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The Output Gap, the Labor Wedge, and the Dynamic Behavior of Hours

Luca Sala Ulf Söderström Antonella Trigari*

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Abstract

We use a standard quantitative business cycle model with nominal price and wage rigidities to estimate two measures of economic inefficiency in recent U.S. data: the *output gap*—the gap between the actual and efficient levels of output—and the *labor wedge*—the wedge between households' marginal rate of substitution and firms' marginal product of labor. We establish three results. (*i*) The output gap and the labor wedge are closely related, suggesting that most inefficiencies in output are due to the inefficient allocation of labor. (*ii*) The estimates are sensitive to the structural interpretation of shocks to the labor market, which is ambiguous in the model. (*iii*) Movements in hours worked are essentially exogenous, directly driven by labor market shocks, whereas wage rigidities generate a markup of the real wage over the marginal rate of substitution that is acyclical. We conclude that the model fails in two important respects: it does not give clear guidance concerning the efficiency of business cycle fluctuations, and it provides an unsatisfactory explanation of labor market and business cycle dynamics.

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

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1 Introduction

A classic question in macroeconomics concerns the extent to which business cycle fluctuations are efficient. Different schools of thought have provided very different answers to this question. Traditional Keynesian theory implied that business cycle fluctuations are mainly inefficient and therefore should be counteracted by economic policy (Modigliani (1977)). In contrast, real business cycle theory suggested that most fluctuations may be driven by the efficient responses of firms and households to exogenous shifts in technology and preferences, reducing the role for countercyclical economic policy (see, for instance, Kydland and Prescott (1982), Long and Plosser (1983), or King, Plosser, and Rebelo (1988)).

Modern monetary business cycle models—starting with Yun (1996), Goodfriend and King (1997), and Rotemberg and Woodford (1997)—introduce Keynesian features such as imperfect competition and nominal rigidities into the real business cycle framework. Recent developments have demonstrated that quantitative versions of these models are competitive with statistical reduced-form models in fitting and forecasting the behavior of aggregate macroeconomic variables (see, for instance, Smets and Wouters (2007)). This class of models is therefore potentially useful to estimate the degree to which business cycle fluctuations are efficient.

In this paper, we use a standard quantitative business cycle model with nominal price and wage rigidities to estimate two measures of economic inefficiency in recent U.S. data: the output gap and the labor wedge. The *output gap* is the deviation of actual output from its "potential" level, defined as the level of output with imperfect competition but in the absence of nominal rigidities. By construction, the potential level of output is at a constant distance from the efficient level, which is the level of output with perfect competition. Variations in the efficient and potential levels of output reflect the neoclassical (or RBC) features of the economy, whereas the output gap reflects the Keynesian features. The output gap thus measures the inefficient fluctuations in output.[1] The output gap is also an important indicator for monetary policy: it is typically one of the arguments in the welfare-based loss function that is relevant for optimal monetary policy (Woodford (2003)), and it is often used in descriptive models of monetary policy, such as Taylor rules. Central banks therefore monitor various output gap estimates, and much work has been aimed at estimating potential output and the output gap in this class of models.[2]

The *labor wedge* is instead a measure of inefficiency in the allocation of labor. It is defined as the deviation of households' marginal rate of substitution between consumption and leisure from firms' marginal product of labor.[3] According to the Lucas and Rapping (1969) theory

[1]The distance between the efficient and potential levels of output is determined by the average price and wage markups that result from imperfect competition in goods and labor markets. These markups are zero in the efficient allocation but positive (and constant) in the potential allocation. The actual level of output is also affected by exogenous shocks to the two markups as well as endogenous movements in the markups due to price and wage rigidities.

[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). Kiley (2010) gives an overview of different definitions and uses of potential output and the output gap.

[3]Chari, Kehoe, and McGrattan (2007) were the first to use the term "labor wedge." Other authors have

of intertemporal substitution in labor supply, the efficient allocation of labor is achieved when the marginal rate of substitution and the marginal product of labor are equalized (and are equal to the real wage). Any deviations from this efficiency condition therefore lead to inefficiencies in the allocation of the labor input.

