Estimating Quarterly Different Price and Wage Rigidity and Its Implication for Monetary Policy

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1 Introduction

In New Keynesian economics, price and wage rigidity is a key factor in determining effects of monetary policy on the real economy. Yun (1996) claims that the sticky price model with money can explain the co-movement of inflation and output in the post-war U.S. data. Erceg et al. (2000) prove that the degree of price and wage rigidity is very important to determine effects of monetary policy. Christiano et al. (2005) show that wage rigidity is the key factor in inertia of inflation and the persistence of output after an expansionary monetary shock. These models show that strong price or wage rigidity leads into more effective monetary policy.

These models assume that price and wage rigidity is constant over time. Thus, effects of monetary shocks are also the same regardless of timing of monetary shocks. However, price and wage rigidity can be different across time within the calendar year. For example, many wage contracts in the U.S. are renewed in the 4th quarter, while wage renegotiation in Japan occurs intensively in spring.[1] These facts imply that wages are the least rigid in the 4th quarter in the U.S. and in the 2nd quarter in Japan. Price rigidity may also have seasonality. Nakamura and Steinsson (2008) show that price changes in the U.S. happen the most often in the 1st quarter (especially in January) and the least often in the 4th

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[1]This is called 'Shunto' (or spring offensive). Shun means spring and hence represents intensive wage renegotiation in spring.

quarter. They also show that price changes occur more often in the first month within the quarter than the last two months. This pattern of price changes would imply that price rigidity in the U.S. has seasonality. These varying price and wage rigidity in the calendar year may yield different effects of monetary policy according to the timing of shocks.

Olivei and Tenreyro (2007) present the first work which shows that effects of monetary policy are different according to timing of shocks. Using a quarter-dependent VAR, they show that effects of monetary policy in the U.S. are stronger when monetary shocks occur in the 1st half than in the 2nd half. Olivei and Tenreyro (2008) also find out that monetary policy in Japan is the most effective when monetary shocks take place in the 3rd quarter. However, Olivei and Tenreyro (2008) fail to find different effects of monetary policy according to timing of shocks from Germany, France, and the United Kingdom. They argue that these varying results on effects of monetary policy according to timing of shocks are caused by different patterns of wage rigidity in these countries and conclude that monetary policy is more effective when monetary shocks happens in the period when wages are more rigid. Using calibration of the DSGE model with quarterly different wage stickiness, Olivei and Tenreyro (2007) also show that effects of monetary policy are different according to when monetary shocks occur. The more rigid are wages at the time of monetary shocks, the stronger are effects of monetary policy.

While Olivei and Tenreyro (2007) assume that wage rigidity varies across quarters, they assume that the price rigidity remains the same over the period in their model. If price rigidity has seasonality as Nakamura and Steinsson (2008) claim, however, we need to assume quarterly different price rigidity and see how these varying price rigidity combined with quarterly different wage rigidity affects effects of monetary policy according to timing of shocks. It is also worthwhile to estimate quarterly different price and wage rigidity and see how this quarterly different rigidity is matched into different effects of monetary policy across quarters.

I assume that not only wage rigidity but also price rigidity differs across quarters. Except quarterly different price rigidity, the model in this paper is the same as that in

Olivei and Tenreyro (2007). The model is given with non-linear form to express quarterly different price and wage rigidity. Therefore, the non-linear algorithm of Bleaky and Fuhrer (1996) is used to solve the model. Estimation of the model parameters is implemented via Minimum Distance Approach (MDA), which finds values of parameters minimizing distances between empirical impulse responses and model impulse responses. Empirical impulse responses are obtained from quarter-dependent VAR of Olivei and Tenreyro (2007), which uses the U.S. data for 1966 $\sim$ 2009.

The results of this paper can be summarized as follows. Firstly, wage rigidity is more influential than price rigidity in determining effects of monetary policy. This result is consistent to that of Christiano et al. (2005) who show that impulse responses do not change very much as values of price rigidity. Thus, quarter-dependent impulse responses according to timing of monetary shocks depend mainly on quarterly varying wage rigidity. This result, however, is dependent on the habit formation in consumption and the price and wage indexation in the model. Secondly, the "price puzzle"[2] occurs if monetary policy is implemented in the period when wage rigidity is strong. This result supports Rabanal (2007) and Henzel et al. (2009) who emphasize the role of wage rigidity in "price puzzle". Lastly, estimation results show that wage rigidity is quarterly different while price rigidity is not. Estimates of wage rigidity are high in the 2nd quarter and low in the 3rd quarter. However, estimates of price rigidity do not have particular patterns across quarters.

MDA matches the model impulse responses from the model closely into the empirical impulse responses from quarter-dependent VAR, so estimates from MDA are very dependent on empirical impulse responses. This implies that we need to pay special attention to interpretation of estimation results from MDA. That is, we should not interpret quarterly different estimates for wage rigidity in this paper as the direct evidence of quarter-dependent DSGE model. Instead, the estimation results should be thought as the set of parameter values for the model which best support the evidence from the

[2]This puzzle refers to phenomenon that the price level goes down even if interest rates fall or the price level goes up even if interest rates rise. Sims (1992) recognized this phenomenon first and Eichenbaum (1992) named it the "price puzzle".

quarter-dependent VAR.

The remainder of this paper proceeds as follows. Section 2 presents the model with quarterly different price and wage rigidity. Section 3 explains model solutions and estimation methods. Section 4 shows the results of calibration and estimation while Section 5 shows robustness of calibration results. Section 6 concludes.

2 The Model

The model in this paper is basically the same as the model in Christiano et al. (2005) and Olivei and Tenreyro (2007). Differences among these three models lie in the probability of reoptimizing prices and wages. Christiano et al. (2005) assume that the probability of reoptimizing price and wage is constant over the period. Olivei and Tenreyro (2007) expand the model of Christiano et al. (2005) by assuming that probability of reoptimizing wage is different across quarters in the calendar year, while the probability of reoptimizing price remains the same. I assume that both price and wage are reoptimized with different probabilities across quarters in the calendar year.

2.1 Firms

The final consumption good at time t, Y_t, is produced by a perfectly competitive firm. The firm combines a continuum of intermediate goods, $Y_{j,t}$, produced by a intermediate good firm j, $j \in (0, 1)$ through the CES technology.

$$Y_t = \left[\int_0^1 Y_{j,t}^{\frac{1}{\lambda_f}} dj \right]^{\lambda_f}, \quad \lambda_f \in [1, \infty).$$

Let P_t and $P_{j,t}$ represent the price of the final consumption good and the intermediate good at time t, respectively. Then, the profit maximization of the final consumption good firm yields the demand function for the intermediate good and the relationship between the price of the final good and the price of the intermediate good as follows.

$$Y_{j,t} = \left(\frac{P_t}{P_{j,t}}\right)^{\frac{\lambda_f}{\lambda_f - 1}} Y_t,$$

$$P_t = \left[\int_0^1 P_{j,t}^{\frac{1}{1-\lambda_f}} dj\right]^{1-\lambda_f}.$$

λ_f in the above expressions is the parameter which shows the degree of difference among goods.[3] When λ_f approaches 1, goods become similar, so firms have less market power. When λ_f approaches infinity, however, goods become different, so firms have more market power.

The intermediate good, $Y_{j,t}$, is produced by a monopolist, whose technology is given by,

$$Y_{j,t} = K_{j,t}^{\alpha} L_{j,t}^{1-\alpha}, \quad \alpha \in (0,1).$$

$K_{j,t}$ and $L_{j,t}$ refer to capital and labor input used in the intermediate good firm j, respectively. If we assume that each intermediate good firm has the same factor price and production function, we can drop subscript j and have the following aggregate output equation.

$$Y_t = K_t^{\alpha} L_t^{1-\alpha}.$$

Log-linearization of the above expression is given as below and becomes the first equation of the model.

$$\widehat{Y}_t = \alpha \widehat{K}_t + (1-\alpha)\widehat{L}_t. \tag{1}$$

Variables with a hat, $\widehat{x}_t$, are defined as $(x_t - x)/x$ and represent percentage deviations of actual value of variables at time t, x_t, from their steady state value, x.

Intermediate good firms rent capital and labor in perfectly competitive factor markets

[3] The price elasticity of demand for Y_j, obtained from the demand function for the intermediate good, is $-\frac{\lambda_f}{\lambda_f - 1}$.

at nominal rental rate on capital, R_t^k, and nominal wage, W_t. If intermediate good firms borrow their wage bill from financial intermediaries at the beginning of the period and repay at the end of the period at the gross interest rate, R_t, we obtain the following real marginal cost, s_t, from cost minimization of intermediate good firms.

$$s_t = \left(\frac{1}{1-\alpha}\right)^{1-\alpha}\left(\frac{1}{\alpha}\right)^{\alpha}(r_t^k)^{\alpha}(w_t R_t)^{1-\alpha}, \quad \text{where} \quad r_t^k = R_t^k/P_t, \quad w_t = W_t/P_t.$$

r_t^k and w_t represent real rental rate on capital and real wage. Log-linearization of the above expression becomes the second equation in the model.

$$\widehat{s}_t = \alpha(\widehat{w}_t + \widehat{R}_t + \widehat{L}_t - \widehat{K}_t) + (1-\alpha)(\widehat{w}_t + \widehat{R}_t). \tag{2}$$

Since the intermediate good firm j is a monopolistic supplier of its product, $Y_{j,t}$, the firm can choose its price, $P_{j,t}$, to maximize profit. $P_{j,t}$ is reset via the mechanism of Calvo (1983). Contrary to the constant probability of reoptimizing the price in any given period in Calvo (1983), however, I assume that the probability of resetting the price varies over the course of the calendar year. Considering many macro data are collected on quarterly basis, it is natural to let the unit of time be equal to a quarter. Then, the probability that the firm resets its price will differ across quarters in the calendar year. The quarter-dependent probability of resetting the price is given by $(1 - \xi_{p,k})$, $k = 1, 2, 3, 4$ at each quarter k. For example, $(1 - \xi_{p,1})$ implies the probability that the firm change its price in the 1st quarter. Therefore, $\xi_{p,k}$ is the probability that the firm cannot change its price at quarter k, so $\xi_{p,k}$ can represent parameters capturing different price rigidities across quarters in the economy.[4] If the firm cannot reoptimize the price, the firm adjusts its price via indexation, $P_{j,t} = \pi_{t-1}P_{j,t-1}$, where π_{t-1} is defined as P_{t-1}/P_{t-2} which represents the inflation rate.

Suppose time t corresponds to the 1st quarter. Then, the jth firm's profit maximiza-

[4] If the price is newly set in the 1st quarter, the probability that the price is not optimized in the 2nd quarter is $\xi_{p,2}$. The probability that the price is not reset for the next two quarters is $\xi_{p,2}\xi_{p,3}$. Probabilities for following quarters are $\xi_{p,2}\xi_{p,3}\xi_{p,4}$, $\xi_{p,2}\xi_{p,3}\xi_{p,4}\xi_{p,1}$, $\xi_{p,2}^2\xi_{p,3}\xi_{p,4}\xi_{p,1}$ and so on.

tion at time t in terms of $P_{j,t}$ is given by[5]

$$\max_{P_{j,t}} \quad E_{t-1}\Bigg\{\sum_{l=0}^{\infty}\prod_{k=1}^{4}\xi_{p,k}^{l}\beta^{4l}\Big[\psi_{t+4l}\big(P_{j,t}X_{t+4l}-s_{t+4l}P_{t+4l}\big)Y_{j,t+4l}$$
$$+\xi_{p,2}\beta\psi_{t+4l+1}\big(P_{j,t}X_{t+4l+1}-s_{t+4l+1}P_{t+4l+1}\big)Y_{j,t+4l+1}$$
$$+\xi_{p,2}\xi_{p,3}\beta^{2}\psi_{t+4l+2}\big(P_{j,t}X_{t+4l+2}-s_{t+4l+2}P_{t+4l+2}\big)Y_{j,t+4l+2}$$
$$+\xi_{p,2}\xi_{p,3}\xi_{p,4}\beta^{3}\psi_{t+4l+3}\big(P_{j,t}X_{t+4l+3}-s_{t+4l+3}P_{t+4l+3}\big)Y_{j,t+4l+3}\Big]\Bigg\}, \quad \beta\in(0,1),$$

$$\begin{aligned}\text{where} \quad X_{t+l} &= \pi_t\pi_{t+1}\pi_{t+2}\cdots\pi_{t+l-2}\pi_{t+l-1}, \quad \text{if} \quad l>0 \\ &= 1, \quad \text{if} \quad l=0.\end{aligned}$$

ψ_t is the marginal value of money to households and β is discount factor. The optimal price is the price which maximizes the expected stream of discounted utility of profit over periods during which firms do not reset their price. Profit is defined as differences between total revenue ($P_{j,t}X_{t+l}Y_{j,t+l}$) and total cost ($s_{t+l}P_{t+l}Y_{j,t+l}$). ψ_{t+4l} plays a role to convert profit into utility.

Since all intermediate good firms which can reset their price in a given quarter will choose the same price, we can drop subscript j from $P_{j,t}$. Then, the F.O.C. for the optimal price at time t, $\tilde{P}_t$ is given by,

$$E_{t-1}\Bigg\{\sum_{l=0}^{\infty}\prod_{k=1}^{4}\xi_{p,k}^{l}\beta^{4l}\Big[\psi_{t+4l}\big(\tilde{P}_tX_{t+4l}-\lambda_f s_{t+4l}P_{t+4l}\big)Y_{j,t+4l}$$
$$+\xi_{p,2}\beta\psi_{t+4l+1}\big(\tilde{P}_tX_{t+4l+1}-\lambda_f s_{t+4l+1}P_{t+4l+1}\big)Y_{j,t+4l+1}$$
$$+\xi_{p,2}\xi_{p,3}\beta^{2}\psi_{t+4l+2}\big(\tilde{P}_tX_{t+4l+2}-\lambda_f s_{t+4l+2}P_{t+4l+2}\big)Y_{j,t+4l+2}$$
$$+\xi_{p,2}\xi_{p,3}\xi_{p,4}\beta^{3}\psi_{t+4l+3}\big(\tilde{P}_tX_{t+4l+3}-\lambda_f s_{t+4l+3}P_{t+4l+3}\big)Y_{j,t+4l+3}\Big]\Bigg\}=0.$$

[5]The profit maximization when time t corresponds to the 2nd (3rd, 4th) quarter is obtained by replacing $\xi_{p,1}$, $\xi_{p,2}$, $\xi_{p,3}$ and $\xi_{p,4}$ with $\xi_{p,2}$ ($\xi_{p,3}$, $\xi_{p,4}$), $\xi_{p,3}$ ($\xi_{p,4}$, $\xi_{p,1}$), $\xi_{p,4}$ ($\xi_{p,1}$, $\xi_{p,2}$) and $\xi_{p,1}$($\xi_{p,2}$, $\xi_{p,3}$), respectively.

Log-linearizing the above F.O.C. after some rearrangements yields,

$$\widehat{\tilde{p}}_t + \widehat{\pi}_t = \Theta_{\xi_{p,1}}(\widehat{\pi}_t + \widehat{s}_t) + \xi_{p,2}\beta\frac{1+\xi_{p,3}\beta+\xi_{p,3}\xi_{p,4}\beta^2+\xi_{p,3}\xi_{p,4}\xi_{p,1}\beta^3}{1+\xi_{p,2}\beta+\xi_{p,2}\xi_{p,3}\beta^2+\xi_{p,2}\xi_{p,3}\xi_{p,4}\beta^3}(\widehat{\tilde{p}}_{t+1} + \widehat{\pi}_{t+1}),$$

$$\text{where} \quad \Theta_{\xi_{p,1}} = \frac{1-\xi_{p,1}\xi_{p,2}\xi_{p,3}\xi_{p,4}\beta^4}{1+\xi_{p,2}\beta+\xi_{p,2}\xi_{p,3}\beta^2+\xi_{p,2}\xi_{p,3}\xi_{p,4}\beta^3}.$$

$\tilde{p}_t$ is defined as $\tilde{P}_t/P_t$ which represents the real optimal price at time t.

Using dummy variables $q_{k,t}$, with k=1,2,3,4, which has the value 1 when time t corresponds to the kth quarter and 0 otherwise, we can generalize the above expression for any quarters as below,

$$\widehat{\tilde{p}}_t + \widehat{\pi}_t = \frac{1-\prod_{k=1}^{4}\xi_{p,k}\beta^4}{\Gamma_{\xi_{p,q}}}(\widehat{\pi}_t + \widehat{s}_t) + \beta\sum_{k=1}^{4} q_{k,t}\xi_{p,k+1}\frac{\Phi_{\xi_{p,q}}}{\Gamma_{\xi_{p,q}}}E_{t-1}(\widehat{\tilde{p}}_{t+1} + \widehat{\pi}_{t+1}), \tag{3}$$

$$\begin{aligned} \text{where} \quad \Gamma_{\xi_{p,q}} &= 1+\beta\big\{q_{1,t}\xi_{p,2}[1+\xi_{p,3}\beta+\xi_{p,3}\xi_{p,4}\beta^2] + q_{2,t}\xi_{p,3}[1+\xi_{p,4}\beta+\xi_{p,4}\xi_{p,1}\beta^2] \\ &\quad + q_{3,t}\xi_{p,4}[1+\xi_{p,1}\beta+\xi_{p,1}\xi_{p,2}\beta^2] + q_{4,t}\xi_{p,1}[1+\xi_{p,2}\beta+\xi_{p,2}\xi_{p,3}\beta^2]\big\}, \\ \Phi_{\xi_{p,q}} &= 1+\beta\big\{q_{1,t}\xi_{p,3}[1+\xi_{p,4}\beta+\xi_{p,4}\xi_{p,1}\beta^2] + q_{2,t}\xi_{p,4}[1+\xi_{p,1}\beta+\xi_{p,1}\xi_{p,2}\beta^2] \\ &\quad + q_{3,t}\xi_{p,1}[1+\xi_{p,2}\beta+\xi_{p,2}\xi_{p,3}\beta^2] + q_{4,t}\xi_{p,2}[1+\xi_{p,3}\beta+\xi_{p,3}\xi_{p,4}\beta^2]\big\}. \end{aligned}$$

The optimal real price, $\tilde{p}_t$, is weighted average between inflation rates and real marginal cost in the current period and the optimal real price and inflation rates in the future. If $\xi_{p,k}$ are the same across quarters, the above equation is quarter-independent. As we assume that $\xi_{p,k}$ are quarterly different, however, the real optimal price are different according to which quarter firms decide their price.

We assume that firms, which can not change the price, index their price to inflation rates at previous period. When time t corresponds to the 1st quarter, therefore, the aggregate price level is given by[6],

$$P_t = \left[(1-\xi_{p,1})\tilde{P}_t^{\frac{1}{1-\lambda_f}} + \xi_{p,1}(\pi_{t-1}P_{t-1})^{\frac{1}{1-\lambda_f}}\right]^{1-\lambda_f}.$$

[6]The expression for the aggregate price level when time t corresponds to the 2nd (3rd, 4th) quarter is obtained by replacing $\xi_{p,1}$ with $\xi_{p,2}$ ($\xi_{p,3}$, $\xi_{p,4}$).

Log-linearizing of the above equation yields,

$$\widehat{\tilde{p}}_t = \frac{\xi_{p,1}}{1-\xi_{p,1}}(\widehat{\pi}_t - \widehat{\pi}_{t-1}).$$

We can generalize the above equation for any quarters by using dummy variable $q_{k,t}$.

$$\widehat{\tilde{p}}_t = \frac{\sum_{k=1}^{4} q_{k,t}\xi_{p,k}}{1-\sum_{k=1}^{4} q_{k,t}\xi_{p,k}}(\widehat{\pi}_t - \widehat{\pi}_{t-1}). \tag{4}$$

Equation 3 and Equation 4 represent the law of motion for the optimal real price and inflation rates. These two equations are the third and fourth equation in the model.

2.2 Households

There is a continuum of households, indexed by $i \in (0,1)$. Households have utility from consumption and disutility from labor efforts. Households follow habit formation in consumption, which allows the model to have the gradual hump-shaped response of output to monetary shocks and thereby increases the model's fit to the data.[7] Households purchase state-contingent securities. Under these assumptions, the preference of ith household is given by,

$$E^i_{t-1}\left\{\sum_{l=0}^{\infty}\beta^{t+l}\big[u(c_{t+l}-e_{t+l}) - z(h_{i,t})\big]\right\}, \quad \beta \in (0,1)$$
$$\text{where} \quad e_{t+l} = \chi e_{t+l-1} + bc_{t+l-1}, \quad \chi \in [0,1) \text{ and } b \in [0,1).$$

c_t is consumption at time t. We drop subscript i from c_t because households are homogenous in consumption choice under state-contingent securities. $h_{i,t}$ represents the number of working hours at time t. u is the utility function of consumption with $u' > 0$ and $u'' < 0$ while z is the disutility function of labor efforts with $z' > 0$ and $z'' > 0$. We specify the functional form of u and z as $u(\cdot) = log(\cdot)$ and $z(\cdot) = \upsilon(\cdot)^2$, where υ is the coefficient

[7] See Fuhrer (2000) for detail.

of the function. b and χ are parameters representing the degree of habit formation in consumption. When $b = \chi = 0$, habit formation in consumption disappears from the preference of households.[8]

The household's dynamic budget constrain is given as below,

$$V_{t+1} + P_t[c_t + inv_t + a(\mu_t)\bar{K}_t] = R_t V_t + R_t^k \mu_t \bar{K}_t + D_t + A_{i,t} + W_{i,t} h_{i,t} - T_t, \quad \forall\ t.$$

V_t is household's financial wealth at the beginning of time t. Financial wealth earns the gross nominal interest rate, R_t. $\bar{K}_t$ and μ_t refers to physical stock of capital and capital utilization rate at time t. At the steady-state, μ is equal to 1. Thus, $\mu_t \bar{K}_t$ represents household's capital supply at time t, K_t, and $R_t^k \mu_t \bar{K}_t$ represents household's income from its capital supply. D_t is firm profits and $A_{i,t}$ is the net cash flow from state contingent securities at time t. $W_{i,t}$ is nominal wage. Thus, $W_{i,t} h_{i,t}$ implies household i's income from labor supply at time t. T_t is lump-sum tax for government expenditure. Lastly, inv_t and $a(\mu_t)$ are investment and the unit adjustment cost of setting the utilization rate of capital at time t to μ_t. Like c_t, we can drop subscript i from V_t, inv_t, μ_t, $\bar{K}_t$ and D_t because state-contingent securities make households homogenous in asset holdings.

