equation over intermediate-good firms show that the capital-labor ratio is identical among intermediate-good firms and is given by

$$\frac{u_t K_{t-1}}{l_t} = \frac{\alpha W_t}{(1 - \alpha) R_t^k}, \quad (17)$$

where $K_t = \int_0^1 K_t(f_c) df_c$ and $l_t = \int_0^1 l_t(f_c) df_c$. Moreover, using this equation to aggregate the production function (13) over intermediate-good firms yields

$$Y_t d_t = (Z_t l_t)^{1 - \alpha} (u_t K_{t-1})^\alpha - \phi Z_t^*, \quad (18)$$

where $d_t = \int_0^1 (P_t(f_c)/P_t)^{-\theta_t^p} df_c$ measures the intermediate-good price dispersion.

Facing the consumption-good firm's demand, each intermediate-good firm sets the price of its product on a staggered basis à la Calvo (1983). Each period a fraction $1 - \xi_p \in (0, 1)$ of intermediate-good firms reoptimizes prices, while the remaining fraction ξ_p indexes prices to a weighted average of (gross) past inflation $\pi_{t-1} = P_{t-1}/P_{t-2}$ and (gross) steady-state inflation π . Then, firms which reoptimize prices in the current period solve the same problem

$$\max_{P_t(f_c)} E_t \sum_{j=0}^{\infty} \xi_p^j \left(\beta^j \frac{\Lambda_{t+j}}{\Lambda_t} \right) \left\{ \frac{P_t(f_c)}{P_{t+j}} \prod_{k=1}^j (\pi_{t+k-1}^{\gamma_p} \pi^{1-\gamma_p}) - mc_{t+j} \right\} Y_{t+j|t}(f_c)$$

subject to

$$Y_{t+j|t}(f_c) = Y_{t+j} \left\{ \frac{P_t(f_c)}{P_{t+j}} \prod_{k=1}^j (\pi_{t+k-1}^{\gamma_p} \pi^{1-\gamma_p}) \right\}^{-\theta_{t+j}^p},$$

where $\gamma_p \in [0, 1]$ is the weight of price indexation to past inflation relative to steady-state inflation. The first-order condition for the reoptimized price P_t^o is given by

$$E_t \sum_{j=0}^{\infty} \left((\beta \xi_p)^j \frac{\Lambda_{t+j}}{\Lambda_t \lambda_{t+j}^p} Y_{t+j} \left[\frac{P_t^o}{P_t} \prod_{k=1}^j \left\{ \left(\frac{\pi_{t+k-1}}{\pi} \right)^{\gamma_p} \frac{\pi}{\pi_{t+k}} \right\} \right]^{-\frac{1+\lambda_{t+j}^p}{\lambda_{t+j}^p}} \right. \\ \left. \times \left[\frac{P_t^o}{P_t} \prod_{k=1}^j \left\{ \left(\frac{\pi_{t+k-1}}{\pi} \right)^{\gamma_p} \frac{\pi}{\pi_{t+k}} \right\} - (1 + \lambda_{t+j}^p) m c_{t+j} \right] \right) = 0, \quad (19)$$

where $\lambda_t^p \equiv 1/(\theta_t^p - 1) > 0$ denotes the intermediate-good price markup. The consumption-good price equation (11) can be reduced to

$$1 = (1 - \xi_p) \left(\left(\frac{P_t^o}{P_t} \right)^{-\frac{1}{\lambda_t^p}} + \sum_{j=1}^{\infty} (\xi_p)^j \left[\frac{P_{t-j}^o}{P_{t-j}} \prod_{k=1}^j \left\{ \left(\frac{\pi_{t-k}}{\pi} \right)^{\gamma_p} \frac{\pi}{\pi_{t-k+1}} \right\} \right]^{-\frac{1}{\lambda_t^p}} \right). \quad (20)$$

Notice that under the staggered price-setting presented above, the intermediate-good price dispersion d_t is of second order.

2.2 Households

We turn next to households' behavior. There is a continuum of households $h \in [0, 1]$, each of which purchases consumption goods $C_t(h)$ and one-period riskless bonds $B_t(h)$ and supplies one kind of differentiated labor services $l_t(h) = \int_0^1 l_t(f, h) df$ to intermediate-good firms under monopolistic competition. Each household's preferences are represented by the utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t \exp(z_t^b) \left\{ \frac{(C_t(h) - \theta C_{t-1}(h))^{1-\sigma}}{1-\sigma} - \frac{(Z_t^*)^{1-\sigma} \exp(z_t^l) (l_t(h))^{1+\chi}}{1+\chi} \right\},$$

where $\sigma > 0$ measures the risk aversion, $\theta \in (0, 1)$ represents habit persistence in consumption preferences, $\chi > 0$ is the inverse of the labor supply elasticity, and z_t^b, z_t^l denote shocks relevant to the subjective discount factor and to labor supply. As in Erceg et al. (2006), we assume the presence of $(Z_{t+j}^*)^{1-\sigma}$ in the labor disutility, which ensures the existence of the balanced growth path for the model economy. This household's budget constraint is given by

$$P_t C_t(h) + B_t(h) = r_{t-1}^n B_{t-1}(h) + P_t W_t(h) l_t(h) + T_t(h),$$

where r_t^n is the (gross) nominal interest rate and $T_t(h)$ consists of a lump-sum public transfer and profits received from firms.

