Unemployment Gap and Monetary Policy

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Preliminary - Comments welcome

Abstract

This paper estimates a DSGE model with sticky prices and equilibrium unemployment on post-1984 US data by using Bayesian techniques. Neutral technology shocks and bargaining power shocks emerge as the main sources of business-cycle fluctuations over the sample period. I use the estimated model to back out the path of the potential rate of unemployment and to construct a model-consistent measure of the unemployment gap. This structural measure of the unemployment gap shares the same turning points as the traditional HP-filter unemployment gap but is more volatile. The historical decomposition of the model's unemployment gap stresses the expansionary effects of monetary policy shocks during each of the three recessions that characterize the sample period. Finally I perform counterfactual experiments to assess the performance of the Fed's setting of the interest rate up to 2009:Q4.

Keywords: DSGE models, business cycles, unemployment gap, monetary policy, frequency-domain analysis

JEL codes: E32, C51, C52

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1 Introduction

Recently, a rapidly growing body of literature has emerged that combines monetary DSGE models of the business cycle with the modern theory of equilibrium unemployment, i.e. the Search and Matching model.[1] This paper builds and estimates a New Keynesian model with search and matching frictions in the labor market. The model incorporates the standard features introduced by Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007) that help fitting the data. Gertler et al. (2008) have shown that this kind of model fits the data equally well as the benchmark model without unemployment exemplified by Christiano et al. (2005) and Smets and Wouters (2007). Moreover, there are three related advantages in introducing equilibrium search unemployment into the standard toolbox for monetary policy analysis: First, this theoretical framework generates predictions about the unemployment rate and other labor market variables such as the vacancy rate. Second, in this framework, sticky wages are not subject to the Barro's critics. Barro (1977)'s argument is that because workers and firms share long-run ongoing relationships, the joint benefits of wage negociations are likely to be much larger than the costs. This, in turn, implies that wages may not have allocational effects for existing firm-worker pairs. This is important because Christiano et al. (2005) and Smets and Wouters (2007) provide evidence suggesting that wage stickiness is a more important ingredient than price stickiness to account for the persistence observed in the data. Unfortunately however, the standard framework without unemployment suffers from the Barro's critics. Third, Hall (1997) and Chari, McGrattan and Kehoe (2007) have stressed the importance of a particular shock, the labor wedge, to account for business cycle fluctuations. The labor wedge is a disturbance to the household's intratemporal efficiency condition which allows the real wage to deviate from the marginal rate of substitution between leisure and consumption. Introducing search and matching frictions into equilibrium business cycles and using additional labor market variables such as the unemployment and vacancy rates, represents a step towards the endogeneization and the identification of the labor wedge.

I use post-1984 quarterly US data on seven key aggregate variables to estimate the model with Bayesian techniques. The estimated model fits several business-cycle stylized facts and points towards technology and bargaining power shocks as the main sources of business-cycle fluctuations. Bargaining power shocks trigger effects similar to those of wage-markup disturbances in the benchmark model without unemployment estimated by Smets and Wouters (2007). This finding is consistent with an important body of research including Hall (1997), Chari et al. (2007) and Smets and Wouters (2007).[2]

I then use the estimated DSGE model to back out the path of the potential rate of unem-

[1] See for example Trigari (2009), Walsh (2005), Krause and Lubik (2007), Sveen and Weinke (2008), Gertler, Sala and Trigari (2008).

[2] Justiniano, Primiceri and Tambalotti (2010) and Gertler et al. (2008) find that shocks to the marginal efficiency of investment are the main source of business cycles. The difference between their results and mine most probably stems from the fact that I am using a shorter sample period. Justiniano et al. (2010) and Gertler et al. (2008) use sample periods starting in 1954:Q3 and 1960:Q1 respectively. Instead, to avoid concerns related to possible structural breaks in the conduct of monetary policy (seeClarida, Gali and Gertler (2000)) and in the standard deviations of shocks (Justiniano and Primiceri (2008*b*)), my sample period starts in 1985:Q1. Consistently with Justiniano et al. (2010) and Gertler et al. (2008), I include durables consumption in investment.

ployment and to construct a model-based measure of the unemployment gaps. Following Smets and Wouters (2007), Justiniano and Primiceri (2008*a*) and Sala, Söderström and Trigari (2008), the potential rate of unemployment is the unemployment rate consistent with flexible prices and wages in absence of price markup shocks and bargaining power shocks. In turn, the unemployment gap is defined as the percent deviation of the actual rate from the potential rate of unemployment. The concept of unemployment gap is an important input in the decision-making process of many central banks. When the unemployment gap is positive, the actual rate of unemployment exceeds its potential value. Productive capacities are underutilized. This in turn sets in motion downward pressures on marginal costs and inflation. Instead, when the unemployment gap is negative, the economy is overheating and inflationary pressures rise. Estimating the current state of the unemployment gap is a crucial task in the practice of monetary policy. The structural measure of the unemployment gap can be decomposed into its different driving forces at each point in time. The historical decomposition of the unemployment gap reveals the strong expansionary role played by monetary shocks during each of the three recessions embedded in the sample period.

2 Model

Firms adjust labor exclusively through job creation and face convex hiring costs as in Yashiv (2006). This feature helps the model to capture the high persistence in vacancies and unemployment. Fluctuations are driven by seven disturbances: a neutral technology shock, an investment-specific technology shock, a risk-premium shock, a price-markup shock, a bargaining-power shock, an exogenous spending shock and a monetary policy shock.[3]

The economy consists of a representative family, a representative finished goods-producing firm, a continuum of intermediate goods-producing firms indexed by $i \in [0, 1]$, a central bank and a government that sets monetary and fiscal policy respectively. I now describe the behavior of these agents.

2.1 The representative household

There is a continuum of identical households of mass one. Each household is a large family, made of a continuum of individuals of measure one. Family members are either working or searching for a job.[4] Following Merz (1995), I assume that family members pool their income before the head of the family chooses optimally per capita consumption.

The representative family enters each period $t = 0, 1, 2, ...,$ with B_{t-1} bonds and $\overline{K}_{t-1}$ units of physical capital. At the beginning of each period, bonds mature, providing B_{t-1} units of money.

[3] Gertler et al. (2008) estimate a similar model with Bayesian techniques on US postwar data. Their model features a preference shock to the representative household's discuunt factor. Instead, my model features a risk-premium shock as in Smets and Wouters (2007). Moreover, Gertler et al. (2008) use data on total hours worked whereas I use data on the vacancy/unemployment ratio. Finaly, their sample period goes from 1960:Q1 to 2005:Q1. Instead my sample starts in 1985:Q1 after the Great Moderation and the Volcker's disinflation.

[4] The model abstracts from the labor force participation decision.

The representative family uses some of this money to purchase B_t new bonds at nominal cost B_t/r_t^B, where r_t^B denotes the gross nominal interest rate between period t and $t+1$.

The representative household owns capital and chooses the capital utilization rate, u_t, which transforms physical capital into effective capital according to

$$K_t = u_t \overline{K}_{t-1}. \tag{1}$$

The household rents $K_t(i)$ units of effective capital to intermediate-goods-producing firm $i \in [0,1]$ at the nominal rate r_t^K. The household's choice of $K_t(i)$ must satisfy

$$K_t = \int_0^1 K_t(i)\, di. \tag{2}$$

The cost of capital utilization is $a(u_t)$ per unit of physical capital. I assume the following functional form for the function a,

$$a(u_t) = \phi_{u1}(u_t - 1) + \frac{\phi_{u2}}{2}(u_t - 1)^2, \tag{3}$$

and that $u_t = 1$ in steady state.

Each period, $N_t(i)$ family members are employed at intermediate goods-producing firm $i \in [0,1]$. Each worker employed at firm i works a fixed amount of hours and earns the nominal wage $W_t(i)$. N_t denotes aggregate employment in period t and is given by

$$N_t = \int_0^1 N_t(i)\, di. \tag{4}$$

The remaining $(1 - N_t)$ family members are unemployed and and each receives nominal unemployment benefits b_t, financed through lump-sum taxes.

During period t, the representative household receives total nominal factor payments $r_t^K K_t + W_t N_t + (1 - N_t) b_t$. In addition, the household also receives nominal profits $D_t(i)$ from each firm $i \in [0,1]$, for a total of

$$D_t = \int_0^1 D_t(i)\, di. \tag{5}$$

In each period $t = 0, 1, 2, ...$,the family uses these resources to purchase finished goods, for both consumption and investment purposes, from the representative finished goods-producing firm at the nominal price P_t. The law of motion of physical capital is

$$\overline{K}_t \leq (1-\delta)\overline{K}_{t-1} + \mu_t \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t, \tag{6}$$

where δ denotes the depreciation rate. The function S captures the presence of adjustment costs in investment, as in Christiano et al. (2005). I assume the following functional form for the function S,

$$S\left(\frac{I_t}{I_{t-1}}\right)=\frac{\phi_I}{2}\left(\frac{I_t}{I_{t-1}}-g_I\right)^2, \tag{7}$$

where g_I is the steady-state growth rate of investment. Hence, along the balanced growth path, $S(g_I)=S'(g_I)=0$ and $S''(g_I)=\phi_I>0$. μ_t is an investment-specific technology shock affecting the efficiency with which consumption goods are transformed into capital. The investment-specific shock follows the exogenous stationary autoregressive process

$$\ln(\mu_t)=\rho_\mu \ln(\mu_{t-1})+\varepsilon_{\mu t}, \tag{8}$$

where $\varepsilon_{\mu t}$ is $i.i.d.N\left(0,\sigma_\mu^2\right)$.

The family's budget constraint is given by

$$\begin{aligned} P_tC_t+P_tI_t+\frac{B_t}{\epsilon_{bt}r_t^B} \leq\ & B_{t-1}+W_tN_t+(1-N_t)\,b_t+r_t^K u_t\overline{K}_{t-1} \\ & -P_t a(u_t)\,\overline{K}_{t-1}-T_t+D_t \end{aligned} \tag{9}$$

for all $t=0,1,2,...$ As in Smets and Wouters (2007), the shock ϵ_{bt} drives a wedge between the central bank's instrument rate r_t^B and the return on assets held by the representative family. As noted by De Graeve, Emiris and Wouters (2009), this disturbance works as an aggregate demand shock and generates a positive comovement between consumption and investment. The risk-premium shock ϵ_{bt} follows the autoregressive process

$$\ln\epsilon_{bt}=\rho_b\ln\epsilon_{bt-1}+\varepsilon_{bt}, \tag{10}$$

where $0<\rho_b<1$, and ε_{bt} is $i.i.d.N\left(0,\sigma_b^2\right)$.

The family's lifetime utility is described by

$$E_t\sum_{s=0}^{\infty}\beta^s\ln\left(C_{t+s}-hC_{t+s-1}\right) \tag{11}$$

where $0<\beta<1$. When $h>0$, the model allows for habit formation in consumption and consumption responds gradually to shocks.

The head of the family chooses C_t, B_t, u_t, I_t, and $\overline{K}_t$ for each $t=0,1,2,...$ to maximize the expected lifetime utility (11) subject to the constraints (6) and (9).

The first order conditions for this problem are

- C_t :

$$\Lambda_t=\frac{1}{C_t-hC_{t-1}}-\beta hE_t\left(\frac{1}{C_{t+1}-hC_t}\right) \tag{12}$$

- B_t :

$$\Lambda_t = \beta \epsilon_{bt} r_t^B E_t \left(\Lambda_{t+1} \frac{P_t}{P_{t+1}} \right) \tag{13}$$

- u_t :

$$(\phi_{u1} - \phi_{u2}) + \phi_{u2} u_t = \widetilde{r}_t^K \tag{14}$$

where $\widetilde{r}_t^K$ denotes the real rental rate of capital

$$\widetilde{r}_t^K \equiv \frac{r_t^K}{P_t}. \tag{15}$$

- I_t :

$$\begin{aligned} 1 \;=\; & \upsilon_t \mu_t \left[1 - \frac{\kappa}{2} \left(\frac{I_t}{I_{t-1}} - g_I \right)^2 - \kappa \left(\frac{I_t}{I_{t-1}} - g_I \right) \left(\frac{I_t}{I_{t-1}} \right) \right] \\ & + \beta E_t \upsilon_{t+1} \mu_{t+1} \frac{\Lambda_{t+1}}{\Lambda_t} \kappa \left(\frac{I_{t+1}}{I_t} - g_I \right) \left(\frac{I_{t+1}}{I_t} \right)^2 \end{aligned} \tag{16}$$

where υ_t is the marginal Tobin's Q, the Lagrange multiplier associated with the investment adjustment constraint, Υ_t, normalized by Λ_t.

- $\overline{K}_t$:

$$\upsilon_t = \beta E_t \left\{ \frac{\Lambda_{t+1}}{\Lambda_t} \left[(1-\delta) \upsilon_{t+1} + \widetilde{r}_{t+1}^K u_{t+1} - a(u_{t+1}) \right] \right\} \tag{17}$$

- Λ_t :

$$\frac{B_{t-1} + W_t N_t + (1 - N_t) b_t + Q_t u_t \overline{K}_{t-1} - T_t + D_t}{P_t} - a(u_t) \overline{K}_{t-1} = C_t + I_t + \frac{B_t}{\epsilon_{bt} r_t^B P_t} \tag{18}$$

where Λ_t denotes the multiplier on (9) and can be interpreted as the utility to the household of an additional unit of wealth at date t.

- Υ_t :

$$\overline{K}_t = (1-\delta) \overline{K}_{t-1} + \mu_t \left[1 - \frac{\kappa}{2} \left(\frac{I_t}{I_{t-1}} - g_I \right)^2 \right] I_t \tag{19}$$

where Υ_t denotes the multiplier on (6) and measures the utility to the household of an additional unit of physical capital at date t.

2.2 The representative finished goods-producing firm

During each period $t = 0, 1, 2, ...$, the representative finished goods-producing firm uses $Y_t(i)$ units of each intermediate good $i \in [0, 1]$, purchased at the nominal price $P_t(i)$, to manufacture Y_t units of the finished good according to the constant-returns-to-scale technology described by

$$\left[\int_0^1 Y_t(i)^{(\theta_t - 1)/\theta_t} di\right]^{\theta_t/(\theta_t - 1)} \geq Y_t, \tag{20}$$

where θ_t translates into a random shock to the markup of price over marginal cost. This markup shock follows the autoregressive process

$$\ln(\theta_t) = (1 - \rho_\theta)\ln(\theta) + \rho_\theta \ln(\theta_{t-1}) + \varepsilon_{\theta t}, \tag{21}$$

where $0 < \rho_\theta < 1$, $\theta > 1$, and $\varepsilon_{\theta t}$ is $i.i.d.N(0, \sigma_\theta^2)$.

Intermediate good i sells at the nominal price $P_t(i)$, while the finished good sells at the nominal price P_t. Given these prices, the finished goods-producing firm chooses Y_t and $Y_t(i)$ for all $i \in [0, 1]$ to maximize its profits

$$P_t Y_t - \int_0^1 P_t(i) Y_t(i) di, \tag{22}$$

subject to the constraint (20) for each $t = 0, 1, 2, ...$ The first-order conditions for this problem are (20) with equality and

$$Y_t(i) = \left[\frac{P_t(i)}{P_t}\right]^{-\theta_t} Y_t \tag{23}$$

for all $i \in [0, 1]$ and $t = 0, 1, 2, ...$

Competition in the market for the finished good drives the finished goods-producing firm's profits to zero in equilibrium. This zero-profit condition determines P_t as

$$P_t = \left[\int_0^1 P_t(i)^{1-\theta_t} di\right]^{1/(1-\theta_t)} \tag{24}$$

for all $t = 0, 1, 2, ...$

2.3 The representative intermediate goods-producing firm

Each intermediate goods-producing firm $i \in [0, 1]$ enters in period t with a stock of $N_{t-1}(i)$ employees carried from the previous period. At the beginning of period t, before production starts, $\rho N_{t-1}(i)$ olds jobs are destroyed, where ρ is the job destruction rate.[5] The pool of workers ρN_{t-1} who have lost their job at the beginning of period t start searching immediately and can possibly be hired in period t. $N_t(i)$ denotes the pool of employees taking part to

[5] The rate of match dissolution is exogenous. This is consistent with Hall (2005) and Shimer (2005)'s finding that recent business cycle fluctuations in the U.S. labor market mostly come from the job creation margin.

production at firm i in period t. The law of motion of the stock of productive workers at firm (i) is

$$N_t(i) = (1-\rho) N_{t-1}(i) + m_t(i). \tag{25}$$

$m_t(i)$ denotes the flow of new employees hired by firm i in period t, and is given by

$$m_t(i) = q_t V_t(i), \tag{26}$$

where $V_t(i)$ denotes vacancies posted by firm i in period t and q_t is the aggregate probability of filling a vacancy in period t. Workers hired in period t take part to period t production. Employment is therefore an *instantaneous* margin. However, each period some vacancies and job seekers remain unmatched. As a consequence, a firm-worker pair enjoys a joint surplus that motivates the existence of a long-run relationship between the two parties.

