Potential Output, the Output Gap, and the Labor Wedge

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Abstract

We estimate a monetary business cycle model on post-war U.S. data. We first show that an i.i.d. shock to the labor market is better interpreted as measurement error, while a persistent labor market shock is the main driver of hours. We then study the behavior of the potential level of output and the output gap, and show that the estimated gap is very sensitive to the structural interpretation of the persistent labor market shock: two observationally equivalent interpretations of the model generate very different behavior of the output gap, and therefore have very different implications for the welfare costs of business cycles and the design of optimal monetary policy. Finally, we demonstrate that the dynamics of the output gap are closely related to the dynamics of hours and the "labor wedge," that is, the wedge between consumers' marginal rate of substitution between leisure and consumption and firms' marginal product of labor. We conclude that the interpretation of labor market fluctuations is crucial when using models in this class for welfare analysis or to design optimal monetary policy.

Keywords: Business cycles, Efficiency, Monetary Policy, Labor markets, Model misspecification.

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1 Introduction

The real business cycle literature (for example, Kydland and Prescott (1982); Long and Plosser (1983); King, Plosser, and Rebelo (1988)) demonstrated that business cycle fluctuations are not all inefficient. On the contrary, a large part of fluctuations may well be driven by the efficient responses of firms and households to exogenous shifts in technology and preferences. This result greatly reduced the scope for economic policymakers to dampen business cycle fluctuations, at least in theory.

Modern monetary business cycle models (starting with Yun (1996); Goodfriend and King (1997); and Rotemberg and Woodford (1997)) extend the real business cycle framework to include imperfect competition and nominal rigidities. These models typically imply that economic policy should counteract fluctuations due to nominal rigidities, but accommodate fluctuations due to shifts in real factors (for example, technology and preferences). In other words, optimal policy should act to make the real economy mimic the RBC model at the core of the monetary model (Goodfriend and King (1997)).

Recent developments of the monetary business cycle model have demonstrated that medium-sized versions of the model that incorporate more frictions and shocks are able to well match the behavior of aggregate macroeconomic variables (Smets and Wouters (2007)). These models are now in use at many central banks for policy simulations and forecasting. A strength of these models relative to traditional macroeconometric frameworks previously used at central banks is that they are based on the optimizing behavior of private agents, and therefore in principle can be used to quantify the welfare consequences of alternative policies. In particular, such models can be used to estimate the degree to which business cycle fluctuations are efficient and therefore advice policymakers about the appropriate response to such fluctuations.

Recently, much work has been aimed at estimating potential output, that is, the level of output that would appear in an allocation without nominal rigidities and where the degree of imperfect competition is constant.[1] This is also the level of output towards which optimal monetary policy should try to steer the economy in order to maximize household welfare.[2] Central banks in many countries also use these estimates to inform their policy decisions.

A related strand of the literature studies the wedge between consumers' marginal rate of substitution and firms' marginal product of labor, what Chari, Kehoe, and McGrattan (2007) call the "labor wedge." For instance, Hall (1997), Galí, Gertler, and López-Salido (2007), and Shimer (2009) all measure this wedge using small structural models. They show that the wedge is procyclical, so the marginal rate of substitution tends to increase relative to the marginal product of labor in expansions and fall in recessions. They also discuss the possible determinants of this wedge, for instance, exogenous shocks to the marginal rate

[1]The potential level of output is thus at a constant difference from the efficient level of output, which is the allocation with perfect competition, the distance being determined by average wage and price markups. The actual level of output is affected also by exogenous shocks to price and wage markups that affect the degree of imperfect competition.

[2]See, for instance, Neiss and Nelson (2003), (2005), Edge, Kiley, and Laforte (2008), Sala, Söderström, and Trigari (2008), Justiniano and Primiceri (2008), Basu and Fernald (2009), or Coenen, Smets, and Vetlov (2009).

of substitution, shocks to the markup of wages over the marginal rate of substitution, or endogenous movements in markups generated by wage and price rigidities.

We bring these two strands of the literature together, using a monetary business cycle model with imperfect competition and nominal rigidities estimated on U.S. data. We do this in three steps. First, to study the role of labor market shocks for business cycle fluctuations, we estimate two versions of the model that differ with respect to the specification of shocks to the labor market. The first model has only a persistent labor market shock, while the second also has an i.i.d. shock in the labor market. Either of these shocks could be interpreted as a shock to the markup of wages over the marginal rate of substitution, or as a shock to consumers' disutility of supplying labor, but for our estimation the exact interpretation is not important. Allowing for measurement errors in wages and prices, following Justiniano and Primiceri (2008), the i.i.d. labor market shock (as well as a shock to the price markup) obtains a posterior variance of zero. Thus, the estimation procedure prefers to interpret these shocks as a measurement error. The persistent labor market shock, on the other hand, is the main driver of hours, but is not important in explaining the behavior of output, which is mainly driven by non-stationary technology shocks.

Second, we study the behavior of the potential level of output and the output gap. We contrast two alternative measures of potential output that differ in the way they treat the current state of the economy. The first measure, advocated by Neiss and Nelson (2003), uses state variables in the hypothetical allocation where prices and wages have been flexible forever. The second measure, suggested by Woodford (2003) instead relies on the actual values of the state variables, relating to an allocation where prices and wages unexpectedly become flexible today and are expected to remain flexible in the future. Following Adolfson, Laséen, Lindé, and Svensson (2008) we call the first measure the "unconditional potential output," and the second measure "conditional potential output."

We show that the two measures of the output gap are closely correlated, and differ mainly in their quantitative implications. On the other hand, the interpretation of the persistent labor market shock has important implications for the estimates of potential output and the output gap. When we interpret this shock as a disturbance to the wage markup, the output gap is closely related to the U.S. business cycle dated by the NBER. If we instead interpret the shock as a disturbance to the disutility of supplying labor, the output gap is more stable and less closely related to the business cycle. As is well known,[3] the two shocks are observationally equivalent in the model, but have different implications for the welfare costs of business cycles and the design of optimal monetary policy, which should lean against wage markup shocks but accommodate labor disutility shocks. We quantify the implications for the output gap in our estimated model.

The differences between the model interpretations depend largely on how they interpret fluctuations in hours over the business cycle. In the final part of the paper, we therefore compare our estimated output gaps to the labor wedge, which is a measure of inefficiency directly related to the labor market. We find that this wedge is approximately proportional to the output gap, independently of how we interpret the labor market shock, and that

[3]See, for example, Smets and Wouters (2007) or Chari, Kehoe, and McGrattan (2009).

movements in the wedge are mainly driven by movements in the marginal rate of substitution, and therefore the markup of wages over the marginal rate of substitution.

Our results give rise to two different conclusions. A pessimistic conclusion, in line with Chari, Kehoe, and McGrattan (2009), is that models in this class are not reliable for normative issues, such as estimates of potential output or the labor wedge, welfare analysis, or the design of optimal policy. A more positive conclusion comes from the importance of the labor market for the output gap. A key issue is whether movements in hours over the business cycle are the result of the efficient adjustment of households and firms in the face of shocks to technology or preferences, or due to inefficiencies in the economy, such as imperfect competition or price and wage rigidities. A better understanding of labor market dynamics thus seems imperative in order to use models in this class to answer normative questions.

Our paper is organized as follows. We develop our model in Section 2. We then discuss our estimation technique and the empirical results in Section 3. In Section 4 we present our evidence on potential output and the output gap, and we relate these concepts to the labor wedge in Section 5. Finally, we discuss the robustness of our results in Section 6 before we conclude in Section 7.

2 A benchmark model

Our model is a monetary Dynamic Stochastic General Equilibrium (DSGE) framework, and is similar to many models used in the literature. This particular specification builds closely on Smets and Wouters (2007) and Justiniano, Primiceri, and Tambalotti (2010). The model consists of five sectors: households, a competitive final goods sector, a monopolistically competitive intermediate goods sector, employment agencies, and a government sector. The model features habit formation, investment adjustment costs, variable capital utilization, monopolistic competition in goods and labor markets, and nominal price and wage rigidities. The model also includes growth in the form of a non-stationary technology shock, as in Altig, Christiano, Eichenbaum, and Lindé (2005).

2.1 Households

The model is populated by a continuum of households, indexed by $j \in [0, 1]$. Each household consumes final goods, supplies a specific type of labor to intermediate goods firms via employment agencies, saves in one-period nominal government bonds, and accumulates physical capital through investment. It transforms physical capital to effective capital by choosing the capital utilization rate, and then rents the effective capital to intermediate goods firms.

Household j chooses consumption $C_t(j)$, labor supply $L_t(j)$, bond holdings $B_t(j)$, the rate of capital utilization ν_t, investment I_t, and physical capital $\bar{K}_t$ to maximize the intertemporal utility function

$$\mathrm{E}_t \left\{ \sum_{s=0}^{\infty} \beta^s \varepsilon_{t+s}^b \left[\log\left(C_{t+s}(j) - hC_{t+s-1}(j)\right) - \varepsilon_{t+s}^l \frac{L_{t+s}(j)^{1+\omega}}{1+\omega} \right] \right\}, \tag{1}$$

where β is a discount factor, h measures the degree of habits in consumption, ω is the inverse

Frisch elasticity of labor supply, ε_t^b is an intertemporal preference shock, and ε_t^l is a shock to the disutility of supplying labor. The intertemporal preference shock has mean unity and is assumed to follow the autoregressive process

$$\log \varepsilon_t^b = \rho_b \log \varepsilon_{t-1}^b + \zeta_t^b, \qquad \zeta_t^b \sim i.i.d.\ N(0, \sigma_b^2), \tag{2}$$

while we explore different processes for the labor disutility shock in the estimated model in Section 3 below.

The capital utilization rate ν_t transforms physical capital $\bar{K}_t$ into efficient capital K_t according to

$$K_t = \nu_t \bar{K}_{t-1}, \tag{3}$$

and the efficient capital is rented to intermediate goods firms at the nominal rental rate R_t^k. The cost of capital utilization per unit of physical capital is given by $\mathcal{A}(\nu_t)$, and we assume that $\nu_t = 1$ in steady state, $\mathcal{A}(1) = 0$, and $\mathcal{A}'(1)/\mathcal{A}''(1) = \eta_\nu$, as in Christiano, Eichenbaum, and Evans (2005) and others.

Physical capital accumulates according to

$$\bar{K}_t = (1-\delta)\bar{K}_{t-1} + \varepsilon_t^i \left[1 - \mathcal{S}\left(\frac{I_t}{I_{t-1}}\right)\right] I_t, \tag{4}$$

where δ is the depreciation rate of capital, ε_t^i is an investment-specific technology shock with mean unity, and $\mathcal{S}(\cdot)$ is an adjustment cost function which satisfies $\mathcal{S}(\gamma_z) = \mathcal{S}'(\gamma_z) = 0$ and $\mathcal{S}''(\gamma_z) = \eta_k > 0$, where γ_z is the steady-state growth rate. The investment-specific technology shock follows the process

$$\log \varepsilon_t^i = \rho_i \log \varepsilon_{t-1}^i + \zeta_t^i, \qquad \zeta_t^i \sim i.i.d.\ N(0, \sigma_i^2). \tag{5}$$

Let P_t be the nominal price level, R_t the one-period nominal (gross) interest rate, $A_t(j)$ the net returns from a portfolio of state-contingent securities, W_t the nominal wage, Π_t nominal lump-sum profits from ownership of firms, and T_t nominal lump-sum transfers. Household j's budget constraint is then given by

$$P_t C_t + P_t I_t + B_t = T_t + R_{t-1} B_{t-1} + A_t(j) + \Pi_t + W_t(j) L_t(j) + r_t^k \nu_t \bar{K}_{t-1} - P_t \mathcal{A}(\nu_t) \bar{K}_{t-1}. \tag{6}$$

Assuming that households have access to a complete set of state-contingent securities, consumption and asset holdings are the same for all households. The households' first-order conditions for consumption, bond holdings, investment, physical capital, and efficient capital are then given by

$$\Lambda_t = \frac{\varepsilon_t^b}{C_t - hC_{t-1}} - \beta h \mathrm{E}_t \left\{ \frac{\varepsilon_{t+1}^b}{C_{t+1} - hC_t} \right\}, \tag{7}$$

$$\Lambda_t = \beta R_t \mathrm{E}_t \left\{ \Lambda_{t+1} \frac{P_t}{P_{t+1}} \right\}, \tag{8}$$

$$1 = Q_t \varepsilon_t^i \left[1 - \mathcal{S}\left(\frac{I_t}{I_{t-1}}\right) - \frac{I_t}{I_{t-1}} \mathcal{S}'\left(\frac{I_t}{I_{t-1}}\right) \right] + \beta \mathrm{E}_t \left\{ \frac{\Lambda_{t+1}}{\Lambda_t} Q_{t+1} \varepsilon_{t+1}^i \left(\frac{I_{t+1}}{I_t}\right)^2 \mathcal{S}'\left(\frac{I_{t+1}}{I_t}\right) \right\}, \tag{9}$$

$$Q_t = \beta \mathrm{E}_t \left\{ \frac{\Lambda_{t+1}}{\Lambda_t} \left[\frac{R_{t+1}^k}{P_{t+1}} \nu_{t+1} - \mathcal{A}(\nu_{t+1}) + (1-\delta) Q_{t+1} \right] \right\}, \tag{10}$$

$$R_t^k = P_t \mathcal{A}'(\nu_t), \tag{11}$$

where Λ_t is the marginal utility of consumption and Q_t is Tobin's Q, that is, the marginal value of capital relative to consumption.

2.2 Final goods producing firms

A perfectly competitive sector combines a continuum of intermediate goods $Y_t(i)$ indexed by $i \in [0,1]$ into a final consumption good Y_t according to the production function

$$Y_t = \left[\int_0^1 Y_t(i)^{1/\varepsilon_t^p} di \right]^{\varepsilon_t^p}, \tag{12}$$

where ε_t^p is a time-varying measure of substitutability across differentiated intermediate goods. This substitutability implies a time-varying (gross) markup of price over marginal cost equal to ε_t^p that is assumed to follow the process

$$\log \varepsilon_t^p = \left(1 - \rho_p\right) \log \varepsilon^p + \rho_p \log \varepsilon_{t-1}^p + \zeta_t^p, \qquad \zeta_t^p \sim i.i.d.\ N(0, \sigma_p^2), \tag{13}$$

where ε^p is the steady-state price markup.

Profit maximization by final goods producing firms yields the set of demand equations

$$Y_t(i) = \left[\frac{P_t(i)}{P_t} \right]^{-\varepsilon_t^p/(\varepsilon_t^p - 1)} Y_t, \tag{14}$$

where $P_t(i)$ is the price of intermediate good i and P_t is an aggregate price index given by

$$P_t = \left[\int_0^1 P_t(i)^{1/(\varepsilon_t^p - 1)} di \right]^{\varepsilon_t^p - 1}. \tag{15}$$

2.3 Intermediate goods producing firms

Each firm in the intermediate goods sector produces a differentiated intermediate good i using capital and labor inputs according to the production function

$$Y_t(i) = \max \left\{ K_t(i)^{\alpha} \left[Z_t L_t(i) \right]^{1-\alpha} - Z_t F, 0 \right\}, \tag{16}$$

where α is the capital share, Z_t is a labor-augmenting productivity factor, whose growth rate $\varepsilon_t^z = Z_t/Z_{t-1}$ follows a stationary exogenous process with steady-state value ε^z which corresponds to the economy's steady-state (gross) growth rate γ_z, and F is a fixed cost that ensures that profits are zero. The rate of technology growth is assumed to follow

$$\log \varepsilon_t^z = (1-\rho_z)\log \varepsilon^z + \rho_z \log \varepsilon_{t-1}^z + \zeta_t^z, \qquad \zeta_t^z \sim i.i.d.\ N(0,\sigma_z^2). \tag{17}$$

Thus, technology is non-stationary in levels but stationary in growth rates, following Altig, Christiano, Eichenbaum, and Lindé (2005). We assume that capital is perfectly mobile across firms and that there is a competitive rental market for capital.