F.O.C. for consumption, c_t, is given by,

$$\frac{b}{c_{t+1} - e_{t+1}} - \beta(b+\chi)\frac{1}{c_{t+1} - e_{t+1}} + \beta\chi\psi_{t+1} = \psi_t.$$

Log-linearizing the above F.O.C. for consumption in the households' utility maximization yields the following Euler equation.

[8]Habit formation in consumption under $e_{t+l} = \chi e_{t+l-1} + bc_{t+l-1}$ is derived as below,

$$\begin{aligned}
e_{t+1} &= \chi e_t + bc_t, \\
e_{t+2} &= \chi e_{t+1} + bc_{t+1} = \chi(\chi e_t + bc_t) + bc_{t+1} = \chi^2 e_t + b(\chi c_t + c_{t+1}), \\
e_{t+3} &= \chi e_{t+2} + bc_{t+2} = \chi^3 e_t + b(\chi^2 c_t + \chi c_{t+1} + c_{t+2}), \\
&\vdots \\
e_{t+l} &= \chi^l e_t + b\sum_{i=0}^{l-1} \chi^{l-i-1} c_{t+i}.
\end{aligned}$$

$$E_{t-1}\left\{\beta\chi\widehat{\psi}_{t+1} - \sigma_c\big(\widehat{c}_t - \frac{b}{1-\chi}\widehat{e}_t\big) + (b+\chi)\beta\sigma_c\big(\widehat{c}_{t+1} - \frac{b}{1-\chi}\widehat{e}_{t+1}\big)\right\} \;=\; \widehat{\psi}_t, \qquad (5)$$

$$\text{where} \quad \sigma_c = \frac{1-\chi}{1-\chi-b}\frac{1-\beta\chi}{1-\beta\chi-\beta b}.$$

$\widehat{e}_{t+1}$ is derived by log-linearization of $e_{t+l} = \chi e_{t+l-1} + bc_{t+l-1}$ and given by,

$$\widehat{e}_{t+1} = \chi\widehat{e}_t + (1-\chi)\widehat{c}_t. \qquad (6)$$

F.O.C. for financial wealth, V_{t+1}, is given by,

$$\psi_{t+1} = \frac{1}{\beta}\frac{1}{R_{t+1}}\pi_{t+1}\psi_t.$$

Log-linearization of the above F.O.C. generates the following Euler equation for marginal value of money.

$$E_{t-1}\widehat{\psi}_{t+1} = \widehat{\psi}_t - E_{t-1}(\widehat{R}_{t+1} - \widehat{\pi}_{t+1}). \qquad (7)$$

Equation 5, 6 and 7 means the followings. Firstly, households' utility from consumption is determined not by consumption only but by consumption adjusted with reference consumption ($\widehat{c}_t - \frac{b}{1-\chi}\widehat{e}_t$). This is because we assume habit formation in consumption. Secondly, the expected consumption adjusted reference consumption in the next period is dependent on current consumption adjusted with reference consumption and on discounted expected real interest rates.

F.O.C. for capital utilization, μ_t, is given by,

$$a'(\mu_t) = r^k_t.$$

Log-linearization of the F.O.C. for capital utilization leads to the following relationship between capital input and capital stock, which says that the marginal benefit from raising utilization should be equal to the marginal cost.

$$E_{t-1}\{\widehat{K}_t - \widehat{\bar{K}}_t\} = \frac{1}{\sigma_a}(\widehat{w}_t + \widehat{R}_t + \widehat{L}_t - \widehat{K}_t), \quad \text{where} \quad \sigma_a = \frac{a''(1)}{a'(1)}. \qquad (8)$$

We assume that the stock of capital accumulates as follows,

$$\bar{K}_{t+1} = (1-\delta)\bar{K}_t + F(inv_t, inv_{t-1}).$$

δ is the depreciation rate. Function F represents the technology which transforms current investment, inv_t, and one period past investment, inv_{t-1}, into future capital, $\bar{K}_{t+1}$. Under the assumption that the transformation technology F has the functional form, $F(inv_t, inv_{t-1}) = \left[1 - S\left(\frac{inv_t}{inv_{t-1}}\right)\right] inv_t$ with $S(1) = S'(1) = 0$ and $S''(1) = \kappa > 0$[9], we have the following capital evolution equation which is the ninth equation in the model.

$$\widehat{\bar{K}}_t = (1-\delta)\widehat{\bar{K}}_{t-1} + \delta \widehat{inv}_{t-1}. \tag{9}$$

To derive the F.O.C. for capital stock and for investment, we need to introduce the hypothetical price of a unit of capital stock, P_t^k. P_t^k is the market price of capital at time t if there is the market for capital. For the decision of capital stock, $\bar{K}_{t+1}$, we assume that households can change their capital stock only through market without investment. That is, households buy new capital, $\bar{K}_{t+1}$, for next period and sell remaining stock of capital after production, $(1-\delta)\bar{K}_t$, in the market at P_t^k. Then, budget constraint for households is given by,

$$\begin{aligned} V_{t+1} + P_t[c_t + \bar{K}_{t+1}P_t^k - (1-\delta)\bar{K}_t P_t^k + a(\mu_t)\bar{K}_t] \\ = R_t V_t + R_t^k \mu_t \bar{K}_t + D_t + A_{i,t} + W_{i,t}h_{i,t} - T_t, \quad \forall\ t. \end{aligned}$$

F.O.C. for capital stock, $\bar{K}_{t+1}$, under the above constraint is given by,

$$E_{t-1}\psi_t P_t^k = \beta E_{t-1}\big\{\psi_{t+1}[(1-\delta)P_{t+1}^k + u_{t+1}r_{t+1}^k - a(\mu_{t+1})]\big\}.$$

Log-linearization of the above F.O.C. yields the following relationship for the price of capital.

$$\begin{aligned} E_{t-1}\widehat{P}_t^k &= E_{t-1}\{\widehat{\psi}_{t+1} - \widehat{\psi}_t\} + (1-\beta(1-\delta))E_{t-1}\{\widehat{w}_{t+1} + \widehat{R}_{t+1} + \widehat{L}_{t+1} \\ &\quad -\widehat{K}_{t+1}\} + \beta(1-\delta)E_{t-1}\widehat{P}_{t+1}^k. \end{aligned} \tag{10}$$

[9] These restrictions enable simple solutions for capital stock and investment at the steady-state.

The above equation implies that the current price of a unit of capital stock depends on the rental rate of capital ($\widehat{w}_{t+1} + \widehat{R}_{t+1} + \widehat{L}_{t+1} - \widehat{K}_{t+1}$) and the price of capital ($\widehat{P}^k_{t+1}$) in the next period.

For the decision of investment, inv_t, we assume that households' investment increases the capital stock via the transformation technology $F(inv_t, inv_{t-1})$ and households sell the capital stock in the market without using it for production. That is, the goal of investment of households is not to use the capital for production but to have capital gains through market trade. Investment at time t, inv_t, increases not only the capital stock at time $t+1$, $\bar{K}_{t+1}$, but also the capital stock at time $t+2$, $\bar{K}_{t+2}$. Since $\bar{K}_{t+1}$ and $\bar{K}_{t+2}$ sell in the market at P^k_t and P^k_{t+1}, respectively, the budget constraint for households is given by,

$$V_{t+1} + P_t[c_t + inv_t] = R_t V_t + D_t + A_{j,t} + F(inv_t, inv_{t-1})P^k_t P_t + W_{i,t}h_{i,t} - T_t, \quad \forall\ t.$$

F.O.C. for investment, inv_t, under the above constraint is given by,

$$E_{t-1}\psi_t = E_{t-1}\{\psi_t P^k_t F_{1,t} + \beta\psi_{t+1}P^k_{t+1}F_{2,t+1}\}. \tag{11}$$

$F_{m,t}$ is partial derivative of $F(inv_t, inv_{t-1})$ in terms of m^{th} argument, $m = 1, 2$. The log-linearization of the above F.O.C for investment yields the following relationship for investment.

$$\widehat{P}^k_t = \kappa E_{t-1}\big\{\widehat{inv}_t - \widehat{inv}_{t-1} - \beta(\widehat{inv}_{t+1} - \widehat{inv}_t)\big\}. \tag{12}$$

Aggregate output, Y_t, is divided into four parts, consumption, c_t, investment, inv_t, government expenditure, g_t, and total adjustment cost, $a(\mu_t)\bar{K}_t$, as follows :

$$Y_t = c_t + inv_t + g_t + a(\mu_t)\bar{K}_t.$$

Log-linearization of the above equation is the twelfth equation in the model.

$$\widehat{Y}_t = s_c\widehat{c}_t + s_g\widehat{g}_t + s_{inv}\left\{\widehat{inv}_t + \left[\frac{1}{\beta} - (1-\delta)\right]\frac{1}{\delta}(\widehat{K}_t - \widehat{\bar{K}}_t)\right\}. \tag{13}$$

s_c, s_g and s_{inv} are defined by $\frac{c}{Y}$, $\frac{g}{Y}$ and $\frac{inv}{Y}$, which imply the ratio of consumption, government expenditure and investment to aggregate output at steady-state, respectively.

Each household has differentiated labor service ,$h_{i,t}$, and sells this service to a representative firm. The firm combines a continuum of individual labor service into an aggregate labor input, L_t, via the following CES technology.

$$L_t = \left[\int_0^1 h_{i,t}^{\frac{1}{\lambda_w}} di\right]^{\lambda_w}, \quad \lambda_w \in [1, \infty).$$

Let $W_{i,t}$ represent the individual wage for $h_{i,t}$ at time t. Then, the profit maximization of the representative firm with regard to labor input yields the demand function for differentiated labor service and the relationship between the aggregate wage and the individual wage as follows

$$h_{i,t} = \left(\frac{W_t}{W_{i,t}}\right)^{\frac{\lambda_w}{\lambda_w - 1}} L_t,$$

$$W_t = \left[\int_0^1 W_{i,t}^{\frac{1}{1-\lambda_w}} dj\right]^{1-\lambda_w}.$$

λ_w in the above expressions is the parameter which shows the degree of difference among labor services.[10] When λ_w approaches 1, labor services become similar, so households have less market power. When λ_w approaches infinity, however, labor services become different, so households have more market power.

Since each household has differentiated labor service, the individual household has the monopoly power over its labor service. Therefore, the household holds the power to set its wage. The way of individual wage setting is the same as that of intermediate good price setting in Section 2.1. The probability that households reset their wage is given by $(1 - \xi_{w,k})$, $k = 1, 2, 3, 4$, at each quarter k. Household's probability of resetting wage differs across quarters according to the value of $\xi_{w,k}$. Thus, $\xi_{w,k}$ are parameter capturing different wage rigidities across quarters. If the household can not reoptimize the wage, the

[10] The price elasticity of demand for h_i, obtained from the demand function for differentiated labor service, is $-\frac{\lambda_w}{\lambda_w - 1}$.

household adjusts its price by using indexation, $W_{i,t} = \pi_{t-1} W_{i,t-1}$.

If time t corresponds to the 1st quarter, the ith household's income maximization at time t with regard to $W_{i,t}$ is given by[11]

$$
\begin{aligned}
\max_{W_{i,t}} \quad E_{t-1} \quad & \Bigg\{ \sum_{l=0}^{\infty} \prod_{k=1}^{4} \xi_{w,k}^{l} \beta^{4l} \Bigg[\Big(\frac{\psi_{t+4l} X_{t+4l} W_{i,t} h_{i,t+4l}}{P_{t+4l}} - z(h_{i,t+4l}) \Big) \\
& + \xi_{w,2} \beta \Big(\frac{\psi_{t+4l+1} X_{t+4l+1} W_{i,t} h_{i,t+4l+1}}{P_{t+4l+1}} - z(h_{i,t+4l+1}) \Big) \\
& + \xi_{w,2} \xi_{w,3} \beta^{2} \Big(\frac{\psi_{t+4l+2} X_{t+4l+2} W_{i,t} h_{i,t+4l+2}}{P_{t+4l+2}} - z(h_{i,t+4l+2}) \Big) \\
& + \xi_{w,2} \xi_{w,3} \xi_{w,4} \beta^{3} \Big(\frac{\psi_{t+4l+3} X_{t+4l+3} W_{i,t} h_{i,t+4l+3}}{P_{t+4l+3}} - z(h_{i,t+4l+3}) \Big) \Bigg] \Bigg\}.
\end{aligned}
$$

$$
\begin{aligned}
\text{where} \quad X_{t+l} \quad &= \quad \pi_t \pi_{t+1} \pi_{t+2} \cdots \pi_{t+l-2} \pi_{t+l-1}, \quad \text{if} \quad l > 0 \\
&= \quad 1, \quad \text{if} \quad l = 0.
\end{aligned}
$$

The optimal wage is the wage which maximizes the expected stream of discounted utility from labor efforts over periods during which households do not reset their price. Utility is defined as differences between utility of wage income $\left(\frac{\psi_{t+4l} X_{t+4l} W_{i,t} h_{i,t+4l}}{P_{t+4l}}\right)$ and disutility of working $(z(h_{i,t+4l}))$.

Since all households which can reset their price in a given quarter will choose the same wage, we can drop subscript i from $W_{i,t}$ and $h_{i,t}$. Then, the F.O.C. for the optimal wage at time t, $\tilde{W}_t$ is given by,

[11] The income maximization when time t corresponds to the 2nd (3rd, 4th) quarter is obtained by replacing $\xi_{w,1}$, $\xi_{w,2}$, $\xi_{w,3}$ and $\xi_{w,4}$ with $\xi_{w,2}$ ($\xi_{w,3}$, $\xi_{w,4}$), $\xi_{w,3}$ ($\xi_{w,4}$, $\xi_{w,1}$), $\xi_{w,4}$ ($\xi_{w,1}$, $\xi_{w,2}$) and $\xi_{w,1}$($\xi_{w,2}$, $\xi_{w,3}$), respectively.

$$
\begin{aligned}
E_{t-1} \quad & \Bigg\{ \sum_{l=0}^{\infty} \prod_{k=1}^{4} \xi_{w,k}^{l} \beta^{4l} \Bigg[h_{t+4l} \psi_{t+4l} \Big(\frac{\tilde{W}_t X_{t+4l}}{P_{t+4l}} - \lambda_w \frac{z_h(h_{t+4l})}{\psi_{t+4l}} \Big) \\
& + \xi_{w,2} \beta h_{t+4l+1} \psi_{t+4l+1} \Big(\frac{\tilde{W}_t X_{t+4l+1}}{P_{t+4l+1}} - \lambda_w \frac{z_h(h_{t+4l+1})}{\psi_{t+4l+1}} \Big) \\
& + \xi_{w,2} \xi_{w,3} \beta^2 h_{t+4l+2} \psi_{t+4l+2} \Big(\frac{\tilde{W}_t X_{t+4l+2}}{P_{t+4l+2}} - \lambda_w \frac{z_h(h_{t+4l+2})}{\psi_{t+4l+2}} \Big) \\
& + \xi_{w,2} \xi_{w,3} \xi_{w,4} \beta^3 h_{t+4l+3} \psi_{t+4l+3} \Big(\frac{\tilde{W}_t X_{t+4l+3}}{P_{t+4l+3}} - \lambda_w \frac{z_h(h_{t+4l+3})}{\psi_{t+4l+3}} \Big) \Bigg] \Bigg\} = 0.
\end{aligned}
$$

Log-linearizing the above F.O.C. after some rearrangements yields,

$$
\begin{aligned}
\widehat{\tilde{w}}_t + \pi_t = \; & \Theta_{\xi_{w,1}} \Big[\widehat{\pi}_t + \frac{\lambda_w - 1}{2\lambda_w - 1} \Big(\frac{\lambda_w}{\lambda_w - 1} \widehat{w}_t + \widehat{L}_t - \widehat{\psi}_t \Big) \Big] \\
& + \xi_{w,2} \beta \frac{1 + \xi_{w,3} \beta [1 + \xi_{w,4} \beta + \xi_{w,4} \xi_{w,1} \beta^2]}{1 + \xi_{w,2} \beta [1 + \xi_{w,3} \beta + \xi_{w,3} \xi_{w,4} \beta^2]} E_{t-1} (\widehat{\tilde{w}}_{t+1} + \pi_{t+1}).
\end{aligned}
$$

$$
\text{where} \quad \Theta_{\xi_{w,1}} = \frac{1 - \xi_{w,1} \xi_{w,2} \xi_{w,3} \xi_{w,4} \beta^4}{1 + \xi_{w,2} \beta + \xi_{w,2} \xi_{w,3} \beta^2 + \xi_{w,2} \xi_{w,3} \xi_{w,4} \beta^3}.
$$

$\tilde{w}_t$ is defined by $\tilde{W}_t / P_t$ which represents real optimal wage at time t.

Using dummy variables $q_{k,t}$, we can generalize the above expression for any quarters as below,

$$
\begin{aligned}
\widehat{\tilde{w}}_t + \widehat{\pi}_t = \; & \frac{1 - \prod_{k=1}^{4} \xi_{w,k} \beta^4}{\Gamma_{\xi_{w,q}}} \Big[\widehat{\pi}_t + \frac{\lambda_w - 1}{2\lambda_w - 1} \Big(\frac{\lambda_w}{\lambda_w - 1} (\widehat{w}_t + \widehat{L}_t - \widehat{\psi}_t \Big) \Big] \\
& + \beta \sum_{k=1}^{4} q_{k,t} \xi_{w,k+1} \frac{\Phi_{\xi_{w,q}}}{\Gamma_{\xi_{w,q}}} E_{t-1} (\widehat{\tilde{w}}_{t+1} + \widehat{\pi}_{t+1}),
\end{aligned} \tag{14}
$$

$$
\begin{aligned}
\text{where}\quad \Gamma_{\xi_{w,q}} &= 1+\beta\big\{q_{1,t}\xi_{w,2}[1+\xi_{w,3}\beta+\xi_{w,3}\xi_{w,4}\beta^2]+q_{2,t}\xi_{w,3}[1+\xi_{w,4}\beta+\xi_{w,4}\xi_{w,1}\beta^2] \\
&\quad +q_{3,t}\xi_{w,4}[1+\xi_{w,1}\beta+\xi_{w,1}\xi_{w,2}\beta^2]+q_{4,t}\xi_{w,1}[1+\xi_{w,2}\beta+\xi_{w,2}\xi_{w,3}\beta^2]\big\}, \\
\Phi_{\xi_{w,q}} &= 1+\beta\big\{q_{1,t}\xi_{w,3}[1+\xi_{w,4}\beta+\xi_{w,4}\xi_{w,1}\beta^2]+q_{2,t}\xi_{w,4}[1+\xi_{w,1}\beta+\xi_{w,1}\xi_{w,2}\beta^2] \\
&\quad +q_{3,t}\xi_{w,1}[1+\xi_{w,2}\beta+\xi_{w,2}\xi_{w,3}\beta^2]+q_{4,t}\xi_{w,2}[1+\xi_{w,3}\beta+\xi_{w,3}\xi_{w,4}\beta^2]\big\}.
\end{aligned}
$$

The optimal real wage, $\tilde{w}_t$, is weighted average between inflation rates and aggregate real wage level in the current period and the optimal real wage and inflation rates in the future. If $\xi_{w,k}$ are the same across quarters, the above equation is quarter-independent. As we assume that $\xi_{w,k}$ are quarterly different, however, the real optimal price are different according to which quarter households decide their wage.

We assume that households, which can not change the wage, index their wage to inflation rates at previous period. When time t corresponds to the 1st quarter, therefore, the aggregate wage level is given by[12],

$$
W_t = \Big[(1-\xi_{w,1})\tilde{W}_t^{\frac{1}{1-\lambda_w}} + \xi_{w,1}(\pi_{t-1}W_{t-1})^{\frac{1}{1-\lambda_w}}\Big]^{1-\lambda_w}.
$$

Log-linearizing of the above equation yields,

$$
\widehat{w}_t = (1-\xi_{w,1})\widehat{\tilde{w}}_t + \xi_{w,1}(\widehat{w}_{t-1}+\widehat{\pi}_{t-1}-\widehat{\pi}_t).
$$

We can generalize the above equation for any quarters by using dummy variable $q_{k,t}$.

$$
\widehat{w}_t = \big(1-\sum_{k=1}^{4} q_{k,t}\xi_{w,k}\big)\widehat{\tilde{w}}_t + \sum_{k=1}^{4} q_{k,t}\xi_{w,k}(\widehat{w}_{t-1}+\widehat{\pi}_{t-1}-\widehat{\pi}_t). \tag{15}
$$

Equations 14 and 15 represent the law of motion for real optimal wage and real aggregate wage level. These two equations are the thirteenth and fourteenth equation in the model.

[12] The expression for the aggregate wage level when time t corresponds to the 2nd (3rd, 4th) quarter is obtained by replacing $\xi_{w,1}$ with $\xi_{w,2}$ ($\xi_{w,3}$, $\xi_{w,4}$).

2.3 Monetary Policy

Monetary policy follows a Taylor-type reaction function which is given by,

$$\widehat{R}_t = \rho \widehat{R}_{t-1} + (1-\rho)\big[a_\pi(\widehat{\pi}_t + \widehat{\pi}_{t-1} + \widehat{\pi}_{t-2} + \widehat{\pi}_{t-3}) + a_y \widehat{Y}_t + a_{y-1}\widehat{Y}_{t-1}\big] + \epsilon_t. \qquad (16)$$

ρ falls on $(0,1)$ and represents the parameter which smoothes nominal interest rates. a_π represent the response of monetary policy to inflation rates. a_y and a_{y-1} are the response of monetary policy to current output and one period previous output. ϵ_t is a monetary shock. Equation 16 is the last equation of the model.

3 Estimation Method

Minimum Distance Approach (MDA) is used to estimate the parameters of the model. MDA finds values of parameters which minimize the distance between empirical impulse responses and model impulse responses. The quarter-dependent VAR of Olivei and Tenreyro (2007) is used to calculate empirical impulse responses. The quarter-dependent VAR permits quarterly variation of effects of monetary policy across quarters. The model impulse responses are obtained from the DSGE model in Section 2. Since the DSGE model of this paper is non-linear due to the dummy variable, $q_{k,t}$, non-linear algorithm of Bleaky and Fuhrer (1996), instead of standard solutions for linear DSGE models, is used to solve the model.