Aggregate employment $N_t = \int_0^1 N_t(i)\, di$ evolves over time according to

$$N_t = (1-\rho) N_{t-1} + m_t, \tag{27}$$

where $m_t = \int_0^1 m_t(i)\, di$ denotes aggregate matches in period t. Similarly, the aggregate vacancies is equal to $V_t = \int_0^1 V_t(i)\, di$. The pool of job seekers in period t, denoted by S_t, is given by

$$S_t = 1 - (1-\rho) N_{t-1}. \tag{28}$$

The matching process is described by the following aggregate CRS function

$$m_t = \zeta S_t^{\sigma} V_t^{1-\sigma}, \tag{29}$$

where ζ is a scale parameter that captures the efficiency of the matching technology. The probability q_t to fill a vacancy in period t is given by

$$q_t = \frac{m_t}{V_t}. \tag{30}$$

The probability, s_t, for a job seeker to find a job is

$$s_t = \frac{m_t}{S_t}. \tag{31}$$

Finally aggregate unemployment is defined by

$$U_t \equiv 1 - N_t. \tag{32}$$

During each period $t = 0, 1, 2, ...$, the representative intermediate goods-producing firm combines $N_t(i)$ homogeneous employees with $K_t(i)$ units of efficient capital to produce $Y_t(i)$ units of intermediate good i according to the constant-returns-to-scale technology described by

$$Y_t(i) = A_t^{1-\alpha} K_t(i)^{\alpha} N_t(i)^{1-\alpha}. \tag{33}$$

A_t is an aggregate labor-augmenting technology shock whose growth rate, $z_t \equiv A_t/A_{t-1}$, follows the exogenous stationary stochastic process

$$\ln(z_t) = (1-\rho_z)\ln(z) + \rho_z \ln(z_{t-1}) + \varepsilon_{zt}, \tag{34}$$

where $z > 1$ denotes the steady-state growth rate of the economy and ε_{zt} is $i.i.d.N(0, \sigma_z^2)$.

Following Yashiv (2006), intermediate goods-producing firms face convex hiring costs, measured in terms of the finished good and given by

$$\frac{\phi_N}{2}\left[\frac{q_t V_t(i)}{N_t(i)}\right]^2 Y_t, \tag{35}$$

where ϕ_N governs the magnitude of these costs.

Intermediate goods substitute imperfectly for one another in the production function of the representative finished goods-producing firm. Hence, each intermediate goods-producing firm $i \in [0,1]$ sells its output $Y_t(i)$ in a monopolistically competitive market, setting $P_t(i)$, the price of its own product, with the commitment of satisfying the demand for good i at that price. Firms take the nominal wage as given when maximizing the discounted value of expected future profits.

Each intermediate goods-producing firm faces costs of adjusting its nominal price between periods, measured in terms of the finished good and given by

$$\frac{\phi_P}{2}\left[\frac{P_t(i)}{\pi_{t-1}^{\varsigma}\pi^{1-\varsigma}P_{t-1}(i)} - 1\right]^2 Y_t. \tag{36}$$

ϕ_P governs the magnitude of the price adjustment cost. $\pi_t = \frac{P_t}{P_{t-1}}$ denotes the gross rate of inflation in period t. $\pi > 1$ denotes the steady-state gross rate of inflation and coincides with the central bank's target. The parameter $0 \leq \varsigma \leq 1$ governs the importance of backward-looking behavior in price setting.[6]

Each intermediate goods-producing firm faces quadratic wage-adjustment costs which are proportional to the size of its workforce and measured in terms of the finished good

$$\frac{\phi_W}{2}\left(\frac{W_t(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)} - 1\right)^2 N_t(i) Y_t, \tag{37}$$

where ϕ_W governs the magnitude of the wage adjustment cost. The parameter $0 \leq \varrho \leq 1$ governs the importance of backward-looking behavior in wage setting.

Adjustment costs on the hiring rate, price and wage changes make the intermediate goods-producing firm's problem dynamic. It chooses $K_t(i)$, $N_t(i)$, $V_t(i)$ and $Y_t(i)$ and $P_t(i)$ for all

[6] See Ireland (2007).

$t = 0, 1, 2, ...$to maximize its total market value, given by

$$E_t \sum_{s=0}^{\infty} \beta^s \Lambda_{t+s} \left[\frac{D_{t+s}(i)}{P_{t+s}} \right] \tag{38}$$

where $\beta^t \Lambda_t / P_t$ measures the marginal utility to the representative household of an additional dollar of profits during period t and where

$$\begin{aligned} D_t(i) &= P_t(i) Y_t(i) - W_t(i) N_t(i) - r_t^K K_t(i) - \frac{\phi_N}{2} \left(\frac{q_t V_t(i)}{N_t(i)} \right)^2 P_t Y_t \\ &\quad - \frac{\phi_P}{2} \left(\frac{P_t(i)}{\pi_{t-1}^{\varsigma} \pi^{1-\varsigma} P_{t-1}(i)} - 1 \right)^2 P_t Y_t \\ &\quad - \frac{\phi_W}{2} \left(\frac{W_t(i)}{z \pi_{t-1}^{\varrho} \pi^{1-\varrho} W_{t-1}(i)} - 1 \right)^2 N_t(i) P_t Y_t, \end{aligned} \tag{39}$$

subject to the constraints

$$Y_t(i) = \left[\frac{P_t(i)}{P_t} \right]^{-\theta_t} Y_t, \tag{40}$$

$$Y_t(i) \leq K_t(i)^{\alpha} \left[A_t N_t(i) \right]^{1-\alpha}, \tag{41}$$

$$N_t(i) = \chi N_{t-1}(i) + q_t V_t(i), \tag{42}$$

where $\chi \equiv 1 - \rho$ is the job survival rate.

The first-order conditions for this problem are

- $K_t(i)$:

$$\left(\frac{r_t^K}{P_t} \right) = \left(\frac{\Xi_t(i)}{\Lambda_t} \right) \alpha K_t(i)^{\alpha-1} \left(A_t N_t(i) \right)^{1-\alpha} \tag{43}$$

- $N_t(i)$:

$$\begin{aligned} \frac{\Psi_t(i)}{\Lambda_t} &= \xi_t(i)(1-\alpha) \frac{Y_t(i)}{N_t(i)} - \frac{W_t(i)}{P_t} + \phi_N \frac{Y_t}{N_t(i)} x_t(i)^2 \\ &\quad - \frac{\phi_W}{2} \left(\frac{W_t(i)}{z \pi_{t-1}^{\varrho} \pi^{1-\varrho} W_{t-1}(i)} - 1 \right)^2 Y_t + \beta \chi \frac{\Lambda_{t+1}}{\Lambda_t} \frac{\Psi_{t+1}(i)}{\Lambda_{t+1}} \end{aligned} \tag{44}$$

  where $x_t(i) \equiv \frac{q_t V_t(i)}{N_t(i)}$ is the hiring rate. This condition tells that the costs and benefits of hiring an additional worker must be equal.

- $V_t(i)$:

$$\frac{\Psi_t(i)}{\Lambda_t} = \phi_N \frac{Y_t}{N_t(i)} x_t(i) \tag{45}$$

- Vacancy posting condition:

$$\begin{aligned}\phi_N x_t(i)\left[1-x_t(i)\right] &= \xi_t(i)(1-\alpha)\frac{Y_t(i)}{Y_t}-\frac{W_t(i)N_t(i)}{P_tY_t} && (46)\\ &\quad -\frac{\phi_W}{2}\left(\frac{W_t(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)}-1\right)^2 N_t(i)\\ &\quad +\beta\chi\phi_N\frac{\Lambda_{t+1}}{\Lambda_t}\frac{N_t(i)}{N_{t+1}(i)}\frac{Y_{t+1}}{Y_t}x_{t+1}(i) && (47)\end{aligned}$$

- $P_t(i)$:

$$\begin{aligned}(1-\theta_t)\left(\frac{P_t(i)}{P_t}\right)^{-\theta_t} &= \phi_P\left(\frac{P_t(i)}{\pi_{t-1}^{\varsigma}\pi^{1-\varsigma}P_{t-1}(i)}-1\right)\left(\frac{P_t}{\pi_{t-1}^{\varsigma}\pi^{1-\varsigma}P_{t-1}(i)}\right) && (48)\\ &\quad -\theta_t\xi_t(i)\left(\frac{P_t(i)}{P_t}\right)^{-(1+\theta_t)}\\ &\quad -\beta\phi_P E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}\left(\frac{P_{t+1}(i)}{\pi_t^{\varsigma}\pi^{1-\varsigma}P_t(i)}-1\right)\left(\frac{P_{t+1}(i)}{\pi_t^{\varsigma}\pi^{1-\varsigma}P_t(i)}\right)\frac{Y_{t+1}}{Y_t}\frac{P_t}{P_t(i)}\right]\end{aligned}$$

- $\Psi_t(i)$:

$$N_t(i)=\chi N_{t-1}(i)+q_tV_t(i) \tag{49}$$

- $\Xi_t(i)$:

$$A_t^{1-\alpha}K_t(i)^{\alpha}N_t(i)^{1-\alpha}=\left(\frac{P_t(i)}{P_t}\right)^{-\theta_t}Y_t \tag{50}$$

The muliplier $\Psi_t(i)$ measures the value to firm i, expressed in utils, of an additional job in period t. The multiplier $\Xi_t(i)$ measures the value to firm i, expressed in utils, of an additional unit of output in period t. Hence, $\xi_t(i)=\Xi_t(i)/\Lambda_t$ represents firm i's real marginal cost in period t.

2.4 Wage setting

Unemployment benefits b_t are proportional to the value of the nominal wage along the balanced growth path, $W_{ss,t}$,

$$b_t=\tau W_{ss,t}, \tag{51}$$

where τ is the replacement ratio. The fact that hiring costs and unemployment benefits both share the common stochastic trend ensures that the unemployment rate is stationary.

Jobs and workers at a given intermediate goods-producing firm are homogeneous. $W_t(i)$ denotes the nominal wage paid for any job at firm i in period t. Each period t, the representative intermediate goods-producing firm bargains with each of its employees separately over $W_t(i)$. The nominal wage is determined through bilateral Nash bargaining,

$$W_t(i) = \arg\max \left[S_t(i)^{\eta_t} J_t(i)^{1-\eta_t} \right]. \tag{52}$$

$S_t(i)$ denotes the surplus of the representative worker at firm i while $J_t(i)$ is the surplus of firm i. Both $S_t(i)$ and $J_t(i)$ are expressed in real terms. η_t denotes the worker's bargaining power which evolves exogenously according to

$$\ln \eta_t = \left(1 - \rho_\eta\right) \ln \eta + \rho_\eta \ln \eta_{t-1} + \varepsilon_{\eta t}, \tag{53}$$

where $0 < \eta < 1$ and $\varepsilon_{\eta t}$ is $i.i.d.N\left(0, \sigma_\eta^2\right)$.

The worker's surplus in terms of final consumption goods is given by

$$S_t(i) = \frac{W_t(i)}{P_t} - \frac{b_t}{P_t} + \beta E_t \left[\chi\left(1 - s_{t+1}\right)\right] \left(\frac{\Lambda_{t+1}}{\Lambda_t}\right) S_{t+1}(i). \tag{54}$$

The surplus of firm i expressed in real terms is given by $J_t(i) = \frac{\Psi_t(i)}{\Lambda_t}$

$$\begin{aligned} J_t(i) &= \xi_t(i)(1-\alpha)\frac{Y_t(i)}{N_t(i)} - \frac{W_t(i)}{P_t} + \frac{\phi_N Y_t x_t(i)^2}{N_t(i)} \\ &\quad - \frac{\phi_W}{2}\left(\frac{W_t(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)} - 1\right)^2 Y_t + \beta\chi E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t} J_{t+1}(i)\right]. \end{aligned} \tag{55}$$

Nash bargaining requires that the equilibrium nominal wage $W_t(i)$ satisfies the following first-order condition

$$\eta_t J_t(i) \frac{\partial S_t(i)}{\partial W_t(i)} = -\left(1 - \eta_t\right) S_t(i) \frac{\partial J_t(i)}{\partial W_t(i)}, \tag{56}$$

where

$$\frac{\partial S_t(i)}{\partial W_t(i)} = \frac{1}{P_t}, \tag{57}$$

$$-\frac{\partial J_t(i)}{\partial W_t(i)} = \left\{ \begin{array}{c} \frac{1}{P_t} + \phi_W Y_t \left(\frac{1}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)}\right)\left(\frac{W_t(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)} - 1\right) \\ -\beta\chi\phi_W E_t\left[\frac{\Lambda_{t+1}Y_{t+1}}{\Lambda_t W_t(i)}\left(\frac{W_{t+1}(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)}\right)\left(\frac{W_{t+1}(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)} - 1\right)\right] \end{array} \right\}. \tag{58}$$

When $\phi_W = 0$, adjusting nominal wages is costless for the firm. In that case, the effects of a marginal increase in the nominal wage on the worker's surplus and on the firm's surplus have the same magnitude (with opposite signs):

$$\text{if } \phi_W = 0, \text{ then } \frac{\partial S_t(i)}{\partial W_t(i)} = -\frac{\partial J_t(i)}{\partial W_t(i)} = \frac{1}{P_t}. \tag{59}$$

In the absence of nominal wage-adjustment costs, Nash bargaining over the nominal wage implies the usual first-order condition

$$S_t(i) = \left(\frac{\eta_t}{1-\eta_t}\right) J_t(i). \tag{60}$$

Thus, as pointed out by Arsenau and Chugh (2008), Nash bargaining over the nominal wage when there are no nominal wage adjustment costs is equivalent to Nash bargaining over the real wage. The presence of nominal wage-adjustment costs (beared by the firm) affects the *effective* bargaining powers of the firm and the worker respectively. In the presence of nominal wage adjustment costs, the first-order condition from Nash bargaining is given by

$$\begin{aligned} S_t(i) &= \frac{\eta_t}{(1-\eta_t)} \frac{[\partial S_t(i)/\partial W_t(i)]}{[-\partial J_t(i)/\partial W_t(i)]} J_t(i), \\ S_t(i) &= \daleth_{it} J_t(i), \end{aligned} \tag{61}$$

where we have introduced the notation

$$\daleth_{it} \equiv \frac{\left(\frac{\eta_t}{1-\eta_t}\right)\left(\frac{\partial S_t(i)}{\partial W_t(i)}\right)}{\left(-\frac{\partial J_t(i)}{\partial W_t(i)}\right)}, \tag{62}$$

$$\daleth_{it} \equiv \frac{\left(\frac{\eta_t}{1-\eta_t}\right)\left(\frac{W_t}{P_t Y_t}\right)}{\left\{\begin{array}{c} \frac{W_t}{P_t Y_t} + \phi_W \left(\frac{W_t(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)} - 1\right)\left(\frac{W_t}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)}\right) \\ -\beta\chi\phi_W E_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}\left(\frac{W_{t+1}(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)} - 1\right)\left(\frac{W_{t+1}(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)}\right)\frac{W_t}{W_t(i)}\frac{Y_{t+1}}{Y_t}\right] \end{array}\right\}}.$$

Finally, the equation governing the dynamics of the real wage at firm i is given by

$$\begin{aligned} \frac{W_t(i)}{P_t} &= \left(\frac{\daleth_{it}}{1+\daleth_{it}}\right) \left[\begin{array}{l} \xi_t(i)(1-\alpha)\frac{Y_t(i)}{N_t(i)} + \frac{\phi_N Y_t x_t(i)^2}{N_t(i)} \\ -\frac{\phi_W}{2}\left(\frac{W_t(i)}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}(i)} - 1\right)^2 Y_t \\ +\beta\chi E_t\left(\frac{\Lambda_{t+1}}{\Lambda_t}\right)\left(\frac{\phi_N Y_{t+1} x_{t+1}(i)}{N_{t+1}(i)}\right) \end{array}\right] \\ &\quad + \frac{1}{(1+\daleth_{it})}\left[\frac{b_t}{P_t} - \beta\chi E_t \daleth_{it+1}(1-s_{t+1})\left(\frac{\Lambda_{t+1}}{\Lambda_t}\right)\left(\frac{\phi_N Y_{t+1} x_{t+1}(i)}{N_{t+1}(i)}\right)\right]. \end{aligned} \tag{63}$$

2.5 Government

The central bank adjusts the short-term nominal gross interest rate r_t^B by following a Taylor type rule

$$\ln\left(\frac{r_t^B}{r^B}\right) = \rho_r \ln\left(\frac{r_{t-1}^B}{r^B}\right) + (1-\rho_r)\left[\rho_\pi \ln\left(\frac{\pi_t}{\pi}\right) + \rho_y \ln\left(\frac{Y_t/Y_{t-1}}{z}\right)\right] + \ln\epsilon_{mpt}, \tag{64}$$

$$\ln\epsilon_{mpt} = \rho_{mp}\ln\epsilon_{mpt-1} + \varepsilon_{mpt}. \tag{65}$$

where $\pi_t = P_t/P_{t-1}$. The monetary policy shock ϵ_{mpt} follows an AR(1) process with $0 \leq \rho_{mp} < 1$ and $\varepsilon_{mpt} \sim i.i.d.N\left(0, \sigma_{mp}^2\right)$. The degree of interest-rate smoothing ρ_r and the reaction coefficients ρ_π, ρ_y are all positive.