Cost minimization implies that nominal marginal cost MC_t is determined by

$$MC_t(i) = \frac{W_t}{(1-\alpha)Z_t^{1-\alpha}\left(L_t(i)/K_t(i)\right)^{-\alpha}} \tag{18}$$

and

$$MC_t(i) = \frac{r_t^k}{\alpha Z_t^{1-\alpha}\left(K_t(i)/L_t(i)\right)^{\alpha-1}}, \tag{19}$$

so nominal marginal cost is common across firms and given by

$$MC_t = \left[\alpha^\alpha (1-\alpha)^{1-\alpha}\right]^{-1} (W_t/Z_t)^{1-\alpha} \left(r_t^k\right)^\alpha. \tag{20}$$

Prices of intermediate goods are set in a staggered fashion, following Calvo (1983). Thus, only a fraction $1-\theta_p$ of firms are able to reoptimize their price in any given period. The remaining fraction are assumed to index their price to a combination of past inflation and steady-state inflation according to the rule

$$P_t(i) = P_{t-1}(i)\pi_{t-1}^{\gamma_p}\pi^{1-\gamma_p}, \tag{21}$$

where $\pi_t = P_t/P_{t-1}$ is the gross rate of inflation with steady-state value π and $\gamma_p \in [0,1]$. If the indexation parameter γ_p is equal to zero, firms index fully to steady-state inflation, as in Yun (1996), while if $\gamma_p = 1$, firms index fully to lagged inflation, as in Christiano, Eichenbaum, and Evans (2005). Firms that are able to set their price optimally instead choose their price $P_t(i)$ to maximize the present value of future profits over the expected life-time of the price contract:

$$\mathrm{E}_t \left\{ \sum_{s=0}^{\infty} (\beta\theta_p)^s \frac{\Lambda_{t+s}}{\Lambda_t} \left\{ \Pi_{t,t+s} P_t(i) Y_{t+s}(i) - W_{t+s}L_{t+s}(i) - R_{t+s}^k K_{t+s}(i) \right\} \right\}, \tag{22}$$

where

$$\Pi_{t,t+s} = \begin{cases} 1 \text{ for } s = 0, \\ \prod_{k=1}^{s} \pi_{t+k-1}^{\gamma_p}\pi^{1-\gamma_p} \text{ for } s \geq 1. \end{cases}, \tag{23}$$

subject to the demand from final goods producing firms in equation (14), As all firms changing their price at time t face the same problem, they all set the same optimal price P_t^*. The first-order condition associated with their maximization problem is

$$\mathrm{E}_t \left\{ \sum_{s=0}^{\infty} (\beta\theta_p)^s \left[\frac{\Lambda_{t+s}}{\Lambda_t} Y_{t,t+s} \left(\Pi_{t,t+s} P_t^* - \varepsilon_{t+s}^p MC_{t+s} \right) \right] \right\} = 0, \tag{24}$$

where $Y_{t,t+s}$ is demand facing the firm at time t, given the price P_t^*. In the limiting case of full price flexibility ($\theta_p = 0$) the optimal price is

$$P_t^* = \varepsilon_t^p MC_t, \tag{25}$$

that is, a markup on nominal marginal cost. With staggered price setting, the price index P_t evolves according to

$$P_t = \left[(1-\theta_p) \left(P_t^* \right)^{1/(\varepsilon_t^p - 1)} + \theta_p \left(\pi_{t-1}^{\gamma_p} \pi^{1-\gamma_p} P_{t-1} \right)^{1/(\varepsilon_t^p - 1)} \right]^{\varepsilon_t^p - 1}. \tag{26}$$

2.4 The labor market

As in Erceg, Henderson, and Levin (2000), each household is a monopolistic supplier of specialized labor $L_t(j)$, which is combined by perfectly competitive employment agencies into labor services L_t according to

$$L_t = \left[\int_0^1 L_t(j)^{1/\varepsilon_t^w} dj \right]^{\varepsilon_t^w}, \tag{27}$$

where ε_t^w is a time-varying measure of substitutability across labor varieties that translates into a time-varying (gross) markup of wages over the marginal rate of substitution between consumption and leisure. As for the labor disutility shock, we will explore different stochastic processes for the wage markup shock below.

Profit maximization by employment agencies yields the set of demand equations

$$L_t(j) = \left[\frac{W_t(j)}{W_t} \right]^{-\varepsilon_t^w/(\varepsilon_t^w - 1)} L_t, \tag{28}$$

for each j, where $W_t(j)$ is the wage received from employment agencies by the household supplying labor variety j, and W_t is the aggregate wage index given by

$$W_t = \left[\int_0^1 W_t(j)^{1/(\varepsilon_t^w - 1)} dj \right]^{\varepsilon_t^w - 1}. \tag{29}$$

In any given period, a fraction $1-\theta_w$ of households are able to set their wage optimally. Similar to the price indexation scheme, the remaining fraction indexes their wage to the steady-state growth rate γ_z and a combination of past inflation and steady-state inflation according to[4]

$$W_t(j) = W_{t-1}(j)\gamma_z \pi_{t-1}^{\gamma_w}\pi^{1-\gamma_w}. \tag{30}$$

The optimizing households choose the wage to maximize

$$\mathrm{E}_t \left\{ \sum_{s=0}^{\infty} (\beta\theta_w)^s \left[\Lambda_{t+s} \frac{W_t(j)}{P_{t+s}} L_{t+s}(j) - \varepsilon_{t+s}^b \varepsilon_{t+s}^l \frac{L_{t+s}(j)^{1+\omega}}{1+\omega} \right] \right\}, \tag{31}$$

subject to the labor demand equation (28). All optimizing households then set the same optimal wage W_t^* to satisfy the first-order condition

$$\mathrm{E}_t \left\{ \sum_{s=0}^{\infty} (\beta\theta_w)^s \Lambda_{t+s} L_{t,t+s} \left[\Pi_{t,t+s}^w \frac{W_t^*}{P_{t+s}} - \varepsilon_{t+s}^w \varepsilon_{t+s}^b \varepsilon_{t+s}^l \frac{L_{t,t+s}^{\omega}}{\Lambda_{t+s}} \right] \right\} = 0, \tag{32}$$

where $L_{t,t+s}$ is labor demand facing the household at time t given the wage W_t^*, and

$$\Pi_{t,t+s}^w = \begin{cases} 1 \text{ for } s = 0, \\ \prod_{k=1}^{s} \gamma_z \pi_{t+k-1}^{\gamma_w} \pi^{1-\gamma_w} \text{ for } s \geq 1. \end{cases} \tag{33}$$

The limiting case of full wage flexibility ($\theta_w = 0$) implies that

$$\frac{W_t^*}{P_t} = \varepsilon_t^w \varepsilon_t^b \varepsilon_t^l \frac{L_t^{\omega}}{\Lambda_t}, \tag{34}$$

so the real wage is set as a markup over the marginal rate of substitution. With staggered wages, the aggregate wage index W_t evolves according to

$$W_t = \left[(1-\theta_w) \left(W_t^*\right)^{1/(\varepsilon_t^w - 1)} + \theta_w \left(\gamma_z \pi_{t-1}^{\gamma_w} \pi^{1-\gamma_w} W_{t-1} \right)^{1/(\varepsilon_t^w - 1)} \right]^{\varepsilon_t^w - 1}. \tag{35}$$

2.5 Government

The government sets public spending G_t according to

$$G_t = \left[1 - \frac{1}{\varepsilon_t^g} \right] Y_t, \tag{36}$$

where ε_t^g is a spending shock with mean unity that follows the process

$$\log \varepsilon_t^g = \rho_g \log \varepsilon_{t-1}^g + \zeta_t^g, \qquad \zeta_t^g \sim i.i.d.\ N(0, \sigma_g^2). \tag{37}$$

The nominal interest rate R_t is set using the monetary policy rule

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_s} \left[\left(\frac{\pi_t}{\pi_t^*} \right)^{r_\pi} \left(\frac{\Delta \log Y_t}{\gamma_z} \right)^{r_y} \right]^{1-\rho_s} \varepsilon_t^r, \tag{38}$$

[4] Justiniano, Primiceri, and Tambalotti (2010) and Justiniano and Primiceri (2008) assume that wages are partly indexed to past nominal productivity growth $\pi_{t-1}\varepsilon_{t-1}^z$ and partly to the nominal steady-state growth rate $\pi\gamma_z$. Our specification instead follows Smets and Wouters (2007).

where π_t^* is a time-varying target for inflation, which follows

$$\log \pi_t^* = (1 - \rho_*) \log \pi + \rho_* \log \pi_{t-1}^* + \zeta_t^*, \qquad \zeta_t^* \sim i.i.d.\ N(0, \sigma_*^2). \tag{39}$$

and ε_t^r is a monetary policy shock which is i.i.d. (in logarithms) with mean unity and variance σ_r^2. Thus the monetary policy rule is affected by two different shock processes: one persistent and one i.i.d. Although we will call the persistent shock an "inflation target shock," it could in principle represent any persistent deviation from the monetary policy rule, such as errors in the perception of the long-run growth rate γ_z.

We specify the monetary policy rule in terms of output growth rather than the output gap, defined as the deviation of output from potential. Thus, we implicitly assume that the central bank either is unable to observe potential output or is unwilling to let monetary policy depend on its estimate of potential output. As a consequence, our estimates of the benchmark model are independent of the evolution of potential output.[5]

2.6 Market clearing

Finally, to close the model, the resource constraint implies that output is equal to the sum of consumption, investment, government spending, and the capital utilization costs:

$$Y_t = C_t + I_t + G_t + \mathcal{A}(\nu_t)\, \bar{K}_{t-1}. \tag{40}$$

2.7 Model summary

The complete model consists of 17 endogenous variables determined by 17 equations: the capital utilization equation (3), the capital accumulation equation (4), the households' first-order conditions (7)–(11), the production function (16), the marginal cost equations (18)–(19), the optimal price and wage setting equations (24) and (32), the aggregate price and wage indices (26) and (35), the rules for government spending and monetary policy in (36) and (38), and the resource constraint (40). In addition there are nine exogenous shocks: to household preferences ε_t^b, the disutility of labor ε_t^l, labor-augmenting technology ε_t^z, investment-specific technology ε_t^i, government spending ε_t^g, the price and wage markups ε_t^p and ε_t^w, the inflation target π_t^*, and monetary policy ε_t^r.

Output, the capital stock, investment, consumption, government spending, and the real wage all share the common stochastic trend introduced by the non-stationary technology shock ε_t^z. Therefore, the model is rewritten on stationary form by normalizing these variables by the non-stationary technology shock, and then log-linearized around its steady state. The stationary model, the steady state, and the log-linearized model are shown in Appendix A.[6]

[5] Justiniano and Primiceri (2008) specify the monetary policy rule in terms the four-quarter growth rate of output and the four-quarter inflation rate. Smets and Wouters (2007) and Justiniano, Primiceri, and Tambalotti (2010) use a rule with the deviation of quarterly inflation from a constant inflation target, the level and first difference of the output gap, and an AR(1) monetary policy shock.

[6] In addition, we supplement the log-linearized model with a block of equations that determines the allocation with flexible prices and wages. While this block is not used when estimating the model, it is useful when constructing different measures of potential output in Section 4.

3 Estimation

3.1 Data and estimation technique

We estimate the log-linearized version of the model using quarterly U.S. data from 1960Q1 to 2009Q3 for seven variables: (1) output growth: the quarterly growth rate of per capita real GDP; (2) investment growth: the quarterly growth rate of per capita real private investment plus real personal consumption expenditures of durable goods; (3) consumption growth: the quarterly growth rate of per capita real personal consumption expenditures of services and nondurable goods; (4) real wage growth: the quarterly growth rate of real compensation per hour; (5) employment: hours of all persons divided by population; (6) inflation: the quarterly growth rate of the GDP deflator; and (7) the nominal interest rate: the quarterly average of the federal funds rate. Many of our results will be driven by the behavior of hours over the business cycle. We use data on hours from Francis and Ramey (2009) that refer to the total economy and are adjusted for low-frequency movements due to sectoral shifts and changes in demographics. These data therefore display less low-frequency behavior than unadjusted data. Data definitions and sources are available in Appendix B.

We estimate the model using Bayesian likelihood-based methods (see An and Schorfheide (2007) for an overview). Letting $\boldsymbol{\theta}$ denote the vector of structural parameters to be estimated and $\mathbf{Y}$ the data sample, we use the Kalman filter to calculate the likelihood $L(\boldsymbol{\theta}, \mathbf{Y})$, and then combine the likelihood function with a prior distribution of the parameters to be estimated, $p(\boldsymbol{\theta})$, to obtain the posterior distribution, $L(\boldsymbol{\theta}, \mathbf{Y})p(\boldsymbol{\theta})$. We use numerical routines to maximize the value of the posterior, and then generate draws from the posterior distribution using the Random-Walk Metropolis-Hastings algorithm.

We use growth rates for the non-stationary variables in our data set (output, consumption, investment, and the real wage, which are non-stationary also in the theoretical model) and we write the measurement equation of the Kalman filter to match the seven observable series with their model counterparts. Thus, the state-space form of the model is characterized by the state equation

$$\mathbf{X}_t = \mathbf{A}(\boldsymbol{\theta})\mathbf{X}_{t-1} + \mathbf{B}(\boldsymbol{\theta})\varepsilon_t, \qquad \varepsilon_t \sim i.i.d.\ N(\mathbf{0}, \boldsymbol{\Sigma}_\varepsilon), \tag{41}$$

where $\mathbf{X}_t$ is a vector of endogenous variables, $\boldsymbol{\varepsilon}_t$ is a vector of innovations, and $\boldsymbol{\theta}$ is a vector of parameters; and the measurement equation

$$\mathbf{Y}_t = \mathbf{C}(\boldsymbol{\theta}) + \mathbf{D}\mathbf{X}_t + \boldsymbol{\eta}_t, \qquad \boldsymbol{\eta}_t \sim i.i.d.\ N(\mathbf{0}, \boldsymbol{\Sigma}_\eta), \tag{42}$$

where $\mathbf{Y}_t$ is a vector of observable variables, that is,

$$\mathbf{Y}_t = 100\left[\Delta \log Y_t,\ \Delta \log I_t,\ \Delta \log C_t,\ \Delta \log W_t,\ \log L_t,\ \log \pi_t,\ \log R_t\right], \tag{43}$$

and $\boldsymbol{\eta}_t$ is a vector of measurement errors, to be specified below.

The model contains 18 structural parameters, not including the parameters that characterize the exogenous shocks and measurement errors. We calibrate four parameters using standard values: the discount factor β is set to 0.99, the capital depreciation rate δ to 0.025, the capital share α in the Cobb-Douglas production function is set to 0.33, and the average ratio of government spending to output G/Y to 0.2.

We estimate the remaining 14 structural parameters: the steady-state growth rate, γ_z; the elasticity of the utilization rate to the rental rate of capital, η_ν;[7] the elasticity of the investment adjustment cost function, η_k; the habit parameter h and the labor supply elasticity ω; the steady-state wage and price ε^w and ε^p; the wage and price rigidity parameters θ_w and θ_p; the wage and price indexing parameters γ_w and γ_p; and the monetary policy parameters r_π, r_y, and ρ_s. In addition, we estimate the autoregressive parameters of the exogenous disturbances, as well as the standard deviations of the innovations and measurement errors.

3.2 Labor market shocks

In the log-linearized model the two labor market shocks—the shock to the disutility of labor ε_t^l and the wage markup shock ε_t^w—only enter the wage equation, and in exactly the same fashion. Letting $\widehat{x}_t$ denote the log deviation of any variable x_t from its steady state x, the log-linearized wage equation is given by

$$\begin{aligned} \widehat{w}_t &= \gamma_b \left[\widehat{w}_{t-1} - \widehat{\pi}_t + \gamma_w \widehat{\pi}_{t-1} - \widehat{\varepsilon}_t^z\right] + \gamma_o \left[\omega \widehat{l}_t - \widehat{\lambda}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l + \widehat{\varepsilon}_t^w\right] \\ &\quad + \gamma_f \left[\widehat{w}_{t+1} + \widehat{\pi}_{t+1} - \gamma_w \widehat{\pi}_t + \widehat{\varepsilon}_{t+1}^z\right], \end{aligned} \tag{44}$$

where γ_b, γ_o, and γ_f are convolutions of the structural parameters (see Appendix A). The real wage is driven by movements in the marginal rate of substitution, given by $\omega \widehat{l}_t - \widehat{\lambda}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l$, adjusted for shocks to the wage markup, $\widehat{\varepsilon}_t^w$. Thus, in the log-linearized model the two shocks are observationally equivalent, and if both shocks are present they can only be separately identified if they are assumed to follow different stochastic processes.

We will estimate two versions of the model that differ in their assumptions about the labor market shocks. In the first model, there is only one shock to the labor market, denoted $\varepsilon_{1,t}$, which follows the auto-regressive process

$$\log \varepsilon_{1,t} = (1-\rho_1) \log \varepsilon_1 + \rho_1 \log \varepsilon_{1,t-1} + \zeta_{1,t}, \qquad \zeta_{1,t} \sim i.i.d.\ N(0, \sigma_1^2). \tag{45}$$

In the second model, there is also a second shock, denoted $\varepsilon_{2,t}$, which is assumed to be i.i.d. normal:

$$\log \varepsilon_{2,t} = \log \varepsilon_2 + \zeta_{2,t}, \qquad \zeta_{2,t} \sim i.i.d.\ N(0, \sigma_2^2). \tag{46}$$

For our estimation, the exact interpretation of these two shocks is not important. Each shock could be interpreted as either a labor disutility shock or a wage markup shock. For normative questions, however, the interpretation of the two shocks is important; we will explore different interpretations in Section 4.[8]

[7] Following Smets and Wouters (2007), we define ψ_ν such that $\eta_\nu = (1-\psi_\nu)/\psi_\nu$ and estimate ψ_ν.

[8] Similar issues of interpretation also apply to the price markup shock, which can be interpreted as an efficient relative-price shock to a flexible-price sector in a two-sector model. See Smets and Wouters (20xx) [reference to be added].

3.3 Priors

Before estimation we assign prior distributions to the parameters to be estimated. These are summarized in Tables 1 and 2. Most of the priors are standard in the literature; see, for example, Smets and Wouters (2007) and Justiniano, Primiceri, and Tambalotti (2010).

The prior distribution for the steady-state growth rate, γ_z is Normal with mean 1.004 and standard deviation 0.001. The prior mean is close to the average gross growth rate per quarter over the sample period. The utilization rate elasticity ψ_ν and the habit parameter h are both assigned Beta priors with mean 0.5 and standard deviation 0.1; while the capital adjustment cost elasticity η_k is assigned a Normal prior with mean 4 and standard deviation 1.5. The labor supply elasticity ω (the inverse of the Frisch elasticity) is given a Gamma prior with mean 2 and standard deviation 0.75.