3.1 Non-linear Algorithm of Bleaky and Fuhrer

Consider a non-linear rational expectation model given by,

$$F(x_-, x, E(x)) = \epsilon.$$

x is a vector of endogenous variables. x_- implies lagged variables in the system. $E(x)$ implies expected variables in the system. ϵ is structural shocks to the system. The structural shocks are linearly separable from the non-linear structure of the economy. The number of shocks, n_ϵ, can not exceed the number of endogenous variables, n_x.

The solution methodology uncover finding a sequence of expectations which satisfy,

$$F(x_t, E(x_t)|\, x_{t-}) = 0, \text{ for all } t.$$

Let $F(x_k)$ denote value of function F at iteration k for any time t. Then, we can approximate $F(x_k)$ via the first order Taylor expansion as below,

$$F(x_k) \approx J_{x_k}(x_{k+1} - x_k).$$

J_{x_k} is the Jacobian matrix, the matrix of partial derivatives of the function F in terms of the variables x at iteration k. x_k are values of endogenous variables at iteration k. If absolute values of $F(x_k)$ are close enough to zero, x_{k+1} becomes the solution of the model.

Instead of having individual solutions for each time t, we can solve the model over entire time path of t by stacking the above expression as below.

$$F(X_k) \approx S_{X_k}(X_{k+1} - X_k).$$

S_{X_k} is the Jacobian matrix over entire time path at iteration k. X_k and $F(X_k)$ are vector of endogenous variables and vector of function values at iteration k over entire time path, respectively. Suppose the maximum lag and lead in the model are τ and θ. For entire time path $t = t_1, t_2, \cdots, t_T$, S_{X_k} is given by

$$S_{X_k} = \begin{bmatrix} H^{t_1}_{-\tau} & \cdots & H^{t_1}_{-1} & H^{t_1}_{0} & H^{t_1}_{1} & \cdots & H^{t_1}_{\theta} & 0 & 0 & \cdots \\ 0 & H^{t_2}_{-\tau} & \cdots & H^{t_2}_{-1} & H^{t_2}_{0} & H^{t_2}_{1} & \cdots & H^{t_2}_{\theta} & 0 & \cdots \\ & & & & \vdots & & & & & \\ \cdots & 0 & 0 & H^{t_T}_{-\tau} & \cdots & H^{t_T}_{-1} & H^{t_T}_{0} & H^{t_T}_{1} & \cdots & H^{t_T}_{\theta} \end{bmatrix}.$$

H^s_l is matrix of partial derivatives of function F at time s with respect to x at lag or lead l.

We need to add initial and terminal conditions to ensure stability of the solution.

Initial conditions are simply that there are no changes in value of lagged data. We can hold initial conditions by adding $n_x\tau$ identity matrix, $I_{n_x\tau}$, in the upper left corner of S_{X_k}. On the other hand, terminal conditions are obtained from stability conditions of Anderson and Moore (1985). Stability conditions of Anderson and Moore (1985), stored at Q, satisfies,

$$Qx^+ = 0.$$

x^+ is matrix of $[x_{T-\tau+1}, \cdots, x_{T-1}, x_T, x_{T+1}, \cdots, x_{T+\theta}]$ and Q is $n_x\theta$ by $n_x(\tau+\theta)$ matrix which solves for $[x_{T+1}, \cdots, x_{T+\theta}]$ in terms of $[x_{T-\tau}, \cdots, x_T]$. Then, terminal conditions are expressed as below,

$$Q^k(x^+_{k+1} - x^+_k) = Q^k x^+_k.$$

Terminal conditions are secured when we insert the matrix Q^k in the bottom right corner of S_{X_k}.

The final system, including initial and terminal conditions, is given by,

$$\begin{bmatrix} 0 \\ \vdots \\ 0 \\ F(x_{t_1,\ k}) \\ F(x_{t_2,\ k}) \\ \vdots \\ F(x_{t_T,\ k}) \\ Q^k x^+_k \end{bmatrix} = \begin{bmatrix} & I_{n_x\tau} & & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\ H^{t_1,k}_{-\tau} & \cdots & H^{t_1}_{-1} & H^{t_1,k}_0 & H^{t_1,k}_1 & \cdots & H^{t_1,k}_\theta & 0 & 0 & \cdots \\ 0 & H^{t_2,k}_{-\tau} & \cdots & H^{t_2,k}_{-1} & H^{t_2,k}_0 & H^{t_2,k}_1 & \cdots & H^{t_2,k}_\theta & 0 & \cdots \\ & & & & \vdots & & & & & \\ \cdots & 0 & 0 & H^{t_T,k}_{-\tau} & \cdots & H^{t_T,k}_{-1} & H^{t_T,k}_0 & H^{t_T,k}_1 & \cdots & H^{t_T,k}_\theta \\ \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \multicolumn{3}{c}{Q^k_{n_x\theta\times n_x(\theta+\tau)}} \end{bmatrix} \begin{bmatrix} x_{t_1-\tau,\ k+1} - x_{t_1-\tau,\ k} \\ \vdots \\ x_{t_1-1,\ k+1} - x_{t_1-1,\ k} \\ x_{t_1,\ k+1} - x_{t_1,\ k} \\ x_{t_2,\ k+1} - x_{t_2,\ k} \\ \vdots \\ x_{t_T,\ k+1} - x_{t_T,\ k} \\ x_{t_{T+1},\ k+1} - x_{t_{T+1},\ k} \\ \vdots \\ x_{t_{T+\theta},\ k+1} - x_{t_{T+\theta},\ k} \end{bmatrix}.$$

$x_{t,\ k}$ and $F(x_{t,\ k})$ are values of variable x and values of function F at time t and iteration k. $H^{t,k}_l$ is value of derivatives at lag or lead l, time t and iteration k. $Q^k_{n_x\theta\times n_x(\theta+\tau)}$ is $n_x\theta$ by $n_x(\tau+\theta)$ matrix which stores stability condition at iteration k. $I_{n_x\tau}$ is $n_x\tau$ identity matrix which secures initial conditions and remains unchanged through all iterations.

The first step of solution is to set initial guesses of solution X_0. Then, we can compute $F(X_0)$, $H^{t,k}_l$ and Q, which yield the first solution of X, X_1. If $F(X_0)$ are not close enough to zero, we set X_1 as our new initial guesses and update F, H and Q. This process is iterated until absolute values of $F(X_k)$ are less than a critical limit. Values of X when iteration stops are our final solutions.

3.2 Quarter-Dependent VAR

Consider the following economic structure[13].

$$\mathbf{Y}_t = \sum_{l=0}^{n} \mathbf{B}_l \mathbf{Y}_{t-l} + \sum_{l=1}^{n} \mathrm{C}_l \mathrm{P}_{t-l} + \mathbf{A}_y \mathbf{v}_t^y, \tag{17}$$

$$\mathrm{P}_t = \sum_{l=0}^{n} \mathbf{D}_l \mathbf{Y}_{t-l} + \sum_{l=0}^{n} \mathrm{G}_l \mathrm{P}_{t-l} + \mathrm{v}_t^p. \tag{18}$$

Boldfaced letters mean vectors or matrices. $\mathbf{Y}_t$ is a vector of non-policy macroeconomic variables (e.g., GDP, GDP deflator etc) and P_t is a scalar of the policy variable (e.g., federal funds rates). $\mathbf{v}_t^y$ and v_t^p are mutually uncorrelated "primitive" or "structural" error terms. For example, v_t^p may indicate monetary shocks. $\mathbf{B}_l$, C_l, $\mathbf{D}_l$ and G_l are coefficient matrices at lag l.

Non-policy variables, $\mathbf{Y}_t$, depend on current and lagged values of $\mathbf{Y}$, lagged values of P and the vector of uncorrelated current disturbances, $\mathbf{v}_t^y$. Thus, the policy variable, P, does not affect non-policy macroeconomic variables within the same period. Yet, the policy variable, P_t, is dependent on current and lagged values of $\mathbf{Y}$, current and lagged values of P and the current monetary policy shock, v_t^p.

The above VAR model contains current values of $\mathbf{Y}$ and P on the right hand side, so we can not estimate this system via the standard VAR method. Therefore, we need to transform the above VAR model as below,

$$\mathbf{Y}_t = (\mathbf{I}\text{-}\mathbf{B}_0)^{-1} \sum_{l=1}^{n} \mathbf{B}_l \mathbf{Y}_{t-l} + (\mathbf{I}\text{-}\mathbf{B}_0)^{-1} \sum_{l=1}^{n} \mathrm{C}_l \mathrm{P}_{t-l} + (\mathbf{I}\text{-}\mathbf{B}_0)^{-1} \mathbf{A}_y \mathbf{v}_t^y,$$

[13]See Bernanke and Blinder (1992) and Bernanke and Mihov (1998) for the detail.

$$
\begin{aligned}
\mathrm{P}_t \;=\; & (1-\mathrm{G}_0)^{-1}\sum_{l=1}^{n}\Big[\mathbf{D}_l + \mathbf{D}_0(\mathbf{I}\text{-}\mathbf{B}_0)^{-1}\mathbf{B}_l\Big]\mathbf{Y}_{t-l} \\
& +(1-\mathrm{G}_0)^{-1}\sum_{l=1}^{n}\Big[\mathrm{G}_l + \mathbf{D}_0(\mathbf{I}\text{-}\mathbf{B}_0)^{-1}\mathrm{C}_l\Big]\mathrm{P}_{t-l} \\
& +\Big[(1-\mathrm{G}_0)^{-1}\mathbf{D}_0(\mathbf{I}\text{-}\mathbf{B}_0)^{-1}\mathbf{A}_y\mathbf{v}_t^y + (1-\mathrm{G}_0)^{-1}\mathrm{v}_t^p\Big].
\end{aligned}
$$

We can rewrite the system more compactly as below,

$$
\begin{aligned}
\mathbf{Y}_t &= \sum_{l=1}^{n}\mathbf{H}_l^y\mathbf{Y}_{t-l} + \sum_{l=1}^{n}\mathrm{H}_i^p\mathrm{P}_{t-i} + \mathbf{u}_t^y, \\
\mathrm{P}_t &= \sum_{l=1}^{n}\mathbf{J}_l^y\mathbf{Y}_{t-l} + \sum_{l=1}^{n}\mathrm{J}_l^p\mathrm{P}_{t-l} + \mathrm{u}_t^p.
\end{aligned}
$$

The above system has the standard VAR form because the system does not contain current values of $\mathbf{Y}_t$ and P. However, this system can not capture the relationship among variables which varies according to specific time of the calendar year because the system is based on assumption that relationship among variables is constant over the entire year.

Olivei and Tenreyro (2007) propose the following economic structure to determine if the relationship among variables differs according to time of the year.

$$
\mathbf{Y}_t = \sum_{l=0}^{n}\mathbf{B}(q_k)_l\mathbf{Y}_{t-l} + \sum_{l=1}^{n}\mathrm{C}(q_k)_l\mathrm{P}_{t-l} + \mathbf{A}^y(\mathrm{q}_k)\mathbf{v}_t^y, \tag{19}
$$

$$
\mathrm{P}_t = \sum_{l=0}^{n}\mathbf{D}_l\mathbf{Y}_{t-l} + \sum_{l=1}^{n}\mathrm{G}_l\mathrm{P}_{t-l} + \mathrm{v}_t^p. \tag{20}
$$

The above economic structure differs from to the structure given by Equation 17 and 18 in that it includes time-dependent coefficient matrices, $\mathbf{B}(q_k)_l$ and $\mathrm{C}(q_k)_l$, in Equation 19. The unit of period correspond to quarter in the calendar year as in Section 2. Then, $\mathbf{B}(q_k)_l$ and $\mathrm{C}(q_k)_l$ depend on not only lags but also the specific quarter in the calendar year, so $\mathbf{B}(q_k)_l$ and $\mathrm{C}(q_k)_l$ imply four different matrices of coefficients at each lag l.

The coefficient matrices, $\mathbf{D}_l$ and G_l, are assumed to be constant throughout a year because we do not have any evidence that the policy decision of the central Bank varies over the quarter. However, P_t is indirectly quarter-dependent because P_t has quarter-dependent variable, $\mathbf{Y}_t$, as its explanatory variable.

If we rearrange the above system to eliminate the current value of $\mathbf{Y}_t$ on the right hand side in Equation 19 and 20, we have the following standard VAR model.

$$
\begin{aligned}
\mathbf{Y}_t &= \Big(\mathbf{I} - \mathbf{B}(q_k)_0\Big)^{-1} \sum_{l=1}^{n} \mathbf{B}(q_k)_l \mathbf{Y}_{t-l} + \Big(\mathbf{I} - \mathbf{B}(q_k)_0\Big)^{-1} \sum_{l=1}^{n} \mathrm{C}(q_k)_l \mathrm{P}_{t-l} \\
&\quad + \Big(\mathbf{I} - \mathbf{B}(q_k)_0\Big)^{-1} \mathbf{A}^y(q_k)\mathbf{v}_t^y, \\
\mathrm{P}_t &= \sum_{l=1}^{n} \Big[\mathbf{D}_0\Big(\mathbf{I} - \mathbf{B}(q_k)_0\Big)^{-1} \mathbf{B}(q_k)_l + \mathbf{D}_l\Big] \mathbf{Y}_{t-l} \\
&\quad + \sum_{l=1}^{n} \Big[\mathbf{D}_0\Big(\mathbf{I} - \mathbf{B}(q_k)_0\Big)^{-1} \mathrm{C}(q_k)_l + \mathrm{G}_l\Big] \mathrm{P}_{t-l} \\
&\quad + \mathbf{D}_0\Big(\mathbf{I} - \mathbf{B}(q_k)_0\Big)^{-1} \mathbf{A}^y(q_k)\mathbf{v}_t^y + v_t^p.
\end{aligned}
$$

The above expressions can be rewritten more compactly as,

$$
\mathbf{Y}_t = \sum_{l=1}^{n} \mathbf{H}(q_k)_l^y \mathbf{Y}_{t-l} + \sum_{l=1}^{n} \mathrm{H}(q_k)_l^p \mathrm{P}_{t-l} + \mathbf{u}(q_k)_t^y, \tag{21}
$$

$$
\mathrm{P}_t = \sum_{l=1}^{n} \mathbf{J}(q_k)_l^y \mathbf{Y}_{t-l} + \sum_{l=1}^{n} \mathrm{J}(q_k)_l^p \mathrm{P}_{t-l} + \mathrm{u}(q_k)_t^p. \tag{22}
$$

Equation 21 and 22 can be estimated via ordinary least squares. Since the quarter-dependent coefficient matrices, $\mathbf{H}(q_k)_l^y$, $\mathrm{H}(q_k)_l^p$, $\mathbf{J}(q_k)_l^y$ and $\mathrm{J}(q_k)_l^p$, are included in the above quarter-dependent VAR system, we can detect quarterly variation in the effects of monetary policy according to timing of shocks.

3.3 Minimum Distance Approach

Minimum Distance Approach (MDA) is an estimation method, which finds parameters minimizing the distance between empirical impulse responses and model impulse responses. MDA is one among very popular methods for DSGE models as in Rotemberg and Woodford (1997) and Christiano et al. (2005), among others. In this paper, MDA minimizes distance between the impulse responses from the DSGE model in Section 2 solved via non-linear algorithm of Bleaky and Fuhrer (1996) explained in Section 3.1 and the impulse responses from quarter-dependent VAR of Olivei and Tenreyro (2007) explained in Section 3.2.

Let γ represent the group of parameters to be estimated and $\Psi(\gamma)$ denote the mapping from γ to the impulse responses of the model. If the impulse responses of the quarter-dependent VAR are given by $\widehat{\Psi}$, estimates of γ are solution of the following minimization problem.

$$J = \min_{\gamma} \big[\widehat{\Psi} - \Psi(\gamma)\big]' \mathbf{V^{-1}} \big[\widehat{\Psi} - \Psi(\gamma)\big]. \tag{23}$$

$\mathbf{V}$ is a diagonal matrix with sample variance of $\widehat{\Psi}$. $\mathbf{V}$ plays a role for $\Psi(\gamma)$ to lie inside confidence intervals of $\widehat{\Psi}$ as much as possible.

4 Results

4.1 Impulse Responses from the Model

Figures 1-6 show impulse responses to monetary shocks (0.25 bp decline in nominal interest rates) from calibration of the model according to various values of $\xi_{p,k}$ and $\xi_{w,k}$. Values of other parameters are fixed and shown in Table 1. Each panel in Figures 1-6 contains four impulse responses according to the quarter when monetary policy shocks take place. The line with squares represents impulse responses when monetary shocks emerge in the 1st quarter. Similarly, the line with diamonds, circles and asterisks corresponds to impulse responses to the 2nd quarter, the 3rd quarter and the 4th quarter monetary shocks, respectively.

Figures 1 and 2 display impulse responses of output and inflation rates to monetary shocks when $\xi_{p,k}$ and $\xi_{w,k}$ are not quarterly dependent. Each panel of Figure 1 and 2 seems to have only one impulse response. This implies that the responses of output and inflation rates are the same regardless of timing of monetary shock if price and wage rigidity do not change across quarters.

The first panel in Figure 1 shows the impulse response of output when $\xi_{p,k}$ and $\xi_{w,k}$ are fixed at 0.35. Output gradually increases, reaches its peak 3 or 4 quarters after shocks and slowly dies out. The second panel shows impulse response of output when $\xi_{p,k}$ rises to 0.85 and $\xi_{w,k}$ remains unchanged at 0.35. The pattern of response in the second panel is fairly similar to response in the first panel. However, the level of response in the second panel becomes greater as $\xi_{p,k}$ increases. The third panel displays impulse response when $\xi_{w,k}$ rises to 0.85 and $\xi_{p,k}$ remain unchanged at 0.35. Responses in the third panel are similar to in the first and second panel. However, response in the third panel is more persistent and much greater than even in the second panel. This implies that wage rigidity is more influential than price rigidity in determining effects of monetary policy on output. This result is consistent to that of Christiano et al. (2005) who show that impulse responses do not change very much as values of price rigidity.

From the impulse responses in Figure 1, we can see that output responds by more monetary shocks as rigidity becomes stronger. These results can be explained as follows. Aggregate demand increases after expansionary monetary shocks. Suppose the price is fixed. Then, firms cannot raise the price to maximize profits in accordance with increase in demand. Instead, firms increase their production. When the price is fixed, marginal revenue is equal to the price. Thus, firms can achieve profit maximization as long as the price (=marginal revenue) exceeds marginal cost. Therefore, stronger price rigidity leads into bigger response of output to monetary shocks. Suppose now wage is fixed. Increase in aggregate demand caused by expansionary monetary shocks raise demand of firms for labor. As wage is fixed, firms have incentives to increase their production by using more labor. Thus, stronger wage rigidity also leads into bigger output response to monetary shocks. As we assume monopolistic competition, the initial price is higher than marginal cost.

The first panel in Figure 2 shows impulse response of inflation rates when $\xi_{p,k}$ and $\xi_{w,k}$ are fixed at 0.35. Inflation rates gradually increase, reach peak 3 or 4 quarters after shocks and disappear. When $\xi_{p,k}$ rises to 0.85 and $\xi_{w,k}$ remains unchanged at 0.35, response of inflation rates becomes weak and delayed a little bit as seen from the second panel. However, differences between impulse response in the first panel and the second panel are not large. The third panel in Figure 2 shows impulse response of output when $\xi_{w,k}$ rises to 0.85 and $\xi_{p,k}$ remains at 0.35. This impulse response is noteworthy in that it shows "price puzzle". Inflation rates stay under zero for first four quarters after monetary shocks and start to rise.

The reason why impulse response in third panel in Figure 2 shows "price puzzle" lies in strong wage rigidity ($\xi_{w,k} = 0.85$). Decreases in interest rates raise aggregate demand and thereby price level (demand-side effect). However, decreases in interest rates also lower the production cost of firms (e.g., financing cost)and thereby price level (supply-side effect). Suppose nominal wage is rigid. Then, real wage does not change much because households set their wage in accordance with inflation rates in previous period. This implies that decreases in production cost caused by lower interest rates are not offset by increases in real wage caused by lower price level, which results from decreases in production cost. Under strong wage rigidity, therefore, supply-side effect dominates demand-side effect and "price puzzle" takes place. This result is consistent with Rabanal (2007) and Henzel et al. (2009). Both papers emphasize the role of wage rigidity for supply-side effect of monetary policy.

Figure 3-6 display impulse responses when we raise one quarter's price or wage rigidity to 0.85 quarter by quarter. Values of rigidity are expressed on the left of each panel. For example, when $\xi_{p,1} = 0.85$ and others $= 0.35$, price rigidity in the 1st quarter is 0.85 and all other rigidities are 0.35. When $\xi_{w,3} = 0.85$ and others $= 0.35$, wage rigidity in the 3rd quarter is 0.85 and other rigidities are 0.35.

The top-left panel in Figure 3 shows four impulse responses of output according to timing of shocks when the price rigidity in the 1st quarter is 0.85 and all other rigidities are 0.35. Based on the impulse responses in Figure 1, we speculate that impulse response of output to the 1st quarter shock is greater than the other three impulse responses because price rigidity is more sticky in the 1st quarter. However, the four impulse responses in the top-left panel are virtually the same in both level and pattern. These results imply that effects of rising price rigidity for only one quarter is not big enough to bring meaningful differences among impulse responses. The other three panels show the impulse responses when we raise price rigidity of another quarter to 0.85. Considering these changes in price rigidity, the impulse responses in these panels are perfectly matched to impulse responses in top-left panel. Figure 4 shows impulse responses of inflation rates when we raise one quarter's price rigidity to 0.85. Like the responses of output in Figure 3, the responses of inflation rates are very similar each other regardless of timing of shock.