Our theoretical model implies a relationship between the output gap and the labor wedge. The two measures are exactly proportional in a simple version of the model, but in our larger model the relationship is more involved. We will show, however, that the output gap and the labor wedge are closely related also in our quantitative model, suggesting that most inefficiencies in output are due to the inefficient allocation of labor. As a consequence, we can gain insights into the sources of output gap fluctuations by studying the determinants of the labor wedge.

We also find that the estimates of the output gap and the labor wedge are sensitive to the structural interpretation of labor market shocks. In this class of models, shocks to the disutility of supplying labor are observationally equivalent to shocks to the markup of the real wage over households' marginal rate of substitution. But these two shocks have different implications in terms of efficiency: labor disutility shocks affect the efficient allocation and therefore lead to efficient movements in labor supply and output, whereas wage markup shocks move the actual allocation relative to the efficient allocation and thus generate inefficient fluctuations in labor and output. The interpretation of the estimated labor market shocks therefore has important consequences for the estimated output gap and labor wedge. We find that the gap and the wedge are strongly procyclical when persistent labor market shocks are interpreted as shocks to the wage markup, but essentially acyclical when the shocks are interpreted as labor disutility shocks.

In order to focus on the fundamental driving forces of business cycle fluctuations, as opposed to the efficient or inefficient nature of those fluctuations, we define a variant of the labor wedge, which in the context of our model we call the "fundamental" labor wedge. The fundamental wedge is closely related to the labor wedge studied in the literature and is independent of the structural interpretation of the shocks. We find that the fundamental wedge is essentially driven by movements in the labor input, hours worked. We then study the determinants of the fundamental wedge and use it to interpret movements in hours, the labor wedge, and the output gap. In principle, fluctuations in the fundamental wedge can be due to endogenous movements in price and wage markups, exogenous shocks to price and wage markups, or exogenous shocks to household preferences. Galí, Gertler, and López-Salido (2007) and Shimer (2009) discuss which of these explanations (endogenous markups or exogenous shocks) is most plausible. Their theoretical analysis provides only indirect evidence as to the driving forces of the labor wedge; our quantitative model instead gives more precise answers.

We find that movements in the fundamental wedge and hours worked are largely exogenous in our model, and are directly driven by persistent labor market shocks. The endogenous component of the wedge, given by movements in the wage markup generated by wage rigidities, is essentially acyclical. In one case—when the persistent labor market shock is interpreted as

also studied the labor wedge, for instance, Hall (1997), Galí, Gertler, and López-Salido (2007), and Shimer (2009). See Shimer (2009) for additional references.

a wage markup shock—the total wage markup is countercyclical, but this is entirely due to exogenous markup shocks. The model therefore does not provide a satisfactory explanation of the joint dynamics of hours and wages: fluctuations in hours are essentially exogenous, and the endogenous markup of the real wage over the marginal rate of substitution (the component of the markup that is due to wage rigidities) is acyclical.

Whether fluctuations in the fundamental wedge and hours are efficient or inefficient depends on the interpretation of the labor market shocks. With persistent wage markup shocks, most fluctuations in hours are inefficient, and generate movements in the output gap and the labor wedge. With persistent labor supply shocks, in contrast, movements in hours are largely efficient, and only the remaining inefficient fluctuations are reflected in the output gap and the labor wedge. Our model is unable to distinguish between these two shocks. More broadly, however, our results suggest that understanding the sources of fluctuations in hours is essential when interpreting movements in output.

We conclude that the model fails in two important respects. First, as the interpretation of labor market shocks is ambiguous, the model does not give clear guidance concerning the efficiency of business cycle fluctuations. Depending on the interpretation of these shocks, most fluctuations in output are either efficient or inefficient. Second, the model provides an unsatisfactory explanation of labor market and business cycle dynamics. Fluctuations in hours worked over the business cycle are directly due to exogenous shocks to the labor market, rather than the endogenous propagation of all shocks in the economy.

The failure of the neoclassical model to reconcile the behavior of hours and the real wage is an old issue in macroeconomics, going back at least to Hall (1980), Altonji (1982), and Mankiw, Rotemberg, and Summers (1985). Our results show that the issue is not resolved in modern business cycle models, despite the presence of imperfect competition and nominal rigidities. This finding casts doubt on the usefulness of this class of models to study the dynamics of labor markets and business cycles.