The two Calvo parameters for wage and price adjustment, θ_w and θ_p, are assigned Beta priors with means 3/4 and 2/3, respectively, and standard deviation 0.1, while the indexation parameters γ_w and γ_p are given Uniform priors over the unit interval. The two steady-state wage and price markups are both given Normal priors centered around 1.15, with a standard deviation of 0.05.

The coefficient r_π on inflation in the monetary policy rule is given a Normal prior with mean 1.7 and standard deviation 0.3, while the coefficient r_y on output growth is given a Gamma prior with mean 0.125 and standard deviation 0.1. The coefficient on the lagged interest rate, ρ_s, is assigned a Beta prior with mean 0.75 and a standard deviation of 0.1. All these are broadly consistent with empirically estimated monetary policy rules.

All persistence parameters for the shocks are given Beta priors with mean 0.5 and standard deviation 0.1. Finally, for the standard deviations of the shock innovations, we assign Gamma priors. We use Gamma priors for the standard deviations instead of Inverse Gamma priors as in Smets and Wouters (2007), Justiniano, Primiceri, and Tambalotti (2010) and others, in order to allow for very small (or zero) standard deviations. The Inverse Gamma distribution, by construction, puts no probability mass on zero, but we want to allow for the possibility that some shocks have zero variance.

As is common in the literature, we normalize some of the shocks before estimation, in order to better define a plausible range of variation. Two shocks—the investment-specific shock ε_t^i and the preference shock ε_t^b—are normalized to have a unitary contemporaneous impact on the physical capital stock and consumption, respectively.[9] The priors assigned to the innovation standard deviations of these shocks (denoted σ_i and σ_b) are Gamma distributions with mean 0.15 and standard deviation 1.0. The same prior is given to the innovation standard deviations of the productivity growth rate, σ_z, government spending, σ_g, the inflation target,

[9] To be more precise, as shown in Appendix A, the log-linearized equation determining the accumulation of physical capital is given by

$$\widehat{\bar{k}}_t = \frac{1-\delta}{\gamma_z}\left[\widehat{\bar{k}}_{t-1} - \widehat{\varepsilon}_t^z\right] + \left(1 - \frac{1-\delta}{\gamma_z}\right)\left[\widehat{i}_t + \widehat{\varepsilon}_t^i\right].$$

Instead of estimating the stochastic process for the investment shock $\widehat{\varepsilon}_t^i$, we define the shock $\widetilde{\varepsilon}_t^i \equiv (1-(1-\delta)/\gamma_z)\widehat{\varepsilon}_t^i$, and estimate the properties of $\widetilde{\varepsilon}_t^i$, which has a unitary contemporaneous impact on the physical capital stock $\widehat{\bar{k}}_t$. The same normalization is used in other equations where the investment shock enters. A similar normalization is applied to the preference shock ε_t^b.

σ_*, and the monetary policy shock, σ_r.

For the shock to the price markup and the two labor market shocks we follow a slightly different strategy. A standard procedure is to normalize these to have a unit impact on the rate of inflation and the real wage, respectively. However, the structural shocks have a very small direct impact on inflation and the real wage. For instance, the direct impact of the labor market shocks on the real wage in the log-linearized equation (44) is governed by the coefficient γ_o, which is a function of four parameters: the discount factor β, the labor supply elasticity ω, the Calvo wage parameter θ_w, and the steady-state wage markup ε^w. Our calibration of β and our prior means for ω, θ_w, and ε^w imply a value for γ_o of 0.0026. Normalizing the labor market shocks and using the same prior as for the other shock then would imply a prior mean for the innovation standard deviations σ_1 or σ_2 of the structural shock of close to 58 percent, Interpreting this shock as a wage markup shock with a mean slightly above unity, such volatility is clearly excessive.

We instead choose the prior mean for the innovations to the price markup and the labor market shocks based on a reasonable range of variation for the total price and wage markups. The steady-state markups have a prior mean of 1.15. We set the prior mean of the markup shock innovation to imply a two-standard deviation range of the total markup of $[1.0, 1.3]$, under the prior mean for the persistence of the markup shock, which is 0.5. This gives us a prior mean for the standard deviation of 5.6 percent, and we set the prior standard deviation also to 5.6, implying a fairly non-informative prior. We use this prior for the price markup shock as well as for the two labor market shocks.

The existing literature has typically found considerably more volatility in the estimated markup shocks than what is implied by our prior distributions.[10] To capture this additional volatility, we also allow for measurement errors in the real wage and inflation. The estimation procedure will then choose the combination of shocks and measurement errors that best fits the data. The measurement errors could be interpreted as proper errors in the measurement of wages and prices, as in Justiniano and Primiceri (2008). Alternatively, the errors could be interpreted as volatility in wages and inflation that cannot be explained by our model, possibly due to model misspecification. The two measurement errors are assumed to be i.i.d. normally distributed, and their standard deviations are assigned a Gamma prior with mean as well as standard deviation equal to the standard deviation of real wage growth and inflation in our sample period: 0.607 and 0.595, respectively.

All prior distributions are summarized in the third column of Tables 1 and 2.

3.4 Parameter estimates

Figure 1 shows the seven data series used for estimation. The four series expressed in quarterly growth rates—output, investment, consumption, and real wage—are clearly dominated by high-frequency fluctuations. In contrast, the remaining three series that are expressed

[10]For example, the estimated posterior median of Smets and Wouters (2007) and Justiniano, Primiceri, and Tambalotti (2010) imply an unconditional standard deviation of the wage markup shock around... [to be completed]. Chari, Kehoe, and McGrattan (2009) criticize these estimated models for implying unrealistically large markup volatility. Our procedure partly meets this criticism by reducing the posterior volatility of markup shocks using a more reasonable prior distribution.

in levels—hours, inflation, and the federal funds rate—all exhibit important low-frequency movements. For inflation and the funds rate, these movements coincide with the great inflation in the 1970s and the Volcker disinflation of the early 1980s. For hours worked, there is a strong cyclical pattern that coincides with expansions and contractions in the U.S. economy. There is also some low-frequency volatility left in hours, even if those related to sectoral shifts and demographics have been removed by Francis and Ramey (2009). The behavior of hours will play a key role in what follows.

Tables 1 and 2 show the mode and the 5th and 95th percentiles of the posterior distribution in the version of the model with two labor market shocks.[11] Two of the shocks in the model, the price markup shock and the i.i.d. labor market shock, obtain a zero standard deviation, while the measurement errors in wages and inflation are large relative to the overall volatility. The estimation procedure thus prefers to interpret these shocks as measurement errors rather than structural shocks. (The measurement error variances correspond to 68 percent of the variance of wage growth and 13 percent of the variance in inflation.) This is in line with Justiniano and Primiceri (2008), who show that i.i.d. shocks to the wage and price markups explain only the fluctuations in wages and inflation, and argue that these shocks therefore can be interpreted as measurement errors. However, our estimates gives an important role to the persistent labor market shock. Thus, not all unexplained movements in wages are interpreted as measurement errors, but there is a large persistent component that is better interpreted as a structural shock.

As the i.i.d. labor market shock obtains a zero variance in the model with two shocks, the model with one shocks yields parameter estimates that are identical with those reported in Tables 1 and 2. As a consequence, we only report results from the second model.

3.5 Interpreting the U.S. business cycle

Figure 2 shows the estimated shock series over the sample period, obtained using the Kalman smoother. There is some evidence of a "great moderation" in the shocks to technology growth, preferences, and monetary policy, that seem to become less volatile after the mid-1980s. There are also strong low-frequency components in several of the shock series.

The investment shock shows a peak in the early 1980s, and the inflation target has a peak in the mid-1970s. These two peaks correspond to the behavior of the federal funds rate and the rate of inflation. Thus, the model attributes much of the funds rate increase to an investment-specific technology shock (that drove up the real interest rate) and the low-frequency movements in inflation to persistent movements in the inflation target. Of course, the inflation target shock could represent any low-frequency deviations from the benchmark monetary policy rule, for instance, persistent errors in the estimated trend growth rate of the economy. It does not necessarily correspond to the actual inflation target of the Federal Reserve.

The exogenous process for government spending shows a strong negative trend over the sample period. This trend is rather similar to the behavior of U.S. net exports (or the U.S. current account), but also to the ratio of government spending to GDP. This is perhaps not

[11] [The posterior distribution remains to be added.]

surprising, as government spending in our model picks up any deviation of GDP from the sum of consumption and investment, and thus consists of both government spending and net exports.

Finally, the persistent labor market shock shows a strong cyclical pattern over the sample period that closely resembles the (inverted) movements in hours worked shown in Figure 1. This pattern is explained by the weak correlation between hours (that are very volatile) and the real wage (that is fairly stable). The driving force of the wage is the marginal rate of substitution, which in turn is determined by hours, the marginal utility of consumption, and the preference and labor market shocks, see equation (44). To reconcile the stable real wage with the volatile hours, the labor market shock has to move to offset the movements in hours. Since wages are also very sticky, the direct impact of the marginal rate of substitution on the wage is small, so the labor market shock moves to offset hours over a longer horizon, and therefore captures the behavior of hours over low and business-cycle frequencies. If wages had been less sticky, then the shock would have offset also the high-frequency movements in hours.

To better understand the behavior of the estimated model, Figures 3–5 show historical decompositions of GDP growth, real wage growth, and hours worked, and Table 3 shows an unconditional (long-run) variance decomposition of the seven variables in our data set.[12] By both metrics, output growth and real wage growth are driven almost entirely by the non-stationary technology shock. This shock explains close to 70 percent of fluctuations in GDP growth and 80 percent of fluctuations in real wage growth, and is also the main driver of GDP and the real wage in our sample. The technology shock is also responsible for most variability in investment growth, while the intertemporal preference shock is the main driver of consumption growth.

Hours, on the other hand, are mainly driven by the persistent labor market shock. Thus, while the introduction of measurement errors in the real wage removed the importance of the i.i.d. labor market shock, persistent shocks to the labor market are still important to explain the behavior of hours.[13]

4 Potential output and the output gap

One advantage of a fully specified structural model is that it can answer both positive and normative questions about the economy. For instance, the model can be used to evaluate whether fluctuations in economic activity are due to the efficient response of households and firms to disturbances to preferences and technology, or the result of different distortions in the economy, such as imperfect competition or price or wage rigidities. The model can then also be used to study the optimal design of economic policy in the face of such fluctuations.

[12][Add variance decompositions over business cycle frequencies.]

[13]In contrast to Justiniano, Primiceri, and Tambalotti (2010), the investment shock is not very important in our model: it explains only 8 percent of the volatility in output, while in Justiniano, Primiceri, and Tambalotti (2010) it explains 50 percent of the variance in output at business cycle frequencies. This is to a large extent due to our specification of the prior distribution for the shocks and the inclusion of measurement errors. With an inverse gamma prior instead of the gamma prior, the investment shock accounts for 25 percent of the volatility in output, and without measurement errors, it accounts for 44 percent.

For such purposes, however, one must take a stand on the interpretation of structural shocks.

Our model economy implies an efficient allocation where competition is perfect and there are no price and wage rigidities. That is, markups are zero and prices and wages are flexible. In this allocation all variables are at their efficient levels and fluctuate over time as agents efficiently respond to structural disturbances to technology and preferences. This hypothetical economy therefore is affected by five of our nine shocks: those to technology, investment, consumer preferences, the disutility of labor, and government spending. We will label these "efficient" shocks. The remaining four shocks—to the wage and price markups, monetary policy, and the inflation target—are instead labelled "inefficient."

Due to imperfect competition (and thus the presence of average wage and price markups), the steady-state level of output in the efficient allocation is higher than in the model with sticky wages and prices. For purposes of economic policy, and in particular monetary policy, a more relevant concept is the "potential" level of output, defined as the allocation with imperfect competition, flexible prices and wages, but constant markups, so there are no shocks to wage and price markups.[14] In the log-linearized model, this allocation has the same average (steady-state) level of output as in the model with sticky wages and prices, so any deviation between the actual and potential levels of output is zero in steady state. We will study the properties of this output gap.

Following Woodford (2003) and Adolfson, Laséen, Lindé, and Svensson (2008), we distinguish between two different measures of potential output. The first is derived from the allocation where prices and wages have been flexible forever, and thus uses the state variables from this allocation.[15] We call this the "unconditional potential output." The second measure instead uses the state variables in the allocation with sticky prices and wages. This measure, which we call "conditional potential output," is taken from an allocation where prices and wages have been sticky in the past, and then unexpectedly become flexible and are expected to remain flexible in the future. While it is straightforward to derive the behavior of the unconditional potential output by setting price and wage rigidities and inefficient shocks to zero, the conditional potential output is more involved. Appendix C describes how we calculate the conditional potential output from the solution of the model.

The existing literature focuses on the unconditional measure.[16] Neiss and Nelson (2003) motivate this choice by the fact that the conditional potential output depends not only on the efficient shocks, but also on past shocks to monetary policy (and other inefficient shocks), through their effect on the current state. Therefore, if monetary policy is set as a function of the conditional output gap, a mistake in monetary policy today is not fully offset in the future, as it has affected both actual and potential output, and therefore may have had a small effect on the output gap. However, Woodford (2003) argues that the conditional potential

[14]This definition follows Woodford (2003). A closely related concept is the "natural" level of output, which is the allocation with flexible prices and wages, but including exogenous shocks to price and wage markups. See also Justiniano and Primiceri (2008).

[15]In our model, the state variables are the physical stock of capital, lagged consumption, and lagged investment.

[16]Examples include Neiss and Nelson (2003), (2005), Edge, Kiley, and Laforte (2008), Sala, Söderström, and Trigari (2008), or Justiniano and Primiceri (2008). Coenen, Smets, and Vetlov (2009) instead focus on the conditional measure.

output is more closely related to the efficient level, which should depend on the current state of the economy. In our model where monopolists' profits are zero due to the fixed cost, there is indeed a constant distance between the efficient and the conditional potential levels of output. Another argument in favor of the conditional measure is that monetary policy that is determined by the unconditional output gap depends not only on the current state of the economy and the current shocks, but also on the entire path of historical shocks, as these affect the state variables in the allocation with flexible prices and wages.

We will not take a strong position regarding which measure is a better guide for monetary policy. Instead we will estimate both measures and show that there is very strong comovement between the conditional and the unconditional measures. Thus, as guides for monetary policy, the two measures will give very similar qualitative advice, even if quantities differ.

We will estimate the path of potential output (conditional and unconditional) and the related output gaps (the deviation of actual GDP from potential GDP) in our model. Importantly, this output gap is not a measure of the business cycle, for instance as defined by the NBER. Instead, the output gap should be seen as a measure of inefficiency in the economy, that is, the output fluctuations that are due to nominal rigidities and inefficient shocks. This is also the part of output fluctuations that monetary policy should lean against. For such normative issues, the interpretation of our two labor market shocks comes to the forefront. This is because one interpretation of the labor market shock (as a shock to the wage markup) implies that the shock is inefficient, while the alternative interpretation (as a shock to the disutility of labor) would make it efficient. The appropriate monetary policy therefore should lean against wage markup shocks but accomodate labor disutility shocks. We will present results under each of these interpretations.

Figure 6 shows actual GDP in our sample and the estimated paths for potential GDP. The top panels show conditional and unconditional potential GDP when the persistent labor market shock is interpreted as an inefficient wage markup shock. The two bottom panels show potential GDP when the shock is interpreted as a shock to the disutility of supplying labor. In all cases there is a close correspondence between the actual and potential levels of GDP. The conditional potential tends to follow actual GDP more closely than does the unconditional measure. This is because the conditional measure is based on the actual realizations of the state variables in the economy, while the unconditional depends on the state variables in the hypothetical economy with flexible prices and wages.

Comparing the two models, the estimates from the model with labor disutility shock are more closely related to actual GDP than in the model with wage markup shocks. Again, this is intuitive, as the model with efficient labor market shocks interprets a larger fraction of the volatility in GDP as efficient fluctuations. In the model with wage markup shocks, the trend in potential output is slightly smoother than that of actual output, as stressed by Sala, Söderström, and Trigari (2008) and Justiniano and Primiceri (2008). However, here potential output also displays some high-frequency movements. In the model with labor disutility shocks, there is no discernible difference between the potential and actual trends.

Figure 7 shows the implied output gaps. The shaded areas represent recessions dated by the NBER. For the reasons mentioned above, the conditional gaps tend to be smaller than the unconditional gaps. But apart from this difference in volatility, the two gaps are very closely correlated: for both models, the correlation between the conditional and unconditional gaps is above 0.97. In what follows we will therefore focus on the conditional output gaps.[17]

The interpretation of the labor market shock instead has important consequences for the behavior of the output gap. The model with wage markup shocks interprets a larger fraction of GDP fluctuations as inefficient, and therefore implies a larger output gap than the model with labor disutility shocks. The gap with markup shocks also has an important low-frequency component, with a falling trend in the 1970s and early 1980s and an increase until the late 1990s. The recession that started in 2008 implied a large fall in the output gap, although to a level higher than in the recessions in the mid-1970s and early 1980s. The peaks and troughs of this output gap also follow closely the NBER dating of expansions and recessions in the U.S. economy. Again, this is similar to the findings of Sala, Söderström, and Trigari (2008) and Justiniano and Primiceri (2008).