In the presence of complete insurance markets, all households purchase the same levels of consumption goods and one-period riskless bonds and hence the first-order conditions for utility maximization with respect to consumption and bond-holdings are given by

$$\Lambda_t = \exp(z_t^b) (C_t - \theta C_{t-1})^{-\sigma} + \beta \theta E_t \exp(z_{t+1}^b) (C_{t+1} - \theta C_t)^{-\sigma}, \quad (21)$$

$$1 = E_t \beta \frac{\Lambda_{t+1}}{\Lambda_t} \frac{r_t^n}{\pi_{t+1}}. \quad (22)$$

In monopolistically competitive labor markets, the demand for labor service h is given by $l_t(h) = l_t(W_t(h)/W_t)^{-\theta^w}$, and nominal wages are set on a staggered basis à la Calvo (1983). Each period a fraction $1 - \xi_w \in (0, 1)$ of wages is reoptimized, while the remaining fraction ξ_w is set by indexation to a weighted average of past inflation π_{t-1} and steady-state inflation π . Then, the reoptimized wages solve the same problem

$$\max_{W_t(h)} E_t \sum_{j=0}^{\infty} (\beta \xi_w)^j \left\{ \frac{\Lambda_{t+j} l_{t+j|t}(h) \frac{P_t W_t(h)}{P_{t+j}} \prod_{k=1}^j (z^* \pi_{t+k-1}^{\gamma_w} \pi^{1-\gamma_w})}{\frac{\exp(z_{t+j}^b) (Z_{t+j}^*)^{1-\sigma} \exp(z_{t+j}^l) (l_{t+j|t}(h))^{1+\chi}}{1+\chi}} \right\}$$

subject to

$$l_{t+j|t}(h) = l_{t+j} \left\{ \frac{P_t W_t(h)}{P_{t+j} W_{t+j}} \prod_{k=1}^j (z^* \pi_{t+k-1}^{\gamma_w} \pi^{1-\gamma_w}) \right\}^{-\theta_{t+j}^w},$$

where $\gamma_w \in [0, 1]$ is the weight of wage indexation to past inflation relative to steady-state inflation. The first-order condition for the reoptimized wage W_t^o is given by

$$E_t \sum_{j=0}^{\infty} \left[\begin{aligned} & (\beta \xi_w)^j \frac{\Lambda_{t+j}}{\lambda_{t+j}^w} l_{t+j} \left[\frac{(z^*)^j W_t^o}{W_{t+j}} \prod_{k=1}^j \left\{ \left(\frac{\pi_{t+k-1}}{\pi} \right)^{\gamma_w} \frac{\pi}{\pi_{t+k}} \right\} \right]^{-\frac{1+\lambda_{t+j}^w}{\lambda_{t+j}^w}} \\ & \times \left\{ \begin{aligned} & (z^*)^j W_t^o \prod_{k=1}^j \left\{ \left(\frac{\pi_{t+k-1}}{\pi} \right)^{\gamma_w} \frac{\pi}{\pi_{t+k}} \right\} \\ & - (1 + \lambda_{t+j}^w) \frac{\exp(z_{t+j}^b) \exp(z_{t+j}^l) (Z_{t+j}^*)^{1-\sigma}}{\Lambda_{t+j}} \end{aligned} \right\} \\ & \times \left(l_{t+j} \left[\frac{(z^*)^j W_t^o}{W_{t+j}} \prod_{k=1}^j \left\{ \left(\frac{\pi_{t+k-1}}{\pi} \right)^{\gamma_w} \frac{\pi}{\pi_{t+k}} \right\} \right]^{-\frac{1+\lambda_{t+j}^w}{\lambda_{t+j}^w}} \right)^\chi \end{aligned} \right] = 0, \quad (23)$$

where $\lambda_t^w \equiv 1/(\theta_t^w - 1) > 0$ denotes the wage markup. The aggregate wage equation (15) can

be reduced to

$$1 = (1 - \xi_w) \left(\left(\frac{W_t^o}{W_t} \right)^{-\frac{1}{\lambda_t^w}} + \sum_{j=1}^{\infty} (\xi_w)^j \left[\frac{(z^*)^j W_{t-j}^o}{W_t} \prod_{k=1}^j \left\{ \left(\frac{\pi_{t+k-1}}{\pi} \right)^{\gamma_w} \frac{\pi}{\pi_{t+k}} \right\} \right]^{-\frac{1}{\lambda_t^w}} \right). \quad (24)$$

2.3 Central bank

Last, we present the central bank's behavior. This bank conducts monetary policy by adjusting the nominal interest rate. Interest rate policy is assumed to be a Taylor (1993) style rule

$$\log r_t^n = \phi_r \log r_{t-1}^n + (1 - \phi_r) \left\{ \log r^n + \phi_\pi \left(\frac{1}{4} \sum_{j=0}^3 \log \frac{\pi_{t-j}}{\pi} \right) + \phi_y \log \frac{Y_t}{Y_t^*} \right\} + z_t^r. \quad (25)$$

Here, $\phi_r \in [0, 1)$ is the degree of interest rate smoothing, r^n is the (gross) steady-state nominal interest rate, $\phi_\pi, \phi_y \geq 0$ are the degrees of interest rate policy responses to inflation and the output gap, and Y_t^* is the potential output given by

$$Y_t^* = (Z_t l)^{1-\alpha} (uk Z_{t-1}^* \Psi_{t-1})^\alpha - \phi Z_t^*, \quad (26)$$

where l, k are steady-state values of the aggregate labor services l_t and a detrended aggregate capital stock k_t defined below. Hence, our output gap, $\log(Y_t/Y_t^*)$, is the gap between output and its trend level, as in line with Taylor (1993). This specification of the output gap is consistent with the Bank of Japan's estimates (Hara et al., 2006), which we use in estimation. The monetary policy shock z_t^r is governed by a stationary first-order autoregressive process.

2.4 Log-linearized equilibrium conditions

Conditions for equilibrium of the model economy are (1)–(4), (8), (10), (12), (16)–(26), together with the stochastic processes of IST and neutral technology levels, (7), (14), and stochastic processes of other exogenous shocks.