The ambiguous interpretation of labor market shocks is another drawback of the standard framework, as highlighted by Chari, Kehoe, and McGrattan (2009). Galí, Smets, and Wouters (2010) approach this identification problem by reinterpreting the model such that the rate of unemployment is proportional to the wage markup. They then use data on unemployment to estimate the model and identify the two shocks. Their approach solves the identification problem, but most features of the model remain unaltered. Labor market dynamics therefore has to be largely exogenous also in their estimated model.

We conclude that a different class of models is needed to make further progress in our understanding of labor market and business cycle dynamics. One promising route involves models with search and matching frictions in the labor market and nominal price and wage rigidities, as in Gertler, Sala, and Trigari (2008).

The paper is organized as follows. We begin by presenting our model framework in Section 2. In Section 3 we show how the output gap and the labor wedge are related in the theoretical model, and we define the fundamental wedge that we use to interpret business cycle fluctuations. We then move on to estimate the model in Section 4, and Section 5 provides our main results. We examine the robustness of our results by analyzing some alternative specifications of the empirical model in Section 6. Finally, in Section 7 we offer some concluding remarks and we point to possible directions for future research. An Appendix provides details about the model and data used.

2 The model economy

Our model is a monetary Dynamic Stochastic General Equilibrium (DSGE) framework, and is similar to many models used in the literature. The particular specification we use builds closely on Smets and Wouters (2007) and Justiniano, Primiceri, and Tambalotti (2010). The model combines a real business cycle core with Keynesian features. The core RBC model features habit formation, investment adjustment costs, and variable capital utilization; the Keynesian features include 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 economy 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

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

where β is a discount factor, h measures the degree of habits in consumption, ω is the inverse Frisch elasticity of labor supply, ε^b_t is an intertemporal preference shock, and ε^l_t is a shock to the disutility of supplying labor. The intertemporal preference shock has mean unity and is assumed to follow the autoregressive process

$$\log \varepsilon^b_t = \rho_b \log \varepsilon^b_{t-1} + \zeta^b_t, \qquad \zeta^b_t \sim i.i.d.\ N(0, \sigma^2_b). \tag{2}$$

The labor disutility shock has mean ε^l. We will explore different processes for this shock in the estimated model in Section 4 below.

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

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

and the effective capital is rented to intermediate goods firms at the nominal rental rate R^k_t. 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 a shock to the marginal efficiency of investment that has 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 economy's (gross) growth rate in steady state. The investment 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 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 first-order conditions for consumption, bond holdings, investment, physical capital, and effective 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 prices 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 in steady state. 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 is able to reoptimize their price in any given period. The remaining fraction is assumed to index the 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); 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:

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

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

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

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, an exogenous markup ε_t^p over nominal marginal cost. With staggered price setting, the price index P_t evolves according to

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

and the markup over marginal cost is endogenous.

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. The wage markup shock has mean ε^w, and as in the case of 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 is able to set their wage optimally. Similar to the price indexation scheme, the remaining fraction indexes the wage to the steady-state growth rate γ_z and a combination of past inflation and steady-state inflation according to

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

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 an exogenous markup ε_t^w over the marginal rate of substitution. With staggered wages, the aggregate wage index W_t evolves according to

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

implying an endogenous wage markup.

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 government spending shock that follows the process

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

The nominal interest rate R_t is set using the monetary policy rule[4]

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

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, for instance, errors in the perception of the long-run growth rate γ_z.

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:

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

[4]We specify the monetary policy rule in terms of output growth rather than the output gap, defined as the deviation of output from its potential level (the level under flexible prices and wages). Thus, we implicitly assume that the central bank either is unable to observe the output gap or is unwilling to let monetary policy depend on its estimate of the output gap. One advantage is that our estimates of the benchmark model are independent of the evolution of the output gap, and therefore of the interpretation of structural shocks, which may be problematic in this class of models (see below). In Section 6 we study a version of the model where the monetary policy rule is specified in terms of the output gap. The quantitative results are largely unchanged relative to the benchmark model.