The government budget constraint is of the form

$$P_tG_t + (1 - N_t)\, b_t = \left(\frac{B_t}{r_t^B} - B_{t-1}\right) + T_t, \tag{66}$$

where T_t denotes total nominal lump-sum transfers. Public spending is an exogenous time-varying fraction of GDP

$$G_t = \left(1 - \frac{1}{\epsilon_{gt}}\right) Y_t, \tag{67}$$

where ϵ_{gt} evolves according to

$$\ln \epsilon_{gt} = \left(1 - \rho_g\right) \ln \epsilon_g + \rho_g \ln \epsilon_{gt-1} + \varepsilon_{gt}, \tag{68}$$

with $\varepsilon_{gt} \sim i.i.d.N\left(0, \sigma_g^2\right)$.

2.6 Symmetric equilibrium

In a symmetric equilibrium, all intermediate goods-producing firms make identical decisions, so that $Y_t(i) = Y_t$, $P_t(i) = P_t$, $N_t(i) = N_t$, $V_t(i) = V_t$, $K_t(i) = K_t$ for all $i \in [0, 1]$ and $t = 0, 1, 2, \ldots$.. Moreover, workers are homogeneous and all workers at a given firm i receive the same nominal wage $W_t(i)$, so that $W_t(i) = W_t$ for all $i \in [0, 1]$ and $t = 0, 1, 2, \ldots$. The aggregate resource constraint is obtained by aggregating the household budget constraint over all intermediate sectors $i \in [0, 1]$,

$$\left[\frac{1}{\epsilon_{gt}} - \frac{\phi_N}{2} x_t^2 - \frac{\phi_P}{2}\left(\frac{\pi_t}{\pi_{t-1}^{\varsigma}\pi^{1-\varsigma}} - 1\right)^2 - \frac{\phi_W}{2}\left(\frac{W_t}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}} - 1\right)^2 N_t\right] Y_t = C_t + I_t + a(u_t)\, \overline{K}_{t-1}. \tag{69}$$

2.7 Model solution

Real output, consumption, investment, capital and wages share the stochastic trend induced by the unit root process for neutral technological progress. In the absence of shocks, the economy converges to a steady-state growth path in which all stationary variables are constant. I first rewrite the model in terms of stationary variables, and then loglinearize the transformed economy around its deterministic steady state. The approximate model can then be solved using standard methods.

3 Econometric strategy

3.1 Data

The estimation is based on quarterly U.S. data on seven key aggregate variables: the yearly growth rate of real output, the yearly growth rate of real consumption, the yearly growth rate of real investment, the yearly growth rate of real wages, the yearly inflation rate, the short-term nominal interest rate and the vacancy/unemployment ratio which summarizes the tightness of the labor market and plays an important role in the Mortensen-Pissarides model. The sample period runs from 1984:QI to 2006:QI. The appendix describes the dataset in details.

Two reasons motivate my choice of using the vacancy/unemployment ratio as an observable variable. First, in the model, labor adjusts exclusively along the extensive margin. Data on employment or unemployment seem therefore better suited than data on total hours. Second, unemployment and vacancies are very persistent and strongly negatively correlated (the Beveridge curve). By considering the vacancy/unemployment ratio, I exploit the Beveridge curve to remove the trend shared by unemployment and vacancies. Figure 1 shows the time series data, expressed in log-deviations from sample mean, used to estimate the model.

3.2 Calibrated parameters and estimation technique

Because of weak identification problems, I calibrate nine parameters prior to estimation. Table 1 summarizes the calibration. The quarterly depreciation rate δ is set equal to 0.025, a value commonly used in the literature. The capital share of output α is calibrated at 0.33. The elasticity of substitution between intermediate goods θ is set equal to 6, impliying a steady-state markup of 20 percents. The calibration of the vacancy filling rate q is just a normalization as q is not identified. I set the government spending/output ratio $G/Y = 0.20$. Finally, the steady-state values of the unemployment rate U, the rate of inflation π, the nominal interest rate r^B, and the growth rate of output z, are set equal to their respective sample averages.

I estimate the remaining 28 parameters using Bayesian techniques (see An and Schorfheide (2007)An and Schorfheide 2007). Prior distributions are standard and are summarized in Table 2.

4 Results

4.1 Parameter estimates

Table 2 reports some summary statistics of the posterior distributions of the parameters. Most parameter estimates are in line with the existing literature. The estimated degree of habit persistence in consumption is relatively low. As explained in Justiniano et al. (2010), a low degree of habit makes consumption and investment more coutercyclical in response to investment shocks, thereby preventing these disturbances to be a major source of macroeconomic fluctuations. This in turn prevent the The posterior median of the elasticity of the matching function to unemployment σ is equal to 0.30, consistent with the evidence provided by Blanchard and Diamond (1990) for the US. The posterior median of the job destruction rate ρ is equal to 0.163. This is value is very close to the one used by Andolfatto (1996). The posterior median and 95 percentile of the replacement rate τ are respectively 27% and 46%. This result suggests does not support the calibration advocated by Hagedorn and Manovskii (2008). Hiring costs account for roughly 50 basis point of output.

4.2 Model fit

Figure 2 plots the empirical spectral densities of the seven observable variables against the 90% posterior bands of the theoretical spectra. The model captures well the shape and magnitude of most empirical spectra. The model significantly overestimates the variance of consumption growth at low frequencies as well as the variance of the interest rate at business-cycle and high frequencies.

Figure 3 compares some empirical coherences with the posterior distribution of the corresponding theoretical coherences.[7] The model matches well the coherences between output growth and inflation, inflation and tightness, and output growth and wage growth. The model overpredicts the coherence between output growth and tightness at high frequencies. This finding suggests that allowing for variations in hours worked per worker may improve the specification of the model. The model fails to replicate the shape of the coherence between output growth and the interest rate and of the coherence between inflation and the interest rate.

4.3 Sources of business cycles

Figures 4 and 5 show the contribution of each shock to the theoretical spectral densities of output growth and the vacancy/unemployment ratio respectively. Neutral technology shocks and wage-markup shocks emerge as the main sources of business cycles. Figures 6 plot the impulse responses to the wage markup shock. This finding is in line with Smets and Wouters (2007), Chari et al. (2007) and Hall (1997).

At first glance, this result conflicts with the evidence provided by Justiniano et al. (2010) and Gertler et al. (2008) which both points towards investment-specific technology shocks as the main source of business cycles.[8] Indeed, my finding regarding the sources of business cycles is in accordance with Justiniano and Primiceri (2008*b*)'s result that the fall in the standard deviation of the investment shock is the main cause of the Great Moderation. Remember that, due to concerns about structural breaks related to the Great Moderation and changes in the conduct of monetary policy at the beginning of the eighties, my sample period starts only in 1985:Q1. Instead, Justiniano et al. (2010) and Gertler et al. (2008) consider longer sample periods which start in the 1954:Q3 and 1960:Q1 respectively.

4.4 Assessing the performance of the Fed's interest rate policy at stabilizing inflation and the unemployment gap

In the remaining of the paper I use the estimated DSGE model and data up to 2009:Q4 to back out the path of the unobserved unemployment gap with the Kalman smoother and to perform some counterfactuals experiments aiming at assessing the performance of the Fed's interest rate policy at stabilizing fluctuations in inflation and the unemployment gap. Figure 7 shows the time series data used to estimate the unemployment gap and perform the counterfactual experiments.

[7] The coherence decomposes the squared correlation between two variables X and Y, frequency by frequency.

[8] Importantly, notice that I measure output, consumption and investment as Justiniano et al. (2010) and Gertler et al. (2008). See Appendix 1.

4.4.1 Measuring the unemployment gap

Following Smets and Wouters (2007), Justiniano and Primiceri (2008*a*) and Sala et al. (2008) I compute the efficient equilibrium by removing nominal rigidities and turining off the two inefficient markup shocks. The efficient (or potential) rate of unemployment is thus defined as the unemployment rate under flexible prices and wages and no price-markup and wage-markup disturbances. Figure 8 compares the actual unemployment rate with the efficient rate of unemployment. Figure 9 also shows the unemployment trend extracted with the HP filter. The HP trend tracks closely movements in the actual unemployment rate and therefore exhibits large smooth swings. Instead the DSGE-consistent efficient rate is not smooth and is characterized by a much smaller variance.

I construct the unemployment gap as the log-deviation of the actual unemployment rate from the efficient rate. Similarly, the HP gap is the log-deviation of the actual rate from the HP trend. Figure 9 shows the DSGE unemployment gap and the HP gap. Shaded areas mark the NBER recessions. Not surprisingly, the DSGE gap is far more volatile than the HP gap. Interestingly however, both measures increase during recessions. Moreover, the turning points are essentially the same across the two measures.

4.4.2 Historical decompositions of the unemployment gap

One advantage of the model's gap over the traditional, purely statistical, HP gap is that it can be decomposed into its differents drivers at each point in time. Figure 10 shows the historical decomposition of the unemployment gap. We observe that the unemployment gap was negative and was falling throughout the second half of the nineties under the effects of negative bargaining power shocks. This evidence is consistent with the belief that globalization and the increased competition from developping countries during this period had forced US industries to improve their cost-competitiveness, prevented US workers to enjoy wage increases.

Another interesting observation is the fact that the three recessions (at the beginning of the nineties; at the beginning of 21st century; and since the ongoing global financial crisis) are periods during which monetary policy shocks are expansionary. Moreover, through the lens of the model, negative risk-premium shocks have played a major role in both the recession that started in 2001 and the one that started in 2008.

4.4.3 Assessing monetary policy shocks

When did large monetary policy shocks occur? What have been the consequences of these disturbances for fluctuations in inflation and the unemployment gap?

The top panel of figure 11 shows the time series of monetary policy shocks estimated by applying the Kalman smoother to the estimated DSGE model and the time series data shown in figure 7. Large monetary policy shocks did occur during the three recessions. To understand the extent to which these disturbances were desirable, the middle and bottom panels of figure 11 show the counterfactual path of inflation and the unemployment gap respectively in the absence of monetary policy shocks. We observe that monetary policy shocks did prevent deflation to happen in 2003-2005 and in 2008-2010.

4.4.4 Assessing the Fed's interest rate rule

Figure 12 shows the counterfactual path of the interest rate, inflation and the unemployment gap under three interest rate rule with no monetary policy shocks. The first rule is the one that was part of the estimated model and is therefore labelled "baseline". The second rule is the original Taylor rule with no interest-rate smoothing and where the output gap is the defined as the percent deviation of actual output from efficient output. The third rule is an inflation targeting rule with some degree of interest-rate smoothing,

$$Baseline \quad : \quad \ln\left(\frac{r_t^B}{r^B}\right) = \rho_r \ln\left(\frac{r_{t-1}^B}{r^B}\right) + (1-\rho_r)\left[\rho_\pi \ln\left(\frac{\pi_t}{\pi}\right) + \rho_y \ln\left(\frac{Y_t/Y_{t-1}}{z}\right)\right]; \tag{70}$$

$$Taylor \quad : \quad \ln\left(\frac{r_t^B}{r^B}\right) = \rho_\pi \ln\left(\frac{\pi_t}{\pi}\right) + \rho_y \ln\left(\frac{Y_t}{Y_t^{efficient}}\right), \quad \rho_\pi = 1.5, \quad \rho_y = 0.5; \tag{71}$$

$$IT \quad : \quad \ln\left(\frac{r_t^B}{r^B}\right) = \rho_r \ln\left(\frac{r_{t-1}^B}{r^B}\right) + (1-\rho_r)\left[\rho_\pi \ln\left(\frac{\pi_t}{\pi}\right)\right], \quad \rho_r = 0.8, \quad \rho_\pi = 1.75; \tag{72}$$

The Taylor rule does not feature any interest rate smoothing and therefore implies a path of the interest rate which much more volatile than the one predicted by the baseline rule and the inflation targeting rule. In the absence of any monetary policy shocks (i.e. unexpected deviations from the rule), the Taylor rule often predicts negative nominal interest rate and is associated with long period of deflation. However, the Taylor rule performs performs best in terms of unemployment gap stabilization.

The baseline rule and the inflation targeting rule imply very similar paths of the interest rate, inflation and the unemployment gap most of the time. Discrepancies between these two rules mainly occur during recessions when the estimated baseline rule (which describe the behavior of the Fed) performs better at stabilizing the unemployment-gap.

5 Concluding remarks

This paper estimates a medium-scale DSGE model with sticky prices and equilibrium unemployment on post-1984 quarterly US data. The model points toward technology and wage markup shocks as the main sources of business cycles. The model allows us to estimate the path of the efficient rate of unemployment and to construct time series for an economically meaningful measure of the unemployment gap.

The estimated unemployment gap increases during each of the three recessions dated by the NBER over the period 1985:Q1 to 2009:Q4. The historical decomposition shows that a series of negative bargaining power shocks was responsible for the negative unemployment gap throughout the second half of the nineties. This suggests that globalization and an associated increased competition from developping countries may have forced US workers to postpone wage increases during this period.

The three recessions emerge as periods during which monetary policy shocks were expansionary. A counterfactual experiment indeed demonstrates that, in the absence of monetary policy shocks, the US economy would have experienced periods of deflation in 2003-2005 and 2008-2010. Finally, the model assigns a major role to risk-premium shocks to explain the recession that started in 2001 and the one that started in 2008.

The structural analysis of the current recession presented in this paper obviously suffers from several shortcomings. The introduction into the model of a housing sector and of financial intermediaries would certainly improve the congruence of the model to the recent experience. Similarly, the model cannot be used to evaluate the non-conventional monetary policy that has been adopted by the Federal Reserve during the financial crisis. It would be interesting, for future research, to examine how the introduction of such features would affect our findings.

Appendix 1: Description of the database

The estimation is based on seven variables: per capita output, consumption and investment in real terms, real wages, labor market tightness (i.e. the ratio of vacancy over unemployment), inflation and the nominal short-term interest rate. I use quarterly U.S. data. The dataset spans a sample from 1984:QI to 2006:QI. All series are downloaded from the FRED database. Following Justiniano et al. (2010), I measure nominal consumption using data on nominal personal consumption expenditures of nondurables and services. Nominal investment corresponds to the sum of personal consumption expenditures of durables and gross private domestic investment. Nominal output is measured by nominal GDP. Per capita real GDP, consumption and investment are obtained by dividing the nominal series by the GDP deflator and population. Real wages corresponds to nominal compensation per hour in the non-farm business sector, divided by the GDP deflator. Consistently with the model, I measure population by the labor force which is itself defined as the sum of official unemployment and official employment. The vacancy rate is measured by the index of Help wanted advertising in newspapers divided by labor force. The unemployment rate is the ratio of official unemployment over labor force. Labor market tightness is the ratio of the vacancy rate over the unemployment rate. Year-on-year inflation corresponds to the year-on-year difference of the log of the GDP deflator. The nominal interest rateis measured by the effective Federal Funds rate.