The output gap in the model with labor disutility shocks instead shows no low-frequency movements, and is less closely related to the NBER business cycle. While this gap tends to fall in recessions, there are also sharp falls that do not coincide with NBER recessions, for instance in the early 1990s and the mid-2000s. In the most recent recession, there is a small fall in the output gap in late 2008 but the gap then bounces back in 2009, and GDP is above potential throughout 2008 and 2009. This model thus interprets the recession as a decline in potential GDP that is greater than the decline in actual GDP (see the bottom panels of Figure 6).

There has been some focus in the literature on the interpretation of the recessions in the early 1980s. These recessions are typically interpreted as due to a monetary contraction during the Volcker disinflation. However, Walsh (2005) finds that the model estimated by Levin, Onatski, Williams, and Williams (2005) interprets this recessions as a larger fall in potential output than in actual output, leading to a positive output gap. A similar result is found by Chari, Kehoe, and McGrattan (2009). In contrast, and as in Sala, Söderström, and Trigari (2008) and Justiniano and Primiceri (2008), our estimated models imply a sharp reduction in the output gap, as actual output fell more than potential. Going back to Figure 2, the reduction in output is mainly explained by negative shocks to technology as well as to the inflation target and monetary policy. Thus, the model interpretation at least partly matches the common view of this period.

The historical decomposition of GDP growth in Figure 3 and the estimated shock series in Figure 2 help to explain why the two models interpret the 2008–09 recession so differently. These figures show that the contraction in GDP was mainly driven by a negative impulses to the investment shock and positive realizations of the persistent labor market shock. If we interpret this shock as a shock to the wage markup, then potential GDP falls due to the investment shock, but actual GDP is reduced also because of the wage markup shock. Then the output gap is negative. Under the alternative interpretation of the labor market shock, potential GDP falls as much as (or more than) actual GDP, due to a reduction in labor supply. The output gap then is positive through 2008 and 2009, implying that the economy was operating above its potential.

[17] [Discuss also discuss the precision of the output gap estimates, using draws from the posterior distribution.]

To understand in more detail the dynamic pattern of the output gaps in the two models, Figures 8 and 9 show a historical decomposition of the conditional output gaps. Both gaps are to a large extent driven by the persistent labor market shock, but this shock implies very different patterns in the output gap. The key issue in understanding the different gaps is whether the fluctuations in hours are a response to efficient or inefficient disturbances. The empirical model interprets movements in hours as mainly driven by the persistent labor market shock (see Figure 5). If these movements are driven by inefficient shocks (as in the model with wage markup shocks), then the inefficient movements in hours spill over to inefficient movements in GDP, and the output gap reflects these movements in hours. If instead fluctuations in hours are driven by efficient shocks, for instance to the disutility from supplying labor, then the output gap will reflect the fluctuations in hours that are not due to this shock.

The main impression from this exercise is that the interpretation of the labor market shock and labor market dynamics in general significantly affects our interpretation and understanding of economic fluctuations. The fact that the same empirical model can give very different interpretations of the efficiency of economic fluctuations has important implications for many applications of these models, such as calculations of the welfare cost of business cycle fluctuations or analyses of optimal monetary policy. The importance of the labor market leads us to analyze the relationship between the output gap and another measure of inefficiency: the so-called labor market wedge.

5 The output gap and the labor wedge

The output gap is one measure of inefficiency in GDP, and we have demonstrated that this gap is mainly driven by the model's interpretation of the labor market. An alternative measure of inefficiency, deriving directly from the labor market, is the wedge between consumers' marginal rate of substitution and firms' marginal product of labor, the so-called labor wedge. In the log-linearized version of our model, the marginal rate of substitution and the marginal product of labor are given by

$$\begin{aligned} \widehat{mrs}_t &= \omega\widehat{l}_t - \widehat{\lambda}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l, && (47) \\ \widehat{mpl}_t &= \alpha\widehat{k}_t - \alpha\widehat{l}_t. && (48) \end{aligned}$$

The labor wedge then is

$$\begin{aligned} \widehat{wedge}_t &= \widehat{mrs}_t - \widehat{mpl}_t \\ &= (\alpha+\omega)\widehat{l}_t - \widehat{\lambda}_t - \alpha\widehat{k}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l. && (49) \end{aligned}$$

In a model without capital and without habits in consumer preferences, it is straightforward to show that the labor wedge is directly proportional to the output gap (see Galí, Gertler, and López-Salido (2003)). In our model with capital and habits, the relationship is slightly more involved, but we show in Appendix D that it is given by

$$\widehat{y}_t - \widehat{y}_t^f = \frac{Y+F}{Y}\frac{1-\alpha}{\alpha+\omega}\left[\widehat{wedge}_t + \left(\widehat{\lambda}_t - \widehat{\lambda}_t^f\right) + \frac{\alpha(1+\omega)}{1-\alpha}\left(\widehat{k}_t - \widehat{k}_t^f\right)\right], \tag{50}$$

where $\widehat{y}_t^f, \widehat{\lambda}_t^f$, and $\widehat{k}_t^f$ are the levels of output, the marginal utility of consumption and the capital stock in the allocation with flexible prices and wages. The output gap, $\widehat{y}_t - \widehat{y}_t^f$, then is proportional to the sum of the labor wedge, a "marginal utility of consumption gap" and a "capital gap." Exactly how close is the relationship between the output gap and the labor wedge depends on parameter values and the behavior of these two other gaps.

Figure 10 shows the output gap and the labor wedge in the two interpretations of our model. Clearly, there is a very strong correspondence between these two concepts: the correlation between the gap and the labor wedge is 0.98 in the model with wage markup shocks and 0.85 in the model with labor disutility shocks. The close correspondence between the output gap and the labor wedge gives rise to two different implications. A negative implication is that the uncertainty surrounding the output gap discussed above is reflected also in uncertainty about the labor wedge. A more positive implication is that by understanding the labor wedge, we may gain some understanding about the behavior of the output gap.

To understand better the labor wedge, Figure 11 shows the wedge and its two components, the marginal rate of substitution and the marginal product of labor, along with the real wage in the two interpretations of the model. In both models, the marginal product of labor and the real wage are very stable, and move closely together. The marginal rate of substitution, on the other hand, is much more volatile. As a consequence, the labor wedge largely reflects movements in the marginal rate of substitution.

As stressed by Galí, Gertler, and López-Salido (2007), the labor wedge can be interpreted as a measure of inefficiency in the economy. Under the assumption that wages are allocative, the wedge can be decomposed into a total wage markup (the deviation of the wage from the marginal rate of substitution) and a total price markup (the deviation of the price from nominal marginal cost) as follows

$$\begin{aligned} \widehat{wedge}_t &= \widehat{mrs}_t - \widehat{mpl}_t \\ &= (\widehat{mrs}_t - \widehat{w}_t) + \left(\widehat{w}_t - \widehat{mpl}_t\right) \\ &= -(\widehat{w}_t - \widehat{mrs}_t) - \left(\widehat{p}_t - \widehat{w}_t^n + \widehat{mpl}_t\right) \\ &= -(\widehat{\mu}_t^w + \widehat{\mu}_t^p), \end{aligned} \tag{51}$$

where $\widehat{w}_t^n$ is the nominal wage and $\widehat{\mu}_t^w$ and $\widehat{\mu}_t^p$ are the total wage and price markups, respectively.

The fact that the wage moves closely with the marginal product of labor implies that the labor wedge is explained mainly by the wage markup. This is confirmed in Figure 12. As mentioned above, in the model with wage markup shocks, the very volatile marginal rate of substitution coupled with the stable real wage implies that the persistent labor market shock needs to offset the movements in the marginal rate of substitution. This model also implies a very volatile labor wedge. In the model with labor disutility shocks, the persistent labor market shock imply less movements in the marginal rate of substitution, and therefore a less volatile labor wedge.

[To be completed. Relate also Hall (1997), Shimer (2009), and others.]

6 Robustness and relation to the literature

[To be written.]

This section will relate our results better to the literature and discuss how alternative specifications of our model affect our results. For instance, we will discuss

- A model without measurement errors
- A model without labor market shocks
- The treatment of hours in the estimation, for example, using hours in first differences and HP filtered hours
- The importance of wage rigidities

7 Conclusions and final remarks

[To be written.]

- A standard business cycle model can generate a reasonable output gap
- But sensitive to shock interpretations
- Output gap closely related to labor wedge
- Key issue: How interpret fluctuations in hours worked?
  - Hours inefficient ⇒ large gap and wedge, important role for monetary policy
  - Hours efficient ⇒ small gap and wedge, less important role for monetary policy
- Practical issue: Treatment of hours key for estimates of output gap and labor wedge
- Future work:
  - Model with intensive and extensive margin. Are hours fluctuations due to intensive or extensive margin? Potentially important.
  - Model where labor market shocks are not observationally equivalent
  - See, for instance, the model by Gertler, Sala, and Trigari (2008)
- Is the NK model useful for policy analysis? Chari, Kehoe, and McGrattan (2009) say no: since the model is not reliable for welfare analysis, it is not useful for policy analysis. We think the model is useful, for instance for forecasting, counterfactual exercises, or to inform policymakers about the potential level of output. But as always, model results need to be interpreted with care.

A Model appendix

A.1 Stationary model

To find the steady state, we express the model in stationary form. Thus, for the non-stationary variables, let lower-case letters denote their value relative to the technology process Z_t:

$$y_t \equiv Y_t/Z_t, \quad k_t \equiv K_t/Z_t, \quad \bar{k}_t \equiv \bar{K}_t/Z_t, \quad i_t \equiv I_t/Z_t, \quad c_t \equiv C_t/Z_t,$$

$$g_t \equiv G_t/Z_t, \quad \lambda_t \equiv \Lambda_t Z_t, \quad w_t \equiv W_t/(Z_t P_t), \quad w_t^* \equiv W_t^*/(Z_t P_t),$$

where we note that the marginal utility of consumption Λ_t will shrink as the economy grows, and we express the wage in real terms. Also, denote the real rental rate of capital and real marginal cost by

$$r_t^k \equiv R_t^k/P_t, \quad mc_t \equiv MC_t/P_t,$$

and the optimal relative price as

$$p_t^* \equiv P_t^*/P_t.$$

Then we can write the model in terms of stationary variables as follows.

Effective capital (equation (3)):

$$k_t = \nu_t \bar{k}_{t-1}/\varepsilon_t^z; \tag{A1}$$

Physical capital accumulation (equation (4)):

$$\bar{k}_t = (1-\delta)\bar{k}_{t-1}/\varepsilon_t^z + \varepsilon_t^i \left[1 - \mathcal{S}\left(\frac{i_t}{i_{t-1}}\varepsilon_t^z\right)\right] i_t; \tag{A2}$$

Marginal utility of consumption (equation (7)):

$$\lambda_t = \frac{\varepsilon_t^b \varepsilon_t^z}{c_t \varepsilon_t^z - h c_{t-1}} - \beta h \mathrm{E}_t \left\{ \frac{\varepsilon_{t+1}^b}{c_{t+1}\varepsilon_{t+1}^z - h c_t} \right\}; \tag{A3}$$

Consumption Euler equation (equation (8)):

$$\lambda_t = \beta R_t \mathrm{E}_t \left\{ \frac{\lambda_{t+1}}{\varepsilon_{t+1}^z \pi_{t+1}} \right\}; \tag{A4}$$

Investment (equation (9)):

$$\begin{aligned} 1 \;\; &= \;\; Q_t \varepsilon_t^i \left[1 - \mathcal{S}\left(\frac{i_t}{i_{t-1}} \varepsilon_t^z \right) - \frac{i_t}{i_{t-1}} \varepsilon_t^z \, \mathcal{S}' \left(\frac{i_t}{i_{t-1}} \varepsilon_t^z \right) \right] \\ & \quad + \beta \mathrm{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t \varepsilon_{t+1}^z} Q_{t+1} \varepsilon_{t+1}^i \left(\frac{i_{t+1}}{i_t} \varepsilon_{t+1}^z \right)^2 \mathcal{S}' \left(\frac{i_{t+1}}{i_t} \varepsilon_{t+1}^z \right) \right\}; \end{aligned} \tag{A5}$$

Tobin's Q (equation (10)):

$$Q_t = \beta \mathrm{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t \varepsilon_{t+1}^z} \left[r_{t+1}^k \nu_{t+1} - \mathcal{A}(v_{t+1}) + (1-\delta) Q_{t+1} \right] \right\}; \tag{A6}$$

Capital utilization (equation (11)):

$$r_t^k = \mathcal{A}'(\nu_t); \tag{A7}$$

Production function (equation (16)):

$$y_t(i) = k_t(i)^{\alpha} L_t(i)^{1-\alpha} - F; \tag{A8}$$

Labor demand (equation (18)):

$$w_t = (1-\alpha)\, mc_t \left(\frac{k_t}{L_t} \right)^{\alpha}; \tag{A9}$$

Capital renting (equation (19)):

$$r_t^k = \alpha \, mc_t \left(\frac{k_t}{L_t} \right)^{\alpha - 1}; \tag{A10}$$

Price setting (equation (24)):

$$\mathrm{E}_t \left\{ \sum_{s=0}^{\infty} (\beta \theta_p)^s \left[\frac{\lambda_{t+s}}{\lambda_t} y_{t,t+s} \left(\Pi_{t,t+s} p_t^* \frac{P_t}{P_{t+s}} - \varepsilon_{t+s}^p mc_{t+s} \right) \right] \right\} = 0; \tag{A11}$$

Aggregate price index (equation (26)):

$$1 = \left[(1-\theta_p) \left(p_t^*\right)^{1/(\varepsilon_t^p - 1)} + \theta_p \left(\pi_{t-1}^{\gamma_p} \pi^{1-\gamma_p} \frac{1}{\pi_t} \right)^{1/(\varepsilon_t^p - 1)} \right]^{\varepsilon_t^p - 1}; \tag{A12}$$

Wage setting (equation (32)):

$$\mathrm{E}_t \left\{ \sum_{s=0}^{\infty} (\beta \theta_w)^s \lambda_{t+s} L_{t,t+s} \left[\Pi_{t,t+s}^w w_t^* \frac{P_t}{P_{t+s}} \frac{Z_t}{Z_{t+s}} - \varepsilon_{t+s}^w \varepsilon_{t+s}^b \varepsilon_{t+s}^l \frac{L_{t,t+s}^{\omega}}{\lambda_{t+s}} \right] \right\} = 0; \tag{A13}$$

Aggregate wage (equation (35)):

$$w_t = \left[(1-\theta_w)\,(w_t^*)^{1/(\varepsilon_t^w - 1)} + \theta_w \left(\gamma_z \pi_{t-1}^{\gamma_w} \pi^{1-\gamma_w} \frac{w_{t-1}}{\pi_t \varepsilon_t^z} \right)^{1/(\varepsilon_t^w - 1)} \right]^{\varepsilon_t^w - 1}; \tag{A14}$$

Government spending (equation (36)):

$$g_t = \left[1 - \frac{1}{\varepsilon_t^g} \right] y_t; \tag{A15}$$

Monetary policy rule (equation (38)):

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_s} \left[\left(\frac{\pi_t}{\pi_t^*} \right)^{r_\pi} \left(\frac{\Delta \log y_t + \log \varepsilon_t^z}{\gamma_z} \right)^{r_y} \right]^{1-\rho_s} \varepsilon_t^r; \tag{A16}$$

Resource constraint (equation (40)):

$$y_t = c_t + i_t + g_t + \mathcal{A}(\nu_t) \bar{k}_{t-1} / \varepsilon_t^z. \tag{A17}$$

A.2 Steady state

We use the stationary version of the model to find the steady state, and we let variables without a time subscript denote steady-state values. First, the expression for Tobin's Q in equation (A6) implies that the rental rate of capital is

$$r^k = \frac{\gamma_z}{\beta} - (1 - \delta) \tag{A18}$$

and the price-setting equation (A11) gives marginal cost as

$$mc = \frac{1}{\varepsilon^p}. \tag{A19}$$

The capital/labor ratio can then be retrieved using the capital renting equation (A10):

$$\frac{k}{L} = \left(\frac{\alpha\, mc}{r^k} \right)^{1/(1-\alpha)}, \tag{A20}$$

and the wage is given by the labor demand equation (A9) as

$$w = (1-\alpha)\, mc \left(\frac{k}{L} \right)^{\alpha}. \tag{A21}$$

The production function (A8) gives the output/labor ratio as

$$\frac{y}{L} = \left(\frac{k}{L} \right)^{\alpha} - \frac{F}{L}, \tag{A22}$$

and the fixed cost F is set to obtain zero profits at the steady state, implying

$$\frac{F}{L} = \left(\frac{k}{L}\right)^{\alpha} - w - r^k \frac{k}{L}. \tag{A23}$$

The output/labor ratio is then given by

$$\begin{aligned} \frac{y}{L} &= w + r^k \frac{k}{L} \\ &= \frac{r^k}{\alpha} \frac{k}{L}. \end{aligned} \tag{A24}$$

Finally, to determine the investment/output ratio, use the expressions for effective capital and physical capital accumulation in equations (A1) and (A2) to get

$$\frac{i}{k} = \left[1 - \frac{1-\delta}{\gamma_z}\right] \gamma_z, \tag{A25}$$

implying that

$$\begin{aligned} \frac{i}{y} &= \frac{i}{k} \frac{k}{L} \frac{L}{y} \\ &= \left[1 - \frac{1-\delta}{\gamma_z}\right] \frac{\alpha \gamma_z}{r^k}. \end{aligned} \tag{A26}$$

Given the government spending/output ratio g/y, the consumption/output ratio is then given by the resource constraint (A17) as

$$\frac{c}{y} = 1 - \frac{i}{y} - \frac{g}{y}. \tag{A27}$$

A.3 Log-linearized model

We log-linearize the stationary model around the steady state. Let $\widehat{x}_t$ denote the log deviation of the variable x_t or X_t from its steady-state level x or X:

$$\widehat{x}_t \equiv \log\left(\frac{x_t}{x}\right), \quad \widehat{x}_t \equiv \log\left(\frac{X_t}{X}\right). \tag{A28}$$

The log-linearized model is then given by the following system of equations for the endogenous variables.