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 households' intertemporal preferences ε_t^b, the disutility of labor ε_t^l, labor-augmenting technology ε_t^z, investment 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 in 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 described in Appendix A.[5]

3 The output gap and the labor wedge in the theoretical model

Below we will estimate our model and use it to study the evolution of the output gap and the labor wedge. In this section we use the theoretical model to define these concepts, we show the relationship between the output gap and the labor wedge, and we discuss how to interpret movements in the labor wedge.

3.1 Efficient and potential output

The RBC model at the core of our model economy implies an efficient allocation where competition is perfect and there are no price and wage rigidities. That is, prices and wages are flexible and markups are zero. In this allocation all variables are at their efficient levels and fluctuate over time as agents respond efficiently to structural disturbances to technology and preferences. This hypothetical economy is affected by five of our nine shocks: those to technology, investment, intertemporal 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—instead appear only in the model with sticky prices and wages and time-varying markups. We therefore label these as "inefficient" shocks.

Due to the presence of imperfect competition (and thus positive average price and wage markups), the steady-state level of output in the model with sticky prices and wages is lower than in the efficient allocation. An alternative allocation that has the same steady-state level

[5] In addition, we supplement the log-linearized model with a block of equations that determines the allocation with flexible prices and wages. Although this block is not used when estimating the benchmark model (where monetary policy does not respond to the output gap), it is useful when constructing different measures of potential output in Section 5.

as actual output is the "potential" level of output, defined as the allocation with flexible prices and wages but imperfect competition and markups held constant at their steady-state levels.[6] The potential level of output is affected by the same shocks as the efficient level, and can be shown to be at a constant distance from the efficient level at all times (see Appendix B). Thus, fluctuations in efficient output are reflected one-for-one in fluctuations in potential output.[7] The focus of our analysis is on this measure of potential output, and we define the output gap as the percent deviation of actual output from potential. (The output gap is therefore zero on average.)

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.[8] 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 conditional potential output from the solution of the model.

Most of the existing literature focuses on the unconditional measure.[9] We will instead focus on conditional potential output, and report only some results for the unconditional measure. Importantly, although conditional potential output moves more closely with actual output than does unconditional potential output, the two measures are highly correlated. Therefore, the two measures give a similar picture of fluctuations in the output gap, and our results do not depend on which measure of potential output we use.

3.2 The output gap and the labor wedge

Over the business cycle, inefficient fluctuations in output should be at least partly due to inefficient fluctuations in the allocation of labor. In the core model with only efficient fluctuations, the labor input is determined by equalizing households' marginal rate of substitution between consumption and leisure and firms' marginal product of labor. Inefficient fluctuations in labor allocation in our full model can therefore be characterized by deviations from

[6] 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).

[7] The constant distance between the efficient and potential levels of output is not a manifestation of the "divide coincidence" discussed by Blanchard and Galí (2007), which relates to the distance between the efficient and natural levels of output. The divine coincidence fails in our model for (at least) two reasons: price markup shocks lead to a time-varying wedge between the efficient and natural levels of output, and wage rigidities mean that it is not optimal for monetary policy to simultaneously stabilize the efficient output gap and price inflation even if this had been feasible.

[8] In the model with flexible prices and wages, the state variables are the physical stock of capital, lagged consumption, and lagged investment.

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

this efficiency condition.[10] Such deviations, labeled the "labor wedge" by Chari, Kehoe, and McGrattan (2007), have been studied extensively in the literature (examples include Hall (1997), Chari, Kehoe, and McGrattan (2007), Galí, Gertler, and López-Salido (2007), and Shimer (2009)).