Appendix 2: The symmetric equilibrium

In a symmetric equilibrium, $Y_t(i) = Y_t$, $P_t(i) = P_t$, $N_t(i) = N_t$, $V_t(i) = V_t$, $K_t(i) = K_t$, $W_t(i) = W_t$ for all $i \in [0,1]$ and $t = 0, 1, 2, ...$Defining the real wage $\widetilde{W_t} = W_t/P_t$, the gross rate of price inflation $\pi_t = P_t/P_{t-1}$, the system of equilibrium conditions becomes

1. Y_t

$$\begin{aligned}
&\left[\frac{1}{\epsilon_{gt}} - \frac{\phi_N}{2}x_t^2 - \frac{\phi_P}{2}\left(\frac{\pi_t}{\pi_{t-1}^{\varsigma}\pi^{1-\varsigma}} - 1\right)^2 - \frac{\phi_W}{2}\left(\frac{W_t}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}} - 1\right)^2 N_t\right] Y_t \\
= \;& C_t + I_t + \left[\phi_{u1}(u_t - 1) + \frac{\phi_{u2}}{2}(u_t - 1)^2\right]\overline{K}_{t-1}
\end{aligned}$$

2. K_t

$$K_t = u_t \overline{K}_{t-1}$$

3. $\overline{K}_t$

$$\overline{K}_t = (1-\delta)\overline{K}_{t-1} + \mu_t\left[1 - \frac{\phi_I}{2}\left(\frac{I_t}{I_{t-1}} - g_I\right)^2\right] I_t$$

4. μ_t

$$\ln\left(\mu_t\right) = \rho_\mu \ln\left(\mu_{t-1}\right) + \varepsilon_{\mu t}$$

5. ϵ_{bt}

$$\ln\left(\epsilon_{bt}\right) = \rho_b \ln\left(\epsilon_{bt-1}\right) + \varepsilon_{bt}$$

6. Λ_t

$$\Lambda_t = \beta \epsilon_{bt} r_t^B E_t \left(\frac{\Lambda_{t+1}}{\pi_{t+1}}\right)$$

7. C_t

$$\Lambda_t = \frac{1}{C_t - hC_{t-1}} - \beta h E_t \left(\frac{1}{C_{t+1} - hC_t}\right)$$

8. $\widetilde{r}_t^K = \frac{r_t^K}{P_t}$

$$\left(\phi_{u1} - \phi_{u2}\right) + \phi_{u2} u_t = \widetilde{r}_t^K$$

9. I_t

$$\begin{aligned} 1 &= \upsilon_t \mu_t \left[1 - \frac{\phi_I}{2}\left(\frac{I_t}{I_{t-1}} - g_I\right)^2 - \phi_I \left(\frac{I_t}{I_{t-1}} - g_I\right)\left(\frac{I_t}{I_{t-1}}\right)\right] \\ & \quad + \beta E_t \upsilon_{t+1} \mu_{t+1} \frac{\Lambda_{t+1}}{\Lambda_t} \phi_I \left(\frac{I_{t+1}}{I_t} - g_I\right)\left(\frac{I_{t+1}}{I_t}\right)^2 \end{aligned}$$

10. $\upsilon_t = \frac{\Upsilon_t}{\Lambda_t}$

$$\upsilon_t = \beta E_t \left\{\frac{\Lambda_{t+1}}{\Lambda_t}\left[\left(1 - \delta\right)\upsilon_{t+1} + \widetilde{r}_{t+1}^K u_{t+1} - a\left(u_{t+1}\right)\right]\right\}$$

11. θ_t

$$\ln\left(\theta_t\right) = \left(1 - \rho_\theta\right)\ln\left(\theta\right) + \rho_\theta \ln\left(\theta_{t-1}\right) + \varepsilon_{\theta t}$$

12. N_t

$$N_t = \chi N_{t-1} + q_t V_t$$

13. S_t

$$S_t = 1 - \chi N_{t-1}$$

14. U_t

$$U_t = 1 - N_t$$

15. VoS_t

$$VoS_t = \frac{V_t}{S_t}$$

16. $\Theta_t = \frac{V_t}{U_t}$

$$\Theta_t = \frac{V_t}{U_t}$$

17. V_t

$$x_t \equiv \frac{q_t V_t}{N_t}$$

18. q_t

$$q_t = \zeta \left[\frac{S_t}{V_t} \right]^{\sigma}$$

19. s_t

$$s_t = \zeta \left[\frac{V_t}{S_t} \right]^{1-\sigma}$$

20. x_t

$$\begin{aligned} \phi_N x_t (1 - x_t) &= \xi_t (1 - \alpha) - \widetilde{W}_t \frac{N_t}{Y_t} - \frac{\phi_W}{2} \left(\frac{W_t}{z \pi_{t-1}^{\varrho} \pi^{1-\varrho} W_{t-1}} - 1 \right)^2 N_t \\ &\quad + \beta \chi \phi_N E_t \left(\frac{\Lambda_{t+1}}{\Lambda_t} \right) \left(\frac{N_t}{N_{t+1}} \right) \left(\frac{Y_{t+1}}{Y_t} \right) x_{t+1} \end{aligned}$$

21. u_t

$$Y_t = A_t^{1-\alpha} {K_t}^{\alpha} {N_t}^{1-\alpha}$$

22. A_t

$$z_t = \frac{A_t}{A_{t-1}}$$

23. $z_t = \frac{A_t}{A_{t-1}}$

$$\ln(z_t) = (1-\rho_z)\ln(z) + \rho_z \ln(z_{t-1}) + \varepsilon_{zt}$$

24. $\xi_t = \frac{\Xi_t}{\Lambda_t}$

$$\widetilde{r}_t^K = \left(\alpha \frac{Y_t}{K_t}\right)\xi_t$$

25. π_t

$$\begin{aligned} 0 \quad = \quad & (1-\theta_t) + \theta_t \xi_t - \phi_P \left(\frac{\pi_t}{\pi_{t-1}^{\varsigma}\pi^{1-\varsigma}} - 1\right)\left(\frac{\pi_t}{\pi_{t-1}^{\varsigma}\pi^{1-\varsigma}}\right) \\ & + \beta \phi_P E_t \left[\left(\frac{\Lambda_{t+1}}{\Lambda_t}\right)\left(\frac{\pi_{t+1}}{\pi_t^{\varsigma}\pi^{1-\varsigma}} - 1\right)\left(\frac{\pi_{t+1}}{\pi_t^{\varsigma}\pi^{1-\varsigma}}\right)\left(\frac{Y_{t+1}}{Y_t}\right)\right] \end{aligned}$$

26. $\widetilde{b}_t = \frac{b_t}{P_t}$

$$\widetilde{b}_t = \tau \widetilde{W}_{ss,t}$$

27. $\widetilde{W}_t = \frac{W_t}{P_t}$

$$\begin{aligned} \widetilde{W}_t \quad = \quad & \left(\frac{\text{Ŋ}_t}{1+\text{Ŋ}_t}\right)\left[\begin{array}{c} \xi_t(1-\alpha)\frac{Y_t}{N_t} + \phi_N \frac{Y_t}{N_t} x_t^2 - \frac{\phi_W}{2}\left(\frac{W_t}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}} - 1\right)^2 Y_t \\ +\beta\chi\phi_N E_t \frac{\Lambda_{t+1}}{\Lambda_t}\frac{Y_{t+1}}{N_{t+1}} x_{t+1} \end{array}\right] \\ & + \frac{1}{(1+\text{Ŋ}_t)}\left[\widetilde{b}_t - \beta\chi\phi_N E_t \text{Ŋ}_{t+1}(1-s_{t+1})\frac{\Lambda_{t+1}}{\Lambda_t}\frac{Y_{t+1}}{N_{t+1}} x_{t+1}\right] \end{aligned}$$

28. Ŋ_t

$$\text{Ŋ}_t = \frac{\left(\frac{\eta_t}{1-\eta_t}\right)\left(\frac{\widetilde{W}_t}{Y_t}\right)}{\frac{\widetilde{W}_t}{Y_t} + \phi_W \left(\frac{W_t}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}} - 1\right)\left(\frac{W_t}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}}\right) - \beta\chi\phi_W E_t \left[\frac{\Lambda_{t+1}}{\Lambda_t}\left(\frac{W_{t+1}}{z\pi_t^{\varrho}\pi^{1-\varrho}W_t} - 1\right)\left(\frac{W_{t+1}}{z\pi_t^{\varrho}\pi^{1-\varrho}W_t}\right)\frac{Y_{t+1}}{Y_t}\right]}$$

29. η_t

$$\ln \eta_t = \left(1-\rho_\eta\right)\ln \eta + \rho_\eta \ln \eta_{t-1} + \varepsilon_{\eta t}$$

30. r_t^B

$$\ln\left(\frac{r_t^B}{r^B}\right) = \rho_r \ln\left(\frac{r_{t-1}^B}{r^B}\right) + (1-\rho_r)\left[\rho_\pi \ln\left(\frac{\pi_t}{\pi}\right) + \rho_y \ln\left(\frac{Y_t}{Y_{t-1}}\right)\right] + \ln \epsilon_{mpt}$$

31. ϵ_{rt}

$$\ln \epsilon_{mpt} = \rho_{mp} \ln \epsilon_{mpt-1} + \varepsilon_{mpt}$$

32. G_t

$$G_t = \left(1 - \frac{1}{\epsilon_{gt}}\right) Y_t$$

33. ϵ_{gt}

$$\ln \epsilon_{gt} = \left(1-\rho_g\right) \ln \epsilon_g + \rho_g \ln \epsilon_{gt-1} + \varepsilon_{gt}$$

34. gy_t

$$gy_t = Y_t / Y_{t-1}$$

35. gc_t

$$gc_t = C_t / C_{t-1}$$

36. gi_t

$$gi_t = I_t / I_{t-1}$$

37. gw_t

$$gw_t = \widetilde{W}_t / \widetilde{W}_{t-1}$$

These 37 equations determine equilibrium values for the 37 variables Y_t, K_t, $\overline{K}_t$, u_t, C_t, Λ_t, r_t^B, G_t, I_t, υ_t, $\widetilde{r}_t^K$, ξ_t, N_t, S_t, U_t, V_t, VoS_t, Θ_t, q_t, s_t, x_t, $\widetilde{W}_t$, $\text{\NG}_t$, $\widetilde{b}_t$, π_t, μ_t, ϵ_{bt}, A_t, z_t, θ_t, η_t, ϵ_{mpt}, ϵ_{gt}, gy_t, gc_t, gi_t, gw_t.

Appendix 3: The transformed stationary economy

Output, consumption, investment, capital and the real wage share the stochastic trend induced by the unit root process of neutral technological progress. I first rewrite the model in terms of stationary variables, and then loglinearize this transformed model economy around its steady state. This approximate model can then be solved using standard methods. The following variables are stationary and need not to be transformed: u_t, r_t^B, $\widetilde{r}_t^K$, $\upsilon_t = \frac{\Upsilon_t}{\Lambda_t}$, ξ_t, N_t, S_t, U_t, V_t, q_t, s_t, x_t, $\pi_t = \frac{P_t}{P_{t-1}}$, μ_t, ϵ_{bt}, z_t, θ_t, η_t, ϵ_{mpt}, ϵ_{gt} and Ŋ_t. I define the transformed variables $y_t = Y_t/A_t$, $k_t = K_t/A_t$, $\overline{k}_t = \overline{K}_t/A_t$, $c_t = C_t/A_t$, $\lambda_t = A_t\Lambda_t$, $i_t = I_t/A_t$, $\widetilde{w}_t = \widetilde{W}_t/A_t$, $\widetilde{\mathbf{b}}_t = \widetilde{b}_t/A_t$, $g_t = G_t/A_t$. The stationarized economy contains only 36 equations in 36 variables because the level of the non-stationary productivity shock A_t is not included.

1. $y_t = Y_t/A_t$

$$\left[\frac{1}{\epsilon_{gt}} - \frac{\phi_N}{2}x_t^2 - \frac{\phi_P}{2}\left(\frac{\pi_t}{\pi_{t-1}^{\varsigma}\pi^{1-\varsigma}} - 1\right)^2 - \frac{\phi_W}{2}\left(\frac{W_t}{z\pi_{t-1}^{\varrho}\pi^{1-\varrho}W_{t-1}} - 1\right)^2 N_t\right] y_t$$
$$= c_t + i_t + \left[\phi_{u1}(u_t - 1) + \frac{\phi_{u2}}{2}(u_t - 1)^2\right]\overline{k}_{t-1}\frac{1}{z_t}$$

2. $k_t = K_t/A_t$

$$k_t = u_t\overline{k}_{t-1}\frac{1}{z_t}$$

3. $\overline{k}_t = \overline{K}_t/A_t$

$$\overline{k}_t = (1-\delta)\,\overline{k}_{t-1}\frac{1}{z_t} + \mu_t\left[1 - \frac{\phi_I}{2}\left(\frac{i_t}{i_{t-1}}z_t - g_I\right)^2\right] i_t$$

4. μ_t

$$\ln(\mu_t) = \rho_\mu \ln(\mu_{t-1}) + \varepsilon_{\mu t}$$

5. ϵ_{bt}

$$\ln(\epsilon_{bt}) = \rho_b \ln(\epsilon_{bt-1}) + \varepsilon_{bt}$$

6. $\lambda_t = A_t\Lambda_t$

$$\lambda_t = \beta\epsilon_{bt}r_t^B E_t\left(\frac{\lambda_{t+1}}{\pi_{t+1}}\frac{1}{z_{t+1}}\right)$$

7. $c_t = C_t/A_t$

$$\lambda_t = \frac{z_t}{z_t c_t - hc_{t-1}} - \beta h E_t\left(\frac{1}{c_{t+1}z_{t+1} - hc_t}\right)$$

8. $\widetilde{r}_t^K = \frac{r_t^K}{P_t}$

$$(\phi_{u1} - \phi_{u2}) + \phi_{u2} u_t = \widetilde{r}_t^K$$

9. $i_t = I_t / A_t$

$$\begin{aligned} 1 &= \upsilon_t \mu_t \left[1 - \frac{\phi_I}{2} \left(\frac{i_t}{i_{t-1}} z_t - g_I \right)^2 - \phi_I \left(\frac{i_t}{i_{t-1}} z_t - g_I \right) \left(\frac{i_t}{i_{t-1}} z_t \right) \right] \\ &\quad + \beta E_t \upsilon_{t+1} \mu_{t+1} \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{z_{t+1}} \phi_I \left(\frac{i_{t+1}}{i_t} z_{t+1} - g_I \right) \left(\frac{i_{t+1}}{i_t} z_{t+1} \right)^2 \end{aligned}$$

10. $\upsilon_t = \frac{\Upsilon_t}{\Lambda_t}$

$$\upsilon_t = \beta E_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \frac{1}{z_{t+1}} \left[(1-\delta) \upsilon_{t+1} + \widetilde{r}_{t+1}^K u_{t+1} - \phi_{u1} (u_{t+1} - 1) - \frac{\phi_{u2}}{2} (u_{t+1} - 1)^2 \right] \right\}$$

11. u_t

$$y_t = k_t^\alpha N_t^{1-\alpha}$$

12. $z_t = \frac{A_t}{A_{t-1}}$

$$\ln(z_t) = (1 - \rho_z) \ln(z) + \rho_z \ln(z_{t-1}) + \varepsilon_{zt}$$

13. $\xi_t \equiv \frac{\Xi_t}{\Lambda_t}$

$$\widetilde{r}_t^K = \alpha \frac{y_t}{k_t} \xi_t$$

14. N_t

$$N_t = \chi N_{t-1} + q_t V_t$$

15. S_t

$$S_t = 1 - \chi N_{t-1}$$

16. U_t

$$U_t = 1 - N_t$$

17. VoS_t

$$VoS_t = \frac{V_t}{S_t}$$

18. $\Theta_t = \frac{V_t}{U_t}$

$$\Theta_t = \frac{V_t}{U_t}$$

19. q_t

$$q_t = \zeta \left[\frac{S_t}{V_t}\right]^{\sigma}$$

20. s_t

$$s_t = \zeta \left[\frac{V_t}{S_t}\right]^{1-\sigma}$$

21. V_t

$$x_t \equiv \frac{q_t V_t}{N_t}$$

22. x_t

$$\begin{aligned} \phi_N x_t (1 - x_t) &= \xi_t (1-\alpha) - \widetilde{w}_t \frac{N_t}{y_t} - \frac{\phi_W}{2} \left(\frac{W_t}{z \pi_{t-1}^{\varrho} \pi^{1-\varrho} W_{t-1}} - 1 \right)^2 N_t \\ &+ \beta \chi \phi_N E_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{N_t}{N_{t+1}} \frac{y_{t+1}}{y_t} x_{t+1} \right) \end{aligned}$$

23. θ_t

$$\ln(\theta_t) = (1-\rho_\theta) \ln(\theta) + \rho_\theta \ln(\theta_{t-1}) + \varepsilon_{\theta t}$$

24. $\pi_t = \frac{P_t}{P_{t-1}}$

$$\begin{aligned} 0 &= (1-\theta_t) + \theta_t \xi_t - \phi_P \left(\frac{\pi_t}{\pi_{t-1}^{\varsigma} \pi^{1-\varsigma}} - 1 \right) \left(\frac{\pi_t}{\pi_{t-1}^{\varsigma} \pi^{1-\varsigma}} \right) \\ &+ \beta \phi_P E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \left(\frac{\pi_{t+1}}{\pi_t^{\varsigma} \pi^{1-\varsigma}} - 1 \right) \left(\frac{\pi_{t+1}}{\pi_t^{\varsigma} \pi^{1-\varsigma}} \right) \frac{y_{t+1}}{y_t} \right] \end{aligned}$$

25. $\widetilde{\mathbf{b}}_t = \widetilde{b}_t / A_t$

$$\widetilde{\mathbf{b}}_t = \widetilde{\mathbf{b}} = \tau \widetilde{w}$$

26. $\widetilde{w}_t = \widetilde{W}_t / A_t$

$$
\begin{aligned}
\widetilde{w}_t \quad = \quad & \left(\frac{\text{Ŋ}_t}{1+\text{Ŋ}_t}\right) \left[\begin{array}{c} \xi_t \left(1-\alpha\right) \frac{y_t}{N_t} + \phi_N \frac{y_t}{N_t} x_t^2 - \frac{\phi_W}{2} \left(\frac{W_t}{z \pi_{t-1}^{\varrho} \pi^{1-\varrho} W_{t-1}} - 1 \right)^2 y_t \\ + \beta \chi \phi_N E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{y_{t+1}}{N_{t+1}} x_{t+1} \end{array} \right] \\
& + \frac{1}{\left(1+\text{Ŋ}_t\right)} \left[\widetilde{\mathbf{b}} - \beta \chi \phi_N E_t \text{Ŋ}_{t+1} \left(1 - s_{t+1}\right) \frac{\lambda_{t+1}}{\lambda_t} \frac{y_{t+1}}{N_{t+1}} x_{t+1} \right]
\end{aligned}
$$