Effective capital:

$$\widehat{k}_t + \widehat{\varepsilon}_t^z = \widehat{\nu}_t + \widehat{\bar{k}}_{t-1}; \tag{A29}$$

Physical capital accumulation:

$$\widehat{\bar{k}}_t = \frac{1-\delta}{\gamma_z}\left[\widehat{\bar{k}}_{t-1} - \widehat{\varepsilon}_t^z\right] + \left(1 - \frac{1-\delta}{\gamma_z}\right)\left[\widehat{i}_t + \widehat{\varepsilon}_t^i\right]; \tag{A30}$$

Marginal utility of consumption:

$$\left(1-\frac{h}{\gamma_z}\right)\left(1-\frac{\beta h}{\gamma_z}\right)\widehat{\lambda}_t=\frac{h}{\gamma_z}\left[\widehat{c}_{t-1}-\widehat{\varepsilon}_t^z\right]-\left(1+\frac{\beta h^2}{\gamma_z^2}\right)\widehat{c}_t$$
$$+\frac{\beta h}{\gamma_z}\mathrm{E}_t\left[\widehat{c}_{t+1}+\widehat{\varepsilon}_{t+1}^z\right]+\left(1-\frac{h}{\gamma_z}\right)\left[\widehat{\varepsilon}_t^b-\frac{\beta h}{\gamma_z}\mathrm{E}_t\widehat{\varepsilon}_{t+1}^b\right]; \tag{A31}$$

Consumption Euler equation:

$$\widehat{\lambda}_t=\mathrm{E}_t\widehat{\lambda}_{t+1}+\left[\widehat{r}_t-\mathrm{E}_t\widehat{\pi}_{t+1}\right]-\mathrm{E}_t\widehat{\varepsilon}_{t+1}^z; \tag{A32}$$

Investment:

$$\widehat{i}_t=\frac{1}{1+\beta}\left[\widehat{i}_{t-1}-\widehat{\varepsilon}_t^z\right]+\frac{1}{\eta_k\gamma_z^2(1+\beta)}\left[\widehat{q}_t+\widehat{\varepsilon}_t^i\right]+\frac{\beta}{1+\beta}\mathrm{E}_t\left[\widehat{i}_{t+1}+\widehat{\varepsilon}_{t+1}^z\right]; \tag{A33}$$

Tobin's Q:

$$\widehat{q}_t=\frac{\beta(1-\delta)}{\gamma_z}\mathrm{E}_t\widehat{q}_{t+1}+\left[1-\frac{\beta(1-\delta)}{\gamma_z}\right]\mathrm{E}_t\widehat{r}_{t+1}^k-\left[\widehat{r}_t-\mathrm{E}_t\widehat{\pi}_{t+1}\right]; \tag{A34}$$

Capital utilization:

$$\widehat{\nu}_t=\eta_\nu\widehat{r}_t^k; \tag{A35}$$

Production function:

$$\widehat{y}_t=\frac{Y+F}{Y}\left[\alpha\widehat{k}_t+(1-\alpha)\widehat{l}_t\right]; \tag{A36}$$

Labor demand:

$$\widehat{w}_t=\widehat{mc}_t+\alpha\widehat{k}_t-\alpha\widehat{l}_t; \tag{A37}$$

Capital renting:

$$\widehat{r}_t^k=\widehat{mc}_t-(1-\alpha)\widehat{k}_t+(1-\alpha)\widehat{l}_t; \tag{A38}$$

Phillips curve (combining equations (A11) and (A12)):

$$\widehat{\pi}_t=\iota_b\widehat{\pi}_{t-1}+\iota_o\left[\widehat{mc}_t+\widehat{\varepsilon}_t^p\right]+\iota_f\mathrm{E}_t\widehat{\pi}_{t+1}, \tag{A39}$$

where

$$\iota_b=\frac{\gamma_p}{1+\beta\gamma_p},\quad \iota_o=\frac{(1-\beta\theta_p)(1-\theta_p)}{\theta_p(1+\beta\gamma_p)},\quad i_f=\frac{\beta}{1+\beta\gamma_p};$$

Aggregate wage (combining equations (A13) and (A14)):

$$\begin{aligned} \widehat{w}_t &= \gamma_b \left[\widehat{w}_{t-1} - \widehat{\pi}_t + \gamma_w \widehat{\pi}_{t-1} - \widehat{\varepsilon}^z_t\right] + \gamma_o \left[\omega \widehat{l}_t - \widehat{\lambda}_t + \widehat{\varepsilon}^b_t + \widehat{\varepsilon}^l_t\right] \\ &\quad + \gamma_f \mathrm{E}_t \left[\widehat{w}_{t+1} + \widehat{\pi}_{t+1} - \gamma_w \widehat{\pi}_t + \widehat{\varepsilon}^z_{t+1}\right] + \gamma_o \widehat{\varepsilon}^w_t, \end{aligned} \tag{A40}$$

where

$$\gamma_b = \frac{1}{(1+\beta)(1+\kappa_w)}, \quad \gamma_o = \frac{\kappa_w}{1+\kappa_w}, \quad \gamma_f = \frac{\beta}{(1+\beta)(1+\kappa_w)},$$

$$\kappa_w = \frac{(1-\beta\theta_w)(1-\theta_w)}{\theta_w(1+\beta)[1+\omega\varepsilon^w/(\varepsilon^w-1)]};$$

Government spending:

$$\widehat{g}_t = \widehat{y}_t + \frac{1-g_y}{g_y}\widehat{\varepsilon}^g_t; \tag{A41}$$

Monetary policy rule:

$$\widehat{r}_t = \rho_s \widehat{r}_{t-1} + (1-\rho_s)\left[r_\pi\left(\widehat{\pi}_t - \pi^*_t\right) + r_y\left(\widehat{y}_t - \widehat{y}_{t-1} + \widehat{\varepsilon}^z_t\right)\right] + \widehat{\varepsilon}^r_t; \tag{A42}$$

Resource constraint:

$$\widehat{y}_t = \frac{c}{y}\widehat{c}_t + \frac{i}{y}\widehat{i}_t + \frac{g}{y}\widehat{g}_t + \frac{r^k k}{y}\widehat{\nu}_t. \tag{A43}$$

A.4 Flexible price/wage model

We complement the model with a version that has flexible prices and wages, that we use to construct our measure of potential output. In this model, real marginal cost is constant, inflation is zero, and the real wage is equal to the marginal rate of substitution. Also, the shocks to the price and wage markups and to monetary policy are all zero. Denoting by $\widehat{x}^f_t$ the log deviation of the variable x_t (or X_t) from steady state in this model, the model is characterized by the following equations:[18]

Effective capital:

$$\widehat{k}^f_t + \widehat{\varepsilon}^z_t = \widehat{\nu}^f_t + \widehat{\bar{k}}^f_{t-1}; \tag{A44}$$

Physical capital accumulation:

$$\widehat{\bar{k}}^f_t = \frac{1-\delta}{\gamma_z}\left[\widehat{\bar{k}}^f_{t-1} - \widehat{\varepsilon}^z_t\right] + \left(1 - \frac{1-\delta}{\gamma_z}\right)\left[\widehat{i}^f_t + \widehat{\varepsilon}^i_t\right]; \tag{A45}$$

[18] Here we write the model in terms of the state variables in the flexible price/wage model, so this version of the model defines the unconditional potential output. Appendix C shows how to construct the conditional potential output from the solution of our model.

Marginal utility of consumption:

$$\left(1-\frac{h}{\gamma_z}\right)\left(1-\frac{\beta h}{\gamma_z}\right)\widehat{\lambda}_t^f = \frac{h}{\gamma_z}\left[\widehat{c}_{t-1}^f - \widehat{\varepsilon}_t^z\right] - \left(1+\frac{\beta h^2}{\gamma_z^2}\right)\widehat{c}_t^f \tag{A46}$$
$$+\frac{\beta h}{\gamma_z}\mathrm{E}_t\left[\widehat{c}_{t+1}^f + \widehat{\varepsilon}_{t+1}^z\right] + \left(1-\frac{h}{\gamma_z}\right)\left[\widehat{\varepsilon}_t^b - \frac{\beta h}{\gamma_z}\mathrm{E}_t\widehat{\varepsilon}_{t+1}^b\right];$$

Consumption Euler equation:

$$\widehat{\lambda}_t^f = \mathrm{E}_t\widehat{\lambda}_{t+1}^f + \widehat{r}_t^f - \mathrm{E}_t\widehat{\varepsilon}_{t+1}^z; \tag{A47}$$

Investment:

$$\widehat{i}_t = \frac{1}{1+\beta}\left[\widehat{i}_{t-1}^f - \widehat{\varepsilon}_t^z\right] + \frac{1}{\eta_k\gamma_z^2(1+\beta)}\left[\widehat{q}_t^f + \widehat{\varepsilon}_t^i\right] + \frac{\beta}{1+\beta}\mathrm{E}_t\left[\widehat{i}_{t+1}^f + \widehat{\varepsilon}_{t+1}^z\right]; \tag{A48}$$

Tobin's Q:

$$\widehat{q}_t^f = \frac{\beta(1-\delta)}{\gamma_z}\mathrm{E}_t\widehat{q}_{t+1}^f + \left[1-\frac{\beta(1-\delta)}{\gamma_z}\right]\mathrm{E}_t\widehat{r}_{t+1}^{kf} - \widehat{r}_t^f; \tag{A49}$$

Capital utilization

$$\widehat{\nu}_t^f = \eta_\nu\widehat{r}_t^{kf}; \tag{A50}$$

Production function

$$\widehat{y}_t^f = \frac{Y+F}{Y}\left[\alpha\widehat{k}_t^f + (1-\alpha)\,\widehat{l}_t^f\right]; \tag{A51}$$

Labor demand

$$\widehat{w}_t^f = \alpha\widehat{k}_t^f - \alpha\widehat{l}_t^f; \tag{A52}$$

Capital renting

$$\widehat{r}_t^{kf} = -(1-\alpha)\widehat{k}_t^f + (1-\alpha)\widehat{l}_t^f; \tag{A53}$$

Labor supply:

$$\widehat{w}_t^f = \omega\widehat{l}_t^f - \widehat{\lambda}_t^f + \widehat{\varepsilon}_t^b; \tag{A54}$$

Government spending:

$$\widehat{g}_t^f = \widehat{y}_t^f + \frac{1-g_y}{g_y}\widehat{\varepsilon}_t^g; \tag{A55}$$

Resource constraint:

$$\widehat{y}_t^f = \frac{c}{y}\widehat{c}_t^f + \frac{i}{y}\widehat{i}_t^f + \frac{g}{y}\widehat{g}_t^f + \frac{r^k k}{y}\widehat{\nu}_t^f. \tag{A56}$$

B Data

GDP Real Gross Domestic Product in billions of chained 2005 dollars. Seasonally adjusted at annual rates. Source: U.S. Department of Commerce, Bureau of Economic Analysis, National Income and Product Accounts, Table 1.1.6. Last Revised: 2009-08-27. Divided by population to obtain real per capita GDP.

Investment Gross private domestic investment plus Personal Consumption Expenditures of durable goods, billions of dollars. Seasonally adjusted at annual rates. Source: U.S. Department of Commerce, Bureau of Economic Analysis, National Income and Product Accounts, Table 1.1.5. Last Revised: 2009-08-27. Deflated by the price level and divided by population to obtain real per capita investment.

Consumption Personal Consumption Expenditures of non-durable goods and services, billions of dollars. Seasonally adjusted at annual rates. Source: U.S. Department of Commerce, Bureau of Economic Analysis, National Income and Product Accounts, Table 1.1.5. Last Revised: 2009-08-27. Deflated by the price level and divided by population to obtain real per capita consumption.

Wages Compensation of employees, paid, billions of dollars. Seasonally adjusted at annual rates. Source: U.S. Department of Commerce, Bureau of Economic Analysis, National Income and Product Accounts, Table 1.10. Last Revised: 2009-08-27. Deflated by the price level and divided by employment to obtain real hourly compensation.

Employment Hours worked, total economy, billions of hours (at annual rate). Source: Francis and Ramey (2009), Valerie Ramey, and Bureau of Labor Statistics. Last Revised: 2009-08-11. Divided by population to obtain hours per worker.

Price level Gross Domestic Product: Implicit Price Deflator, index numbers, 2005=100. Seasonally adjusted. Source: U.S. Department of Commerce, Bureau of Economic Analysis, National Income and Product Accounts, Table 1.1.4. Last Revised: 2009-08-27.

Federal funds rate Effective federal funds rate, percent. Not Seasonally Adjusted. Source: Board of Governors of the Federal Reserve System

Population Civilian Noninstitutional Population, thousands. Source: FRED database, Federal Reserve Bank of St. Louis (Series ID CNP16OV); U.S. Department of Labor: Bureau of Labor Statistics. Not Seasonally Adjusted. Last Updated: 2009-09-04.

C Unconditional and conditional potential output

The unconditional potential output is defined as the level of output in the allocation where prices and wages have been flexible since the economy was initialized, and are expected to remain so in the future, while the conditional potential output is defined as the level of output in the allocation where prices and wages unexpectedly become flexible in the current period, and are expected to remain flexible in the future. The unconditional allocation comes out directly from the solution of the model with flexible prices and wages. Letting $\mathbf{X}_t^s$ and $\mathbf{X}_t^f$ be vectors that contain the variables in the equilibria with sticky and flexible prices and wages, respectively, $\boldsymbol{\varepsilon}_t$ a vector of exogenous shock processes, and $\boldsymbol{\zeta}_t$ a vector of innovations, the solution is of the form

$$\begin{bmatrix} \mathbf{X}_t^s \\ \mathbf{X}_t^f \\ \boldsymbol{\varepsilon}_t \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{ss} & \mathbf{A}_{sf} & \mathbf{A}_{s\varepsilon} \\ \mathbf{A}_{fs} & \mathbf{A}_{ff} & \mathbf{A}_{f\varepsilon} \\ \mathbf{A}_{\varepsilon s} & \mathbf{A}_{\varepsilon f} & \mathbf{A}_{\varepsilon\varepsilon} \end{bmatrix} \begin{bmatrix} \mathbf{X}_{t-1}^s \\ \mathbf{X}_{t-1}^f \\ \boldsymbol{\varepsilon}_{t-1} \end{bmatrix} + \begin{bmatrix} \mathbf{B}_{s\zeta} \\ \mathbf{B}_{f\zeta} \\ \mathbf{B}_{\varepsilon\zeta} \end{bmatrix} \begin{bmatrix} \boldsymbol{\zeta}_t \end{bmatrix}. \tag{C1}$$

As the monetary policy rule is written in terms of output growth, the flexible price/wage block is exogenous to the sticky price/wage block, so $\mathbf{A}_{sf} = \mathbf{0}$. Furthermore, as the flexible price/wage model depends on the state variables in that same allocation, also $\mathbf{A}_{fs} = \mathbf{0}$, and $\mathbf{A}_{ff}$ has non-zero entries only in the columns corresponding to the three state variables: $\bar{k}_t$, c_{t-1}, and i_{t-1}.

To define the conditional potential output, which depends on current state variables in the sticky price/wage model but expectations are consistent with flexible prices in the future, we manipulate the submatrices $\mathbf{A}_{ff}$ and $\mathbf{A}_{fs}$, so that the non-zero entries in $\mathbf{A}_{ff}$ are moved to the corresponding columns in $\mathbf{A}_{fs}$. That way, the flexible price/wage allocation depends on the state variables $\bar{k}_t, c_{t-1}, i_{t-1}$ in the sticky price/wage model, but we ensure that expectations are consistent with flexible prices and wages in the future, as in the unconditional allocation.

D The output gap and the labor wedge

This appendix derives the relationship between the output gap, the labor wedge, and the price and wage markups. Households' instantaneous utility is given by

$$\varepsilon_t^b \left[\log\left(C_t - hC_t\right) - \varepsilon_t^l \frac{L_t^{1+\omega}}{1+\omega} \right]. \tag{D1}$$

The marginal rate of substitution between consumption and leisure is then given by

$$MRS_t = \frac{\varepsilon_t^b \varepsilon_t^l L_t^{\omega}}{\Lambda_t}, \tag{D2}$$

where Λ_t is the marginal utility of consumption. In the stationary version of the model, the marginal rate of substitution is

$$mrs_t = \frac{MRS_t}{Z_t} = \frac{\varepsilon_t^b \varepsilon_t^l L_t^{\omega}}{\lambda_t}, \tag{D3}$$

where $\lambda_t = \Lambda_t Z_t$. (See Appendix A.1.)