Letting $\widehat{x}_t$ denote the log deviation of any variable X_t from its steady-state level, the log-linearized version of our model implies that the marginal rate of substitution and the marginal product of labor are given by[11]

$$\widehat{mrs}_t = \omega\widehat{l}_t - \widehat{\lambda}_t + \widehat{\varepsilon}^b_t + \widehat{\varepsilon}^l_t, \tag{41}$$

$$\widehat{mpl}_t = \alpha\widehat{k}_t - \alpha\widehat{l}_t. \tag{42}$$

The labor wedge is then determined as

$$\begin{aligned}\widehat{wedge}_t &\equiv \widehat{mrs}_t - \widehat{mpl}_t \\ &= (\alpha+\omega)\widehat{l}_t - \widehat{\lambda}_t - \alpha\widehat{k}_t + \widehat{\varepsilon}^b_t + \widehat{\varepsilon}^l_t,\end{aligned} \tag{43}$$

and is a measure of inefficiency in the allocation of labor.

To characterize the inefficient fluctuations in output caused by the inefficient allocation of labor, we relate the labor wedge to the output gap. We use the fact that the labor wedge is zero in the log-linearized efficient allocation, as well as in the potential allocation (that differs from the efficient allocation only by a constant). We can then write the wedge in equation (43) in terms of the deviations of hours, the marginal utility of consumption, and effective capital from their levels in the potential allocation (indexed by "p") as

$$\widehat{wedge}_t = (\alpha+\omega)\left(\widehat{l}_t - \widehat{l}^p_t\right) - \left(\widehat{\lambda}_t - \widehat{\lambda}^p_t\right) - \alpha\left(\widehat{k}_t - \widehat{k}^p_t\right). \tag{44}$$

The production function (16) implies that the log-linearized output gap is given by

$$\widehat{y}_t - \widehat{y}^p_t = \frac{Y+F}{Y}\left[\alpha\left(\widehat{k}_t - \widehat{k}^p_t\right) + (1-\alpha)\left(\widehat{l}_t - \widehat{l}^p_t\right)\right]. \tag{45}$$

Combining equations (44) and (45) we can write the output gap in terms of the labor wedge as

$$\widehat{y}_t - \widehat{y}^p_t = \frac{Y+F}{Y}\frac{1-\alpha}{\alpha+\omega}\left[\widehat{wedge}_t + \left(\widehat{\lambda}_t - \widehat{\lambda}^p_t\right) + \frac{\alpha(1+\omega)}{1-\alpha}\left(\widehat{k}_t - \widehat{k}^p_t\right)\right]. \tag{46}$$

[10] In the efficient allocation, the condition MRS=MPL is obtained through the optimal labor supply choice of households that equalize the real wage and the MRS together with the optimal labor demand choice of firms equalizing the real wage and the MPL. In the context of our model, deviations from this efficiency condition can be generated either by imperfections in the labor market (such as sticky wages) that create a wedge between the MRS and the real wage, or by imperfections in the goods market (such as sticky prices) that drive a wedge between prices and nominal marginal cost, that is, between the real wage and the MPL. Other frictions that are not present in our model may also drive a wedge between the MRS and the MPL and generate an inefficient allocation of labor. For example, Jermann and Quadrini (2010) develop a model where financial frictions generate such a wedge.

[11] As output, investment, the capital stock, consumption, the marginal utility of consumption, and the real wage are non-stationary in our model, so are the MRS and the MPL. The log-linearized model is defined in terms of the ratios of these variables to the non-stationary technology shock that generates the common stochastic trend. The wedge, however, is stationary in the original model.

In a simple version of our model, without capital, a government sector, fixed costs in production, and habits in consumption, the output gap is exactly proportional to the wedge:[12]

$$\widehat{y}_t - \widehat{y}_t^p = \frac{1}{1+\omega}\widehat{wedge}_t, \tag{47}$$

since $\widehat{\lambda}_t - \widehat{\lambda}_t^p = -(\widehat{c}_t - \widehat{c}_t^p) = -(\widehat{y}_t - \widehat{y}_t^p)$ and $\widehat{k}_t = \widehat{k}_t^p = 0$. In our more elaborate model, the output gap also depends on the gaps for the marginal utility of consumption and effective capital.[13] We will show below that the output gap is close to proportional to the labor wedge also in our estimated model. Therefore, understanding the labor wedge will help us understand movements in the output gap. In particular, it allows us to understand if movements in the output gap are mainly due to exogenous disturbances or to the endogenous effects of price and wage rigidities.