27. Ŋ_t

$$
\text{Ŋ}_t = \frac{\left(\frac{\eta_t}{1-\eta_t}\right) \frac{\widetilde{w}_t}{y_t}}{\frac{\widetilde{w}_t}{y_t} + \phi_W \left(\frac{W_t}{z \pi_{t-1}^{\varrho} \pi^{1-\varrho} W_{t-1}} - 1 \right) \left(\frac{W_t}{z \pi_{t-1}^{\varrho} \pi^{1-\varrho} W_{t-1}} \right) - \beta \chi \phi_W E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \left(\frac{W_{t+1}}{z \pi_t^{\varrho} \pi^{1-\varrho} W_t} - 1 \right) \left(\frac{W_{t+1}}{z \pi_t^{\varrho} \pi^{1-\varrho} W_t} \right) \frac{y_{t+1}}{y_t} \right]}
$$

28. η_t

$$
\ln \eta_t = \left(1 - \rho_\eta\right) \ln \eta + \rho_\eta \ln \eta_{t-1} + \varepsilon_{\eta t}
$$

29. r_t^B

$$
\ln \left(\frac{r_t^B}{r^B} \right) = \rho_r \ln \left(\frac{r_{t-1}^B}{r^B} \right) + (1 - \rho_r) \left[\rho_\pi \ln \left(\frac{\pi_t}{\pi} \right) + \rho_y \ln \left(\frac{y_t}{y_{t-1}} z_t \right) \right] + \ln \epsilon_{mpt}
$$

30. ϵ_{rt}

$$
\ln \epsilon_{mpt} = \rho_{mp} \ln \epsilon_{mpt-1} + \varepsilon_{mpt}
$$

31. $g_t = G_t / A_t$

$$
g_t = \left(1 - \frac{1}{\epsilon_{gt}}\right) y_t
$$

32. ϵ_{gt}

$$
\ln \epsilon_{gt} = \left(1 - \rho_g\right) \ln \epsilon_g + \rho_g \ln \epsilon_{gt-1} + \varepsilon_{gt}
$$

33. $gy_t = Y_t / Y_{t-1}$

$$
gy_t = \frac{y_t}{y_{t-1}} z_t
$$

34. $gc_t = C_t / C_{t-1}$

$$
gc_t = \left(\frac{c_t}{c_{t-1}} \right) z_t
$$

35. $gi_t = I_t / I_{t-1}$

$$gi_t = \left(\frac{i_t}{i_{t-1}} \right) z_t$$

36. $gw_t = \widetilde{W}_t / \widetilde{W}_{t-1}$

$$gw_t = \left(\frac{\widetilde{w}_t}{\widetilde{w}_{t-1}} \right) z_t$$

Appendix 4: The steady state of the transformed stationary economy

In the absence of shocks, the economy converges to a steady-state growth path in which all stationary variables are constant: for all t, $y_t = y$, $k_t = k$, $\overline{k}_t = \overline{k}$, $u_t = u = 1$, $\lambda_t = \lambda$, $\upsilon_t = \upsilon$, $\xi_t = \xi$, $c_t = c$, $\widetilde{r}_t^K = \widetilde{r}^K$, $i_t = i$, $g_t = g$, $N_t = N$, $S_t = S$, $U_t = U$, $V_t = V$, $x_t = x$, $q_t = q$, $s_t = s$, $\text{Ŋ}_t = \text{Ŋ}$, $\widetilde{w}_t = \widetilde{w}$, $\widetilde{\mathbf{b}} = \widetilde{\mathbf{b}}$, $r_t^B = r^B$, $\pi_t = \pi$, $\mu_t = \mu = 1$, $\epsilon_{bt} = \epsilon_b = 1$, $z_t = z$, $\theta_t = \theta$, $\eta_t = \eta$, $\epsilon_{gt} = \epsilon_g$, $\epsilon_{rt} = \epsilon_r$, $g_{yt} = g_{ct} = g_{It} = g_{At} = z$, $cyr_t = cyr$, $iyr_t = iyr$, $\Theta_t = \Theta$. Notice that the steady-state values μ, u and ϵ_b are normalized to 1.

1. μ_t

$$\ln \mu = 0 \Rightarrow \mu = 1$$

2. ϵ_{bt}

$$\ln \epsilon_b = 0 \Rightarrow \epsilon_b = 1$$

3. u_t

$$u = 1$$

4. z_t

z : calibrated at sample mean of gross quarterly growth rate of per-capita real output

5. gy_t

$$gy = z$$

6. gc_t

$$gc = z$$

7. gi_t

$$gi = z$$

8. gw_t

$$gw = z$$

9. g_t

$$\frac{g}{y} = \left(1 - \frac{1}{\epsilon_g}\right) := 0.20 \text{ (calibrated)}$$

10. ϵ_{gt}

$$\left(\frac{1}{\epsilon_g} - \frac{\phi_N}{2}x^2\right) y = c + i$$

11. k_t

$$zk = \overline{k}$$

12. $\overline{k}_t$

$$(z - 1 + \delta)\,\overline{k} = zi$$

13. λ_t

$$\beta = \frac{\pi z}{r^B}$$

14. c_t

$$\lambda c = \frac{z - \beta h}{z - h}$$

15. $\widetilde{r}_t^K$

$$\phi_{u1} = \widetilde{r}^K$$

16. i_t

$$1 = \upsilon$$

17. υ_t

$$\frac{z}{\beta} = 1 - \delta + \widetilde{r}^K$$

18. N_t

$$\rho N = qV \quad \text{where} \quad \rho \equiv 1 - \chi$$

19. S_t

$$S = 1 - \chi N$$

20. U_t

$$U : \text{calibrated at sample mean of unemployment rate}$$

21. VoS_t

$$VoS = \frac{V}{S}$$

22. $\Theta_t = \frac{V_t}{U_t}$

$$\Theta = \frac{V}{U}$$

23. q_t

$$q = \zeta \left(\frac{S}{V}\right)^{\sigma} := 0.7 \text{ (calibrated)}$$

24. s_t

$$s = \zeta \left(\frac{V}{S}\right)^{1-\sigma}$$

25. y_t

$$y = k^{\alpha} N^{1-\alpha}$$

26. ξ_t

$$\widetilde{r}^K = \alpha \frac{y}{k} \xi$$

27. V_t

$$x = \frac{qV}{N}$$

28. x_t

$$(1 - x - \beta\chi)\,\phi_N x = \xi\,(1 - \alpha) - \frac{\widetilde{w}N}{y}$$

29. θ_t

$$\xi = \frac{\theta - 1}{\theta}$$

30. π_t

π : calibrated at sample mean of gross quarterly growth rate GDP deflator

31. $\widetilde{\mathbf{b}}_t$

$$\widetilde{\mathbf{b}} = \tau\widetilde{w}$$

32. $\widetilde{w}_t$

$$\begin{aligned} \left[\frac{1 - (1 - \eta)\,\tau}{\eta}\right]\frac{\widetilde{w}N}{y} &= \xi\,(1 - \alpha) + \phi_N x^2 + \beta\chi\phi_N x s \\ \frac{1 - (1 - \eta)\,\tau}{\eta} &= \frac{[\xi\,(1 - \alpha) + \phi_N x^2 + \beta\chi\phi_N x s]}{\frac{\widetilde{w}N}{y}} \end{aligned}$$

33. Ŋ$_t$

$$\text{Ŋ} = \frac{\eta}{1 - \eta}$$

34. η_t

$$\eta = ?$$

35. ϵ_{rt}

$$\epsilon_{mp} = 1$$

36. r_t^B

r^B : calibrated at sample mean of gross quarterly nominal rate of interest

37. $\widetilde{r}_t^B$

$$\widetilde{r}^B = \frac{r^B}{\pi}$$

38. π_t^w

$$\pi^w = z\pi$$

Appendix 5: The log-linearized model

1. y_t

$$\left(\frac{1}{\epsilon_g} - \frac{\phi_N}{2}x^2\right)\widehat{y}_t = \frac{c}{y}\widehat{c}_t + \frac{i}{y}\widehat{i}_t + \left(\phi_{u1}\frac{k}{y}\right)\widehat{u}_t + \left(\phi_N x^2\right)\widehat{x}_t + \frac{1}{\epsilon_g}\widehat{\epsilon}_{gt}$$

2. k_t

$$\widehat{z}_t + \widehat{k}_t = \widehat{u}_t + \widehat{\overline{k}}_{t-1}$$

3. $\overline{k}_t$

$$z\widehat{\overline{k}}_t = (1-\delta)\left(\widehat{\overline{k}}_{t-1} - \widehat{z}_t\right) + (z-1+\delta)\left(\widehat{\mu}_t + \widehat{i}_t\right)$$

4. λ_t

$$\widehat{\lambda}_t = \widehat{\epsilon}_{bt} + \widehat{r}_t^B + \widehat{\lambda}_{t+1} - \widehat{\pi}_{t+1} - \widehat{z}_{t+1}$$

5. c_t

$$\begin{aligned}\widehat{\lambda}_t \;\; = \;\; & \frac{\beta hz}{(z-\beta h)(z-h)}\widehat{c}_{t+1} - \frac{z^2+\beta h^2}{(z-\beta h)(z-h)}\widehat{c}_t + \frac{hz}{(z-\beta h)(z-h)}\widehat{c}_{t-1} \\ & + \frac{\beta hz}{(z-\beta h)(z-h)}\widehat{z}_{t+1} - \frac{hz}{(z-\beta h)(z-h)}\widehat{z}_t\end{aligned}$$

6. $\widetilde{r}_t^K$

$$\widehat{\widetilde{r}}_t^K = \left(\frac{\phi_{u2}}{\phi_{u1}}\right)\widehat{u}_t$$

7. i_t

$$\widehat{\upsilon}_t = \left(\phi_I z^2\right)\left(\widehat{i}_t - \widehat{i}_{t-1} + \widehat{z}_t\right) - \widehat{\mu}_t - \left(\beta\phi_I z^2\right)\left(\widehat{i}_{t+1} - \widehat{i}_t + \widehat{z}_{t+1}\right)$$

8. υ_t

$$\widehat{\upsilon}_t = \widehat{\lambda}_{t+1} - \widehat{\lambda}_t - \widehat{z}_{t+1} + \left[(1-\delta)\,\beta z^{-1}\right]\widehat{\upsilon}_{t+1} + \left(\beta z^{-1}\widetilde{r}^K\right)\widehat{\widetilde{r}}^K_{t+1}$$

9. u_t

$$\widehat{y}_t = \alpha\widehat{k}_t + (1-\alpha)\,\widehat{N}_t$$

10. ξ_t

$$\widehat{\widetilde{r}}^K_t = \widehat{\xi}_t + \widehat{y}_t - \widehat{k}_t$$

11. N_t

$$\widehat{N}_t = \chi\widehat{N}_{t-1} + x\left(\widehat{q}_t + \widehat{V}_t\right)$$

12. S_t

$$\widehat{S}_t = -\left(\frac{\chi N}{S}\right)\widehat{N}_{t-1}$$

13. U_t

$$\widehat{U}_t = -\frac{N}{U}\widehat{N}_t$$

14. VoS_t

$$\widehat{VoS}_t = \widehat{V}_t - \widehat{S}_t$$

15. Θ_t

$$\widehat{\Theta}_t = \widehat{V}_t - \widehat{U}_t$$

16. q_t

$$\widehat{q}_t = -\sigma\widehat{VoS}_t$$

17. s_t

$$\widehat{s}_t = (1-\sigma)\,\widehat{VoS}_t$$

18. V_t

$$\widehat{x}_t \equiv \widehat{q}_t + \widehat{V}_t - \widehat{N}_t$$

19. x_t

$$\begin{aligned} \widehat{x}_t &= \left[\frac{(1-\alpha)\,\xi}{\phi_N x\,(1-2x)}\right]\widehat{\xi}_t - \left[\frac{1}{\phi_N x\,(1-2x)}\frac{\widetilde{w}N}{y}\right]\left(\widehat{\widetilde{w}}_t + \widehat{N}_t - \widehat{y}_t\right) \\ &\quad + \left[\frac{\beta\chi}{1-2x}\right]\left(\widehat{\lambda}_{t+1} - \widehat{\lambda}_t + \widehat{N}_t - \widehat{N}_{t+1} + \widehat{y}_{t+1} - \widehat{y}_t + \widehat{x}_{t+1}\right) \end{aligned}$$

20. π_t

$$\widehat{\pi}_t = \left(\frac{\varsigma}{1+\beta\varsigma}\right)\widehat{\pi}_{t-1} + \left(\frac{\beta}{1+\beta\varsigma}\right)\widehat{\pi}_{t+1} + \left(\frac{1}{1+\beta\varsigma}\right)\left(\frac{\theta-1}{\phi_P}\right)\widehat{\xi}_t - \left(\frac{1}{1+\beta\varsigma}\right)\left(\frac{1}{\phi_P}\right)\widehat{\theta}_t$$

21. $\widetilde{\mathbf{b}}_t = \widetilde{\mathbf{b}} = \tau\widetilde{w}$

$$\widehat{\widetilde{\mathbf{b}}}_t = 0$$

22. $\widetilde{w}_t$

$$\begin{aligned} \left(\frac{1}{\eta}\frac{\widetilde{w}N}{y}\right)\widehat{\widetilde{w}}_t &= [(1-\alpha)\,\xi]\,\widehat{\xi}_t + \left[(1-\alpha)\,\xi + \phi_N x^2\right]\left(\widehat{y}_t - \widehat{N}_t\right) + \left(2\phi_N x^2\right)\widehat{x}_t \\ &\quad - \left[\frac{\widetilde{w}N}{y} - (1-\alpha)\,\xi - \phi_N x^2 - \beta\chi\phi_N x\right]\widehat{\text{Ŋ}}_t \\ &\quad + (\beta\chi\phi_N x)\left[s\left(\widehat{\lambda}_{t+1} - \widehat{\lambda}_t + \widehat{y}_{t+1} - \widehat{N}_{t+1} + \widehat{x}_{t+1} + \widehat{s}_{t+1}\right) - (1-s)\,\widehat{\text{Ŋ}}_{t+1}\right] \end{aligned}$$

23. Ŋ_t

$$\widehat{\text{Ŋ}}_t = \left(\frac{1}{1-\eta}\right)\widehat{\eta}_t + \phi_W\left(\frac{y}{\widetilde{w}}\right)\left[\beta\chi\left(\widehat{z}_{t+1} + \widehat{\pi}_{t+1} + \widehat{\widetilde{w}}_{t+1} - \widehat{\widetilde{w}}_t - \varrho\widehat{\pi}_t\right) - \left(\widehat{z}_t + \widehat{\pi}_t + \widehat{\widetilde{w}}_t - \widehat{\widetilde{w}}_{t-1} - \varrho\widehat{\pi}_{t-1}\right)\right]$$

24. r_t^B

$$\widehat{r}_t^B = \rho_r\widehat{r}_{t-1}^B + (1-\rho_r)\left[\rho_\pi\widehat{\pi}_t + \rho_y\left(\widehat{y}_t - \widehat{y}_{t-1} + \widehat{z}_t\right)\right] + \widehat{\epsilon}_{mpt}$$

25. $g_t = G_t/A_t$

$$\widehat{g}_t = \widehat{y}_t + \left(\frac{y}{g} - 1\right)\widehat{\epsilon}_{gt}$$

26. $gy_t = Y_t/Y_{t-1}$

$$\widehat{gy}_t = \widehat{y}_t - \widehat{y}_{t-1} + \widehat{z}_t$$

27. $gc_t = C_t/C_{t-1}$

$$\widehat{gc}_t = \widehat{c}_t - \widehat{c}_{t-1} + \widehat{z}_t$$

28. $gi_t = I_t/I_{t-1}$

$$\widehat{gi}_t = \widehat{i}_t - \widehat{i}_{t-1} + \widehat{z}_t$$

29. $gw_t = \widetilde{W}_t/\widetilde{W}_{t-1}$

$$\widehat{gw}_t = \widehat{\widetilde{w}}_t - \widehat{\widetilde{w}}_{t-1} + \widehat{z}_t$$

30. μ_t

$$\widehat{\mu}_t = \rho_\mu \widehat{\mu}_{t-1} + \varepsilon_{\mu t}$$

31. ϵ_{bt}

$$\widehat{\epsilon}_{bt} = \rho_b \widehat{\epsilon}_{bt-1} + \varepsilon_{bt}$$

32. z_t

$$\widehat{z}_t = \rho_z \widehat{z}_{t-1} + \varepsilon_{zt}$$

33. θ_t

$$\widehat{\theta}_t = \rho_\theta \widehat{\theta}_{t-1} + \varepsilon_{\theta t}$$

34. η_t

$$\widehat{\eta}_t = \rho_\eta \widehat{\eta}_{t-1} + \varepsilon_{\eta t}$$

35. ϵ_{gt}

$$\widehat{\epsilon}_{gt} = \rho_g \widehat{\epsilon}_{gt-1} + \varepsilon_{gt}$$

36. ϵ_{rt}

$$\widehat{\epsilon}_{mpt} = \rho_{mp}\widehat{\epsilon}_{mpt-1} + \varepsilon_{mpt}$$