In the model, the levels of neutral technology and IST have unit roots with different drift. As a consequence, the growth rate of variables regarding investment and capital accumulation is different from that of variables regarding other real economic activities. Thus we rewrite equilibrium conditions in terms of stationary variables detrended by Z_t^* and Ψ_t : $y_t = Y_t/Z_t^*$, $c_t = C_t/Z_t^*$, $w_t = W_t/Z_t^*$, $\lambda_t = \Lambda_t(Z_t^*)^\sigma$, $i_t = I_t/(Z_t^* \Psi_t)$, $k_t = K_t/(Z_t^* \Psi_t)$, $r_t^k = R_t^k \Psi_t$, and $q_t = Q_t \Psi_t$. Log-linearizing the equilibrium conditions represented in terms of the detrended

variables and using steady-state conditions to rearrange the resulting equations lead to

$$\begin{aligned}
\hat{k}_t &= \frac{1 - \delta - r^n \psi / \pi}{z^* \psi} \hat{u}_t + \frac{1 - \delta}{z^* \psi} \left(\hat{k}_{t-1} - z_t^* - z_t^\psi \right) + \left(1 - \frac{1 - \delta}{z^* \psi} \right) \hat{i}_t, \\
\hat{u}_t &= \mu \left(\hat{r}_t^k - \hat{q}_t \right), \\
\hat{q}_t &= E_t \hat{\lambda}_{t+1} - \hat{\lambda}_t - \sigma E_t z_{t+1}^* - E_t z_{t+1}^\psi + \left(1 - \frac{\pi(1 - \delta)}{r^n \psi} \right) E_t \hat{r}_{t+1}^k + \frac{\pi(1 - \delta)}{r^n \psi} E_t \hat{q}_{t+1}, \\
\hat{r}_t^i &= z_t^\nu - z_{t-1}^\nu - z_t^\psi, \\
\hat{q}_t &= \frac{1}{\zeta} \left(\hat{i}_t - \hat{i}_{t-1} + z_t^* + z_t^\psi + z_t^i \right) - \frac{z^* \pi}{\zeta r^n} \left(E_t \hat{i}_{t+1} - \hat{i}_t + E_t z_{t+1}^* + E_t z_{t+1}^\psi + E_t z_{t+1}^i \right) + z_t^\nu, \\
\hat{m}c_t &= (1 - \alpha) \hat{w}_t + \alpha \hat{r}_t^k, \\
\hat{r}_t^k &= \hat{w}_t - \left(\hat{u}_t + \hat{k}_{t-1} - \hat{l}_t - z_t^* - z_t^\psi \right), \\
\hat{y}_t &= \left(1 + \frac{\phi}{y} \right) \left\{ (1 - \alpha) \hat{l}_t + \alpha \left(\hat{u}_t + \hat{k}_{t-1} - z_t^* - z_t^\psi \right) \right\}, \\
\hat{\pi}_t &= \gamma_p \hat{\pi}_{t-1} + \frac{z^* \pi}{r^n} (E_t \hat{\pi}_{t+1} - \gamma_p \hat{\pi}_t) + \frac{(1 - \xi_p)(1 - \xi_p z^* \pi / r^n)}{\xi_p} \hat{m}c_t + z_t^p, \\
\hat{\lambda}_t &= -\frac{1}{1 - \theta \pi / r^n} \left\{ \frac{\sigma}{1 - \theta / z^*} \left(\hat{c}_t - \frac{\theta}{z^*} (\hat{c}_{t-1} - z_t^*) \right) - z_t^b \right\} \\
&\quad + \frac{\theta \pi / r^n}{1 - \theta \pi / r^n} \left\{ \frac{\sigma}{1 - \theta / z^*} \left(E_t \hat{c}_{t+1} + E_t z_{t+1}^* - \frac{\theta}{z^*} \hat{c}_t \right) - E_t z_{t+1}^b \right\}, \\
\hat{\lambda}_t &= E_t \hat{\lambda}_{t+1} - \sigma E_t z_{t+1}^* + \hat{r}_t^n - E_t \hat{\pi}_{t+1}, \\
\hat{w}_t &= \hat{w}_{t-1} - \hat{\pi}_t + \gamma_w \hat{\pi}_{t-1} - z_t^* + \frac{z^* \pi}{r^n} (E_t \hat{w}_{t+1} - \hat{w}_t + E_t \hat{\pi}_{t+1} - \gamma_w \hat{\pi}_t + E_t z_{t+1}^*) \\
&\quad + \frac{(1 - \xi_w)(1 - \xi_w z^* \pi / r^n)}{\xi_w \{1 + \chi(1 + \lambda w) / \lambda w\}} \left(\chi \hat{l}_t - \hat{\lambda}_t - \hat{w}_t + z_t^b \right) + z_t^w, \\
\hat{r}_t^n &= \phi_r \hat{r}_{t-1}^n + (1 - \phi_r) \left\{ \frac{\phi \pi}{4} \sum_{j=0}^3 \hat{\pi}_{t-j} + \phi_y (\hat{y}_t - \hat{y}_t^*) \right\} + z_t^r, \\
\hat{y}_t^* &= -\alpha \left(1 + \frac{\phi}{y} \right) \left(z_t^* + z_t^\psi \right), \\
\hat{y}_t &= \frac{c}{y} \hat{c}_t + \frac{i}{y} \hat{i}_t + \left(1 - \frac{c}{y} - \frac{i}{y} \right) \tilde{z}_t^g = \frac{c}{y} \hat{c}_t + \frac{i}{y} \hat{i}_t + z_t^g,
\end{aligned}$$

where hatted variables represent log-deviations from steady-state values associated with the capital utilization rate of one, $z_t^* = z_t^z + \alpha / (1 - \alpha) z_t^\psi$ is the composite technology shock, z_t^ν, z_t^p are shocks associated with the price markup λ_t^i, λ_t^p , and z_t^w is a composite shock relevant to the labor disutility z_t^l and the wage markup λ_t^w . Each of exogenous variables $z_t^x, x \in \{\psi, \nu, i, p, b, w, r, g, z\}$ follows a univariate stationary first-order autoregressive process with a persistence parameter ρ_x and an innovation variance σ_x^2 .