Contrary to the case of price rigidity, however, output and inflation rates respond differently according to timing of shocks when we raise one quarter's wage rigidity. The top-left panel in Figure 5 shows four impulse responses of output according to timing of shocks when wage rigidity in the 1st quarter rises to 0.85 and all the other rigidities remain at 0.35. Output responds strongest to 1st quarter monetary shocks. The response to 4th quarter monetary shocks is the second. Responses to the 3rd quarter and 2nd quarter monetary shocks follow next. This order of response strength is the same as the order of cumulative wage rigidity according to timing of shocks.[14] The same explanation can be made for impulse responses in the other panels in Figure 5.

The panels of Figure 6 show impulse responses of inflation rates when we raise one quarter's wage rigidity to 0.85 quarter by quarter. Inflation rates respond differently according to timing of shocks. Differences among responses are mainly due to the "price puzzle", which happens if monetary shocks occur in the quarter when wage rigidity is high. Suppose wage rigidity is high in the 1st quarter as in top-left panel in Figure 6. Then, the "price puzzle" is shown in the impulse response corresponding to the 1st quarter monetary shocks. If wage rigidity is high in the 2nd quarter, the "price puzzle" appears in the impulse response to 2nd quarter shocks as we can see from top-right panel.

[14]Under $\xi_{w,1} = 0.85$ and $\xi_{w,2} = \xi_{w,3} = \xi_{w,4} = 0.35$, the order of cumulative wage rigidity according to timing of shocks is given by the 1st quarter, 4th quarter, 3rd quarter and 2nd quarter as calculated in Table 2

Based on impulse responses in Figure 1-6, we may reach the following conclusions. Firstly, higher price and wage rigidity yields a stronger response of output to monetary policy shocks. However, wage rigidity is more influential in determining the strength of output response. Secondly, high wage rigidity causes the "price puzzle"while high price rigidity does not. Lastly, quarterly different wage rigidity brings different impulse responses of output and inflation rates according to timing of monetary shocks. However, quarterly differences in price rigidity are not strong enough to have different impulse responses according to timing of shocks.

4.2 Impulse Responses from the Quarter-Dependent VAR

Impulse responses in Figure 7 and 8 are obtained from the quarter-dependent VAR described in Section 3.2. The log of real GDP and GDP deflator in the U.S. and the index of spot commodity prices are used as non-policy variables. Federal funds rate (FFR) is used as a policy variable. The index of spot commodity prices are included as a variable to mitigate the "price puzzle".[15] The sample period of VAR is 1966:1Q to 2009:4Q. The number of lags is 4. These conditions for the quarter-dependent VAR in this paper are the same as those of Olivei and Tenreyro (2007) except that the sample period extends to 2009.4Q from 2002.4Q. Figure 7 and Figure 8 have four panels which show different impulse responses according to quarter when monetary policy shocks happen. The timing of shocks are written below each panel. Monetary shocks are given by a 25 basis point decline in the FFR.

We can see from the panels in Figure 7 that real GDP responds differently according to timing of shocks. The impulse response to the 2nd quarter monetary shocks in the top-right panel is much faster and stronger than other impulse responses. Real GDP reaches its peak three quarters after shocks and die out fast. However, real GDP responds very

[15]The central banks use not only past data but also future forecasts for decision of their policy to prevent inflation. However, VAR use past data only. Sims (1992) claims that the failure of VAR to include data for future inflation leads into the "price puzzle"and the inclusion of a leading indicator for future inflation (e.g., commodity price or asset price) in VAR can mitigate the "price puzzle".

weakly to the 3rd quarter shocks. The response to the 3rd quarter shocks is less than half of response to the 2nd quarter shock at its peak. On the other hand, impulse responses of real GDP to the 1st quarter and the 4th quarter shocks are fairly persistent even though their responses are not so large as response to the 2nd quarter shock.

The pattern and strength of impulse responses in Figure 7 are similar to those in the top-right panel in Figure 5. Price and wage rigidity for the panel are $\xi_{w,2}$ is 0.85 and all other rigidities are 0.35. Therefore, we can infer from impulse responses of real GDP in Figure 7 that wage rigidity is the strongest in the 2nd quarter. The strongest wage rigidity in the 2nd quarter also implies that cumulative wage rigidity including future periods according to timing of monetary shocks is the strongest in the 2nd quarter shocks and the weakest in the 3rd quarter shocks.[16]

Panels in Figure 8 show that inflation rate also responds differently to monetary shocks according to when monetary shocks takes place. Responses of inflation rates to the 1st and 2nd quarter monetary shocks in top panels show the "price puzzle". As shown in Figure 6, "price puzzle"happens when there are strong wage rigidity. Thus, "price puzzle"in Figure 8 can be interpreted that wage rigidity is strong when monetary shocks happen in the 1st and 2nd quarter. On the other hand, impulse responses to the 3rd quarter and the 4th shocks in the bottom panels do not show the "price puzzle". Instead, they are positive and persistent. Especially, responses of inflation rates to the 3rd quarter shocks in bottom-left panel is stronger than other impulse responses. However, differences between impulse responses of inflation rates according to timing of shocks are not so evident as those of real GDP.

The impulse responses in this paper are basically similar to those in Olivei and Tenreyro (2007) except output response to the 1st monetary shocks. The impulse response of output to the 1st quarter shocks in this paper are a little bit delayed but more persistent in comparison with that in Olivei and Tenreyro (2007). However, differences between the

[16]Under $\xi_{w,2} = 0.85$ and all others $= 0.35$, the order of cumulative wage rigidity according to timing of monetary shocks is given by the 2nd quarter, the 1st quarter, the 4th quarter and the 3rd quarter via the same way used in Footnote 14.

two impulse responses are not big. Therefore, features of the impulse responses in this paper also hold for the impulse responses in Olivei and Tenreyro (2007).

4.3 Estimation Results

Estimation results are shown in Table 3. These estimates are obtained from MDA in Section 3.3. The first twelve impulse responses of real GDP and inflation rates from quarter-dependent VAR in Section 4.2 are used for $\widehat{\Psi}$. Impulse responses of output and inflation rates from the model in Section 4.1 are used for $\Psi(\gamma)$. $\mathbf{V}$ is obtained via bootstrapping of quarter-dependent VAR.

The first columns in Table 3 shows estimation results for quarterly different wage rigidity when quarterly different price rigidity is fixed at 0.35 for all quarters and other parameters are fixed as in Table 1. Wage rigidity is the strongest in the 2nd quarter with $\xi_{w,2} = 0.6849$. However, the 1st quarter and the 3rd quarter have weak wage rigidity with $\xi_{w,1} = 0.3035$ and $\xi_{w,3} = 0.3170$. The wage rigidity in the 4th quarter is intermediate among quarters with $\xi_{w,4} = 0.5259$.

It may seem strange that $\xi_{w,3}$ is greater than $\xi_{w,1}$ because impulse responses from quarter-dependent VAR imply that the wage is more rigid in the 1st quarter than in the 3rd quarter. As shown in Table 4, however, cumulative wage rigidity including future periods is greater when monetary shocks happen in the 1st quarter than in the 3rd quarter. When monetary shocks hit in the 1st quarter, the 2nd quarter, which has the strongest wage rigidity, follows the very next. When monetary shocks hit in the 3rd quarter, however, the 2nd quarter follows after two quarters (4th quarter and 1st quarter) pass. If wage rigidity in the 3rd quarter is not bigger enough than wage rigidity in the 1st quarter, therefore, output comes to respond bigger to the 1st quarter monetary shocks. away when monetary shocks hit in the 3rd quarter.

The second column in Table 3 shows estimates for quarterly different price rigidity $\xi_{p,k}$ when quarterly different wage rigidity $\xi_{w,k}$ is fixed at 0.35 for all quarters and other parameters are fixed as in Table 1. The quarterly pattern of price rigidity is very similar to that of wage rigidity. Price rigidity is the strongest in the 2nd quarter ($\xi_{p,2} = 0.8161$) and the lowest in the 1st quarter ($\xi_{p,1} = 0.5976$). However, the level of price rigidity is higher than level of wage rigidity. This result seems to be caused by the fact that price rigidity has weaker effects on output and inflation rates than wage rigidity as shown in 4.1. That is, price rigidity must be stronger than wage rigidity to have the same impulse responses of output and inflation rates.

The third column in Table 3 shows estimates of quarterly different wage and price rigidity when quarterly different wage and price rigidity are estimated simultaneously, with other parameters fixed as in Table 1. Overall level of quarterly different wage and price rigidity in the third column is similar to level in the first and the second column. However, differences of price and wage rigidity among quarters in the third column are much smaller than those in the second and third column.

Wage rigidity in the third column is the strongest in the 2nd quarter ($\xi_{w,2} = 0.5817$) and the weakest in the 3rd quarter ($\xi_{w,3} = 0.4023$). Wage rigidity in the 1st quarter and 4th quarter is similar each other with $\xi_{w,1} = 0.4484$ and $\xi_{w,4} = 0.4481$, respectively. This wage rigidity pattern in the third column is comparable to the pattern in the first column even though wage rigidity in the 1st quarter increases a lot ($0.3035 \rightarrow 0.4484$). The pattern of price rigidity in the third column, however, is quite different from the pattern in the second column. Estimates for price rigidity in third column are centered around 0.68∼0.70. Differences between the strongest and weakest rigidities are only 0.0262. Therefore, price rigidity is almost the same across quarters.

The last column in Table 3 shows estimates of quarterly different wage and price rigidity when λ_w, σ_a and κ are estimated in addition to quarterly different wage and price rigidity with the other parameters fixed as in Table 1. The point estimate for λ_w is 1.0990, which is not so different from 1.15 in Table 1. Estimates for σ_a and κ are 1.8764 and 62.3568, respectively. These estimates are much larger than values in Table 1. As three parameters are newly estimated, there are big changes in estimates for price and wage rigidity. Especially, overall level of price and wage rigidity rises. The pattern of price rigidity is also different from that in the second and third column. However, the pattern of wage rigidity across quarters remains similar to that in the first and the third column. Wage rigidity is strong in the 2nd quarter ($\xi_{w,2} = 0.9255$) and weak in the 3rd quarter ($\xi_{w,3} = 0.4001$) like wage rigidity in the first and third column.

Figure 9 and 10 show impulse responses from the model using estimation results in the last column in Table 3, together with impulse responses from quarter dependent VAR in Figure 7 and 8. Solid lines are the impulse response of the quarter-dependent VAR and lines with asterisks represent the impulse responses from model. Dashed lines represent 80% confidence intervals for impulse responses from quarter dependent VAR. Timing of shocks are written below each panel.

From the impulse responses of output from the model in Figure 9, we can see that impulse responses of output according to timing of shocks are strong in the order of the 1st quarter, the 4th quarter, the 2nd quarter and the 3rd quarter shocks. This order, however, is not consistent to the order of real GDP impulse response from quarter dependent VAR, where response to the 2nd quarters shocks is stronger than responses to the 3rd quarter and 4th quarter shocks. This change in strength of impulse responses according to timing of shock between the model and quarter dependent VAR is caused by strong wage rigidity in the 1st quarter ($\xi_{w,1} = 0.9089$). Strong wage rigidity in the 1st quarter makes the cumulative wage rigidity corresponding to the 1st quarter and 4th quarter shocks relatively higher than cumulative wage rigidity corresponding to the 2nd quarter shocks.

The reason why we have strong wage rigidity in the 1st quarter in the last column in Table 3, unlike the first and third column, is related to "price puzzle", which is shown in impulse response of inflation rates to the 1st quarter from quarter dependent VAR. As explained in Section 4.1, the "price puzzle" happens under strong wage rigidity. When three parameters are additionally estimated, the "price puzzle" from quarter dependent VAR is better matched than before, which leads into strong wage rigidity in the 1st quarter. Figure 10 shows that the model impulse responses of inflation rates to the 1st and 2nd quarter have "price puzzle" while responses to the 3rd and 4th quarter shocks do not.

In this section, I show estimation results of quarterly different wage and price rigidity for 4 cases as in Table 3. Values of estimates for wage and price rigidity are quite different for each case. However, I find that the wage rigidity is consistently strong in the 2nd quarter and weak in the 3rd quarter. This implies that the cumulative wage rigidity is strong in the 2nd quarter and weak in the 3rd quarter. Given this wage rigidity, therefore, monetary policy is more effective in the 2nd quarter and less effective in the 3rd quarter as in impulse responses in quarter dependent VAR. But, the wage rigidity in the 1st quarter varies a lot according to how well the "price puzzle" in quarter dependent VAR are matched for each case.

5 Robustness

The model in Section. 2 assumes the habit formation in consumption and the price and wage indexation to increase the model's fit to the data. However, the habit formation in consumption violates rational expectation and the price and wage indexation does not reflect the behavior of firms and households in the price and wage setting. In this section, therefore, I test how output and inflation rates respond to monetary shocks without the habit or the indexation under quarterly different price and wage rigidity.

The model without the habit formation in consumption is easily obtained by simply plugging 0 into b and χ in Equation 5. Any other new assumptions and equations are not necessary for the model without the habit formation. To derive the model without the price and wage indexation, we need to eliminate the indexation terms, X_{t+l} in expressions for profit and income maximization, and π_{t-1} in expressions for overall current price and wage level. Then, Equation 3, 4, 14, and 15 are transformed into following equations, respectively.

$$\widehat{\tilde{p}}_t = \frac{1-\prod_{k=1}^{4}\xi_{p,k}\beta^4}{\Gamma_{\xi_{p,q}}}\widehat{s}_t + \beta\sum_{k=1}^{4} q_{k,t}\xi_{p,k+1}\frac{\Phi_{\xi_{p,q}}}{\Gamma_{\xi_{p,q}}}E_{t-1}(\widehat{\tilde{p}}_{t+1} + \widehat{\pi}_{t+1}), \quad (24)$$

$$\widehat{\tilde{p}}_t = \frac{\sum_{k=1}^{4} q_{k,t}\xi_{p,k}}{1-\sum_{k=1}^{4} q_{k,t}\xi_{p,k}}\widehat{\pi}_t, \tag{25}$$

$$\widehat{\tilde{w}}_t = \frac{1-\prod_{k=1}^{4}\xi_{w,k}\beta^4}{\Gamma_{\xi_{w,q}}}\frac{\lambda_w-1}{2\lambda_w-1}\left[\frac{\lambda_w}{\lambda_w-1}\widehat{w}_t+\widehat{L}_t-\widehat{\psi}_t\right] \tag{26}$$

$$+\beta\sum_{k=1}^{4} q_{k,t}\xi_{w,k+1}\frac{\Phi_{\xi_{w,q}}}{\Gamma_{\xi_{w,q}}}E_{t-1}(\widehat{\tilde{w}}_{t+1}+\widehat{\pi}_{t+1}),$$

$$\widehat{w}_t = \big(1-\sum_{k=1}^{4} q_{k,t}\xi_{w,k}\big)\widehat{\tilde{w}}_t+\sum_{k=1}^{4} q_{k,t}\xi_{w,k}(\widehat{w}_{t-1}-\widehat{\pi}_t). \tag{27}$$

The other equations for the model without the price and wage indexation are the same as in Section. 2.

5.1 No Habit Formation in Consumption

Figures 11-17 show impulse responses to monetary shocks (0.25 bp decline in nominal interest rates) from calibration of the model without the habit formation in consumption under various values of $\xi_{p,k}$ and $\xi_{w,k}$. Impulse responses in Figures 11-17 are derived from the same conditions as in 4.1 except that the model assumes no habit formation in consumption.

Figures 11 and 12 display impulse responses of output and inflation rates to monetary shocks when $\xi_{p,k}$ and $\xi_{w,k}$ remain the same across quarters, respectively. The line with diamonds represents impulse responses from the model without the habit formation while the line with asterisks represents impulse responses from the model with the habit formation in Figure 1 and 2 in Section 4.1. These impulse responses are similar each other in that output responds stronger as price or wage rigidity increases and the "price puzzle"appears when wage rigidity is strong.

However, impulse responses from no habit formation model differ from those from the habit formation model in the following respects: Firstly, output responds more instantly to monetary shocks and returns rapidly to original level. This is because output smoothing effects of the habit formation in consumption disappear in the model without the habit formation. Secondly, inflation rates is higher and the degree of the "price puzzle"is weaker. Under no habit formation, output responds instantly to monetary shocks. This makes the demand-side effects of monetary policy stronger. Lastly, price rigidity becomes more powerful in determining effects of monetary policy on output. The quick and strong response of output under no habit formation can be severely crowded out if inflation rates are high. When price rigidity is strong, however, the price level remains the original level, which leads into the small crowding-out of output. Thus, the importance of price rigidity becomes greater under no habit formation. However, output still responds stronger to shocks when we raise wage rigidity than when we raise price rigidity.

Figure 13 shows quarter-dependent impulse responses to monetary shocks from no habit formation model when we raise the 1st quarter's price or wage rigidity from 0.35 to 0.85. Like quarter-dependent impulse responses from the habit formation model in Figures 3-6, we have the exactly symmetric quarter-dependent impulse responses from no habit formation model when we raise another quarter's price or wage rigidity. Figures 14-17 compares quarter-dependent impulse responses from no habit formation model in Figure 13 to those from the habit formation model.

The left panels in Figure 13 show quarter-dependent responses of output and inflation rates according to timing of shock when we raise the 1st quarter's price rigidity, $\xi_{p,1}$, from 0.35 to 0.85. Contrary to the virtually same quarter-dependent impulse responses under the habit formation model in Figures 3 and 4, however, these impulse responses are quarterly differentiable. The top-left panel shows that output reacts greater to the 1st quarter shocks than other quarter's shocks and the bottom-left panel shows that inflation rates respond less to the 1st quarter shocks. These results imply that price rigidity, under no habit formation model, becomes more influential to yield quarterly different impulse responses according to timing of shocks.

The right panels in Figure 13 show quarter-dependent responses of output and inflation rates according to timing of shock when we raise the 1st quarter's wage rigidity, $\xi_{w,1}$, from 0.35 to 0.85. Similar to quarter-dependent impulse responses from the habit formation model in Figures 5 and 6, these impulse responses are quarterly differentiable. The top-left panel shows that output reacts greater to the 1st quarter shocks than other quarter's shocks and the bottom-left panel shows that the "price puzzle"appears if monetary shocks occur in the 1st quarter. These results imply that wage rigidity, not only under the habit formation but also under no habit formation, has influence to generate quarterly different impulse responses according to timing of shocks.

All in all, output under no habit formation in consumption responds instantly to monetary. In accordance with instant response of output, inflation rates also reacts stronger. This instant and strong responses make price rigidity more influential in determining effects of monetary policy. Under no habit formation, therefore, we can have quarterly differentiable impulse responses according to timing of shocks when we raise one quarter's price rigidity.

5.2 No Price and Wage Indexation

Figures 18-24 show impulse responses to monetary shocks (0.25 bp decline in nominal interest rates) from calibration of the model without price and wage indexation under various values of $\xi_{p,k}$ and $\xi_{w,k}$. Like the case of no habit formation in consumption, impulse responses in Figures 18-24 are derived from the same conditions as in 4.1 except that the model assumes no price and wage indexation.

Figures 18 and 19 display impulse responses of output and inflation rates to monetary shocks when $\xi_{p,k}$ and $\xi_{w,k}$ remain the same across quarters, respectively. The line with diamonds represents impulse responses from the model without the indexation while the line with asterisks represents impulse responses from the model with the indexation in Figure 1 and 2 in Section 4.1. Similarly to the case of no habit formation in consumption, impulse responses from the indexation model maintain the basic features of impulse responses from no indexation model.

However, there are following differences between impulse responses from no indexation model and impulse responses from the indexation model. Firstly, inflation rates respond more instantly to monetary shocks and returns rapidly to original level. This is because effects of the price and wage indexation, inflation smoothing, disappear in the model without the indexation. No inflation smoothing effects without the indexation makes the "price puzzle"disappear more quickly. In third panel in Figure 19, the "price puzzle"in no indexation model lasts only for one quarter while that in the indexation model lasts for four quarters under indexation. Secondly, output is more persistent. More persistent output under no indexation happens due to less persistent inflation rates because lower inflation rates lead into smaller crowding-out of output. Lastly, wage rigidity becomes less influential powerful in determining effects of monetary policy on output. When wage rigidity is strong, the "price puzzle"happens. Under the wage indexation, the "price puzzle"can lower overall wage level, which leads into higher output increases. Under no wage indexation, however, wage is not affected by the "price puzzle". Thus, overall wage level is higher under no indexation than under the indexation. Higher wage level under no indexation lowers output increases when wage rigidity rises. This implies that the importance of wage rigidity becomes smaller under no indexation.

Figure 20 shows quarter-dependent impulse responses to monetary shocks from no indexation model when we raise the 1st quarter's price or wage rigidity from 0.35 to 0.85. When we raise another quarter's price or wage rigidity, we have the exactly symmetric quarter-dependent impulse responses as in Figure 20. Figures 21-24 compares quarter-dependent impulse responses from no indexation model in Figure 20 to those from the indexation model.

The left panels in Figure 20 show quarter-dependent responses of output and inflation rates according to timing of shock when we raise the 1st quarter's price rigidity, $\xi_{p,1}$, from 0.35 to 0.85. Similarly to quarter-dependent impulse responses from no indexation model in Figure 3, quarter-dependent impulse responses of output from no indexation model in top-left panel are virtually the same regardless of timing of shocks. However, impulse responses of inflation rates in bottom-left panel show different patterns according to timing of shocks. This is because inflation rates drop at different impulse period according to timing of shocks. That is, inflation rates drop nearly to zero right after the impulse period when price rigidity is strong. When monetary shocks occurs in the 1st quarter, inflation rates are nearly zero at impulse period of 1 and 5. When monetary shocks occurs in the 3rd quarter, inflation rates are nearly to zero at impulse period of 3 and 7. No indexation makes inflation rates more sensitive to price rigidity. Thus, inflation rates react discontinuously as price rigidity varies across quarters.

The right panels in Figure 20 show quarter-dependent responses of output and inflation rates according to timing of shock when we raise the 1st quarter's wage rigidity, $\xi_{w,1}$, from 0.35 to 0.85. Similar to quarter-dependent impulse responses from the indexation model in Figures 5 and 6, impulse responses from no indexation model are quarterly differentiable. As seen in Figure 23, however, impulse responses from no indexation have lower level than those from the indexation model. This causes quarter-dependent impulse responses of output from no indexation model to be less distinct according to timing of shocks. Quarter-dependent impulse responses of inflation rates from no indexation model have similar level to those from the indexation model. Thus, quarter-dependent impulse responses of inflation rates are as differentiable according to timing of shocks as those from the indexation model even though the former responds stronger at start and weaker at end.