Appendix 6: Rescaling two shocks prior to estimation

Two disturbances are normalized prior to estimation: the price-markup shock $\widehat{\theta}_t$ and the wage-markup shock $\widehat{\eta}_t$. The 2 rescaled disturbances which enter into the estimated model are

$$\begin{aligned}
\widehat{\theta}_t^* &= \left[\frac{1}{(1+\beta\varsigma)\,\phi_P}\right]\widehat{\theta}_t, \\
\widehat{\theta}_t^* &= \rho_{\theta^*}\widehat{\theta}_{t-1}^* - \varepsilon_{\theta^* t}, \\
\rho_{\theta^*} &= \rho_\theta, \\
\varepsilon_{\theta^* t} &\sim i.i.d.N\left(0, \sigma_{\theta^*}^2\right), \\
\sigma_{\theta^*} &= \left[\frac{1}{(1+\beta\varsigma)\,\phi_P}\right]\sigma_\theta,
\end{aligned}$$

$$\begin{aligned}
\widehat{\eta}_t^* &= \left(\frac{1}{1-\eta}\right)\widehat{\eta}_t, \\
\widehat{\eta}_t^* &= \rho_{\eta^*}\widehat{\eta}_{t-1}^* + \varepsilon_{\eta^* t}, \\
\rho_{\eta^*} &= \rho_\eta, \\
\varepsilon_{\eta^* t} &\sim i.i.d.N\left(0, \sigma_{\eta^*}^2\right), \\
\sigma_{\eta^*} &= \left(\frac{1}{1-\eta}\right)\sigma_\eta.
\end{aligned}$$

The two rescaled disturbances enter with a unit coefficient in the following two equations respectively:

1. π_t

$$0 = \widehat{\pi}_t - \left(\frac{\varsigma}{1+\beta\varsigma}\right)\widehat{\pi}_{t-1} - \left(\frac{\beta}{1+\beta\varsigma}\right)\widehat{\pi}_{t+1} - \left(\frac{1}{1+\beta\varsigma}\right)\left(\frac{\theta-1}{\phi_P}\right)\widehat{\xi}_t + \widehat{\theta}_t^*,$$

2. Ŋ_t

$$\begin{aligned}
0 \;=\;& \widehat{\text{Ŋ}}_t - \widehat{\eta}_t^* - \left(\beta\chi\phi_W\frac{y}{\widetilde{w}}\right)\widehat{z}_{t+1} - \left(\beta\chi\phi_W\frac{y}{\widetilde{w}}\right)\widehat{\pi}_{t+1} - \left(\beta\chi\phi_W\frac{y}{\widetilde{w}}\right)\widehat{\widetilde{w}}_{t+1} + \left[\left(\phi_W\frac{y}{\widetilde{w}}\right)(1+\beta\chi)\right]\widehat{\widetilde{w}}_t \\
&+ \left[\left(\phi_W\frac{y}{\widetilde{w}}\right)(1+\beta\chi\varrho)\right]\widehat{\pi}_t + \left(\phi_W\frac{y}{\widetilde{w}}\right)\widehat{z}_t - \left(\phi_W\frac{y}{\widetilde{w}}\right)\widehat{\widetilde{w}}_{t-1} - \left(\phi_W\frac{y}{\widetilde{w}}\right)\varrho\widehat{\pi}_{t-1}.
\end{aligned}$$

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Table 1: Calibrated parameters

Capital depreciation rate	δ	0.0250
Capital share	α	0.33
Elasticity of substitution btw goods	θ	6.00
Probability to fill a vacancy within a quarter	q	0.7000
Exogenous spending/output ratio	g/y	0.2000
Unemployment rate	U	0.0575
Quarterly growth rate	z	1.0044
Quarterly inflation rate	π	1.0062
Quarterly nominal interest rate	r^B	1.0129

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Table 2: Prior and posterior distributions of structural parameters

		Prior	Posterior distributions			
		distribution	Median	Std dev	5%	95%
Job destruction rate	ρ	Normal (0.07,0.02)	0.163	0.015	0.137	0.188
Replacement rate	10τ	Normal (5,2)	2.745	1.284	0.275	4.584
Hiring cost/output ratio	$1000\frac{\phi_N}{2}x^2$	Normal (5,0.5)	4.642	0.428	3.887	5.362
Habit persistence in comsump.	h	Beta (0.65,0.15)	0.477	0.045	0.398	0.542
Elasticity of matches to unemp.	σ	Beta (0.6,0.1)	0.307	0.047	0.228	0.3834
Investment adjustment cost	ϕ_I	Normal (5,1)	1.246	0.421	0.714	2.061
Capital utilization cost	ϕ_{u2}	Normal (0.5,0.15)	0.587	0.106	0.439	0.791
Price adjustment cost	ϕ_P	IGamma (80,40)	41.63	7.506	32.32	57.81
Wage adjustment cost	ϕ_W	IGamma (20,20)	10.75	2.814	7.407	17.21
Price indexation	ς	Beta (0.5,0.2)	0.166	0.063	0.085	0.288
Wage indexation	ϱ	Beta (0.5,0.2)	0.599	0.166	0.295	0.822
Interest rate smoothing	ρ_r	Beta (0.7,0.15)	0.801	0.022	0.758	0.834
Response to inflation	ρ_π	Normal (1.5,0.2)	2.136	0.117	1.921	2.328
Response to output gap	ρ_y	Normal (0.15,0.05)	0.217	0.040	0.155	0.282

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Table 3: Prior and posterior distributions of shock parameters

		Prior	Posterior distributions			
		distribution	Median	Std dev	5%	95%
Technology growth	ρ_z	Beta (0.35,0.15)	0.182	0.064	0.078	0.289
Technology growth	$100\sigma_z$	IGamma (0.1,2)	0.756	0.054	0.678	0.851
Monetary policy	ρ_{mp}	Beta (0.5,0.2)	0.483	0.183	0.195	0.808
Monetary policy	$100\sigma_{mp}$	IGamma (0.1,2)	0.150	0.013	0.132	0.176
Investment	ρ_μ	Beta (0.5,0.2)	0.940	0.022	0.900	0.969
Investment	$100\sigma_\mu$	IGamma (0.1,2)	1.886	0.293	1.450	2.476
Risk-premium	ρ_b	Beta (0.5,0.2)	0.946	0.017	0.914	0.972
Risk-premium	$100\sigma_b$	IGamma (0.1,2)	0.107	0.017	0.085	0.143
Price markup	ρ_θ	Beta (0.5,0.2)	0.845	0.042	0.764	0.905
Price markup	$100\sigma_\theta$	IGamma (0.1,2)	0.129	0.015	0.103	0.153
Bargaining power	ρ_η	Beta (0.5,0.2)	0.550	0.077	0.399	0.660
Bargaining power	$100\sigma_\eta$	IGamma (0.1,2)	14.41	2.765	11.16	19.63
Government spending	ρ_g	Beta (0.7,0.2)	0.969	0.012	0.946	0.983
Government spending	$100\sigma_g$	IGamma (0.1,2)	0.353	0.023	0.317	0.390

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Table 4: Parameters derived from steady-state conditions

Employment adjustment cost	ϕ_N	$\phi_N = \frac{2\times\left(\frac{\phi_N}{2}x^2\right)}{x^2}$
Discount factor	β	$\beta = \frac{z\pi}{r^B}$
Job survival rate	χ	$\chi = 1 - \rho$
Employment rate	N	$N = 1 - U$
Hiring rate	x	$x = \rho$
Mean of exogenous spending shock	ϵ_g	$\epsilon_g = \frac{1}{1-g/y}$
Real marginal cost	ξ	$\xi = \frac{\theta-1}{\theta}$
Quarterly net real rental rate of capital	$\widetilde{r}^K$	$\widetilde{r}^K = \frac{z}{\beta} - 1 + \delta$
Capital utilization cost first parameter	ϕ_{u1}	$\phi_{u1} = \widetilde{r}^K$
Capital/output ratio	k/y	$\frac{k}{y} = \frac{\alpha\xi}{\widetilde{r}^K}$
Investment/capital ratio	i/k	$\frac{i}{k} = z - 1 + \delta$
Investment/output ratio	i/y	$\frac{i}{y} = \frac{i}{k}\frac{k}{y}$
Consumption/output ratio	c/y	$\frac{c}{y} = \frac{1}{\epsilon_g} - \frac{\phi_N}{2}x^2 - \frac{i}{y}$
Vacancies	V	$V = N\frac{x}{q}$
Pool of job seekers	S	$S = 1 - \chi N$
Matching function efficiency	ζ	$\zeta = q\left(\frac{V}{S}\right)^{\sigma}$
Job finding rate	s	$s = \zeta\left(\frac{V}{S}\right)^{1-\sigma}$
Employees' share of output	$\widetilde{w}n/y$	$\frac{\widetilde{w}N}{y} = \xi(1-\alpha) - (1 - x - \beta\chi)\phi_N x$
Bargaining power	η	$\eta = \frac{1-\tau}{\vartheta-\tau}$ where $\vartheta \equiv \frac{\left[\xi(1-\alpha)+\phi_N x^2+\beta\chi\phi_N x s\right]}{\frac{\widetilde{w}N}{y}}$
Effective bargaining power	Ŋ	$\text{Ŋ} = \frac{\eta}{1-\eta}$

Figure 1: Time series data used to estimate the model.

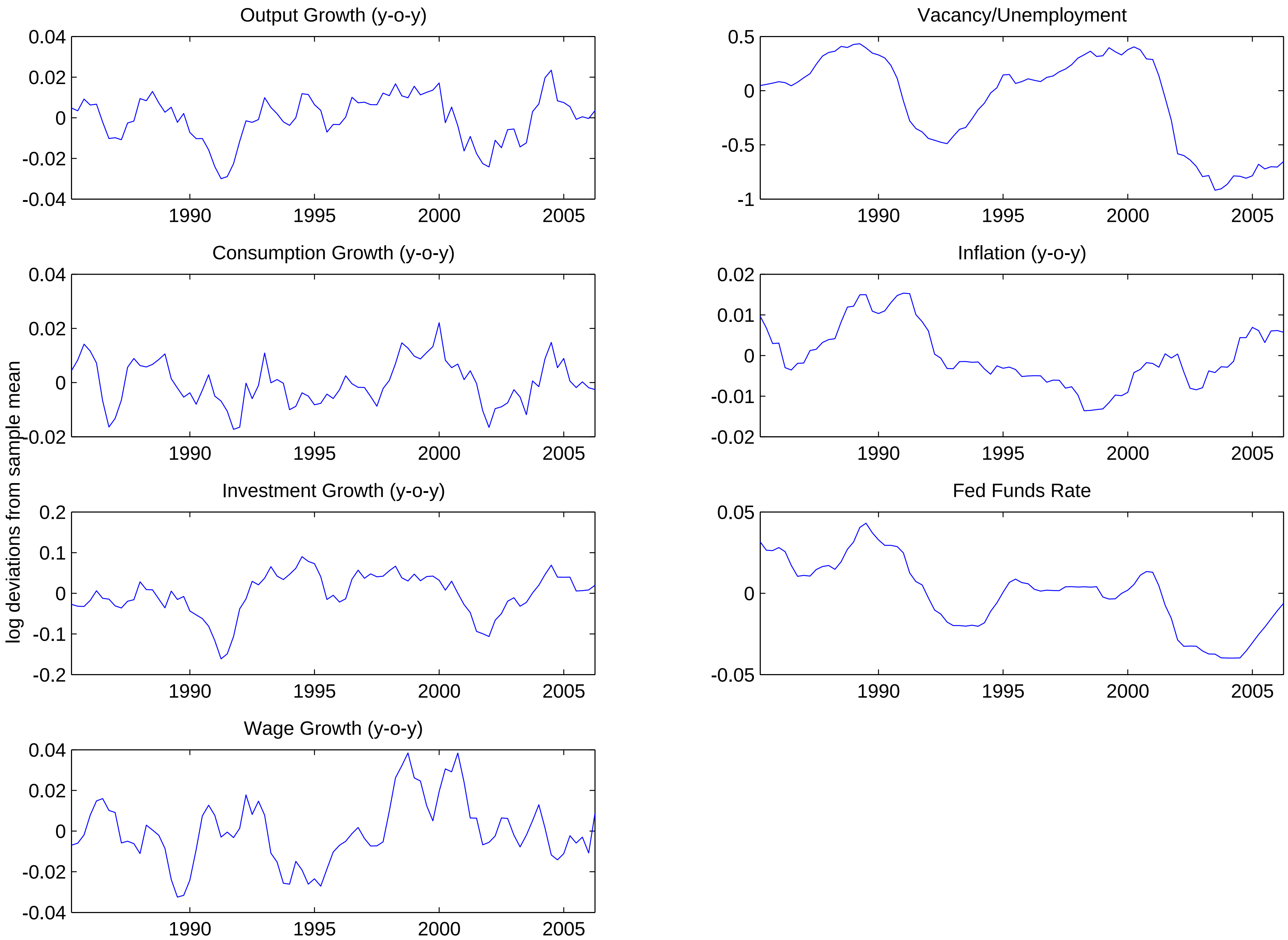

Figure 2: Data and model' spectral densities.

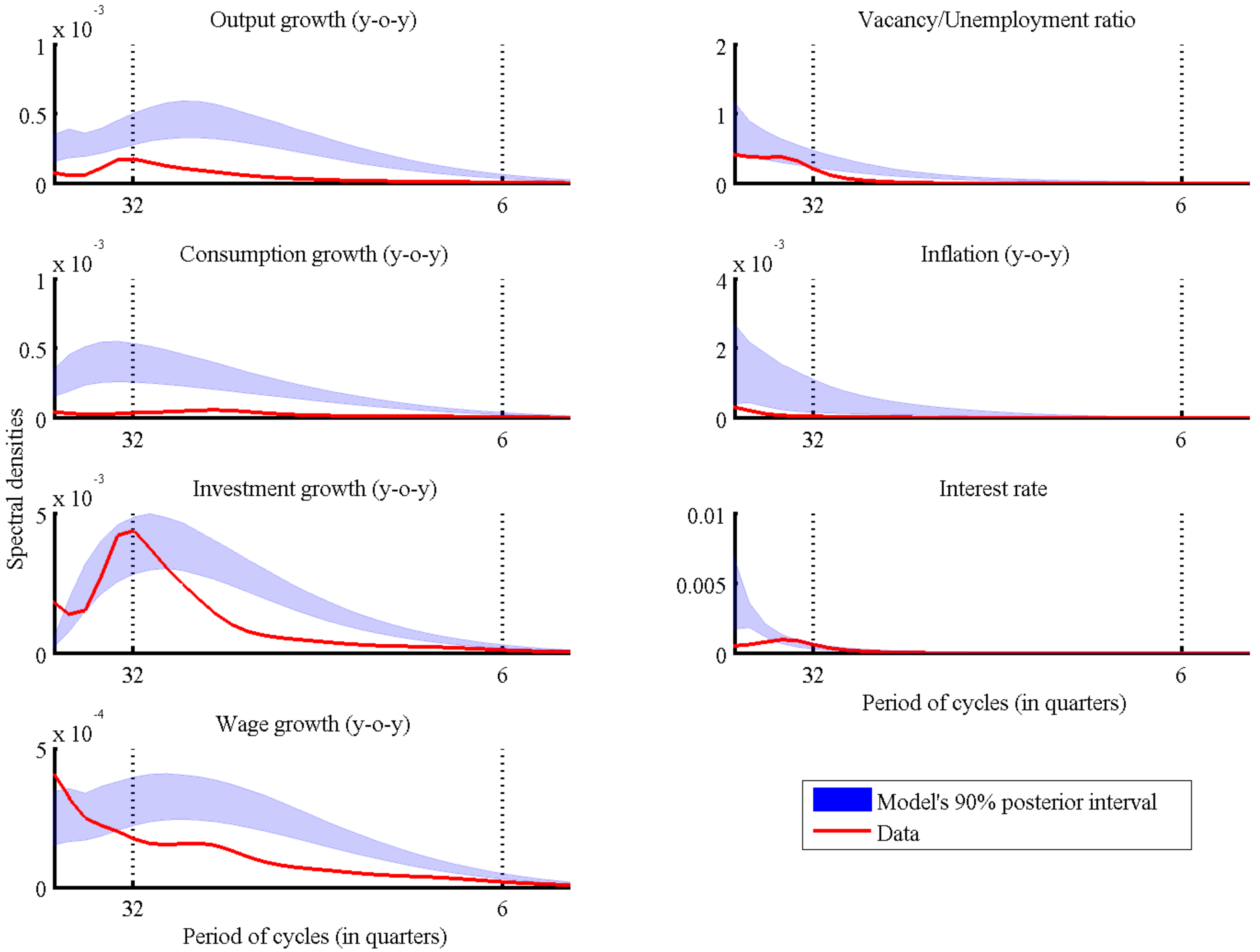

Figure 3: Data and model's coherences.