3 Data and estimation strategy

We use nine quarterly Japanese time series as observable variables. Seven of them are the same as used in Sugo and Ueda (2008), except that we do not detrend these data: per capita real GDP (GDP), per capita real consumption (C), per capita real investment (I), real wage (W), labor hour (L), the consumer price index (CPI), and the overnight call rate (CALL).⁶ We also use the Bank of Japan's estimates of the output gap (GAP).⁷ The remaining one data is the relative price of investment goods, for which we exploit the investment deflator divided by the CPI (RPI).

As is similar to previous studies on estimated DSGE models of Japan's economy, the sample period is from 1981:1Q to 1998:4Q. This is because the effect of zero lower bounds on nominal interest rates emerges thereafter but our estimation strategy is not able to take account of such an effect. The corresponding measurement equations are

$$\begin{bmatrix} \Delta \log \text{GDP}_t \\ \Delta \log C_t \\ \Delta \log I_t \\ \Delta \log W_t \\ \log L_t \\ \Delta \log \text{CPI}_t \\ \text{CALL}_t \\ \text{GAP}_t \\ \Delta \log \text{RPI}_t \end{bmatrix} = \begin{bmatrix} z^* \\ z^* \\ z^* + \psi \\ z^* \\ l \\ \pi \\ r^n \\ 0 \\ -\psi \end{bmatrix} + \begin{bmatrix} \hat{y}_t - \hat{y}_{t-1} + z_t^* \\ \hat{c}_t - \hat{c}_{t-1} + z_t^* \\ \hat{i}_t - \hat{i}_{t-1} + z_t^* + z_t^\psi \\ \hat{w}_t - \hat{w}_{t-1} + z_t^* \\ \hat{l}_t \\ \hat{\pi}_t \\ \hat{r}_t^n \\ \hat{y}_t - \hat{y}_t^* \\ \hat{r}_t^i \end{bmatrix},$$

where we set the steady-state values l , r^n at the sample mean and $\pi = 1/4$.

We estimate most parameters of the model but some parameters are calibrated to avoid identification issues. As in Sugo and Ueda (2008), we set the steady-state depreciation rate at $\delta = 0.06$, the capital elasticity of output at $\alpha = 0.37$, and the steady-state wage markup at $\lambda^w = 0.20$. The steady-state ratios of consumption and investment to output, c/y , i/y , are set at the sample mean.

Prior distributions of parameters are shown in the second to fourth columns of Table 1. The priors of parameters that describe the private-sector behavior (i.e. $\sigma, \theta, \chi, 1/\zeta, \mu, \phi/y, \gamma_w, \xi_w, \gamma_p, \xi_p$)

⁶For details on these seven time series, see Sugo and Ueda (2008).

⁷See Hara et al. (2006) for this output-gap measure.

are the same as those of Sugo and Ueda (2008) and the priors of the interest rate policy rule’s parameters (i.e. ϕ_r, ϕ_π, ϕ_y) are the same as those of Iiboshi et al. (2006), since the private-sector part of our model is close to that of Sugo and Ueda and the interest rate policy rule of our model is close to that of Iiboshi et al. The priors of trend rates of balanced growth and IST changes (i.e. $100 \log z^*, 100 \log \psi$) are set to be the Gamma distribution with a standard deviation of 0.20 and a mean based on the sample mean of $\Delta \log \text{GDP}_t$ and $\Delta \log \text{RPI}_t$. For parameters regarding shocks, we choose fairly wide prior distributions. The priors of shock persistence parameters (i.e. $\rho_x, x \in \{b, i, g, w, p, r, \nu, z, \psi\}$) are set to be the Beta distribution with a mean of 0.50 and a standard deviation of 0.20, and the priors of standard deviations of shock innovations (i.e. $\sigma_x, x \in \{b, i, g, a, w, p, r, \nu, z, \psi\}$) are set to be the Inverse Gamma distribution with a mean of 0.50 and a standard deviation of an infinity.

As in recent studies taking Bayesian likelihood approaches to estimate DSGE models, we use the Kalman filter to evaluate a likelihood function of the system of log-linearized equilibrium conditions and apply the Metropolis-Hastings algorithm to generate draws from the posterior distribution of model parameters.⁸ Based on the posterior draws, we make inference on the parameters, historical and variance decompositions, and Kalman smoothed estimates of model variables.

4 Estimation results

We now present our estimation results. We first illustrate the estimates of parameters and then discuss historical and variance decompositions of business fluctuations.

4.1 Parameter estimates

The posterior mean of each parameter and its 90% HPD (Highest Posterior Density) interval are reported in the last two columns of Table 1. Our posterior estimates of the structural parameters are similar to those of Sugo and Ueda (2008) and Iiboshi et al. (2006). The estimates of the risk aversion, the consumption habit persistence, and the inverse labor supply elasticity are respectively $\sigma = 1.52$, $\theta = 0.33$, and $\chi = 5.11$, which are in line with the estimates of

⁸For the subsequent analysis, 200,000 draws are generated and the first half of these draws are discarded. We adjust the scale factor for the jumping distribution in the Metropolis-Hastings algorithm so that the acceptance rate of 25% is obtained. Brooks and Gelman (1998)’s measure is used to check the convergence of parameters.

previous studies with DSGE models. For the parameters regarding firms' activities, we have the estimates of $1/\zeta = 7.00$, $\mu = 2.90$, and $\phi/y = 0.09$. These estimates are quite similar to those of Sugo and Ueda. The parameters regarding wage and price rigidities are estimated reasonably; $\gamma_w = 0.35$, $\xi_w = 0.47$, $\gamma_p = 0.53$, and $\xi_p = 0.67$. These suggest that the weights of wage and price indexation are respectively one-third and a half and that the average frequencies of wage and price reoptimization are two quarters and three quarters, respectively. The posterior mean of interest rate smoothing ($\phi_r = 0.66$) is a mild one and the estimate of the interest rate policy response to inflation ($\phi_\pi = 1.67$) is much larger than that of the policy response to the output gap ($\phi_y = 0.09$). The trend rates of balanced growth and IST changes are estimated at $100 \log z^* = 0.42$ and $100 \log \psi = 0.46$.