The production function in the intermediate goods sector is given by

$$Y_t = \max\left\{ K_t^{\alpha} \left(Z_t L_t\right)^{1-\alpha} - Z_t F, 0 \right\}, \tag{D4}$$

so the marginal product of labor is

$$MPL_t = (1-\alpha) K_t^{\alpha} Z_t^{1-\alpha} L_t^{-\alpha}, \tag{D5}$$

and in the stationary model it is

$$mpl_t = \frac{MPL_t}{Z_t} = (1-\alpha) k_t^{\alpha} L_t^{-\alpha}, \tag{D6}$$

where $k_t = K_t / Z_t$.

The labor wedge in the stationary model is then given by

$$wedge_t = \frac{mrs_t}{mpl_t} = \frac{\varepsilon_t^b \varepsilon_t^l L_t^{\alpha+\omega}}{(1-\alpha)\lambda_t k_t^{\alpha}}, \tag{D7}$$

and in the log-linearized model it is

$$\begin{aligned} \widehat{wedge}_t &= \widehat{mrs}_t - \widehat{mpl}_t \\ &= (\alpha+\omega)\widehat{l}_t - \widehat{\lambda}_t - \alpha \widehat{k}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l. \end{aligned} \tag{D8}$$

Using the log-linearized production function in (A36), we can write employment as

$$\widehat{l}_t = \frac{1}{1-\alpha} \left[\frac{Y}{Y+F} \widehat{y}_t - \alpha \widehat{k}_t \right], \tag{D9}$$

so the wedge can be written as

$$\widehat{wedge}_t = \frac{\alpha+\omega}{1-\alpha}\frac{Y}{Y+F}\widehat{y}_t - \widehat{\lambda}_t - \frac{\alpha(1+\omega)}{1-\alpha}\widehat{k}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l. \tag{D10}$$

Under the assumption that wages are allocational, the labor wedge can be written in terms of the price and wage markups as

$$\begin{aligned} \widehat{wedge}_t &= \left[\widehat{mrs}_t - (\widehat{w}_t^n - \widehat{p}_t)\right] - \left[\widehat{mpl}_t - (\widehat{w}_t^n - \widehat{p}_t)\right] \\ &= -\left(\widehat{\mu}_t^w + \widehat{\mu}_t^p\right), \end{aligned} \tag{D11}$$

where $\widehat{w}_t^n$ is the nominal wage, so $\widehat{\mu}_t^w = (\widehat{w}_t^n - \widehat{p}_t) - \widehat{mrs}_t$ is the markup of the real wage over the marginal rate of substitution and $\widehat{\mu}_t^p = \widehat{p}_t - \left(\widehat{w}_t^n - \widehat{mpl}_t\right)$ is the markup of prices over nominal marginal cost. (See Galí, Gertler, and López-Salido (2007).)

In the equilibrium with flexible prices and wages and no inefficient shocks, the markups are constant at their steady-state values, so $\widehat{\mu}_t^w = \widehat{\mu}_t^p = 0$ and also $\widehat{wedge}_t = 0$. Using the expression for the wedge in (D10) we can then write output in the allocations with sticky prices and wages and flexible prices and wages as

$$\widehat{y}_t = \frac{Y+F}{Y}\frac{1-\alpha}{\alpha+\omega}\left[\widehat{wedge}_t + \widehat{\lambda}_t + \frac{\alpha(1+\omega)}{1-\alpha}\widehat{k}_t - \left(\widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l\right)\right] \tag{D12}$$

and

$$\widehat{y}_t^f = \frac{Y+F}{Y}\frac{1-\alpha}{\alpha+\omega}\left[\widehat{\lambda}_t^f + \frac{\alpha(1+\omega)}{1-\alpha}\widehat{k}_t^f - \left(\widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l\right)\right]. \tag{D13}$$

Finally, the output gap can be written in terms of the labor wedge as

$$\widehat{y}_t - \widehat{y}_t^f = \frac{Y+F}{Y}\frac{1-\alpha}{\alpha+\omega}\left[\widehat{wedge}_t + \left(\widehat{\lambda}_t - \widehat{\lambda}_t^f\right) + \frac{\alpha(1+\omega)}{1-\alpha}\left(\widehat{k}_t - \widehat{k}_t^f\right)\right]. \tag{D14}$$

References

Adolfson, Malin, Stefan Laséen, Jesper Lindé, and Lars E.O. Svensson (2008), "Optimal monetary policy in an operational medium-sized DSGE model," Working Paper No. 225, Sveriges Riksbank.

Altig, David E., Lawrence J. Christiano, Martin Eichenbaum, and Jesper Lindé (2005), "Firm-specific capital, nominal rigidities and the business cycle," Working Paper No. 11034, National Bureau of Economic Research.

An, Sungbae and Frank Schorfheide (2007), "Bayesian analysis of DSGE models," *Econometric Reviews* 26 (2–4), 113–172.

Basu, Susanto and John Fernald (2009), "What do we know and not know about potential output?" Working Paper No. 2009-05, Federal Reserve Bank of San Francisco.

Calvo, Guillermo A. (1983), "Staggered prices in a utility-maximizing framework," *Journal of Monetary Economics* 12 (3), 383–398.

Chari, V.V., Patrick J. Kehoe, and Ellen R. McGrattan (2007), "Business cycle accounting," *Econometrica*, 75 (3), 781–836.

Chari, V.V., Patrick J. Kehoe, and Ellen R. McGrattan (2009), "New Keynesian models: Not yet useful for policy analysis," *American Economic Journal: Macroeconomics*, 1 (1), 242–266.

Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans (2005), "Nominal rigidities and the dynamic effects of a shock to monetary policy," *Journal of Political Economy* 113 (1), 1–45.

Coenen, Günter, Frank Smets, and Igor Vetlov (2009), "Estimation of the Euro Area output gap using the NAWM" Working Paper No. 5/2009, Bank of Lithuania.

Edge, Rochelle M., Michael T. Kiley, and Jean-Philippe Laforte (2008), "Natural rate measures in an estimated DSGE model of the U.S. economy," *Journal of Economic Dynamics and Control* 32 (8), 2512–2535.

Erceg, Christopher J., Dale W. Henderson, and Andrew T. Levin (2000), "Optimal monetary policy with staggered wage and price contracts," *Journal of Monetary Economics* 46 (2), 281–313.

Francis, Neville and Valerie A. Ramey (2009), "Measures of per capita hours and their implications for the technology-hours debate," *Journal of Money, Credit, and Banking* 41 (6), 1071–1097.

Galí, Jordi, Mark Gertler, and J. David López-Salido (2003), "Markups, gaps, and the welfare cost of business fluctuations," Manuscript, CREI.

Galí, Jordi, Mark Gertler, and J. David López-Salido (2007), "Markups, gaps, and the welfare cost of business fluctuations," *Review of Economics and Statistics* 89 (1), 44–59.

Gertler, Mark, Luca Sala, and Antonella Trigari (2008), "An estimated monetary DSGE model with unemployment and staggered nominal wage bargaining," *Journal of Money, Credit, and Banking* 40 (8), 1713–1764.

Goodfriend, Marvin and Robert G. King (1997), "The new neoclassical synthesis and the role of monetary policy," in Ben S. Bernanke and Julio J. Rotemberg (eds.), *NBER Macroeconomics Annual*, The MIT Press.

Hall, Robert E. (1997), "Macroeconomic fluctuations and the allocation of time," *Journal of Labor Economics* 15 (1, part 2), S223–S250.

Justiniano, Alejandro and Giorgio E. Primiceri (2008), "Potential and natural output," Unpublished manuscript, Northwestern University.

Justiniano, Alejandro, Giorgio E. Primiceri, and Andrea Tambalotti (2010), "Investment shocks and business cycles," *Journal of Monetary Economics* 57 (2), 132–145.

King, Robert G., Charles I. Plosser, and Sergio T. Rebelo (1988), "Production, growth and business cycles : I. The basic neoclassical model," *Journal of Monetary Economics*, 21 (2–3), 195–232.

Kydland, Finn E. and Edward C. Prescott (1982), "Time to build and aggregate fluctuations," *Econometrica*, 50 (6), 1345–1370.

Levin, Andrew T., Alexei Onatski, John C. Williams, and Noah Williams (2005), "Monetary policy under uncertainty in micro-founded macroeconometric models," in Gertler, Mark and Kenneth Rogoff (eds.), *NBER Macroeconomics Annual*, The MIT Press.

Long, John B. and Charles I. Plosser (1983), "Real business cycles," *Journal of Political Economy*, 91 (1), 39–69.

Neiss, Katharine S. and Edward Nelson (2003), "The real-interest-rate gap as an inflation indicator," *Macroeconomic Dynamics*, 7 (2), 239–262.

Neiss, Katharine S. and Edward Nelson (2005), "Inflation dynamics, marginal cost, and the output gap: Evidence from three countries," *Journal of Money, Credit, and Banking* 37 (6), 1019–1045.

Rotemberg, Julio J. and Michael Woodford (1997), "An optimization-based econometric framework for the evaluation of monetary policy," in Ben S. Bernanke and Julio J. Rotemberg (eds.), *NBER Macroeconomics Annual*, The MIT Press.

Sala, Luca, Ulf Söderström, and Antonella Trigari (2008), "Monetary policy under uncertainty in an estimated model with labor market frictions," *Journal of Monetary Economics*, 55 (5), 983–1006.

Shimer, Robert (2009), "Convergence in macroeconomics: The labor wedge," *American Economic Journal: Macroeconomics*, 1 (1), 280–297.

Smets, Frank and Raf Wouters (2003), "An estimated dynamic stochastic general equilibrium model of the Euro area," *Journal of the European Economic Association* 1 (5), 1123–1175.

——— (2007), "Shocks and frictions in U.S. business cycles: A Bayesian DSGE approach," *American Economic Review* 97 (3), 586–606.

Walsh, Carl E. (2005), "Discussion of 'Monetary policy under uncertainty in micro-founded macroeconometric models'," in Gertler, Mark and Kenneth Rogoff (eds.), *NBER Macroeconomics Annual*, The MIT Press.

Woodford, Michael (2003), *Interest and Prices: Foundations of a Theory of Monetary Policy*, Princeton University Press.

Yun, Tack (1996), "Nominal price rigidity, money supply endogeneity, and business cycles," *Journal of Monetary Economics*, 37 (2), 345–370.

Table 1: Prior and posterior distributions of structural parameters

		Prior distribution	Posterior distribution		
			Mode	5%	95%
Steady-state growth rate	γ_z	N (1.004,0.001)	1.0029		
Utilization rate elasticity	ψ_ν	B (0.5,0.1)	0.889		
Capital adjustment cost elasticity	η_k	N (4,1.5)	0.071		
Habit parameter	h	B (0.5,0.1)	0.913		
Labor supply elasticity	ω	G (2,0.75)	2.355		
Calvo wage parameter	θ_w	B (0.75,0.1)	0.730		
Calvo price parameter	θ_p	B (0.66,0.1)	0.802		
Wage indexing parameter	γ_w	U (0,1)	0.999		
Price indexing parameter	γ_p	U (0,1)	0.000		
Steady-state wage markup	ε^w	N (1.15,0.05)	1.156		
Steady-state price markup	ε^p	N (1.15,0.05)	1.199		
Policy response to inflation	r_π	N (1.7,0.3)	2.807		
Policy response to output	r_y	N (0.125,0.1)	0.272		
Policy inertia	ρ_s	B (0.75,0.1)	0.347		

This table reports the prior and posterior distribution of the estimated structural parameters. For the uniform distribution, the two numbers in parentheses are the lower and upper bounds; for the other distributions the two numbers are the mean and the standard deviation of the distribution.

Table 2: Prior and posterior distributions of shock and measurement error parameters

		Prior distribution	Posterior distribution		
			Mode	5%	95%
(a) Autoregressive parameters					
Productivity growth rate	ρ_z	B (0.5,0.15)	0.317		
Preferences	ρ_b	B (0.5,0.15)	0.418		
Investment-specific technology	ρ_i	B (0.5,0.15)	0.928		
Price markup	ρ_p	B (0.5,0.15)	0.500		
Government spending	ρ_g	B (0.5,0.15)	0.983		
Inflation target	ρ_*	B (0.5,0.15)	0.945		
AR(1) labor market shock	ρ_1	B (0.5,0.15)	0.968		
(b) Standard deviations					
Productivity growth rate	σ_z	G (0.15,1.0)	1.176		
Preferences	σ_b	G (0.15,1.0)	0.276		
Investment-specific technology	σ_i	G (0.15,1.0)	0.044		
Price markup	σ_p	G (5.6,5.6)	0.000		
Government spending	σ_g	G (0.15,1.0)	0.516		
Inflation target	σ_*	G (0.15,1.0)	0.081		
Monetary policy	σ_r	G (0.15,1.0)	0.148		
AR(1) labor market shock	σ_1	G (5.6,5.6)	5.696		
i.i.d. labor market shock	σ_2	G (5.6,5.6)	0.000		
(c) Measurement error standard deviations					
Wage growth	$\sigma_{\eta w}$	G (0.607,0.607)	0.501		
Inflation	$\sigma_{\eta\pi}$	G (0.595,0.595)	0.211		

This table reports the prior and posterior distribution of the estimated parameters of the exogenous shock processes and measurement errors. The two numbers in parentheses are the mean and the standard deviation of the distribution.

Table 3: Unconditional variance decomposition

Shock	Output	Investment	Consumption	Real wage	Hours	Inflation	Interest rate
Variance in model	1.67	14.66	0.47	0.27	44.48	0.20	0.58
Fraction of model variance due to							
Technology	0.67	0.58	0.28	0.80	0.20	0.06	0.05
Preference	0.00	0.08	0.58	0.01	0.00	0.00	0.01
Investment	0.08	0.11	0.02	0.05	0.05	0.22	0.65
Govt spending	0.03	0.06	0.03	0.01	0.03	0.01	0.02
Price markup	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Monetary policy	0.08	0.08	0.00	0.00	0.01	0.01	0.00
Inflation target	0.04	0.04	0.00	0.04	0.02	0.70	0.23
AR(1) labor market	0.09	0.05	0.08	0.10	0.70	0.01	0.04
iid labor market	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 1: Data