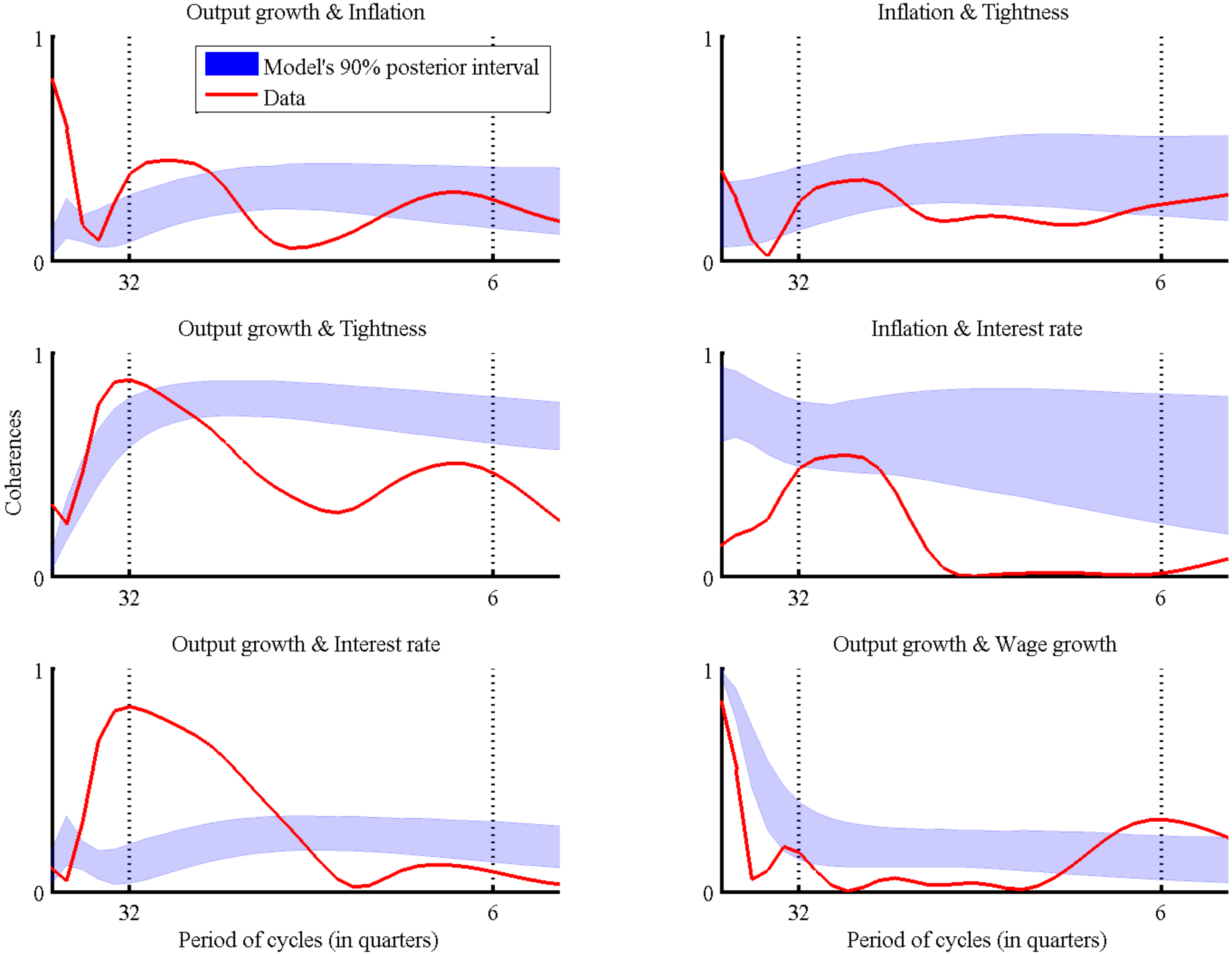

Figure 4: Posterior median spectral densities of output growth (y-o-y) conditional on one shock at a time.

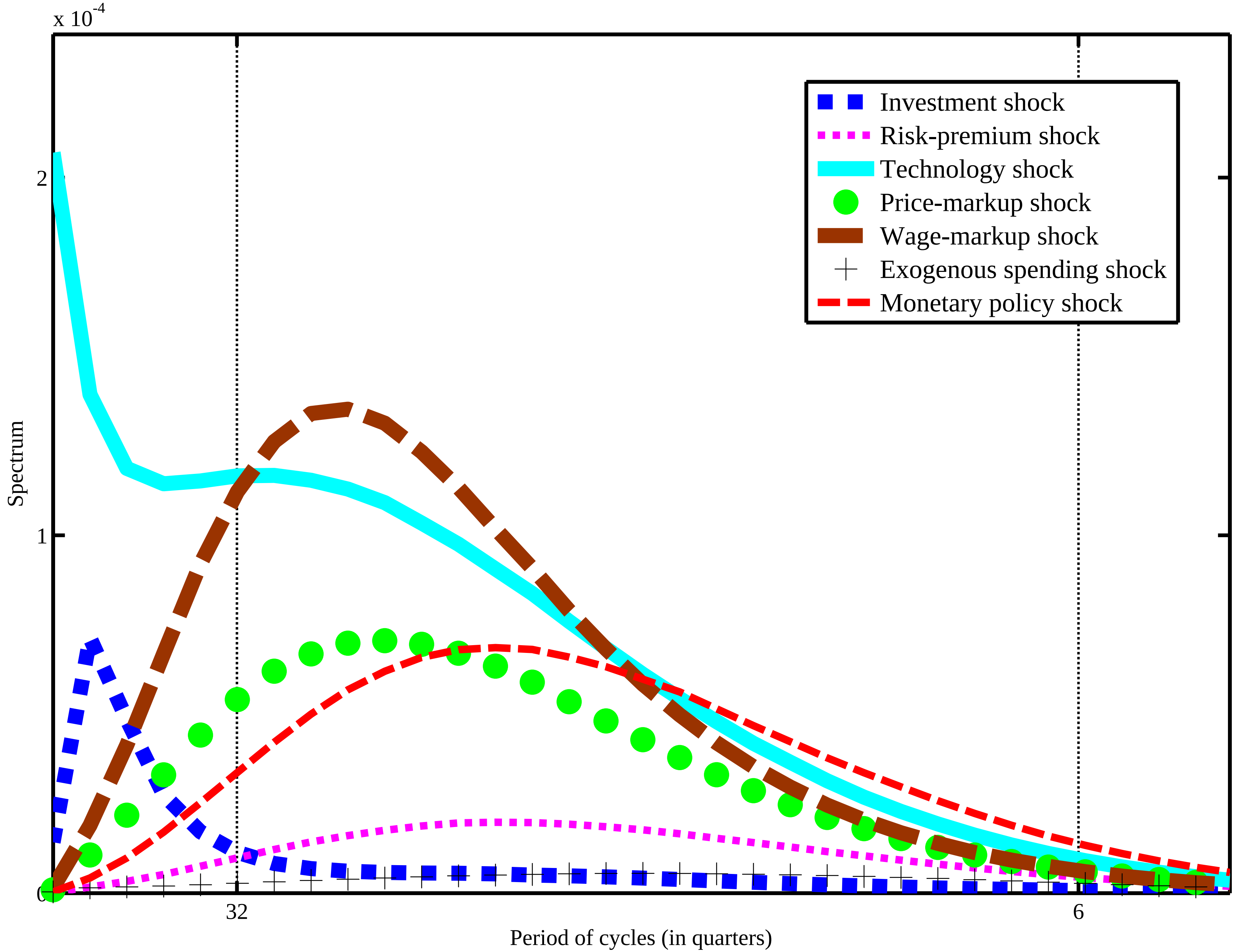

Figure 5: Posterior median spectral densities of the vacancy/unemployment ratio conditional on one shock at a time.

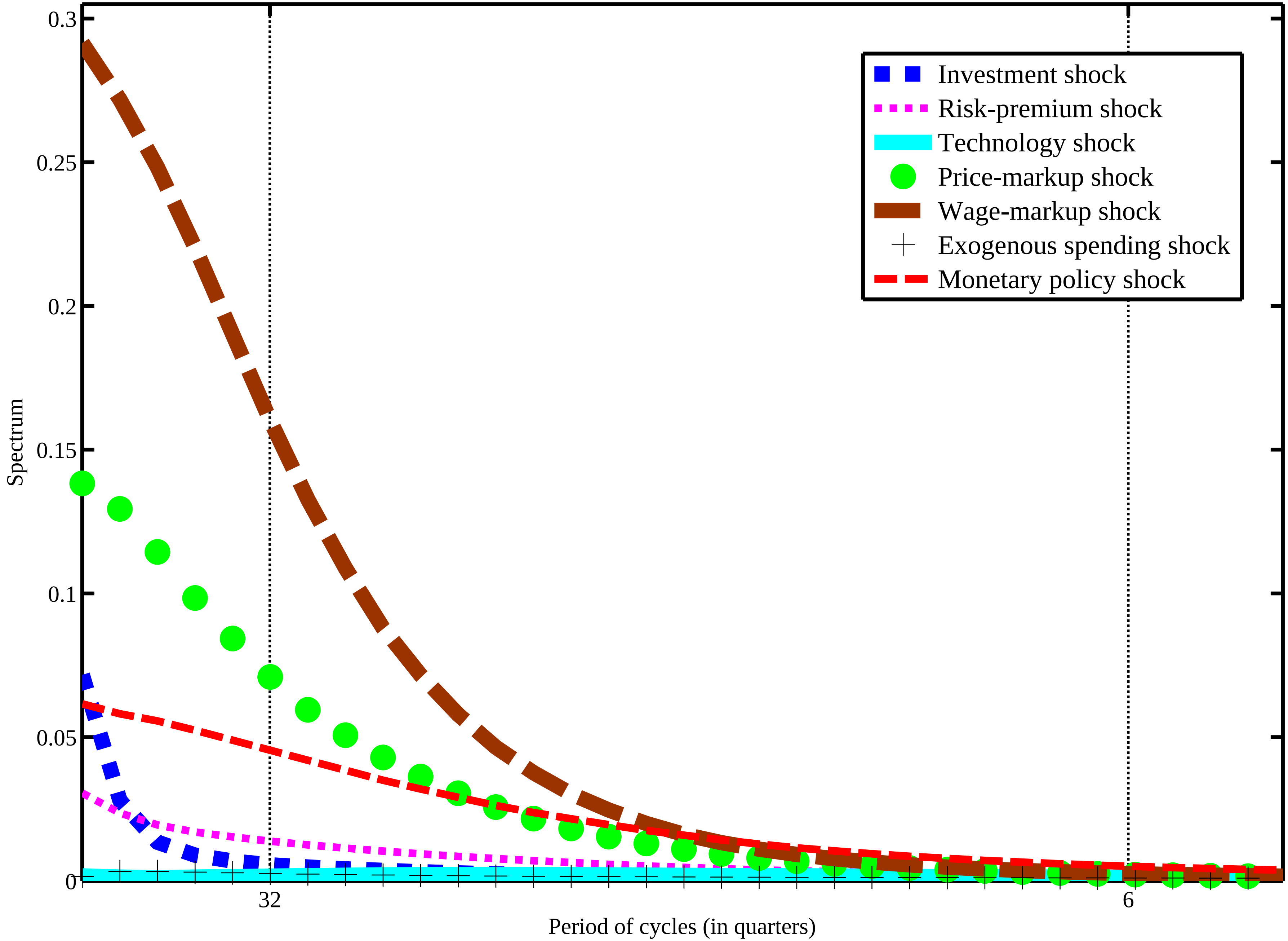

Figure 6: Impulse responses to a one-standard-deviation wage-markup shock.

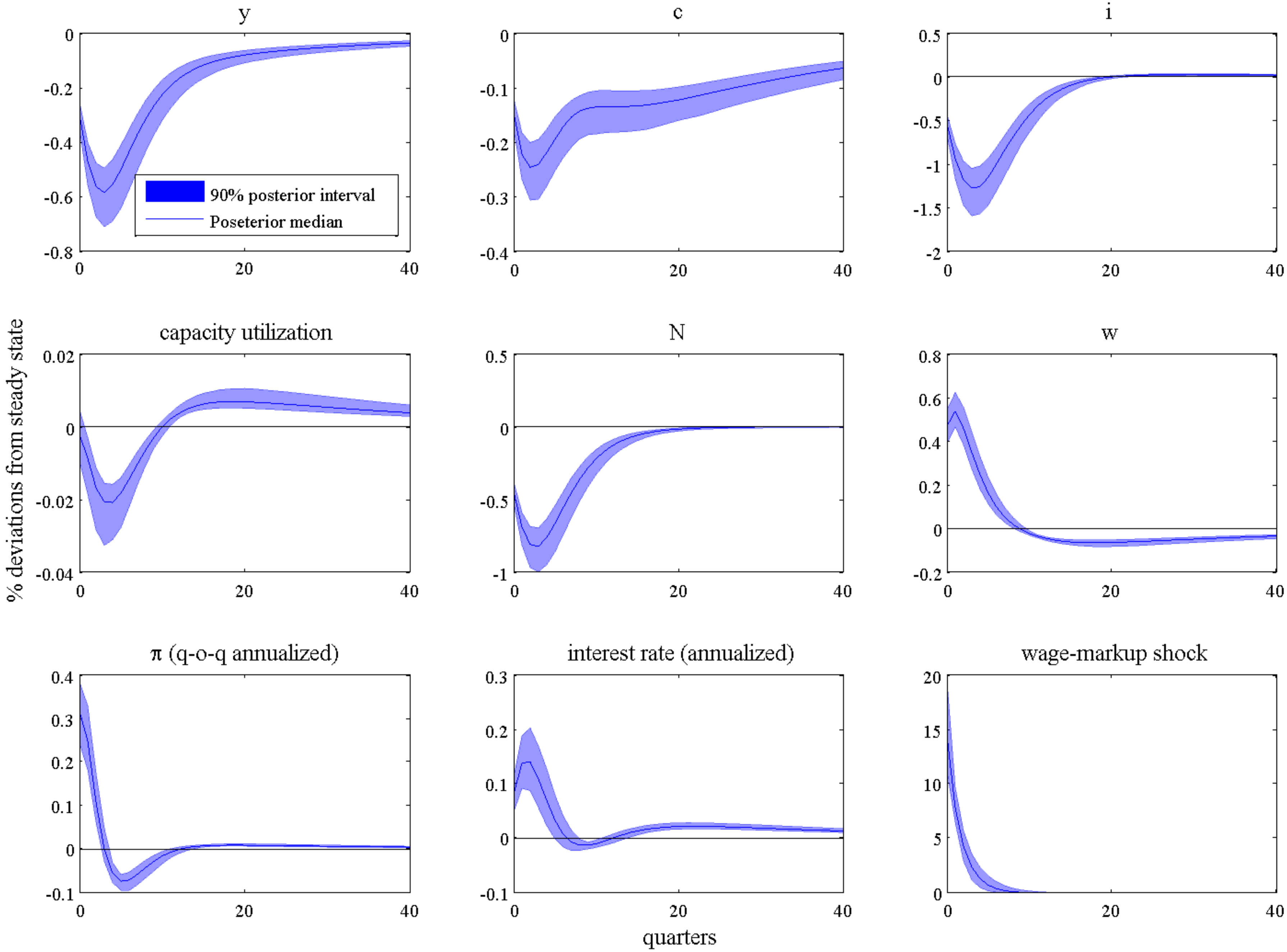

Figure 7: Time series data used to perform counterfactual experiments.

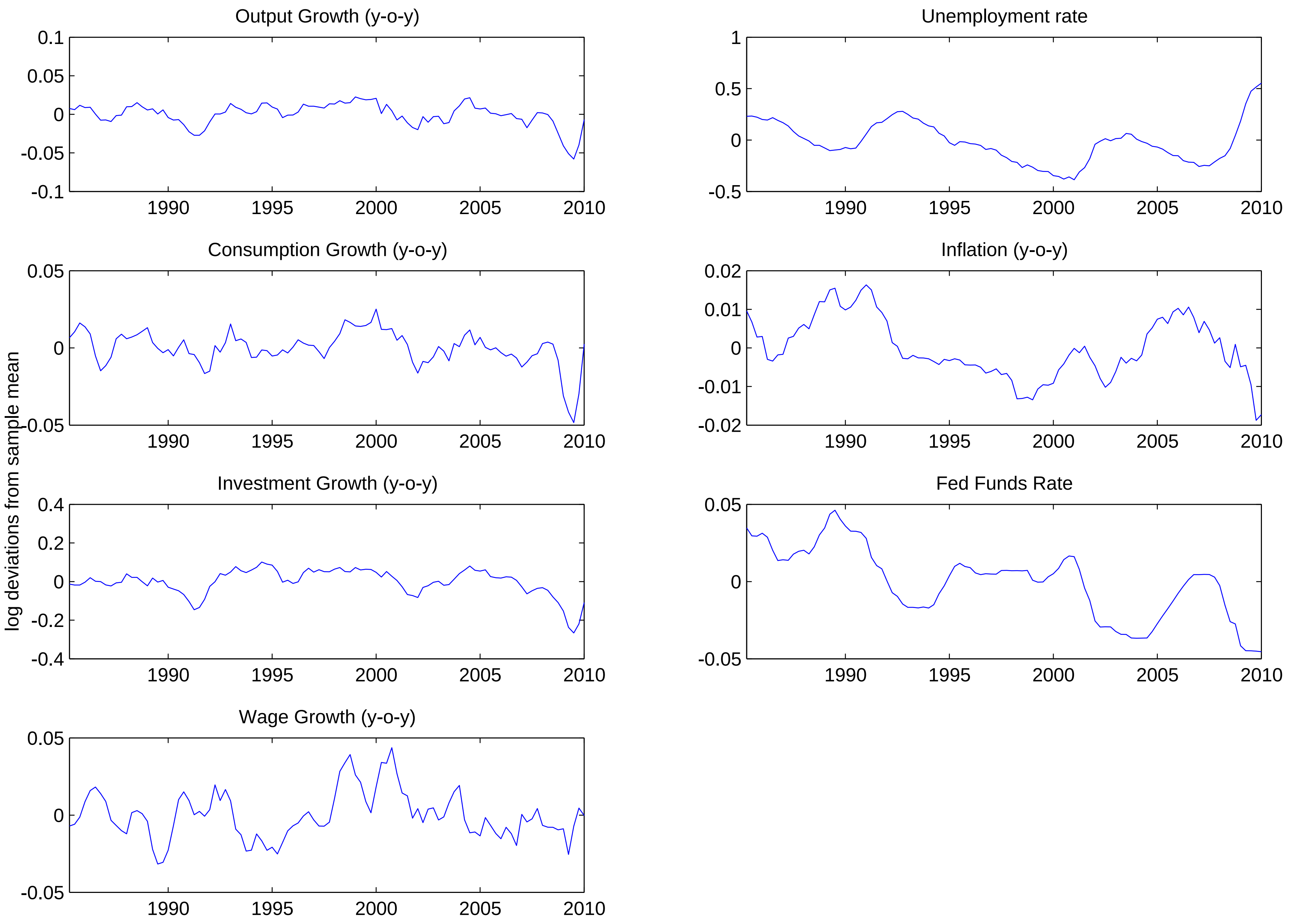

Figure 8: The efficient rate of unemployment.