As for shock parameters, the estimated shocks to the rates of neutral technological changes and IST changes are not persistent ($\rho_z = 0.10$, $\rho_\psi = 0.07$). This is because the log levels of neutral technology and IST have unit roots. The shocks to the subjective discount factor and to demand other than consumption and investment are persistent ($\rho_b = 0.88$, $\rho_g = 0.92$). Although the persistence of the investment adjustment cost shock is not high ($\rho_i = 0.47$), the magnitude of its innovations is fairly large ($\sigma_i = 4.84$). The shocks to intermediate-good and investment-good price markups exhibit quite high persistence ($\rho_p = 0.97$, $\rho_v = 0.99$) whereas the shock to the wage markup is not persistent ($\rho_w = 0.18$).

4.2 Historical decompositions

We next investigate whether IST changes are of crucial importance in explaining Japan's business fluctuations. We first begin with historical decompositions of growth rates of output and investment based on smoothed mean estimates of shocks. Such decompositions identify the contribution of the shocks to the growth rates in each period.

Figure 2 shows the historical decomposition of the output growth rate. In this figure, we can see that neutral technological changes are the main driving force of output growth and are much more important than IST changes. We can also see that investment adjustment cost shocks play a crucial role in explaining output fluctuations. In particular, from the late 1980s to the early 1990s, the adjustment cost shocks contribute to the rapid expansion and the sharp downfall of output growth. The IST changes, however, play a minor role or sometimes an offsetting role in explaining output fluctuations. This result is in stark contrast with that of

Braun and Shioji (2007), who find that the IST changes are at least as important as neutral technological changes in Japan’s output fluctuations, by estimating a SVAR model in which sign restrictions are derived from implications that are common to DSGE models with IST changes.

The historical decomposition of the investment growth rate is shown in Figure 3. This figure illustrates that investment fluctuations are mainly driven by the investment adjustment cost shocks rather than the IST changes. In particular, the huge swing in investment growth from the late 1980s to the mid-1990s is explained by the adjustment cost shocks. Using Hayashi and Prescott (2002)’s neoclassical growth model for Japan, Braun and Shioji (2007) indicate that the introduction of IST changes improves overall fit of their calibrated model to data. Our estimation result, however, suggests that incorporating IST changes into DSGE models is still not able to explain output and investment fluctuations during 1990s very well without investment adjustment cost shocks.

4.3 Variance decompositions

We turn next to variance decompositions. Table 2 reports the relative contribution of each shock to variances of growth rates of output, investment and consumption and to the variance of the inflation rate over each forecast horizon of $T = 8, 32, \infty$. In this table, we can see that the neutral technology shock (z^z) is the main driving force of output and consumption fluctuations. This shock accounts for about a half of these fluctuations. By contrast, the contribution of the IST shock (z^ψ) is marginal for all the variables, even for investment. We can also see that investment fluctuations are mainly driven by the investment adjustment cost shock (z^i). This shock accounts for most of the investment fluctuations.

It is worth noting that the variance decompositions do not capture the entire effects of neutral technological changes and IST changes on the growth rates of aggregate variables. This is because the log level of each technology has a unit root and therefore the variance decompositions only capture the effects of the neutral technology shock component (z^z) and the IST shock component (z^ψ) around each trend rate of the technological changes. Consequently, the variance decompositions miss out the contributions of trend rates of the technological changes.⁹

⁹By contrast, the historical decompositions presented in the preceding subsection take account of the contri-

4.4 Investment adjustment cost shock and firms' financial constraint

The historical and variance decompositions have shown that the investment adjustment cost shock is the main driving force of investment fluctuations in Japan. As mentioned above, the investment adjustment cost shock represents variations of costs associated with changing investment spending, such as financial intermediation costs. We thus investigate the estimated series of investment adjustment cost shocks from the perspective of financial intermediation.

Figure 4 plots the Financial Position Diffusion Index (all industries, all enterprises) in the *Tankan*, Short-term Economic Survey of Enterprises in Japan, and the mean smoothed estimates of investment adjustment cost shocks (z_t^i). In this figure, we can see that the index of firms' financial position and the estimated investment adjustment cost shocks are highly correlated. This suggests that the series of the shocks can be considered as a measure for firms' financial constraint regarding investment spending.

As for investment growth in 1990s, Hayashi and Prescott (2002) indicate that although bank lending declined during 1990s, firms still found other sources of investment finance. Based on our measure for firms' financial position, however, we argue that the sharp drop and the long-lasting stagnation in Japan's investment spending in the early 1990s are due to firms' tight financial constraint stemming from the crisis in Japan's banking and financial sectors after the collapse of the asset price bubble.

5 Concluding Remarks

In this paper we have estimated a DSGE model with IST changes and investment adjustment cost shocks by Bayesian methods in order to examine whether the IST changes are a major source of business fluctuations in Japan. Our estimation result shows that the IST changes are less important than neutral technological changes in explaining output fluctuations in Japan. This finding is in stark contrast with that of Braun and Shioji (2007), who estimate a SVAR model to reach the conclusion that IST changes are at least as important as neutral technological changes. We also demonstrate that investment fluctuations are mainly driven by the investment adjustment cost shocks, which represent variations of costs involved in changing investment spending, such as financial intermediation costs. Further, we find that the estimated investment

Contributions of trend rates of the technological changes.

adjustment cost shocks correlate strongly with the diffusion index of firms' financial position in the Tankan. We thus argue that the large decline in investment growth in the early 1990s is due to an increase in investment adjustment costs reflecting firms' tight financial constraint after the collapse of Japan's asset price bubble. This view is in stark contrast with that of Hayashi and Prescott (2002), who indicate that firms were not constrained from financing investment at that time.