In conclusion, impulse response of inflation rates from no indexation model is less persistent. Less persistent response of inflation rates leads into more persistent response of output. When wage rigidity is strong, overall wage level is higher under no indexation because wage is not affected by the "price puzzle". Since higher wage level causes output to decrease, increases in output due to rising in wage rigidity are smaller under no indexation than under indexation. This implies that wage rigidity under no indexation has less influence in determining effects of monetary policy.

6 Conclusion

In this paper, I show how output and inflation rates react to monetary shocks under quarterly different wage and price rigidity. The model in Section 2 incorporates price and wage rigidity which vary across quarters. Since the model is non-linear, non-linear algorithm of Bleaky and Fuhrer (1996) is used to solve the model. Wage rigidity turns out to be more influential than price rigidity to determine effects of monetary policy. Output responds by more to monetary shocks and the "price puzzle" appears if shocks occur in the quarter when the cumulative wage rigidity is high. However, these results are dependent on assumptions of the habit formation in consumption and the price and wage indexation. The importance of price rigidity increases in the model without the habit formation model and the importance of wage rigidity decreases in the model without the price and wage indexation even though wage rigidity is still more influential than price rigidity.

I also estimate quarterly different wage and price rigidity using MDA which minimized distances between impulse responses of the model and quarterly dependent VAR. Estimation results reveal a certain-pattern in wage rigidity over the year. That is, wage rigidity is strong in the 2nd quarter and weak in the 3rd quarter. Wage rigidity in the 1st quarter shows big differences according to how well "price puzzle" in quarter dependent VAR are matched. However, price rigidity does not seem to have any particular pattern across quarters.

The implication of results in this paper for monetary policy can be summarized as follows. Firstly, wage rigidity should be considered more important than price rigidity since wage rigidity is more influential in determining the responses of output and inflation rates to monetary shocks. Secondly, the effects of monetary policy are different over the calendar year if wage rigidity has seasonality. Monetary policy is more effective if implemented in the period when cumulative wage rigidity is strong. This implies that monetary shocks in the period which has weak (strong) cumulative wage rigidity should be large (small) for monetary policy to have the same effects. Lastly, supply-side effects of monetary policy dominate demand-side effects when there is strong wage rigidity. Thus, we may observe the “price puzzle”if monetary policy is implemented in the periods when wage rigidity is strong.

However, we have to exercise caution when interpreting the estimation results of this paper. Estimation results in this paper are obtained from MDA and MDA finds the set of parameter values that best match impulse responses from quarter-dependent VAR into impulse responses from the model. As such, the parameter estimates are quite dependent on impulse responses from quarter-dependent VAR. Therefore, the estimation results should be interpreted as parameter values which fits the best what we find from quarter-dependent VAR into the model, instead of the evidence for quarter dependent DSGE model. Thus, a more structural estimation approach is needed to corroborate results of this paper.

This paper finds that the habit formation in consumption and the price and wage indexation are important factors to determine the influence of price and wage rigidity on effects of monetary policy. However, it is still not clear why wage rigidity is more influential than price rigidity. More studies on influence of price and wage rigidity are necessary.

Table 1: Value of Fixed Parameters

α	β	λ_w	δ	s_c	s_g	s_i	χ	b	κ	σ_a	ρ	a_π	a_y	a_{y-1}
0.36	0.99264	1.15	0.025	0.50	0.17	0.33	0.20	0.65	8.00	0.10	0.92	2.00	0.65	-0.65

Table 2: Cumulative Wage Rigidity according to Timing of Shocks under $\xi_{w,1} = 0.85$ and $\xi_{w,2} = \xi_{w,3} = \xi_{w,4} = 0.35$

		Impulse Period					
		0	1	2	3	·········	Total
timing of shocks	1st Q	0.85 $(= \xi_{w,1})$	0.2975 $(= \xi_{w,1}\xi_{w,2})$	0.1041 $(= \xi_{w,1}\xi_{w,2}\xi_{w,3})$	0.036 $(= \xi_{w,1}\xi_{w,2}\xi_{w,3}\xi_{w,4})$	·········	1.3368
	2nd Q	0.35 $(= \xi_{w,2})$	0.1225 $(= \xi_{w,2}\xi_{w,3})$	0.0429 $(= \xi_{w,2}\xi_{w,3}\xi_{w,4})$	0.036 $(= \xi_{w,2}\xi_{w,3}\xi_{w,4}\xi_{w,1})$	·········	0.5727
	3rd Q	0.35 $(= \xi_{w,3})$	0.1225 $(= \xi_{w,3}\xi_{w,4})$	0.1041 $(= \xi_{w,3}\xi_{w,4}\xi_{w,1})$	0.036 $(= \xi_{w,3}\xi_{w,4}\xi_{w,1}\xi_{w,2})$	·········	0.6363
	4th Q	0.35 $(= \xi_{w,4})$	0.2975 $(= \xi_{w,4}\xi_{w,1})$	0.1041 $(= \xi_{w,4}\xi_{w,1}\xi_{w,2})$	0.036 $(= \xi_{w,4}\xi_{w,1}\xi_{w,2}\xi_{w,3})$	·········	0.8179

Table 3: Estimation Results

	Different Wage & Same† Price Rigidity	Same‡ Wage & Different Price Rigidity	Different Wage & Different Price Rigidity	Different Wage & Different Price Rigidity + λ_w, σ_a, κ
$\xi_{w,1}$	0.3035 (0.0045)	N/A	0.4484 (0.0173)	0.9089 (0.0998)
$\xi_{w,2}$	0.6849 (0.0130)	N/A	0.5817 (0.0262)	0.9255 (0.1037)
$\xi_{w,3}$	0.3170 (0.0055)	N/A	0.4023 (0.0171)	0.4001 (0.1227)
$\xi_{w,4}$	0.5259 (0.0082)	N/A	0.4481 (0.0169)	0.5053 (0.1490)
$\xi_{p,1}$	N/A	0.5976 (0.0100)	0.7009 (0.0132)	0.8361 (0.0177)
$\xi_{p,2}$	N/A	0.8161 (0.0135)	0.6747 (0.0143)	0.9462 (0.0256)
$\xi_{p,3}$	N/A	0.6845 (0.0117)	0.7005 (0.0134)	0.8418 (0.0174)
$\xi_{p,4}$	N/A	0.7760 (0.0114)	0.6786 (0.0118)	0.7687 (0.0163)
λ_w	N/A	N/A	N/A	1.0990 (0.0872)
σ_a	N/A	N/A	N/A	1.8764 (0.3046)
κ	N/A	N/A	N/A	62.3586 (6.3086)

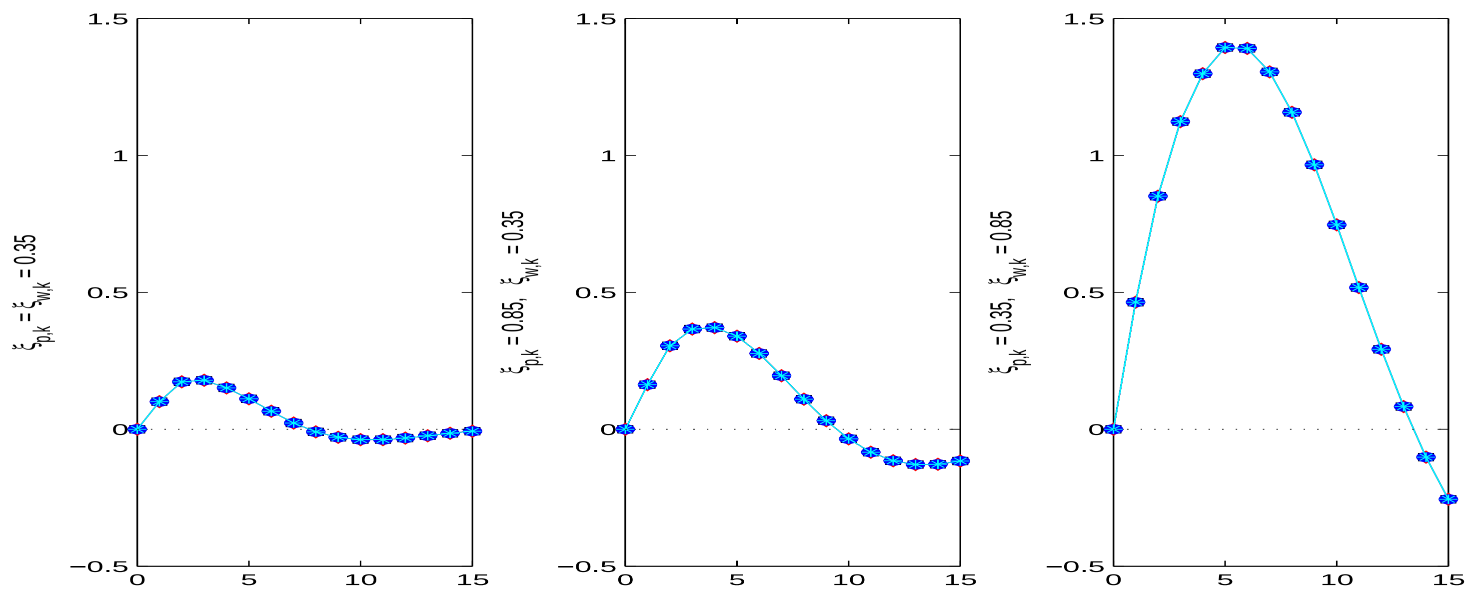
† Price rigidity is fixed at 0.35 for all quarters.
‡ Wage rigidity is fixed at 0.35 for all quarters.
$*$ Numbers in parentheses are standard errors.

Table 4: Cumulative Wage Rigidity Based on Estimation Results under Different Wage and Same Price Rigidity

		Impulse Period						
		0	1	2	3	4	·········	Total
timing of shocks	1st Q	0.3035	0.2079	0.0659	0.0347	0.0105	·········	0.6338
	2nd Q	0.6849	0.2171	0.1142	0.0347	0.0237	·········	1.0886
	3rd Q	0.3170	0.1667	0.0506	0.0347	0.0110	·········	0.5894
	4th Q	0.5259	0.1596	0.1093	0.0347	0.0182	·········	0.8593

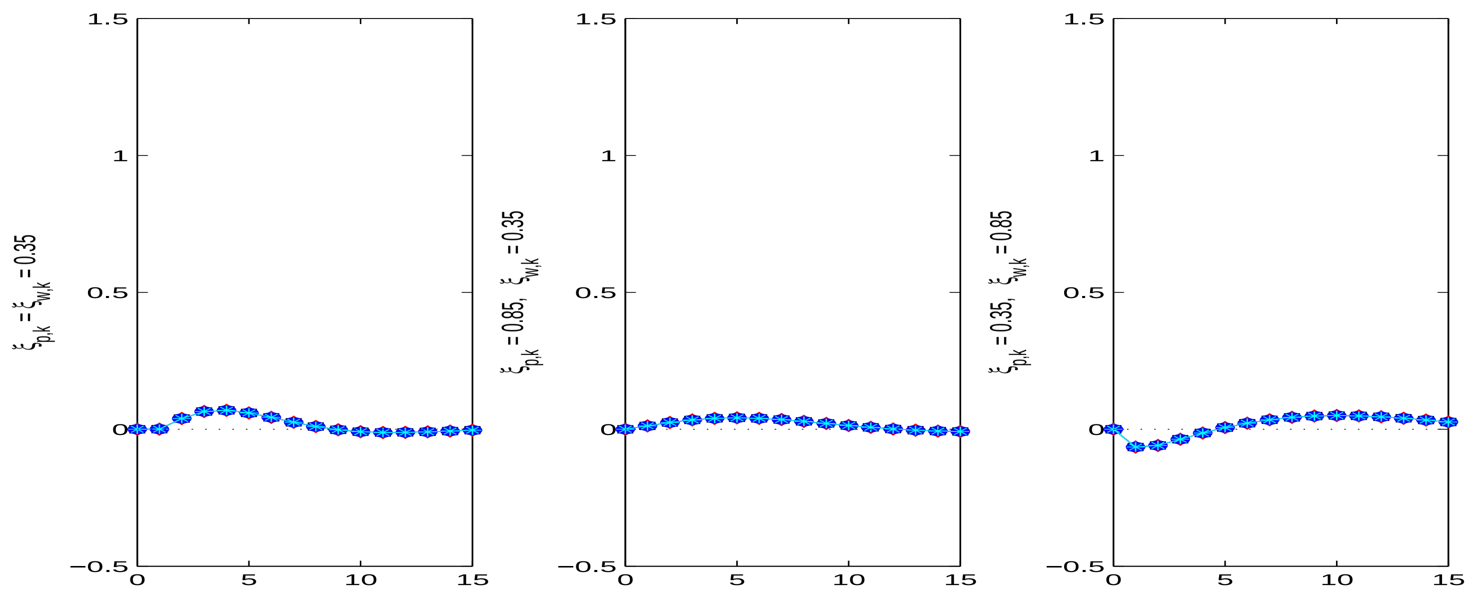
* Estimates for wage rigidity in the first column in Table 3 are used for calculation

Figure 1: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with the Quarterly Same Price and Wage Rigidity



■ : 1st quarter shock ⧫ : 2nd quarter shock ● : 3rd quarter shock ∗ : 4th quarter shock

Figure 2: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with the Quarterly Same Price and Wage Rigidity



■ : 1st quarter shock ⧫ : 2nd quarter shock ● : 3rd quarter shock ∗ : 4th quarter shock