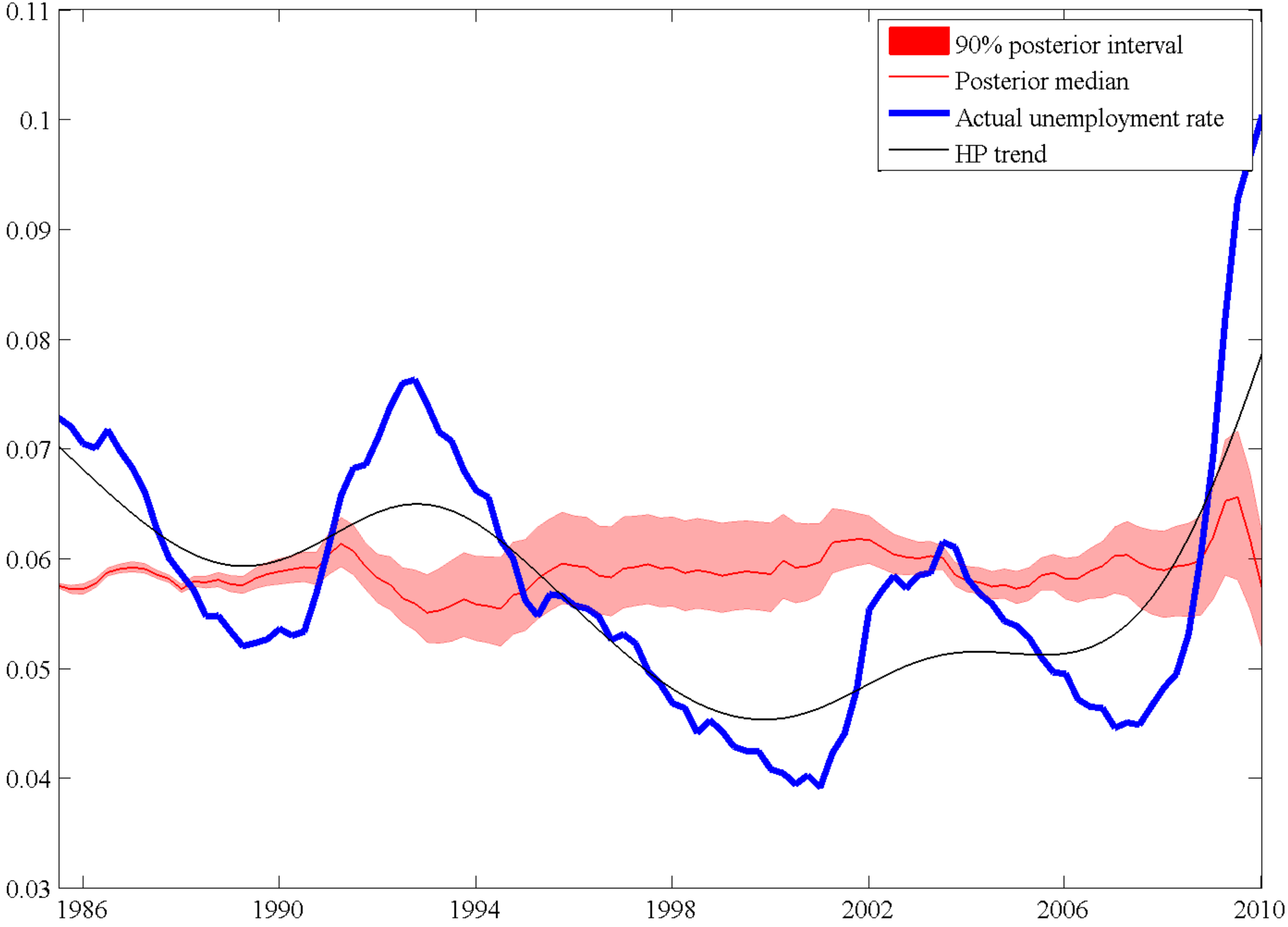

Figure 9: Unemployment gap.

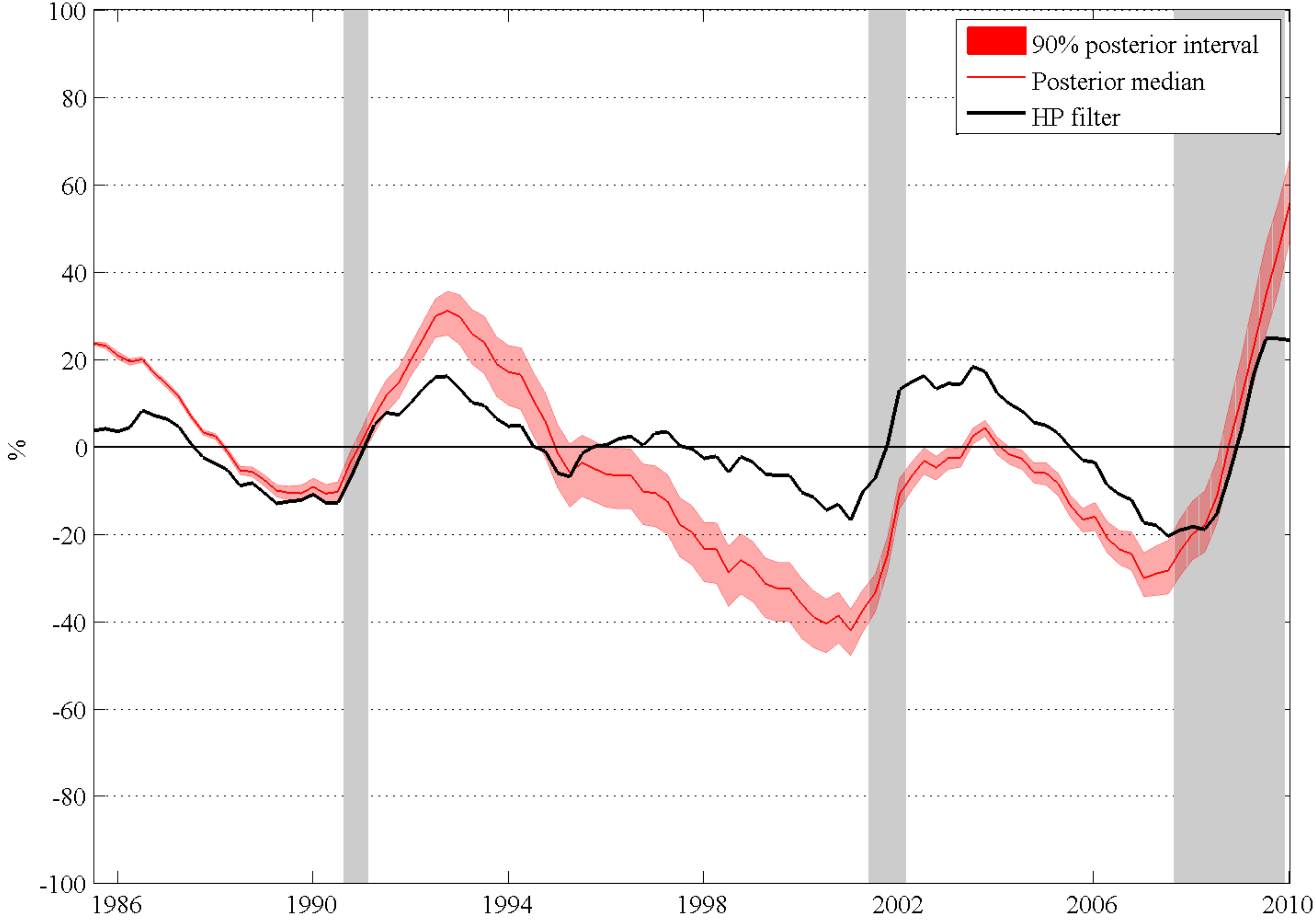

Figure 10: Historical decomposition of the unemployment gap

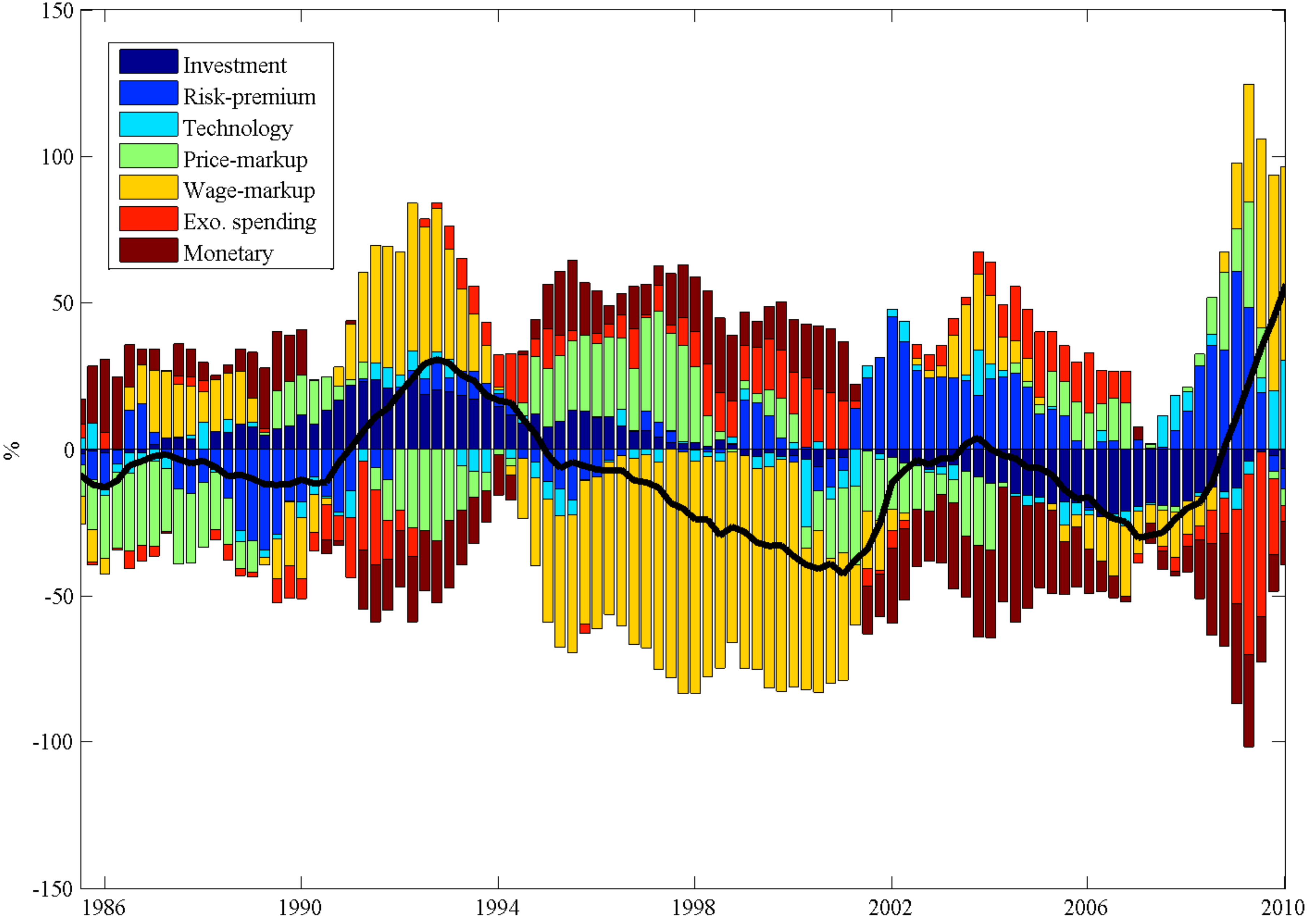

Figure 11: Effects of monetary policy shocks

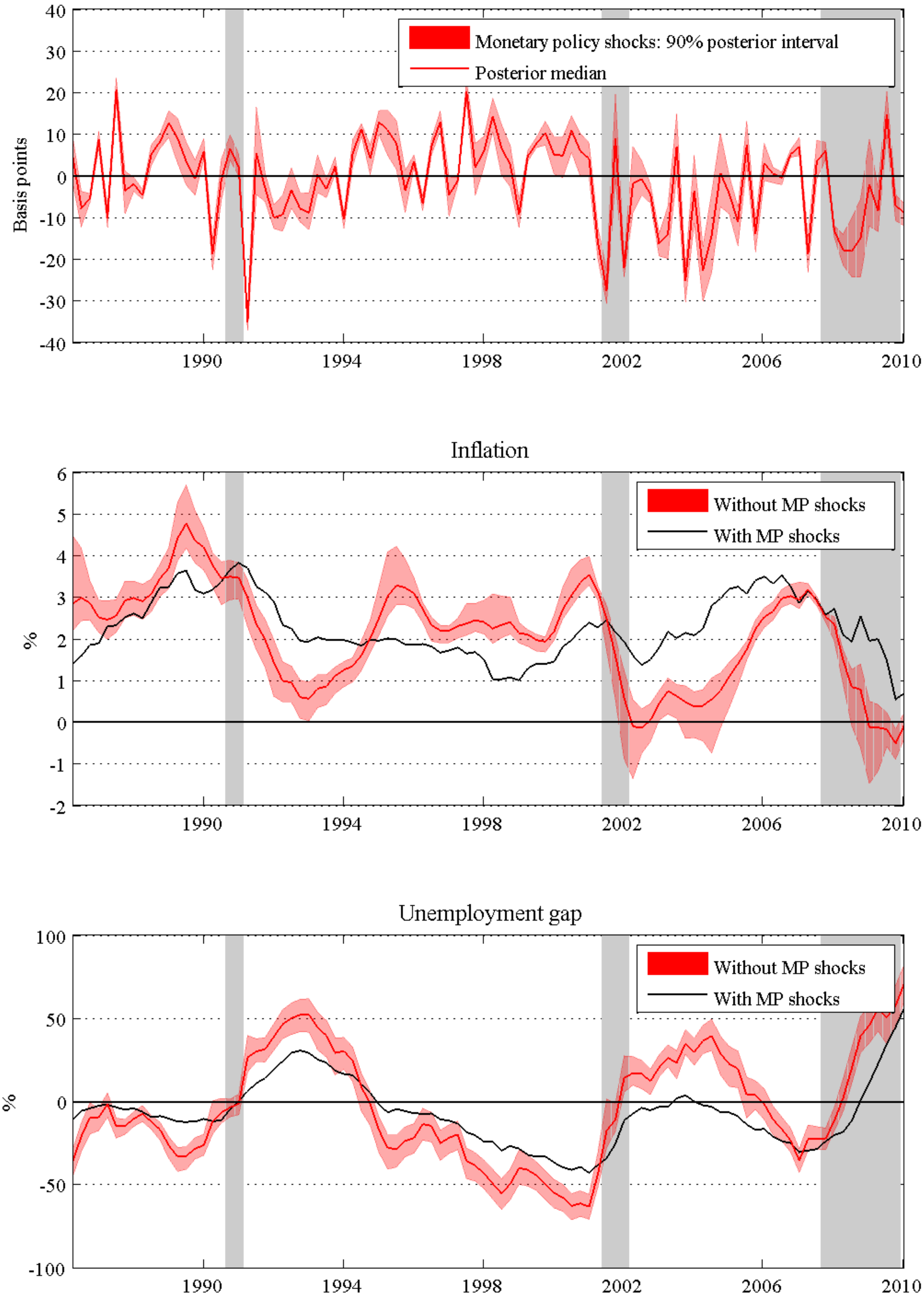

Figure 12: Interest rate, inflation and unemployment gap implied by alternative monetary policy rules