In our model, the financial mechanism generating the estimated investment adjustment cost shocks is a black box. To make it clear, we need to introduce financial market imperfection into the model along the lines of Bernanke et al. (1999) and Carlstrom and Fuerst (1997). Specifically, financial intermediation needs to be explicitly incorporated (e.g. Christiano et al., 2009; Meh and Moran, 2010; Hidakata et al., 2010). Such an extension allows us to structurally understand the relationship between financial intermediation costs and investment fluctuations. We leave this issue for future research.

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Table 1: Prior and posterior distributions of parameters.

Parameter	Prior distribution			Posterior distribution	
	Distribution	Mean	S.D.	Mean	90% interval
σ	Gamma	1.000	0.375	1.516	[0.967, 2.094]
θ	Beta	0.700	0.150	0.326	[0.210, 0.438]
χ	Gamma	2.000	0.750	5.105	[3.509, 6.770]
$1/\zeta$	Gamma	4.000	1.500	6.998	[3.940, 9.857]
μ	Gamma	1.000	1.000	2.899	[1.467, 4.238]
ϕ/y	Gamma	0.075	0.013	0.087	[0.064, 0.110]
γ_w	Beta	0.500	0.250	0.347	[0.015, 0.643]
ξ_w	Beta	0.375	0.100	0.468	[0.374, 0.567]
γ_p	Beta	0.500	0.250	0.530	[0.241, 0.839]
ξ_p	Beta	0.375	0.100	0.666	[0.608, 0.732]
ϕ_r	Beta	0.800	0.100	0.660	[0.570, 0.746]
ϕ_π	Gamma	1.700	0.100	1.670	[1.538, 1.800]
ϕ_y	Gamma	0.125	0.100	0.093	[0.064, 0.123]
$100 \log z^*$	Gamma	0.400	0.200	0.419	[0.241, 0.241]
$100 \log \psi$	Gamma	0.460	0.200	0.464	[0.272, 0.272]
ρ_b	Beta	0.500	0.200	0.877	[0.793, 0.968]
ρ_i	Beta	0.500	0.200	0.466	[0.341, 0.606]
ρ_g	Beta	0.500	0.200	0.919	[0.847, 0.990]
ρ_w	Beta	0.500	0.200	0.184	[0.027, 0.332]
ρ_p	Beta	0.500	0.200	0.965	[0.936, 0.994]
ρ_r	Beta	0.500	0.200	0.442	[0.298, 0.584]
ρ_ν	Beta	0.500	0.200	0.987	[0.977, 0.998]
ρ_z	Beta	0.500	0.200	0.099	[0.026, 0.168]
ρ_ψ	Beta	0.500	0.200	0.065	[0.008, 0.120]
σ_b	Inv. gamma	0.500	Inf	2.920	[1.945, 3.952]
σ_i	Inv. gamma	0.500	Inf	4.838	[3.951, 5.751]
σ_g	Inv. gamma	0.500	Inf	0.457	[0.396, 0.515]
σ_w	Inv. gamma	0.500	Inf	0.572	[0.462, 0.684]
σ_p	Inv. gamma	0.500	Inf	0.179	[0.112, 0.244]
σ_r	Inv. gamma	0.500	Inf	0.131	[0.112, 0.151]
σ_ν	Inv. gamma	0.500	Inf	1.043	[0.900, 1.191]
σ_z	Inv. gamma	0.500	Inf	1.272	[1.087, 1.448]
σ_ψ	Inv. gamma	0.500	Inf	1.062	[0.903, 1.206]

Notes: The table summarizes the prior and posterior distributions of the parameters. For the posterior distribution, 200,000 draws are created using the Metropolis-Hastings algorithm, and the first half of these draws are discarded.

Table 2: Variance decompositions

Forecast horizon	$T = 8$	$T = 32$	$T = \infty$	$T = 8$	$T = 32$	$T = \infty$
	Output			Investment		
z^b	10.0	10.0	10.1	1.5	1.8	2.0
z^i	17.5	17.9	18.0	86.9	86.6	85.7
z^g	6.1	6.1	6.1	0.1	0.1	0.1
z^w	0.5	0.5	0.5	0.1	0.2	0.2
z^p	5.4	5.4	5.6	3.2	3.3	3.5
z^r	1.0	1.0	1.1	0.1	0.1	0.1
z^ν	1.6	1.6	1.7	2.5	2.5	2.7
z^z	54.2	53.8	53.2	2.8	2.7	2.8
z^ψ	3.7	3.7	3.8	2.8	2.8	2.9
	Consumption			Inflation		
z^b	32.5	32.7	32.4	16.4	16.9	12.4
z^i	0.4	0.6	0.7	1.4	6.4	4.7
z^g	2.9	2.9	3.2	0.4	0.8	0.8
z^w	0.8	0.9	0.9	6.6	3.6	2.2
z^p	7.7	7.6	7.7	51.7	41.2	32.5
z^r	2.3	2.3	2.3	3.6	2.0	1.2
z^ν	1.0	1.1	1.1	8.5	16.9	38.2
z^z	48.5	48.0	47.4	6.8	5.5	3.6
z^ψ	4.0	4.0	4.1	4.6	6.7	4.4

Notes: The table shows posterior mode estimates of forecast error variance decompositions of the output growth rate, the investment growth rate, the consumption growth rate, and the inflation rate for each forecast horizon. The infinite horizon decompositions are computed by solving a dynamic Lyapunov equation for the system of log-linearized equilibrium conditions.