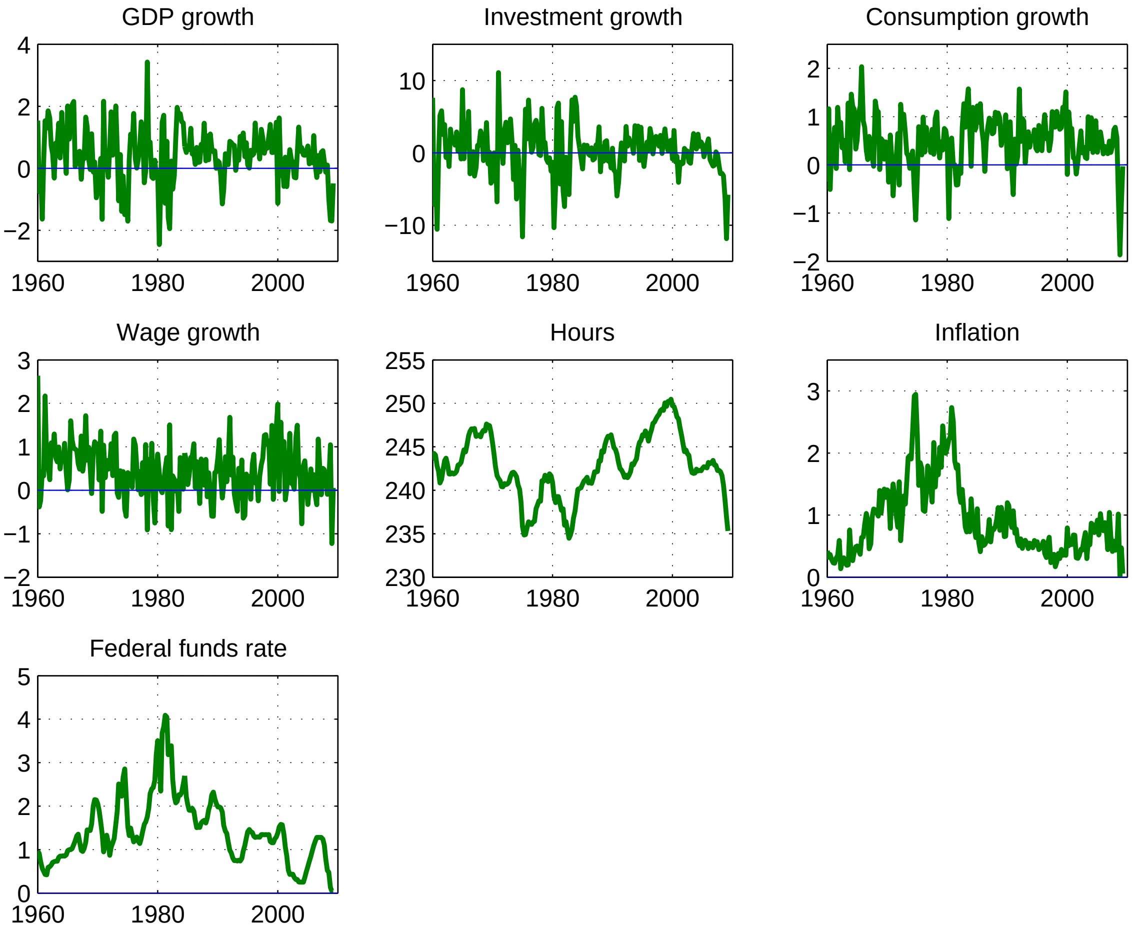

Figure 2: Estimated shocks

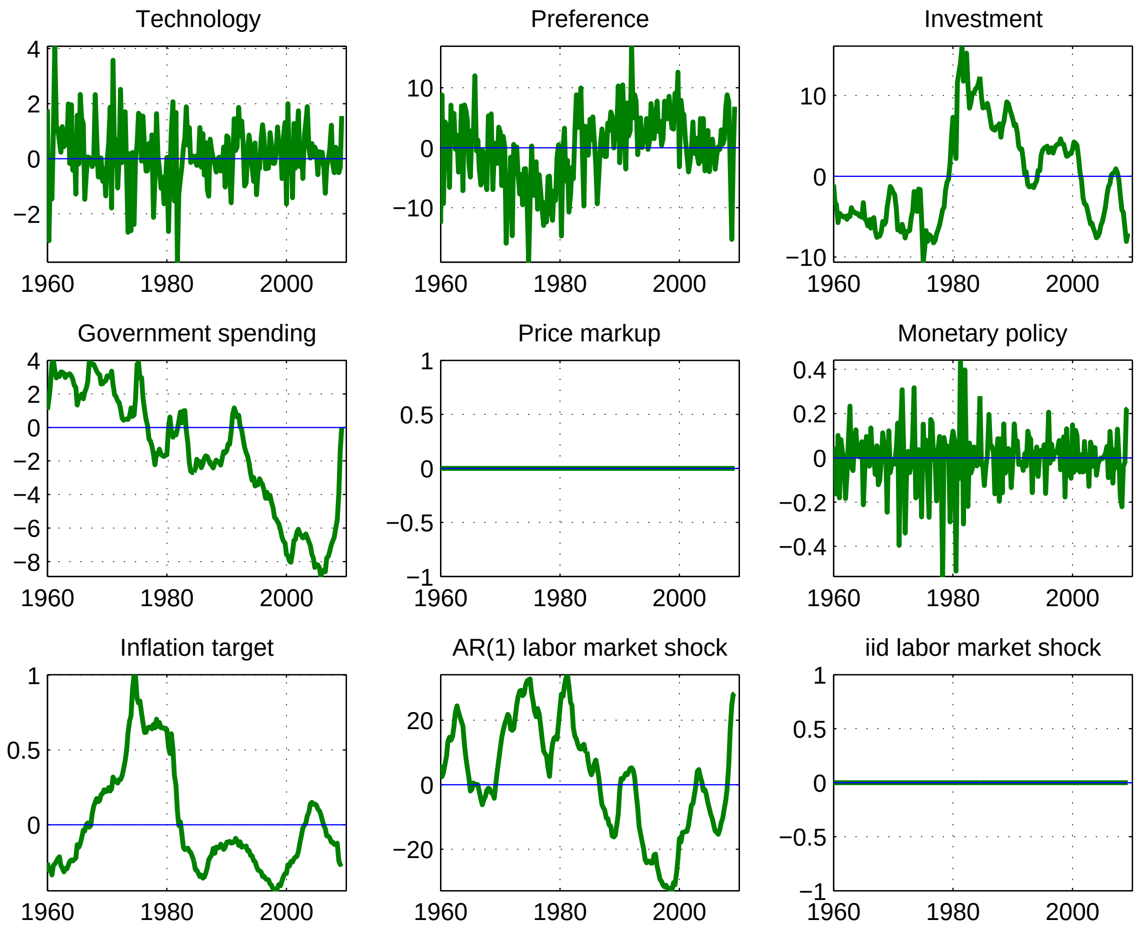

Figure 3: Historical decomposition of output growth

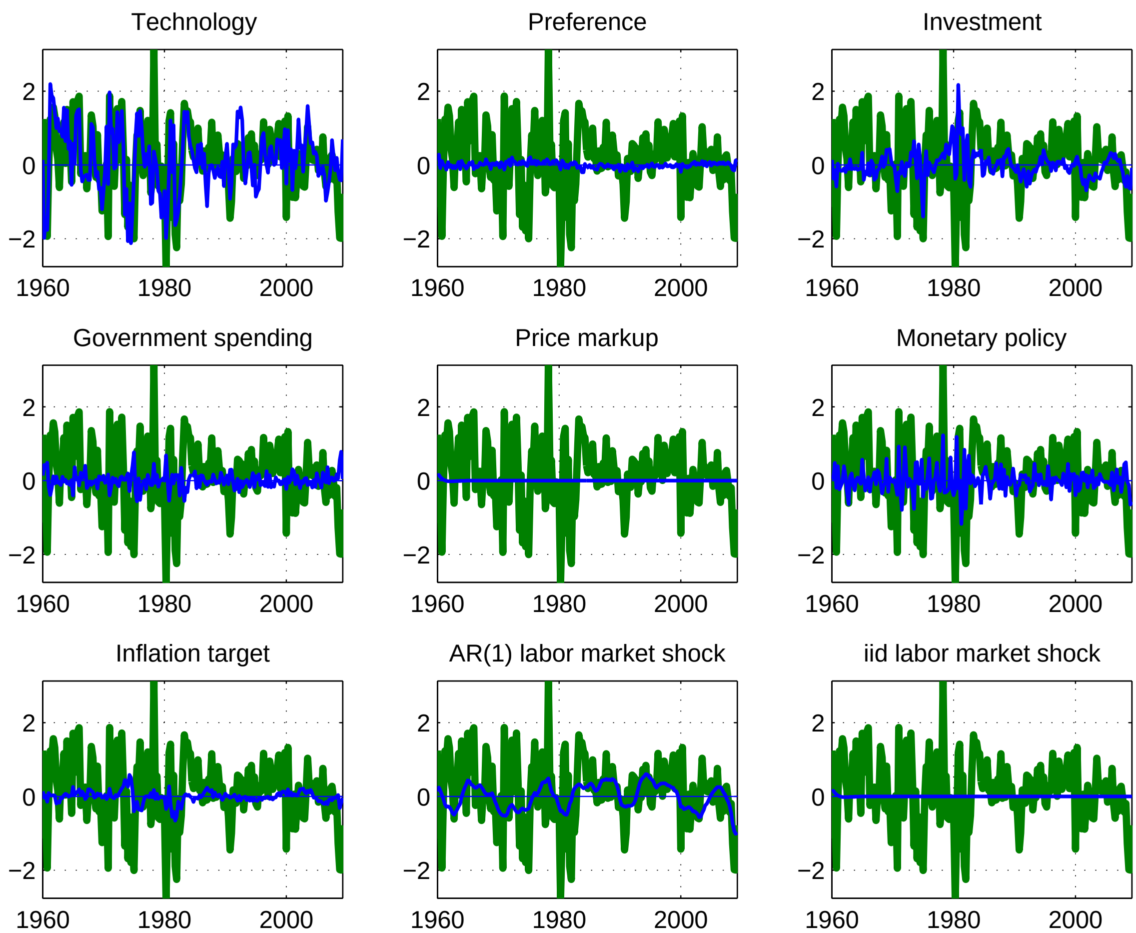

Figure 4: Historical decomposition of real wage growth

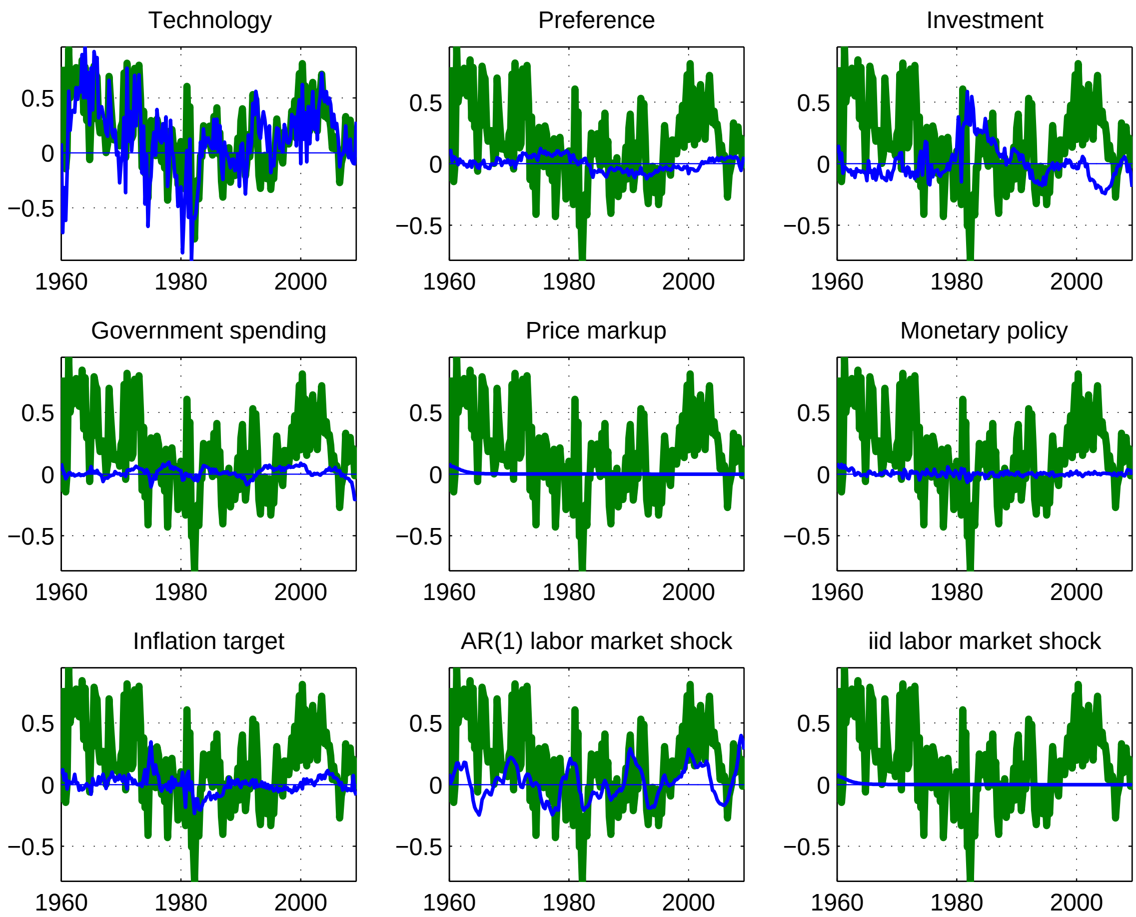

Figure 5: Historical decomposition of hours

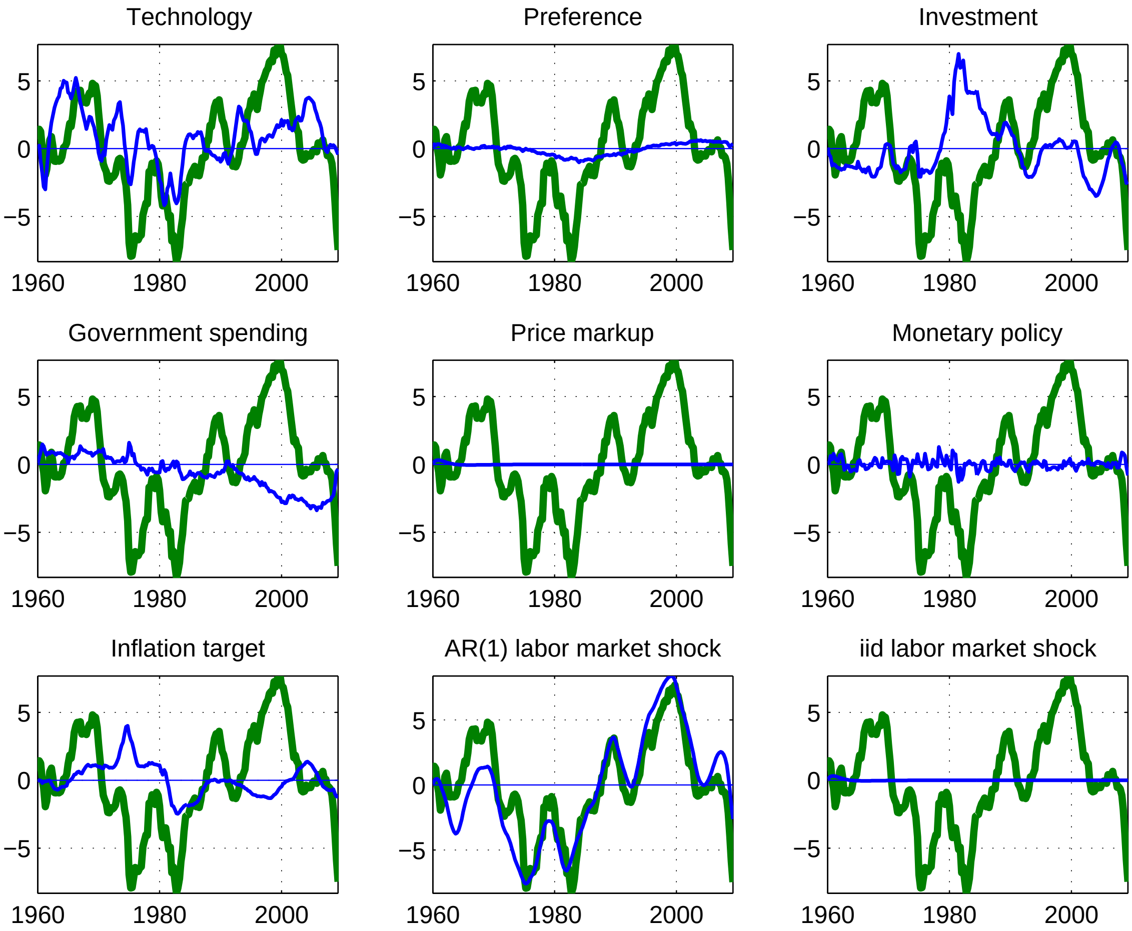

Figure 6: Actual and potential GDP

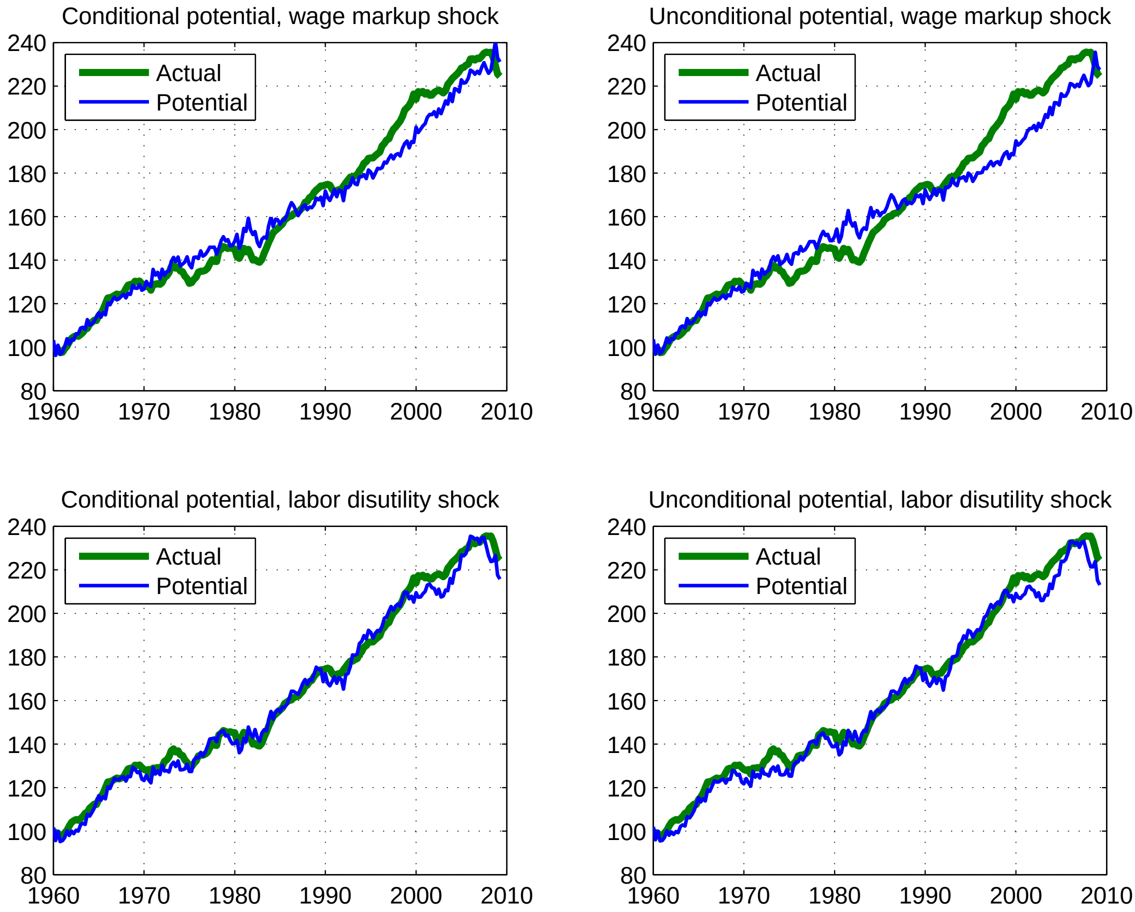

Figure 7: Estimated output gaps

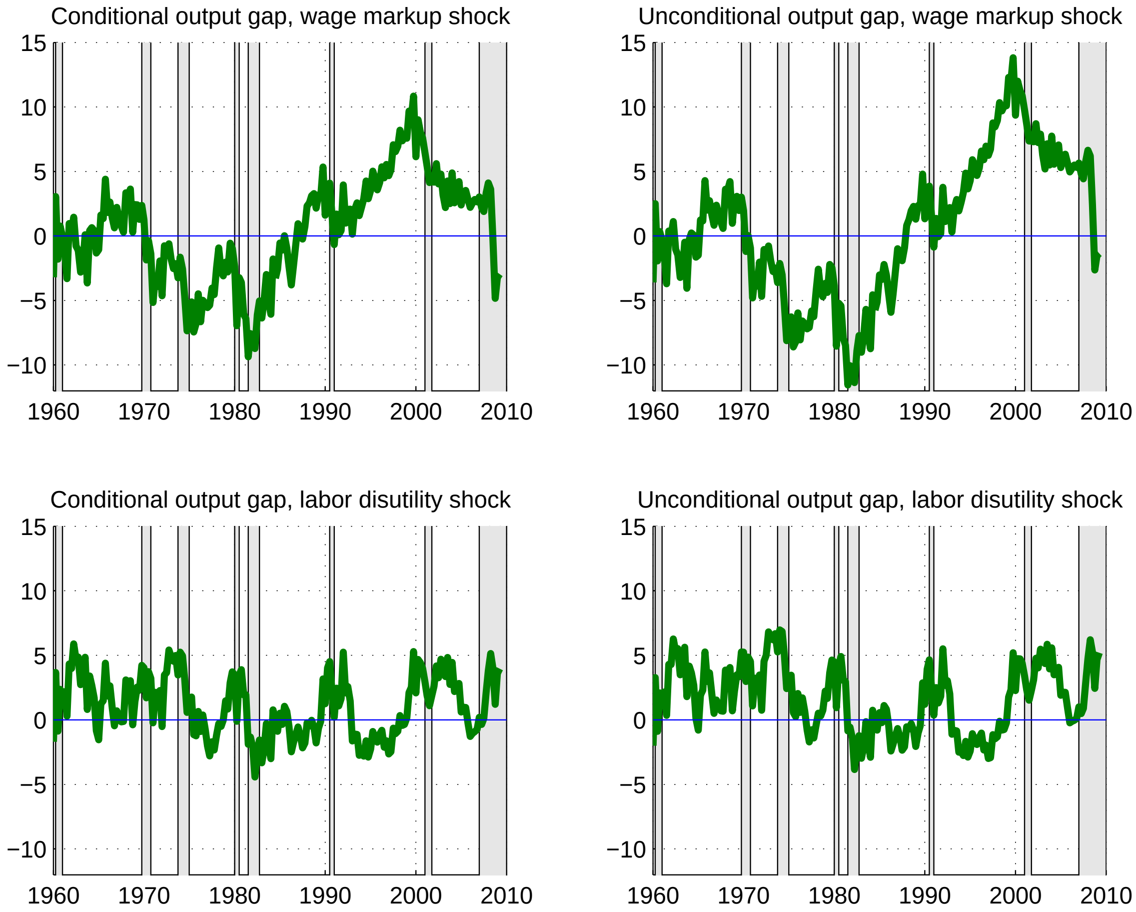