Figure 3: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Price Rigidity

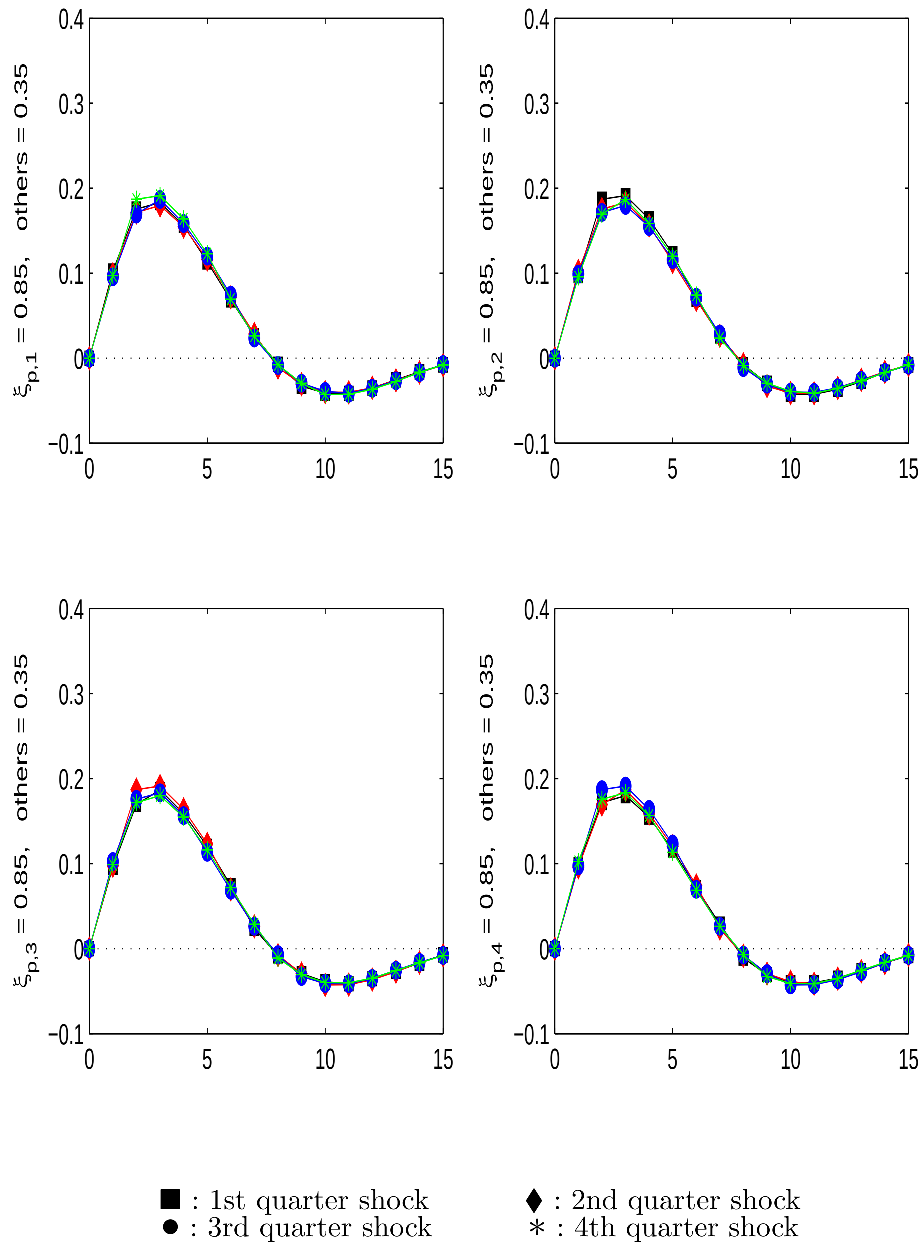


Figure 4: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Price Rigidity

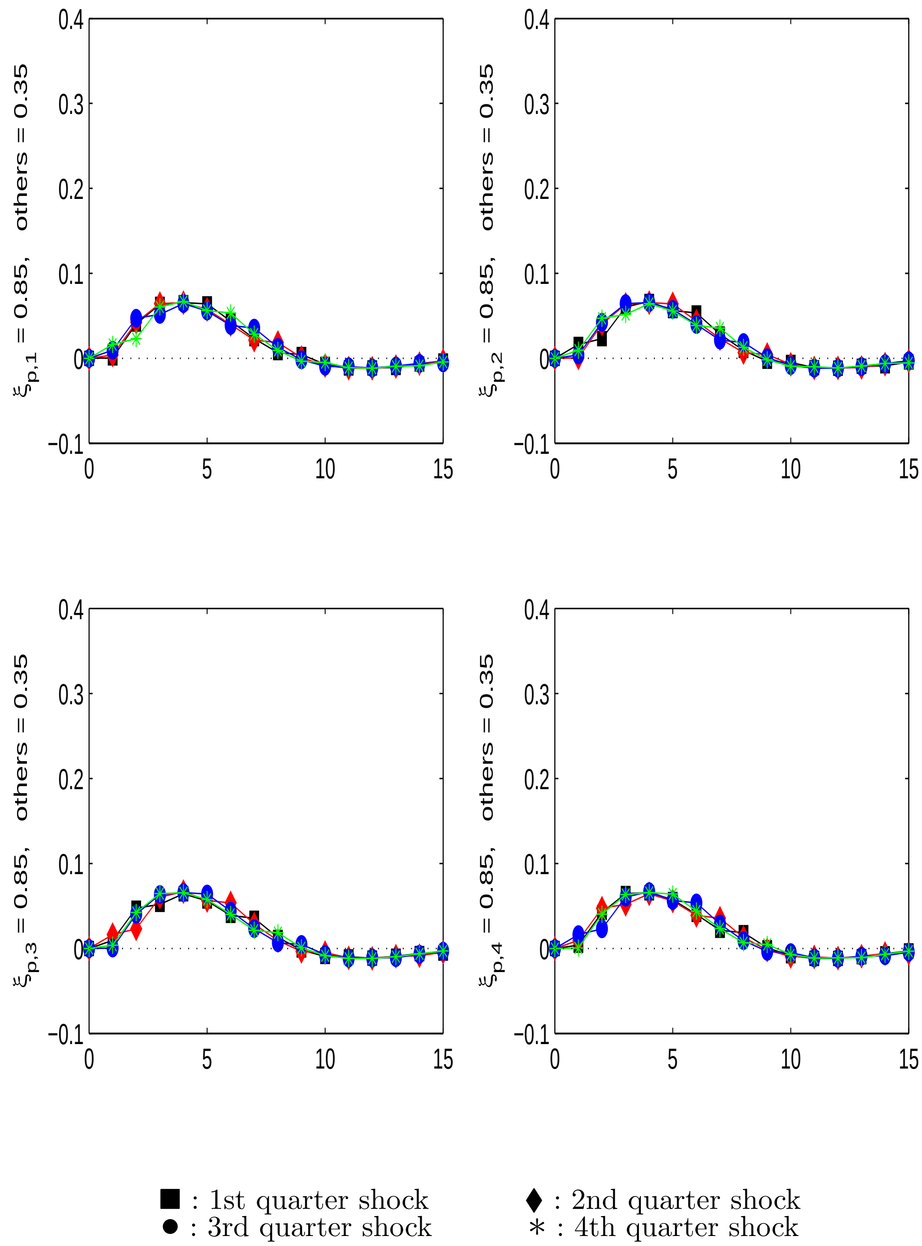


Figure 5: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Wage Rigidity

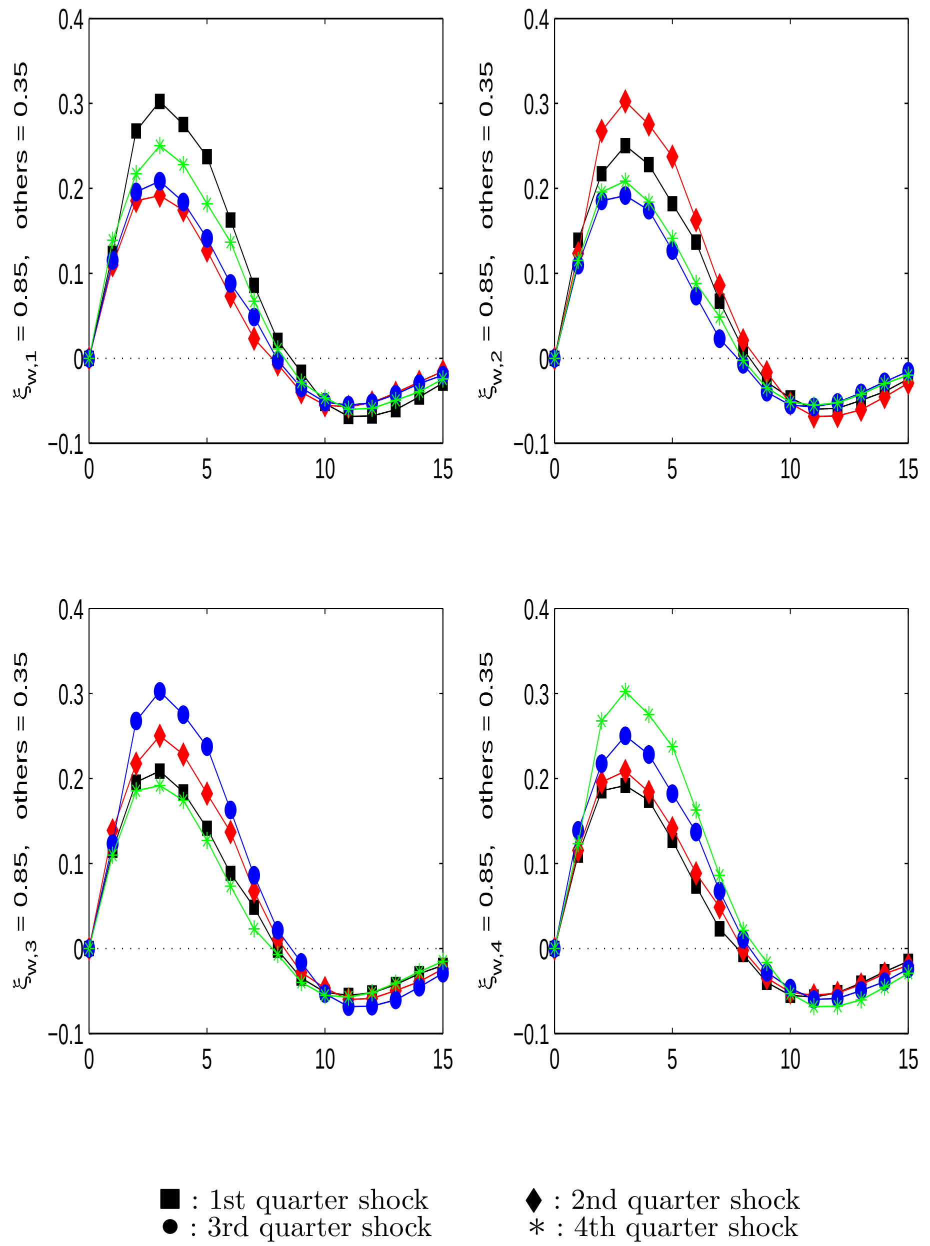


Figure 6: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Wage Rigidity

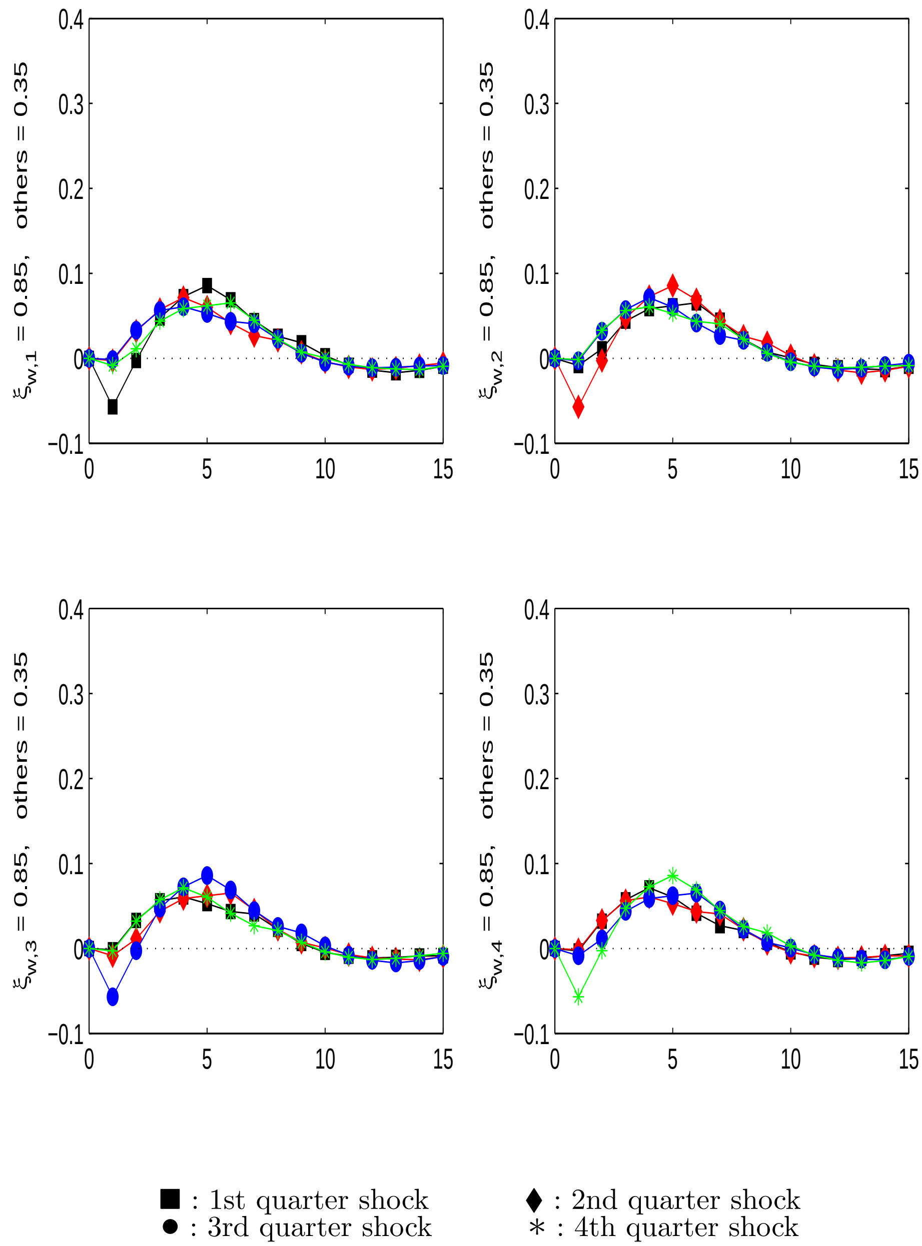
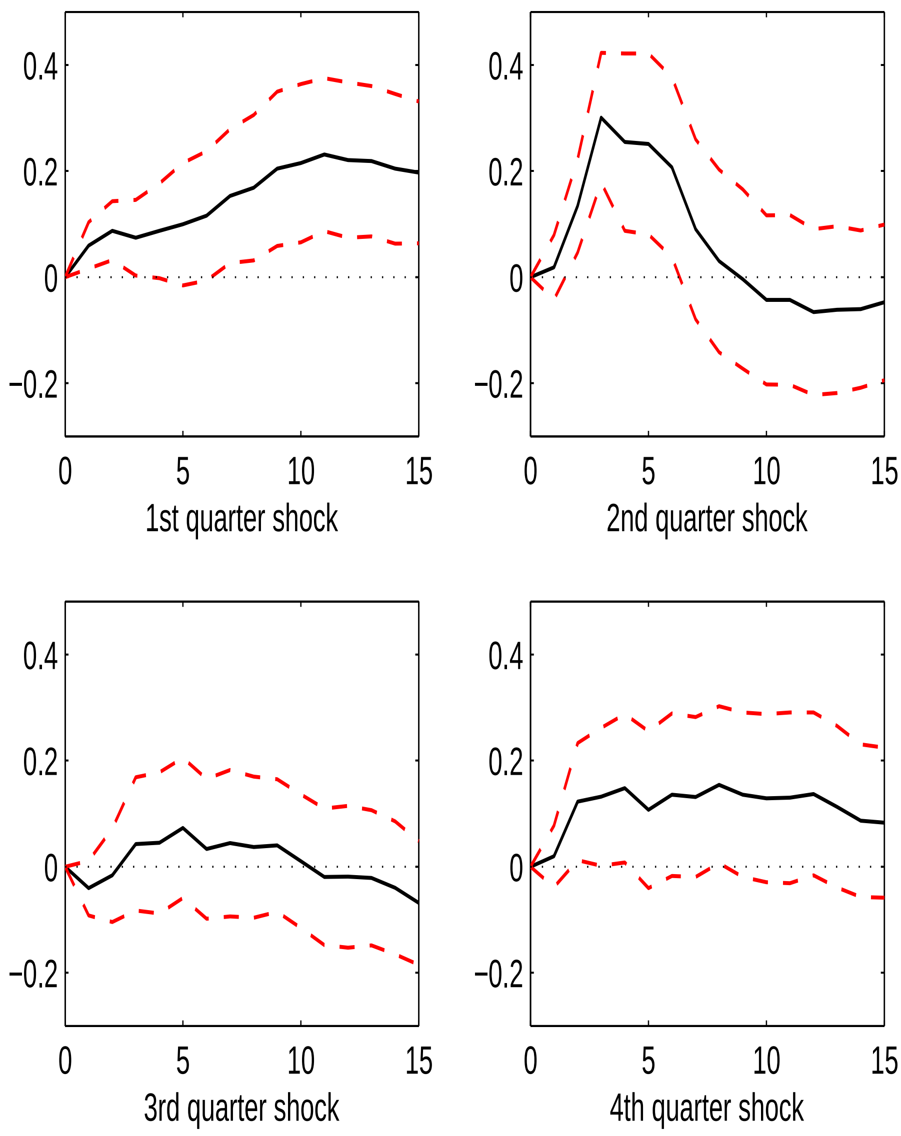
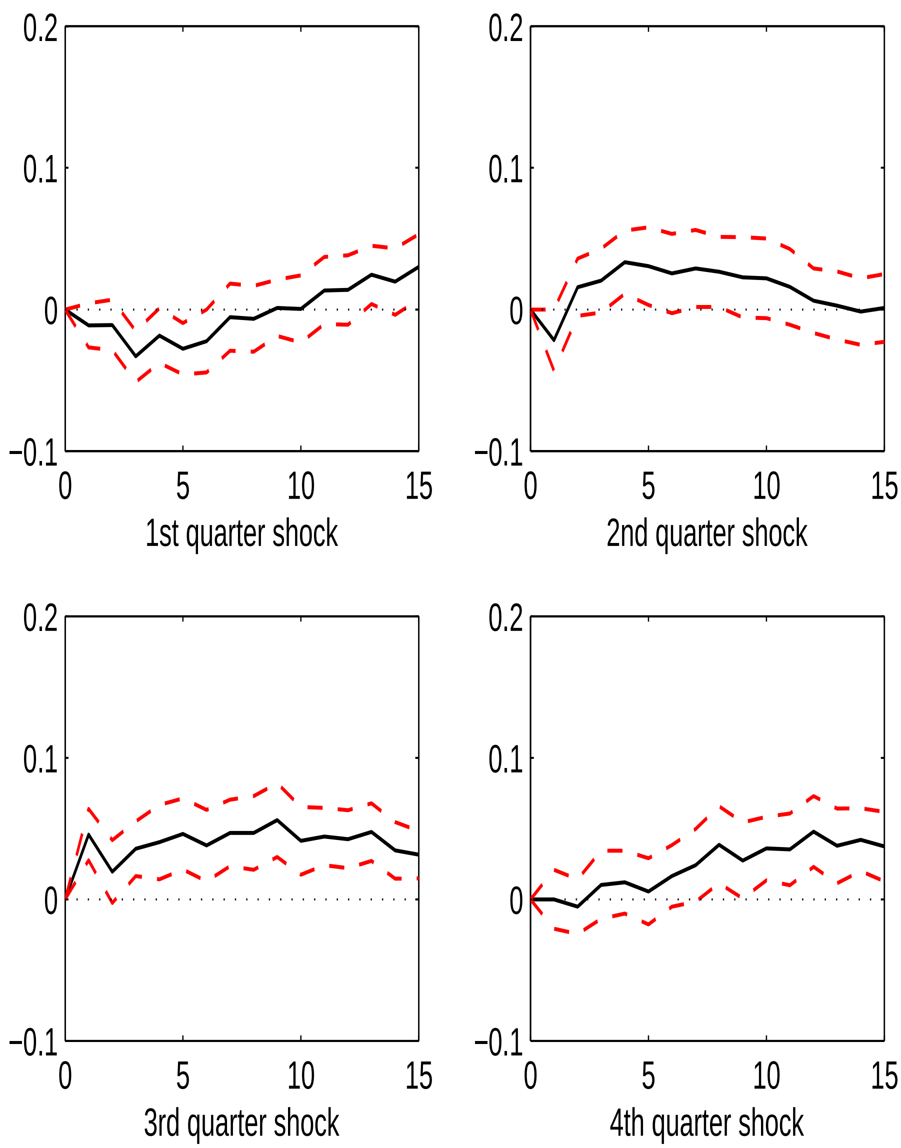


Figure 7: Impulse Response of Real GDP to a 25-Basis Point Decline in FFR from Quarter Dependent VAR, 1966.1Q ~ 2009.4Q



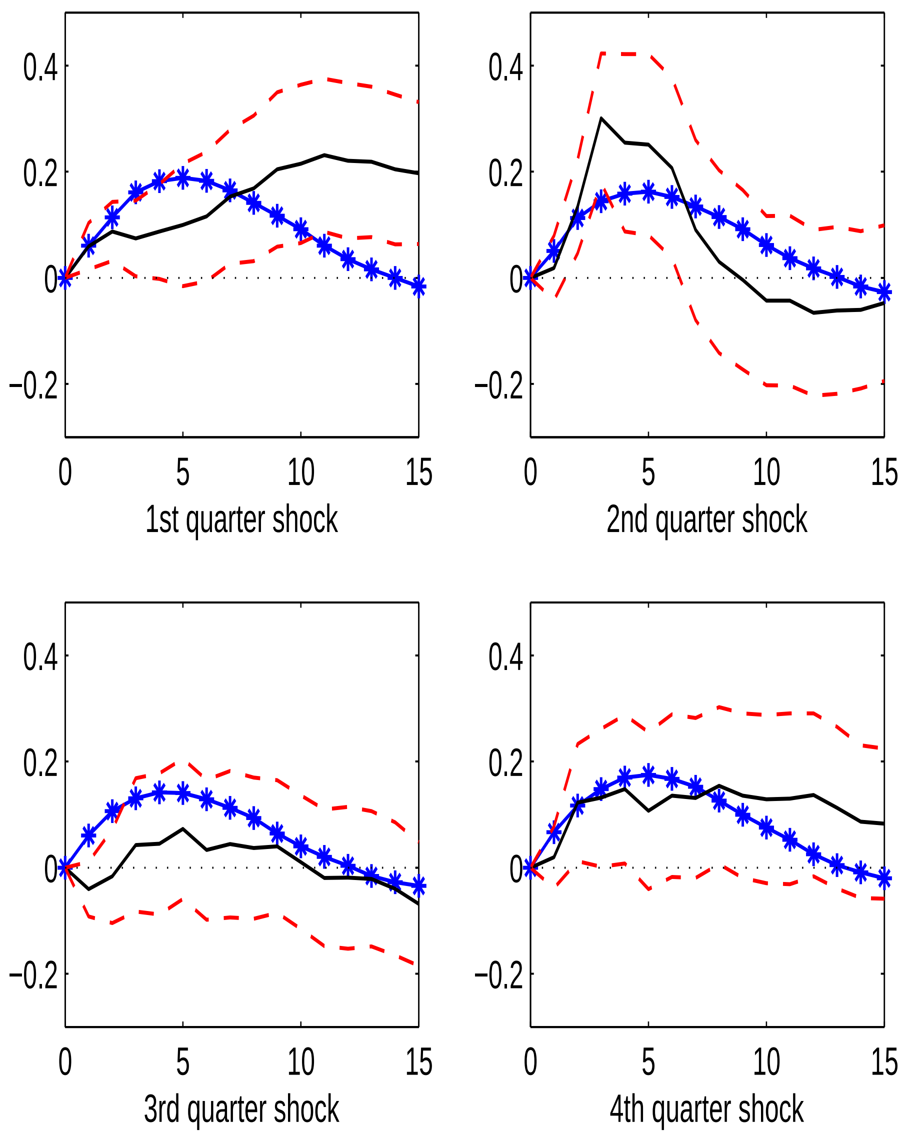
Note : Dashed lines represent 80% confidence intervals

Figure 8: Impulse Response of Inflation Rates to a 25-Basis Point Decline in FFR from Quarter Dependent VAR, 1966.1Q $\sim$ 2009.4Q



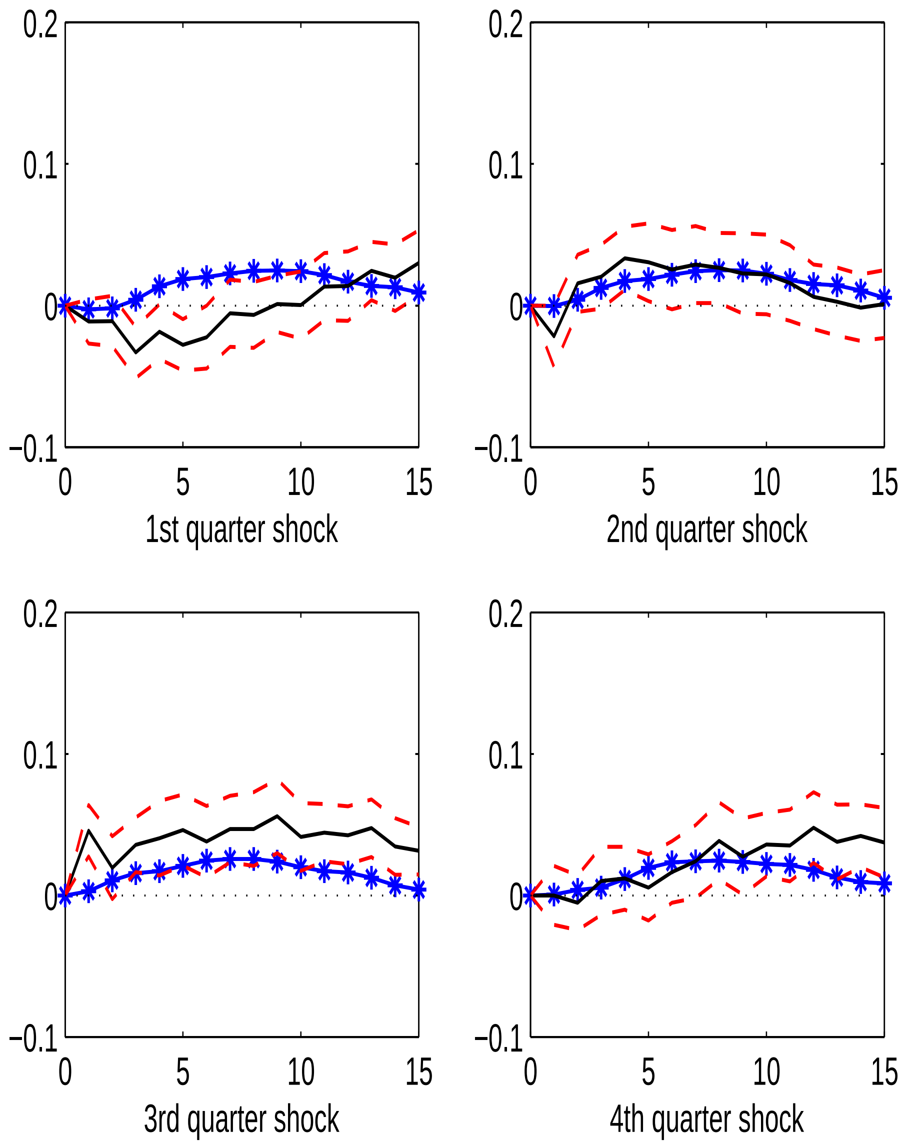
Note : Dashed lines represent 80% confidence intervals

Figure 9: Model and Quarter Dependent VAR Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates



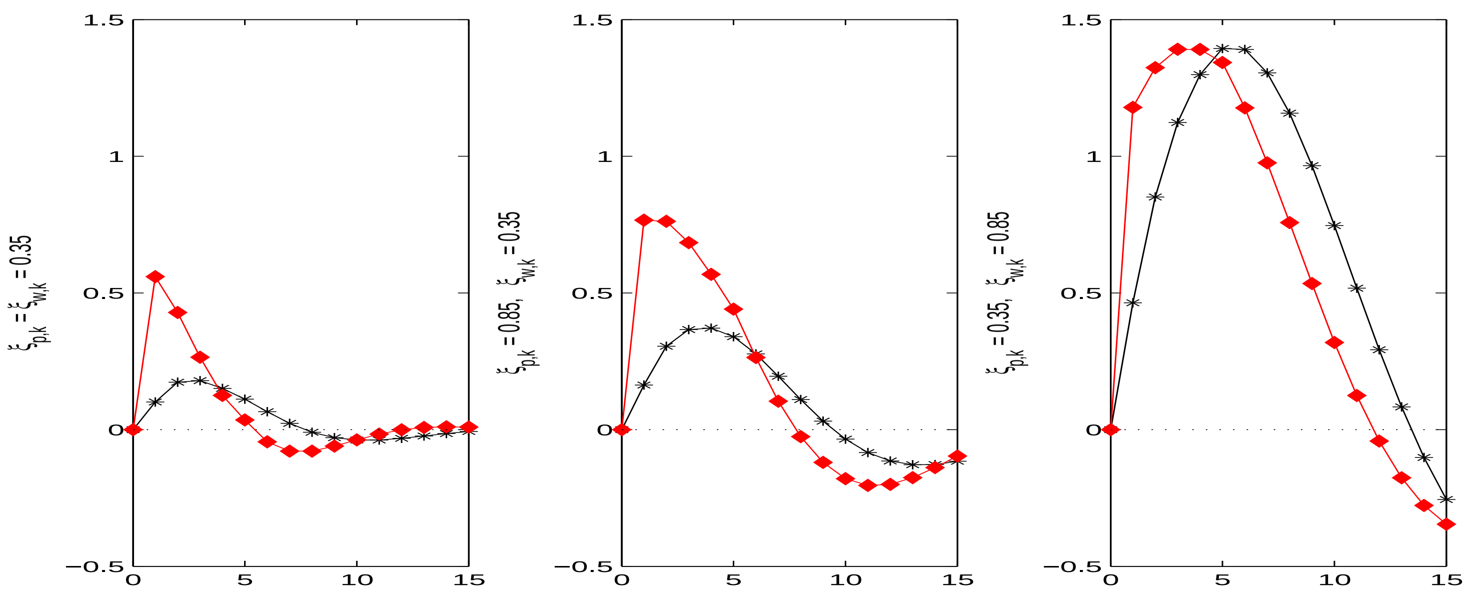
Note : Solid lines are impulse response of quarter dependent VAR and lines with asterisks represent impulse response from model. Dashed lines represent 80% confidence intervals.