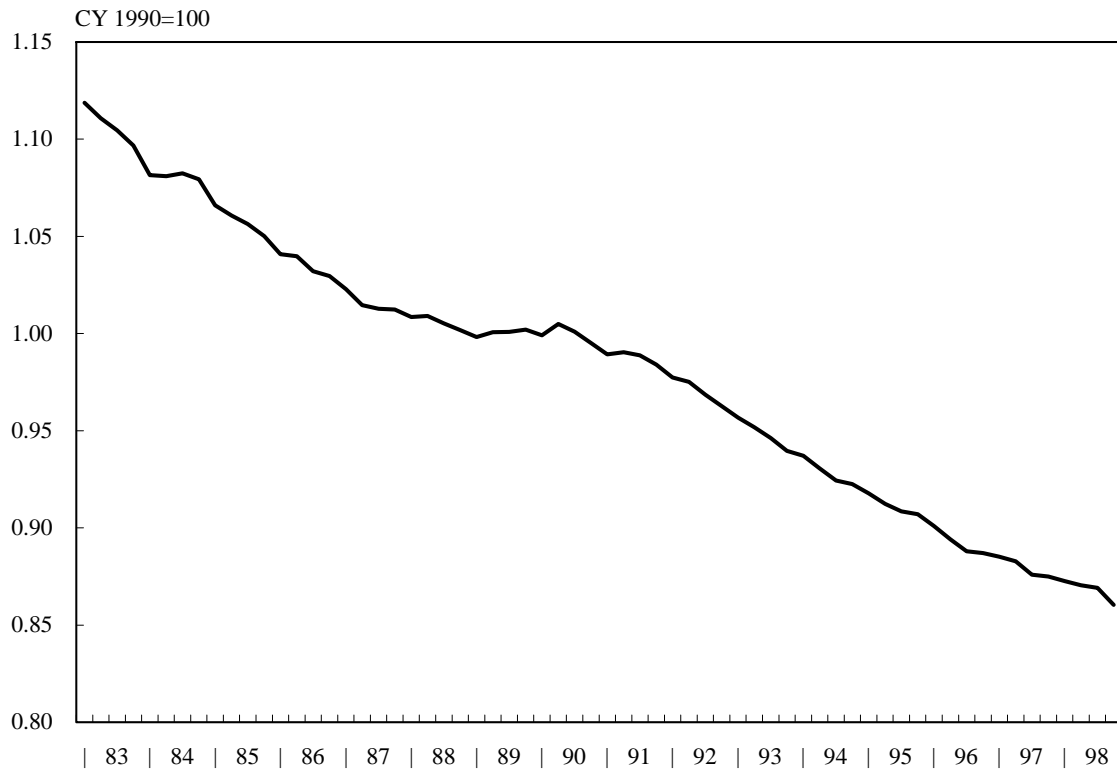


Figure 1: Relative price of investment goods in Japan

Note: The figure shows the relative price of investment goods in terms of the investment deflator divided by the consumer price index.

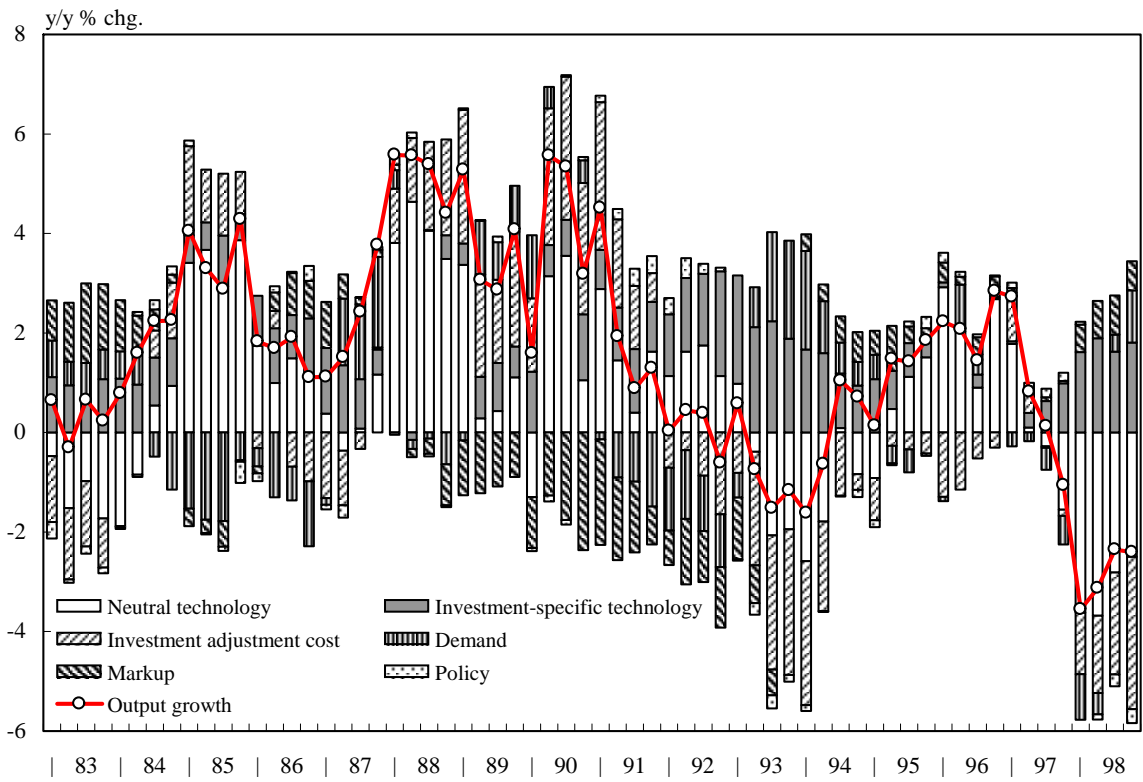


Figure 2: Historical decomposition of output growth

Notes: The figure shows the historical decomposition of the output growth rate evaluated at the posterior mean parameters. The markup shocks include z_t^w , z_t^p and z_t^v , and the demand shocks include z_t^b and z_t^g .