Figure 8: Historical decomposition of conditional output gap in model with wage markup shocks

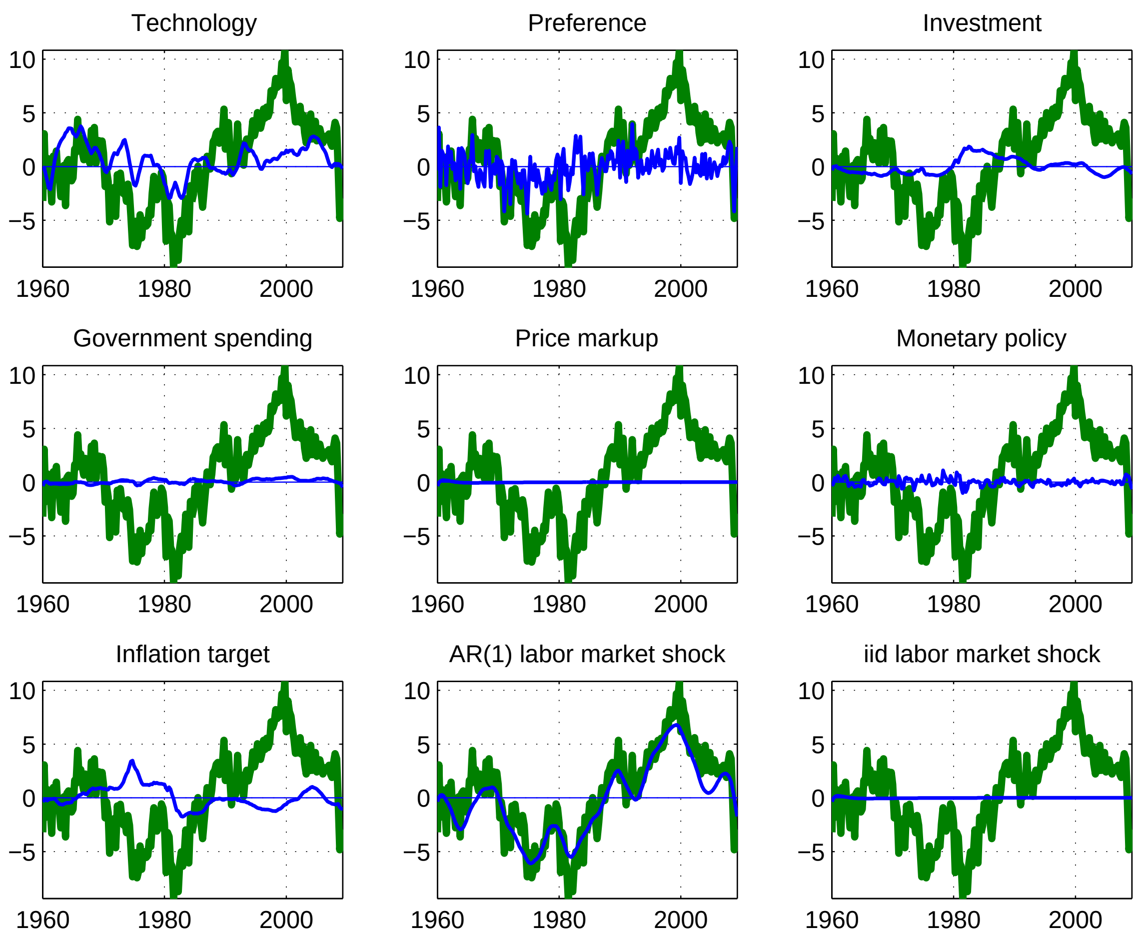

Figure 9: Historical decomposition of conditional output gap in model with labor disutility shocks

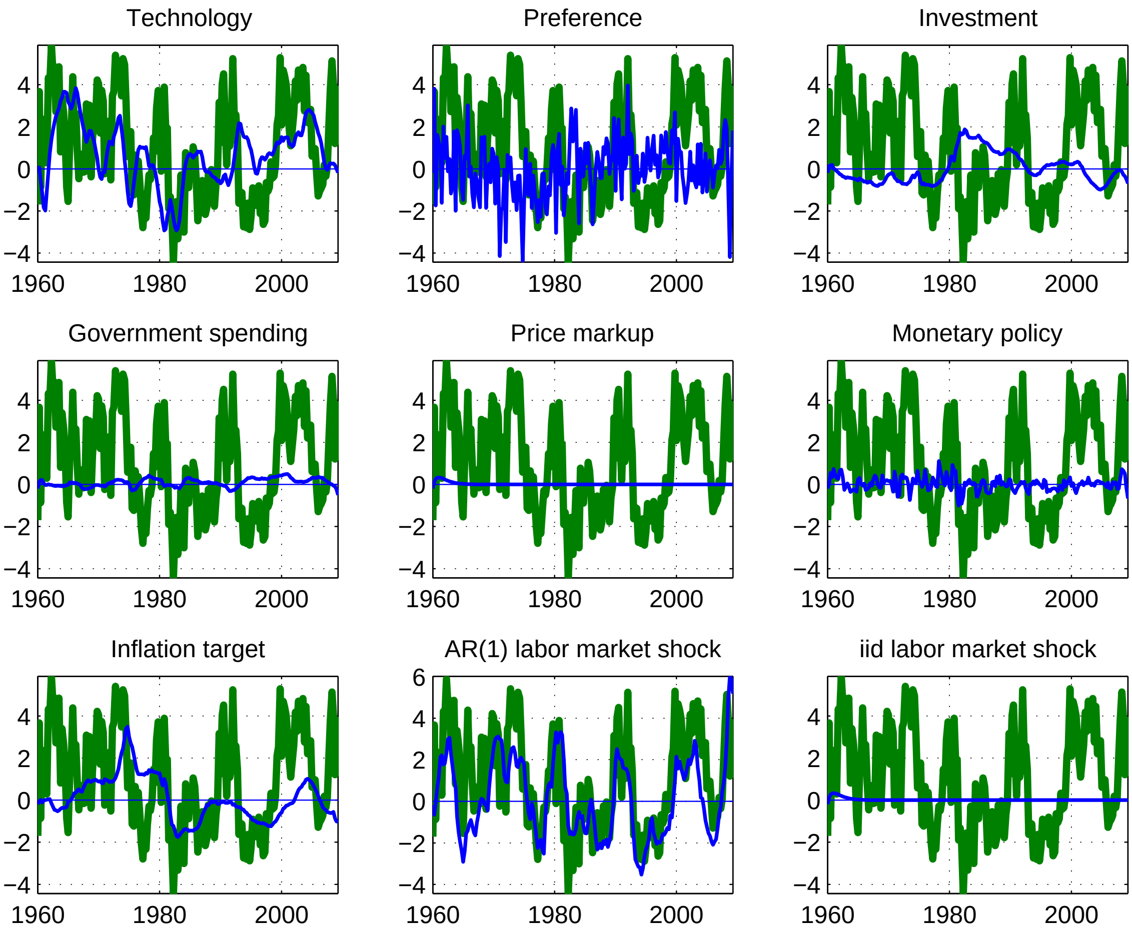

Figure 10: The conditional output gap and the labor wedge

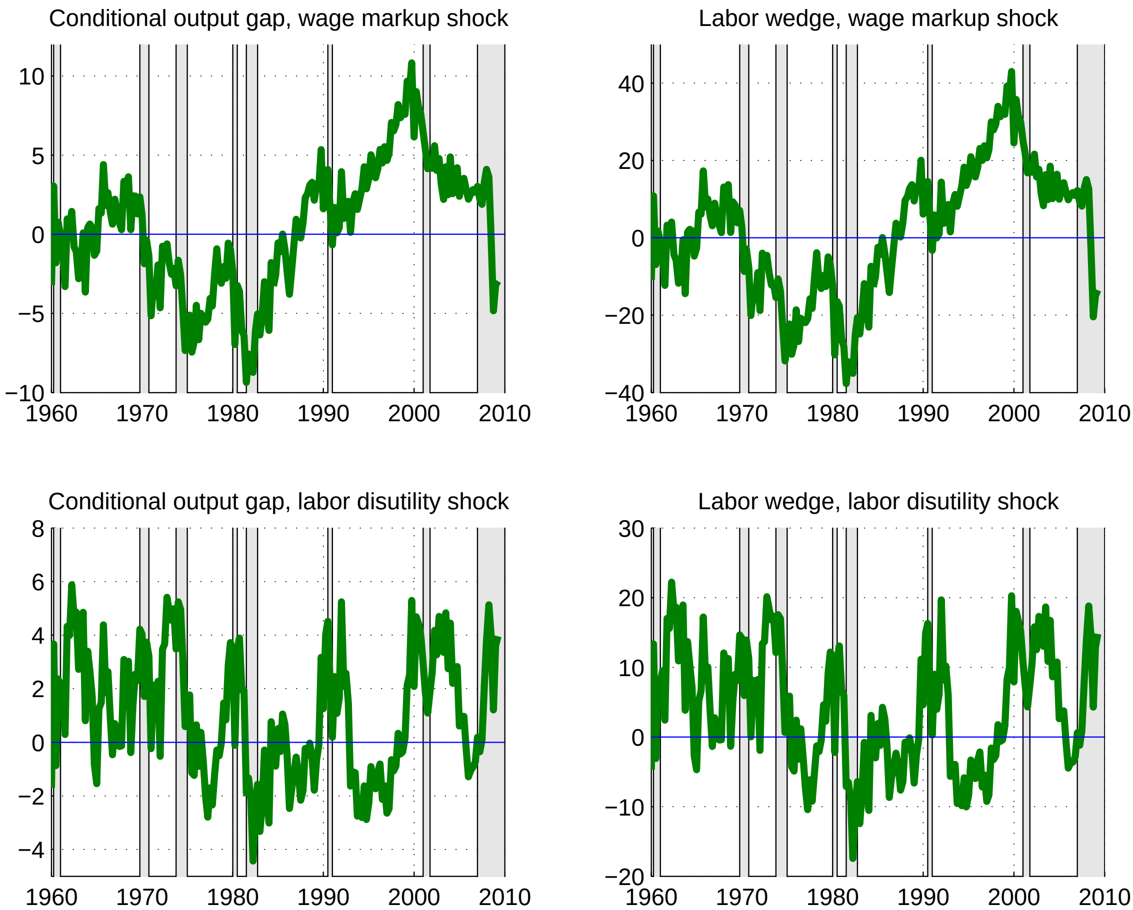

Figure 11: The labor wedge and components

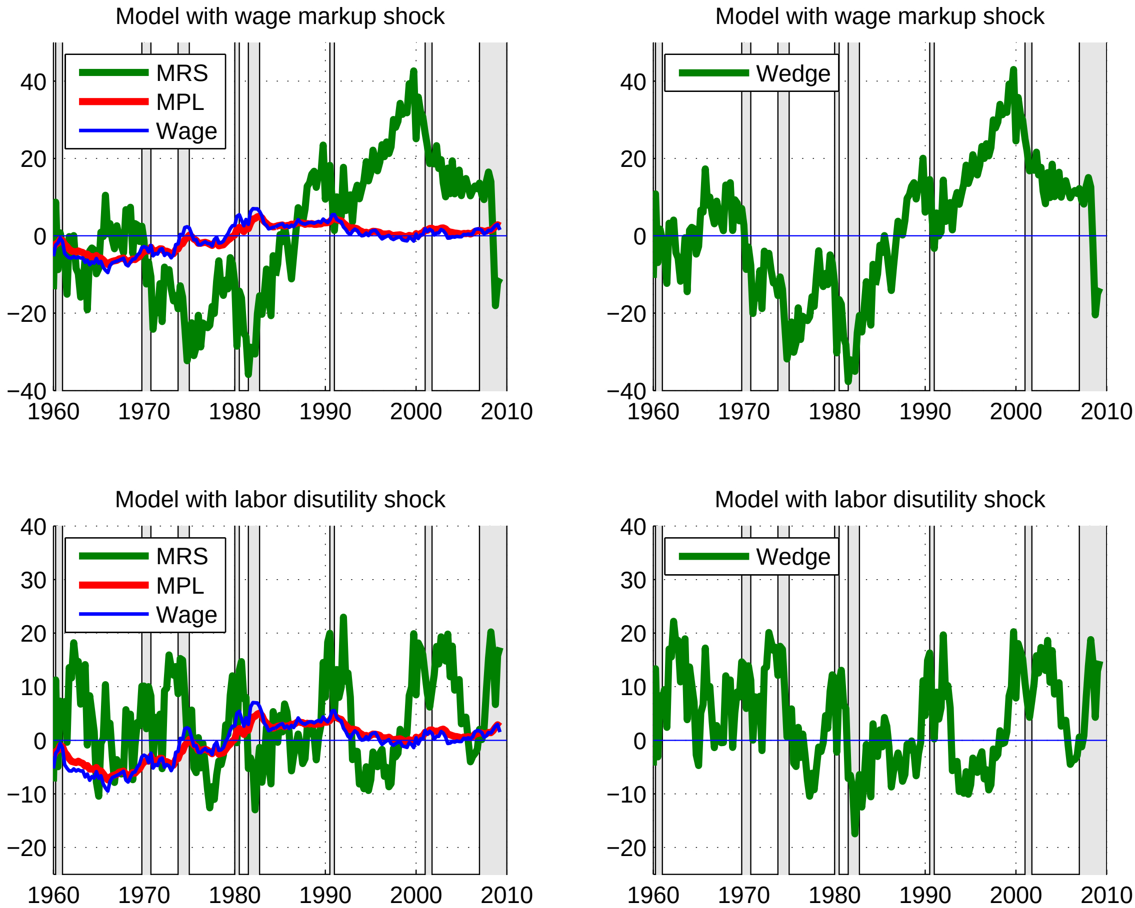

Figure 12: The labor wedge, the wage markup and the price markup