Figure 10: Model and Quarter Dependent VAR Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates



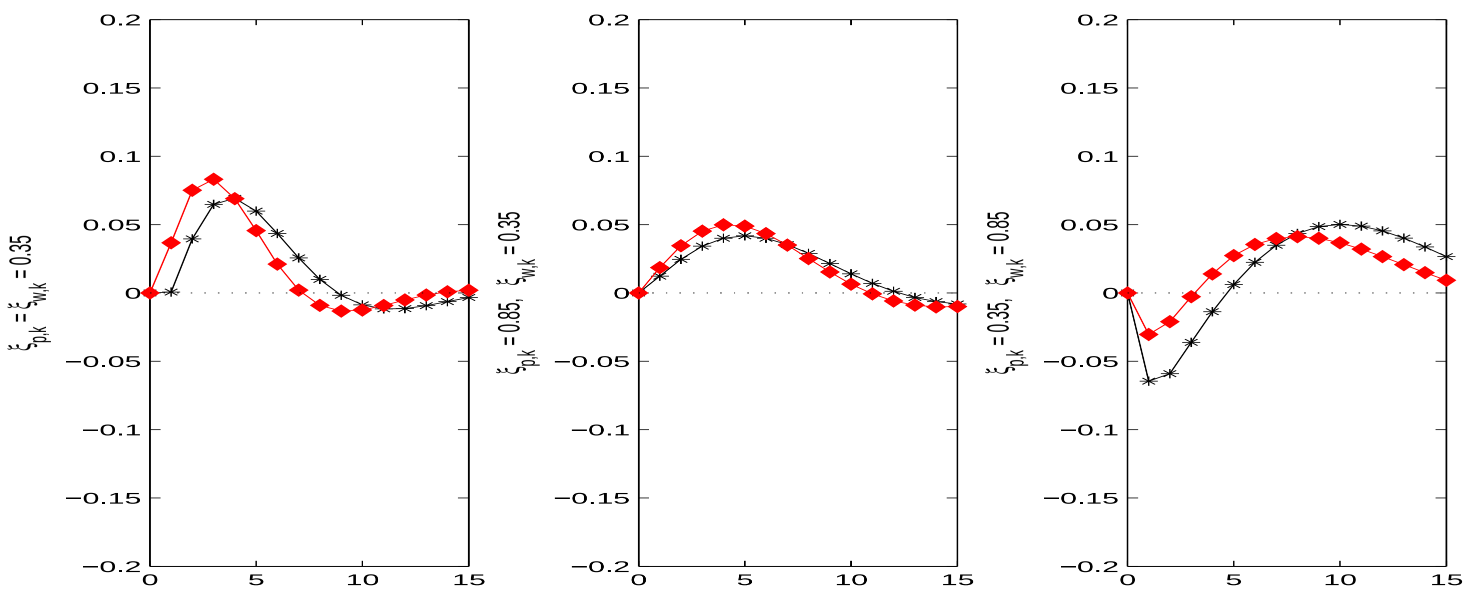
Note : Solid lines are impulse response of quarter dependent VAR and lines with asterisks represent impulse response from model. Dashed lines represent 80% confidence intervals.

Figure 11: No Habit Formation in Consumption: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with the Quarterly Same Price and Wage Rigidity



♦ : no habit formation ∗ : habit formation

Figure 12: No Habit Formation in Consumption: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with the Quarterly Same Price and Wage Rigidity



♦ : no habit formation　　　∗ : habit formation

Figure 13: No Habit Formation in Consumption: Impulse Responses to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Rigidity

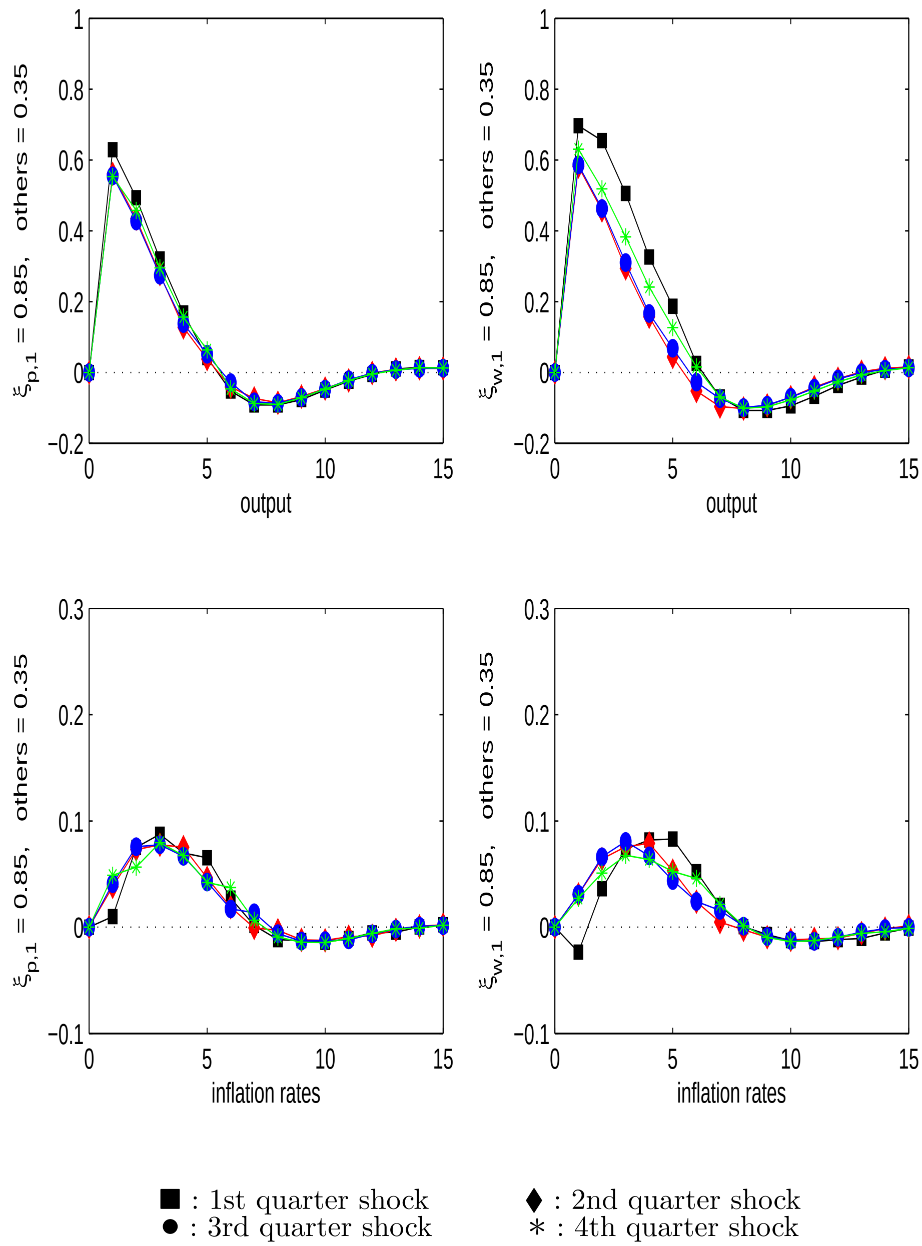
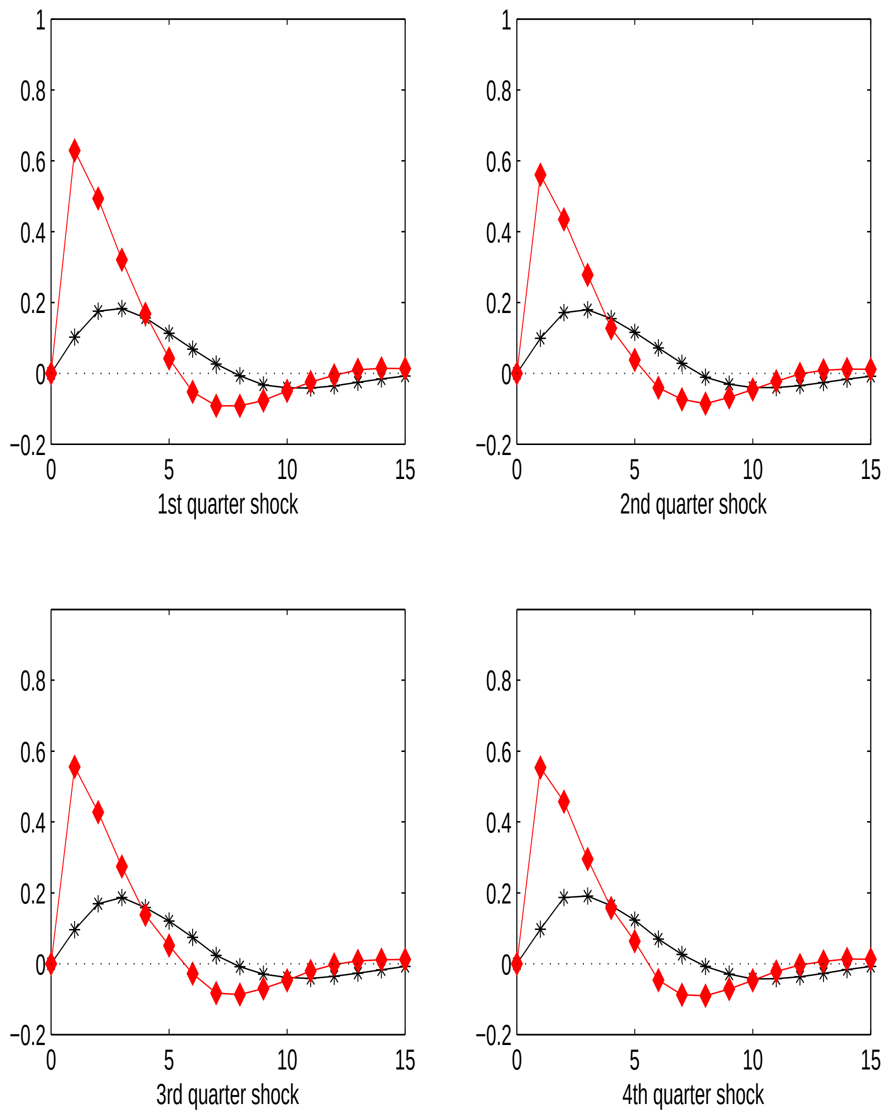
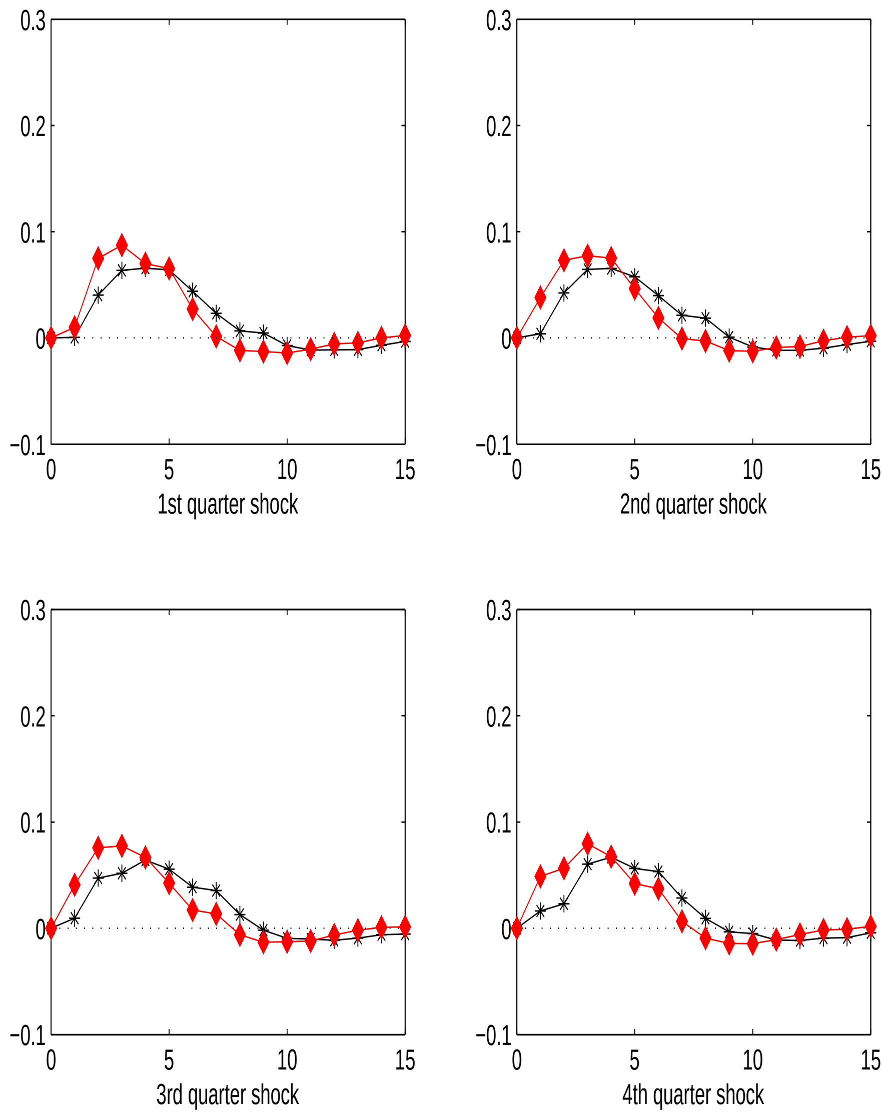


Figure 14: No Habit Formation in Consumption: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Price Rigidity ($\xi_{p,1} = 0.85$, all other rigidities = 0.35)



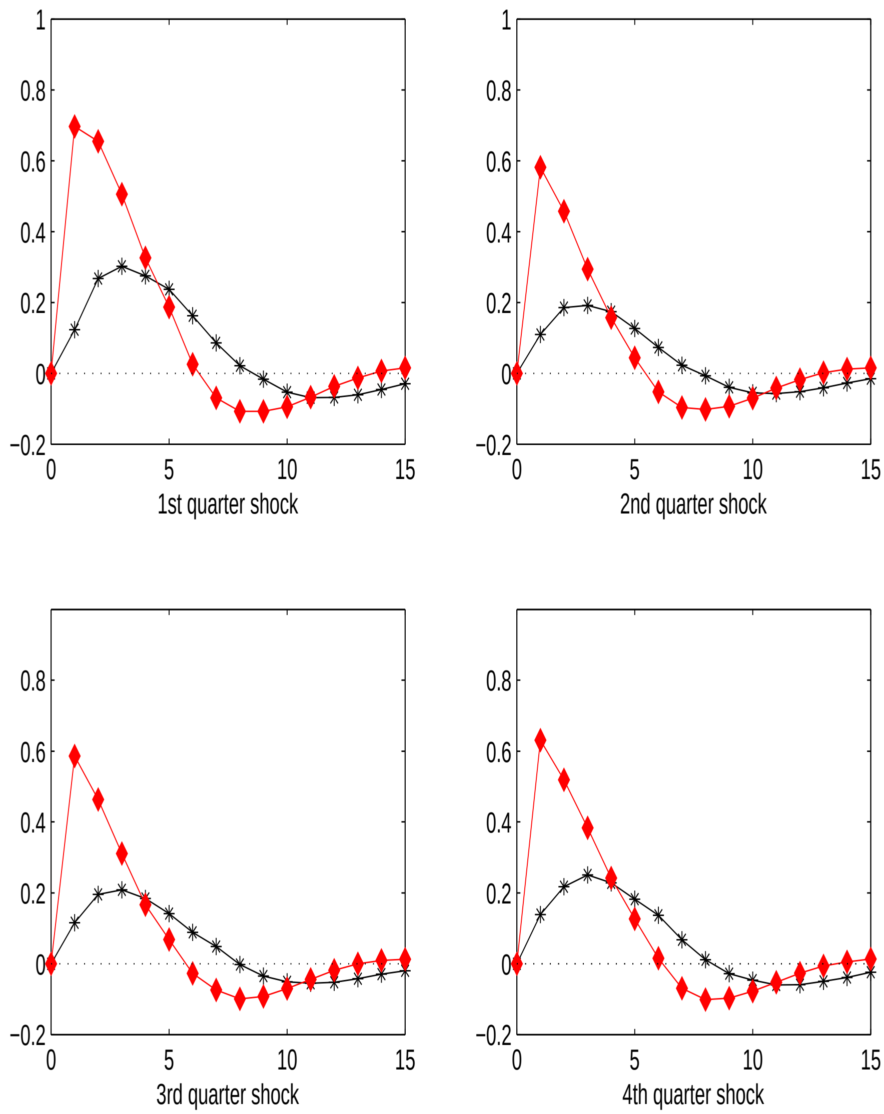
♦ : no habit formation ∗ : habit formation

Figure 15: No Habit Formation in Consumption: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Price Rigidity ($\xi_{p,1} = 0.85$, all other rigidities $= 0.35$)



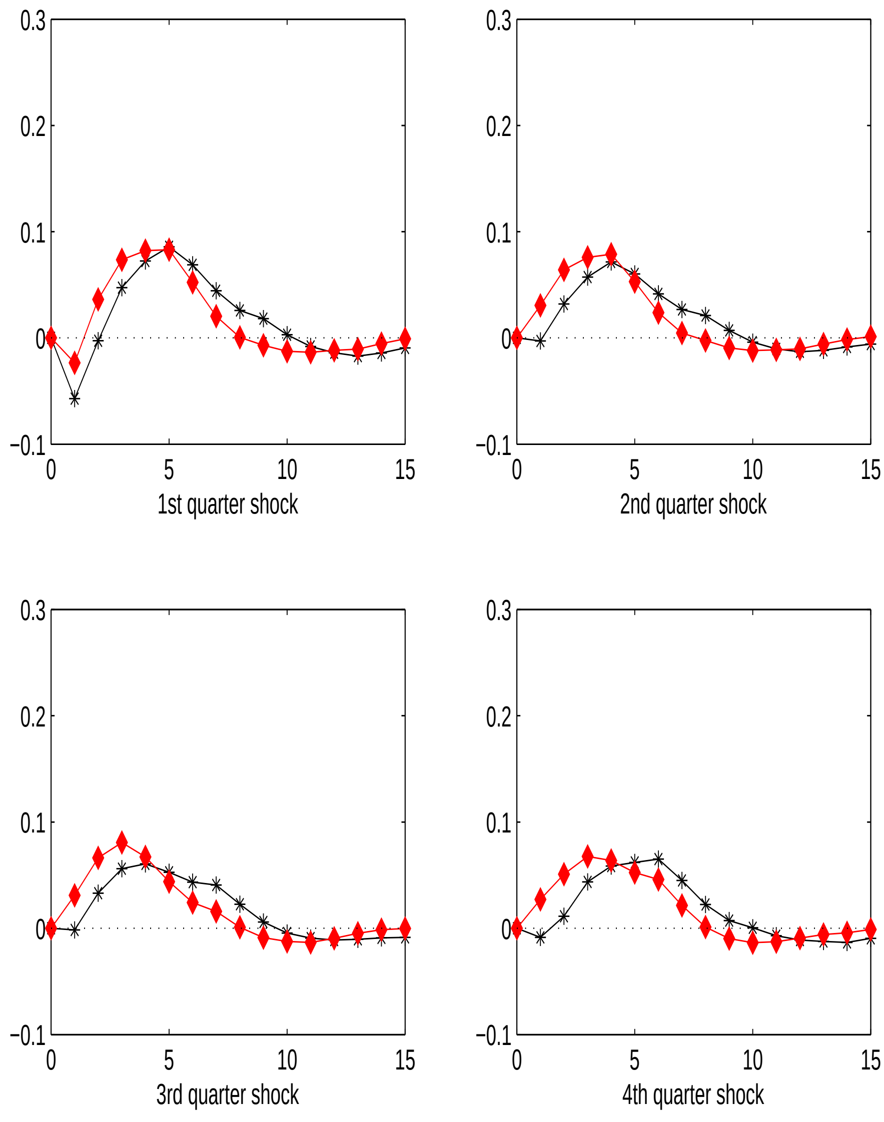
♦ : no habit formation $\quad\quad$ $*$: habit formation

Figure 16: No Habit Formation in Consumption: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Wage Rigidity ($\xi_{w,1} = 0.85$, all other rigidities = 0.35)



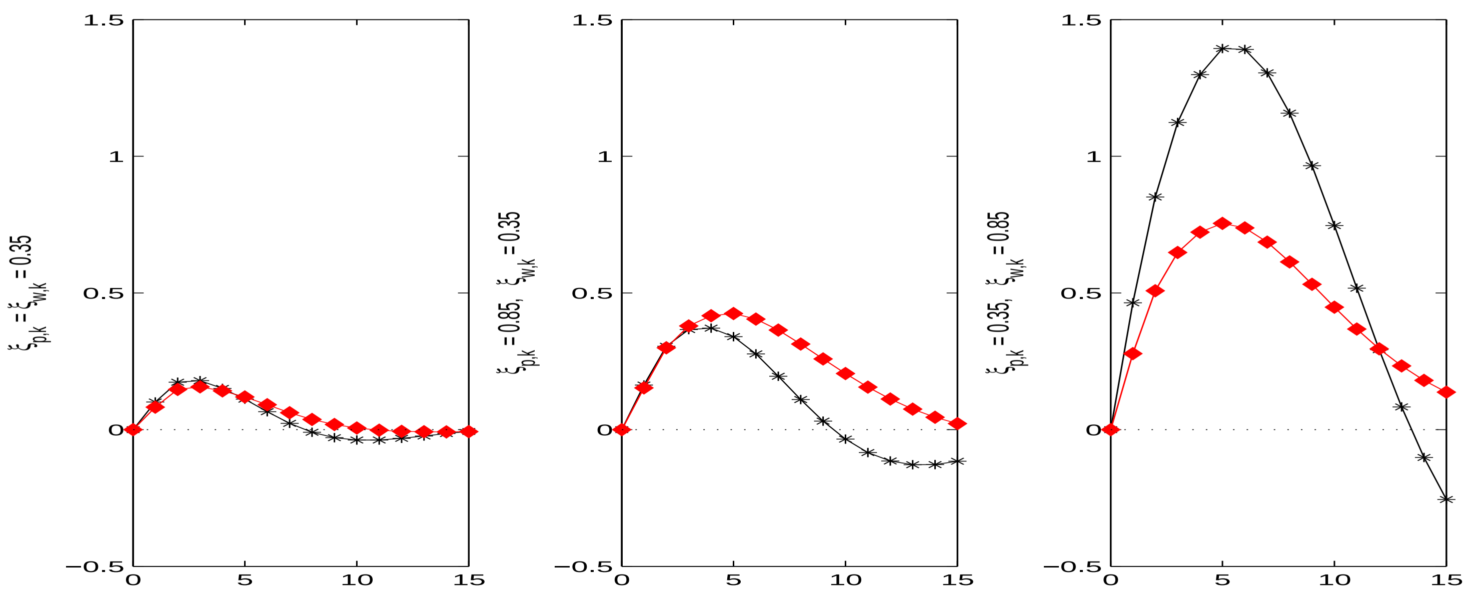
♦ : no habit formation $\ast$: habit formation