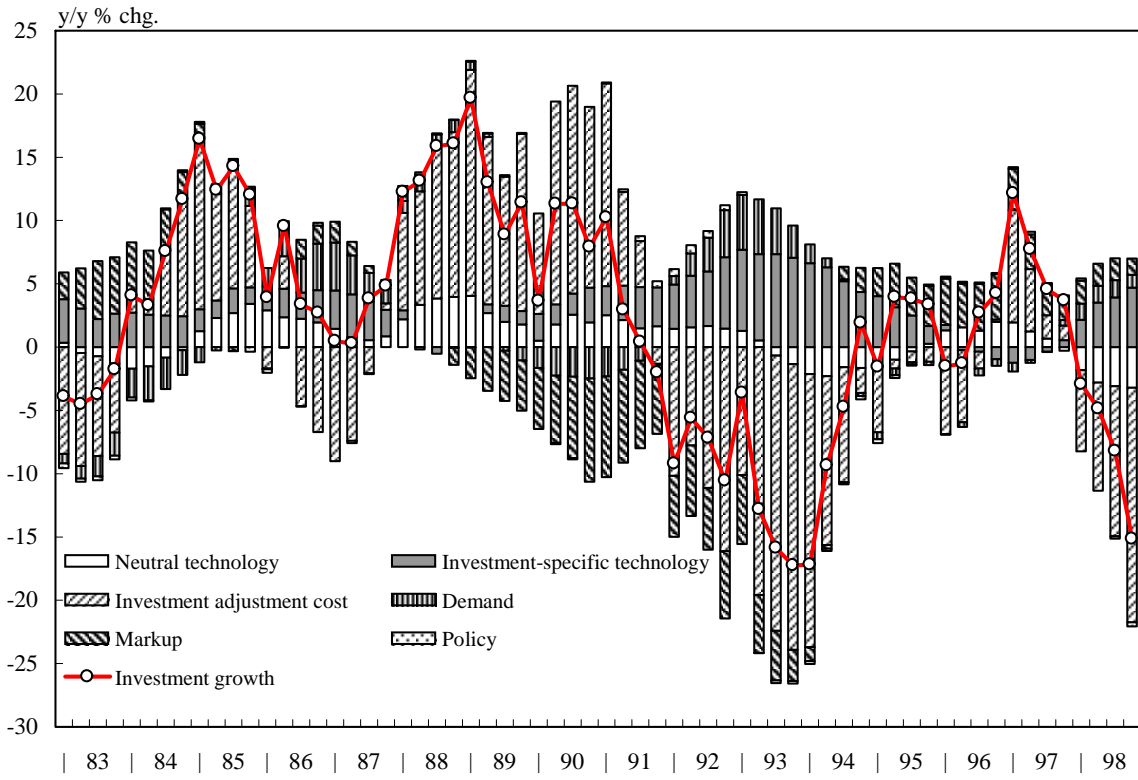


Figure 3: Historical decomposition of investment growth

Notes: The figure shows the historical decomposition of the investment growth rate evaluated at the posterior mean parameters. The markup shocks include z_t^w , z_t^p and z_t^v , and the demand shocks include z_t^b and z_t^g .

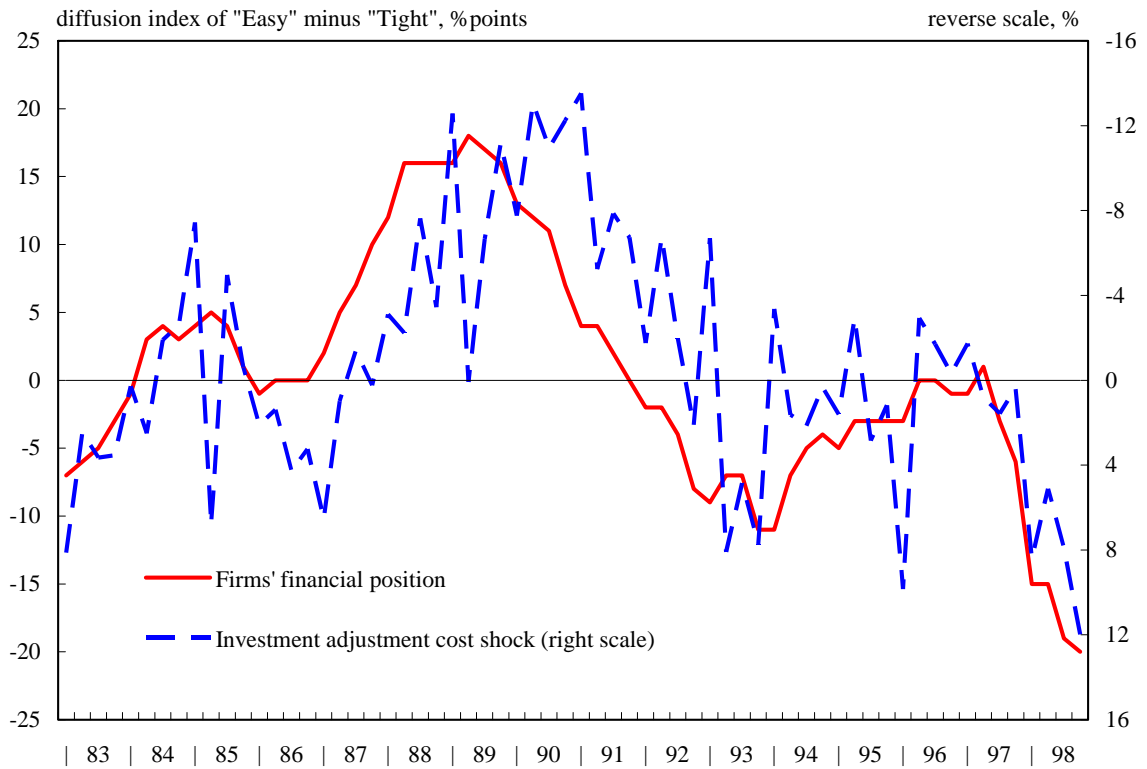


Figure 4: Investment adjustment cost shock and firms' financial position

Note: The figure compares the diffusion index of firms' financial position in the Tankan, Short-term Economic Survey of Enterprises in Japan, and the smoothed estimates of investment adjustment cost shocks z_t^i evaluated at the posterior mean.