Figure 17: No Habit Formation in Consumption: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Wage Rigidity ($\xi_{w,1} = 0.85$, all other rigidities $= 0.35$)



♦ : no habit formation $\ast$: habit formation

Figure 18: No Price and Wage Indexation: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with the Quarterly Same Price and Wage Rigidity



♦ : no indexation   ∗ : indexation

Figure 19: No Price and Wage Indexation: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with the Quarterly Same Price and Wage Rigidity

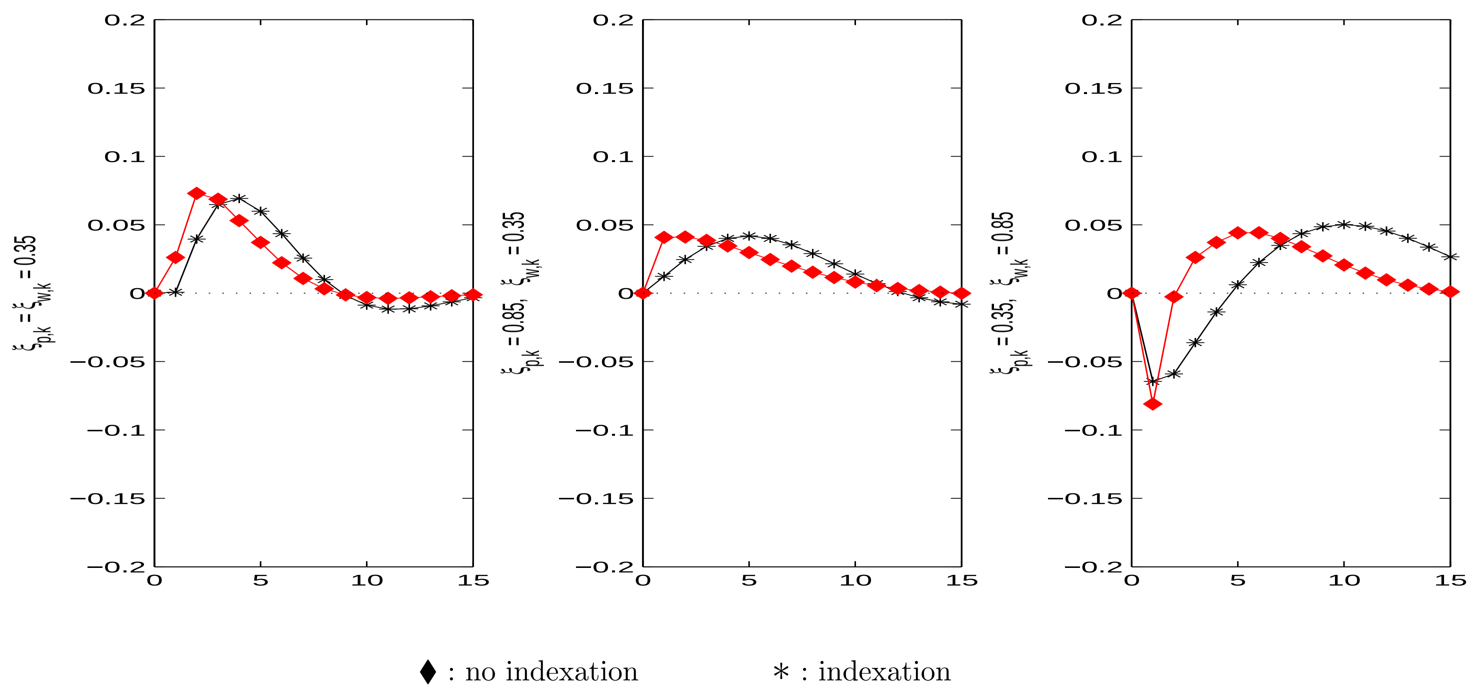


Figure 20: No Price and Wage Indexation: Impulse Responses to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Rigidity

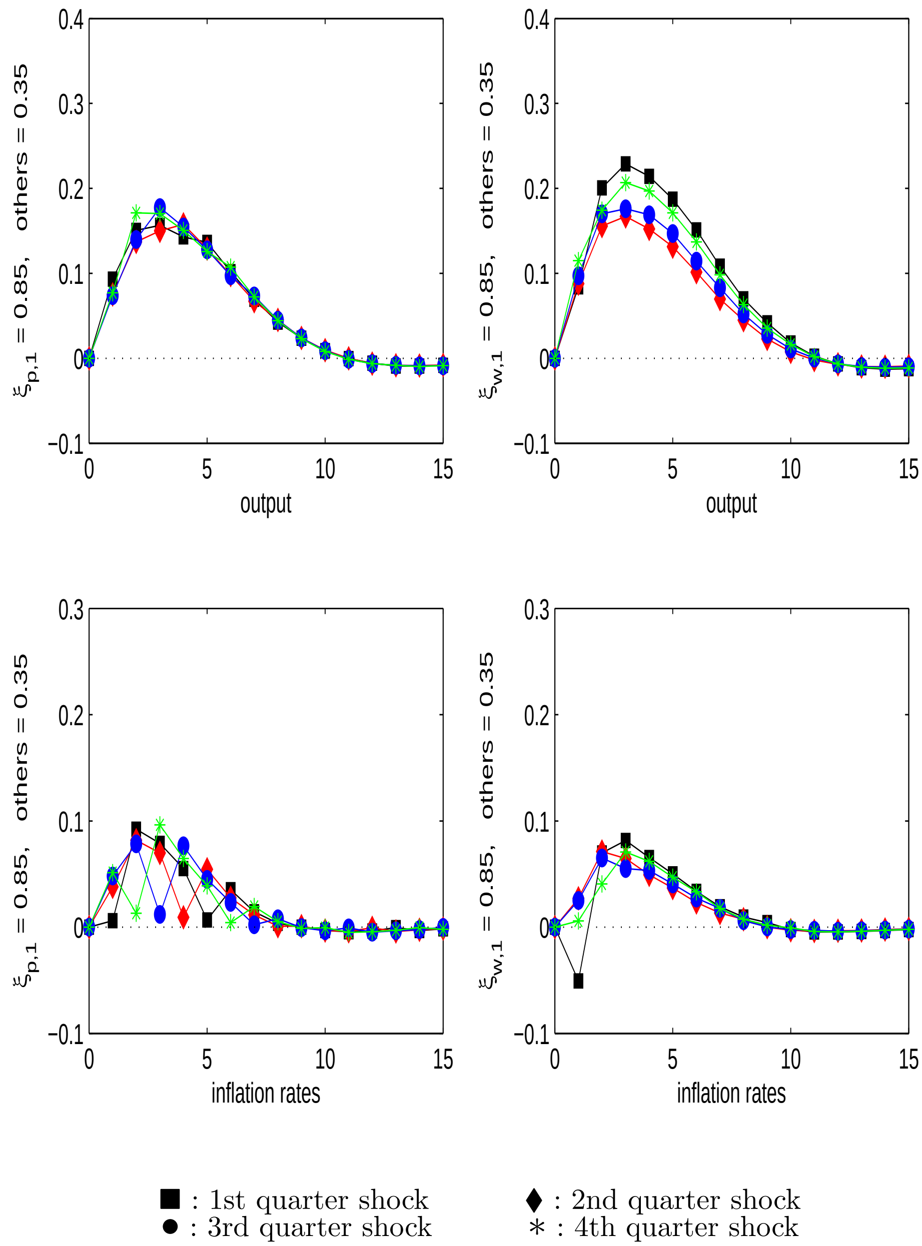
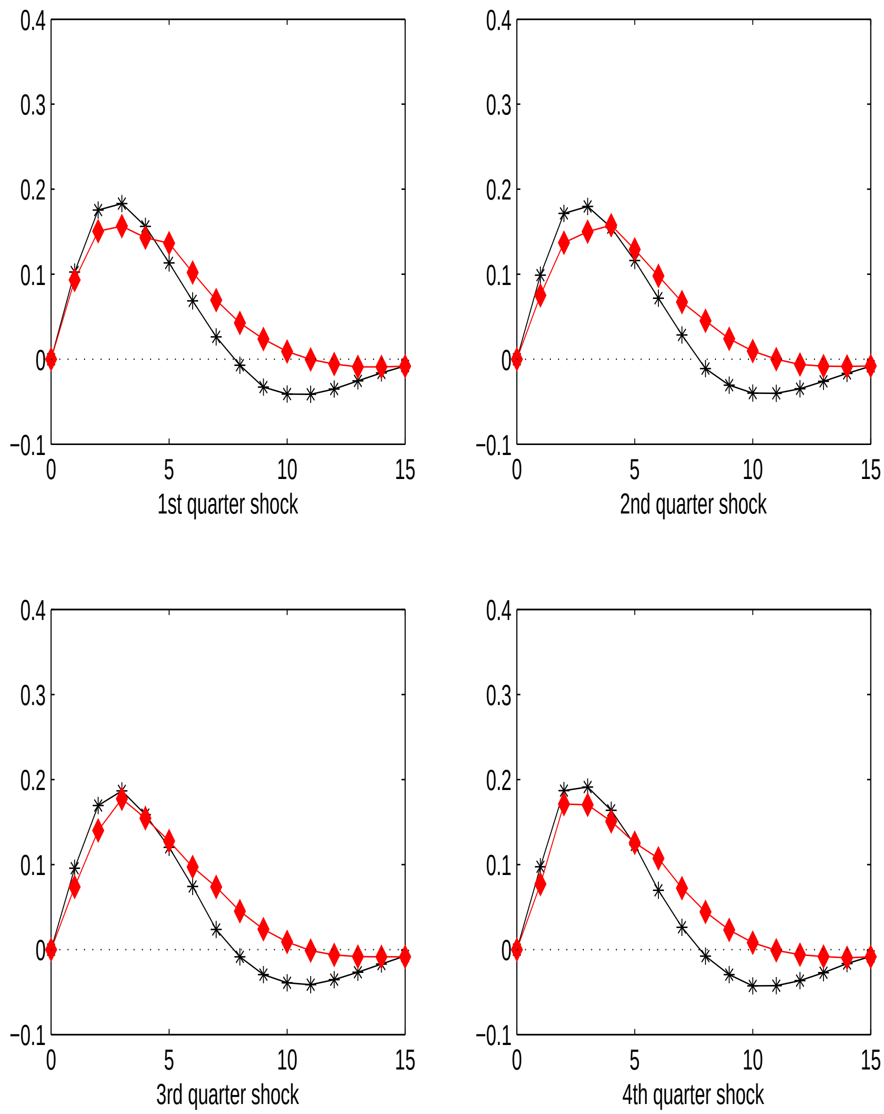
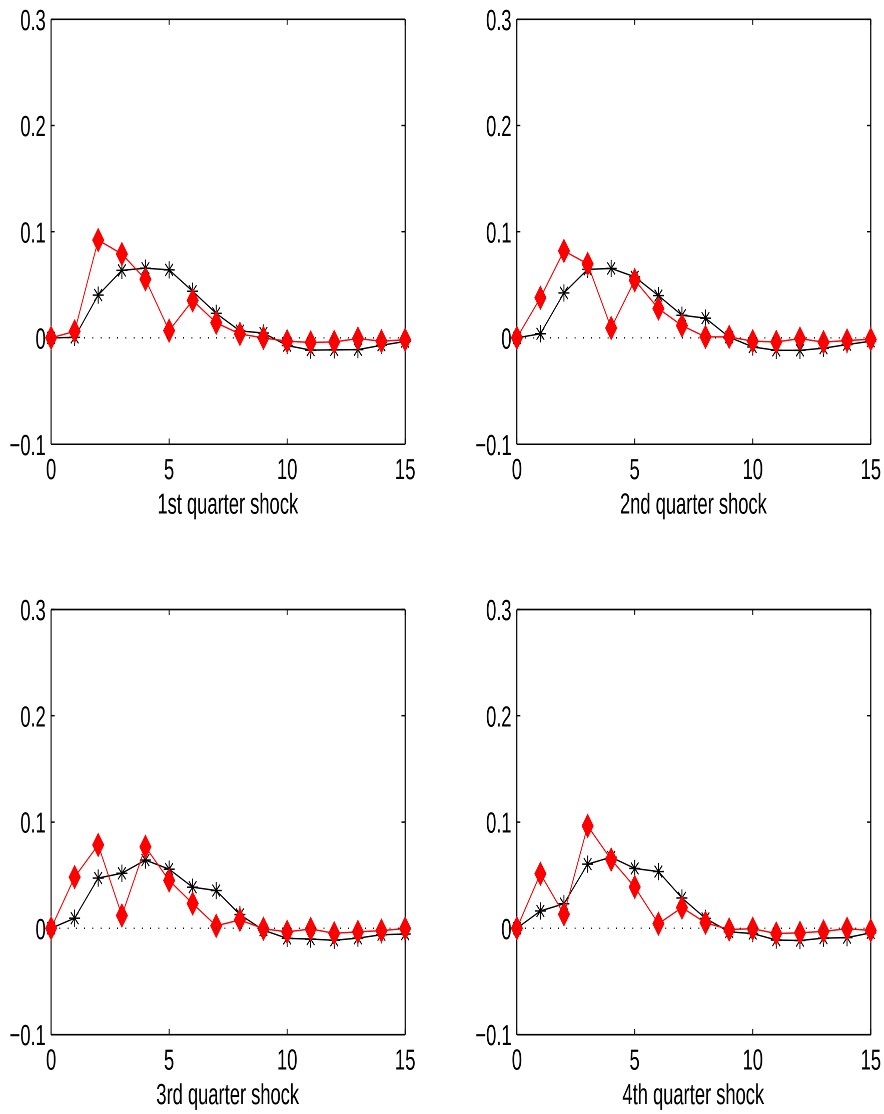


Figure 21: No Price and Wage Indexation: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Price Rigidity ($\xi_{p,1} = 0.85$, all other rigidities $= 0.35$)



♦ : no indexation $\quad\quad$ $*$: indexation

Figure 22: No Price and Wage Indexation: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Price Rigidity ($\xi_{p,1} = 0.85$, all other rigidities $= 0.35$)



♦ : no indexation $\quad\quad$ $*$: indexation

Figure 23: No Price and Wage Indexation: Impulse Response of Output to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Wage Rigidity ($\xi_{w,1} = 0.85$, all other rigidities $= 0.35$)

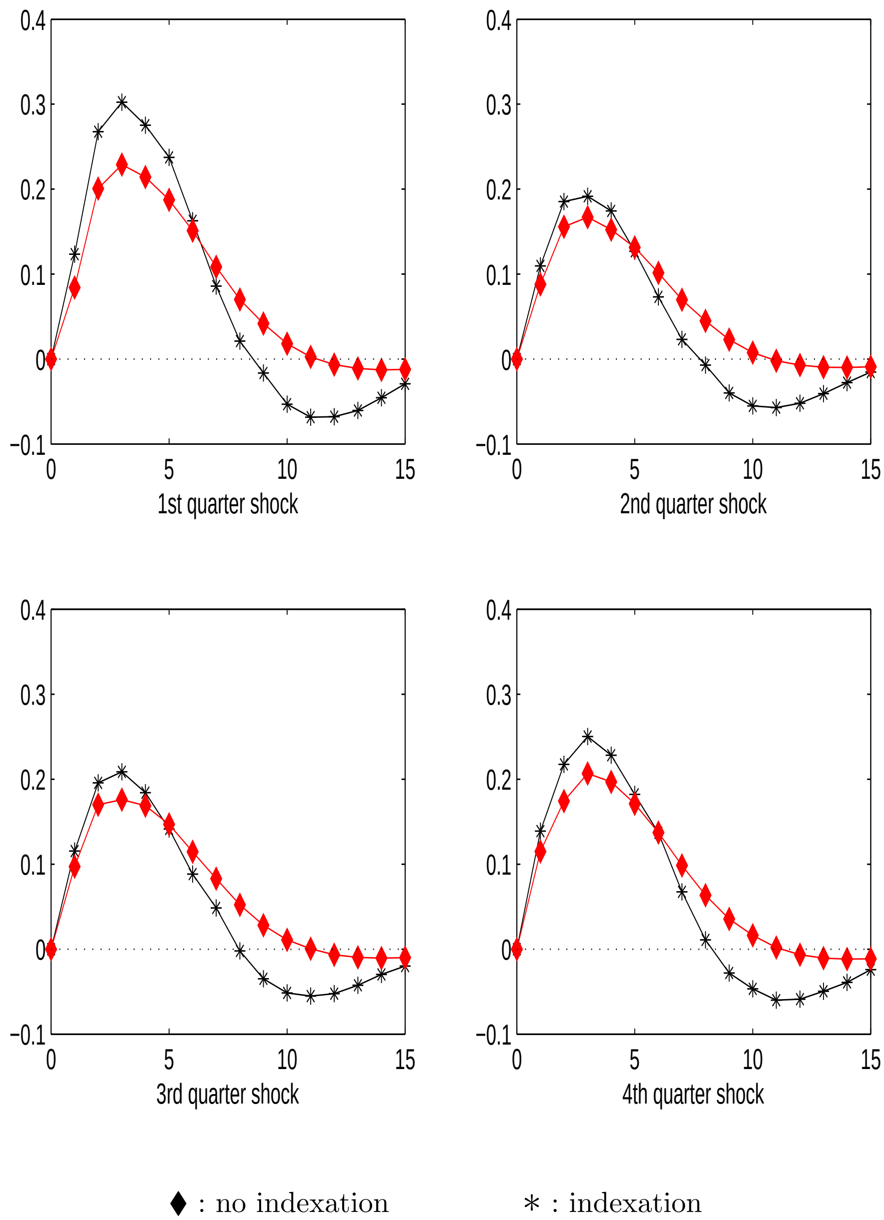
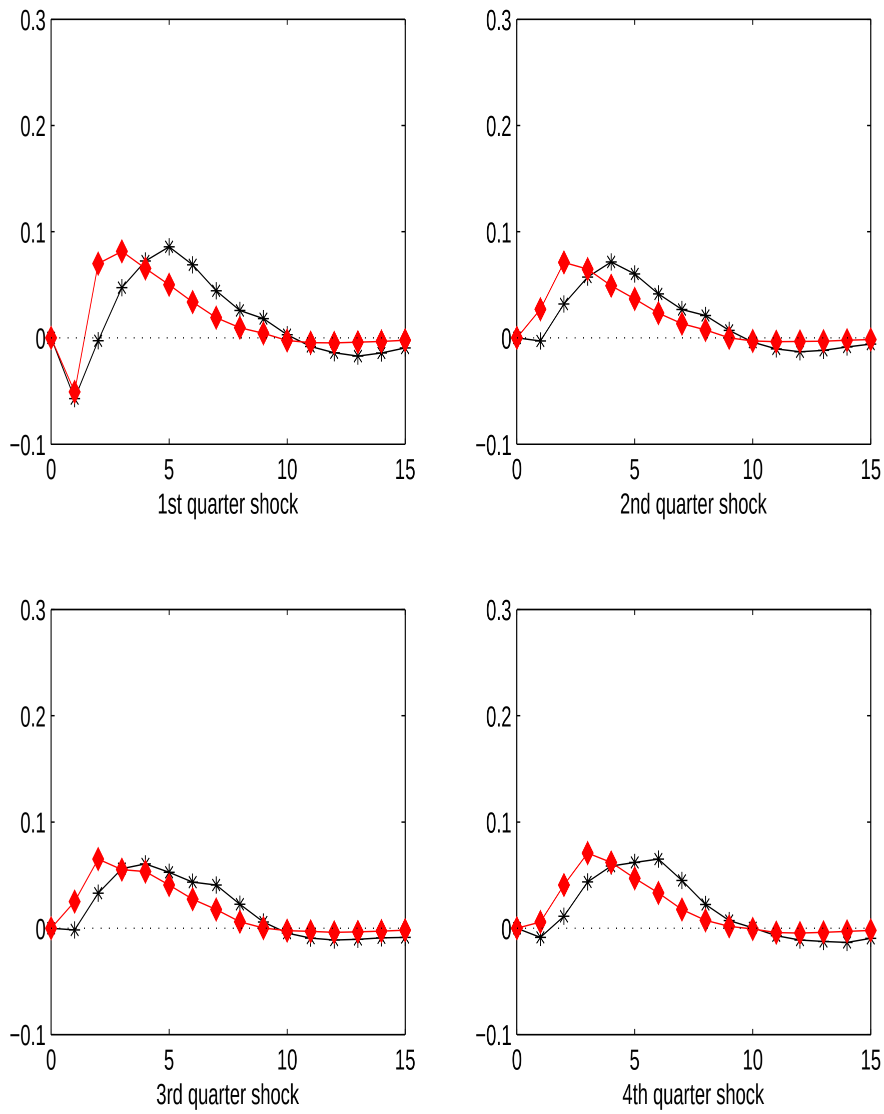


Figure 24: No Price and Wage Indexation: Impulse Response of Inflation Rates to a 25-Basis Point Decline in Nominal Interest Rates from the Model with Quarterly Different Wage Rigidity ($\xi_{w,1} = 0.85$, all other rigidities = 0.35)



♦ : no indexation   ∗ : indexation

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