Other authors—for instance, Hall (1997) and Shimer (2009)—have studied closely related variants of our labor wedge. Their interest, however, mainly focused on understanding the fundamental driving forces of business cycle fluctuations, as opposed to the efficiency of those fluctuations. To relate to that literature in the context of our more elaborate model, it is useful to write the labor wedge as the sum of a "fundamental" component and two unobservable shocks:

$$\widehat{wedge}_t = \widetilde{wedge}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l, \tag{48}$$

where the fundamental component is closely related to the labor wedge studied by Hall (1997) and Shimer (2009), and is given by[14]

$$\widetilde{wedge}_t = (\alpha+\omega)\widehat{l}_t - \widehat{\lambda}_t - \alpha\widehat{k}_t. \tag{49}$$

In the simple version of our model, without capital, a government sector, fixed costs in production, and habits in consumption, the fundamental wedge is exactly proportional to hours worked:

$$\widetilde{wedge}_t = (1+\omega)\widehat{l}_t, \tag{50}$$

since $\widehat{\lambda}_t = -\widehat{c}_t = -\widehat{y}_t = -(1-\alpha)\widehat{l}_t$ and $\widehat{k}_t = 0$. Again, we will show below that the fundamental wedge is roughly proportional to hours also in our estimated model. This strong relationship between the fundamental wedge and hours implies that by understanding the behavior of the fundamental wedge we may gain insights into the determinants of the labor input. This is the sense in which the fundamental wedge is a measure of the driving force of

[12]This is also demonstrated by Erceg, Henderson, and Levin (2000) and Galí, Gertler, and López-Salido (2003)

[13]The effective capital gap is composed of a capital utilization gap and a gap for the physical capital stock: $\widehat{k}_t - \widehat{k}_t^p = (\widehat{\nu}_t - \widehat{\nu}_t^p) + (\widehat{\overline{k}}_{t-1} - \widehat{\overline{k}}_{t-1}^p)$. Using the conditional potential allocation, the latter gap is zero, so the effective capital gap is entirely due to capital utilization.

[14]Our fundamental wedge differs from the labor wedge in Hall (1997) and Shimer (2009) because of habits in consumption and fixed costs in production.

business cycle fluctuations, as opposed to a measure of the inefficiency of those fluctuations.[15]

3.3 Interpreting the labor wedge

To understand and interpret fluctuations in the labor wedge, hours, and the output gap it is useful to decompose the fundamental wedge in equation (49) along two dimensions: an efficient versus an inefficient component, and an endogenous versus an exogenous component.

Imperfect competition in labor and product markets implies that the real wage is set as a markup over the marginal rate of substitution, and prices as a markup over nominal marginal cost, given by the nominal wage adjusted for the marginal product of labor. By adding and subtracting the real wage from the expression for the labor wedge, we can write the wedge in terms of the wage and price markups (denoted $\widehat{\mu}_t^w$ and $\widehat{\mu}_t^p$):[16]

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

Each markup can be decomposed into an endogenous component (due to price and wage rigidities) and an exogenous component (equal to the markup shock, or the desired markup in the absence of price and wage rigidities) as

$$\widehat{\mu}_t^w = \widetilde{\mu}_t^w + \widehat{\varepsilon}_t^w, \tag{52}$$

$$\widehat{\mu}_t^p = \widetilde{\mu}_t^p + \widehat{\varepsilon}_t^p, \tag{53}$$

where $\widetilde{\mu}_t^w$ and $\widetilde{\mu}_t^p$ are the endogenous markups.

Using this markup decomposition in the definition of the fundamental wedge in equation (48), we can write

$$\begin{aligned} \widetilde{wedge}_t &= \overbrace{-\left(\widetilde{\mu}_t^w + \widetilde{\mu}_t^p\right) - \left(\widehat{\varepsilon}_t^w + \widehat{\varepsilon}_t^p\right)}^{\text{Inefficient}} \overbrace{- \left(\widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l\right)}^{\text{Efficient}} \\ &= \underbrace{-\left(\widetilde{\mu}_t^w + \widetilde{\mu}_t^p\right)}_{\text{Endogenous}} \underbrace{- \left(\widehat{\varepsilon}_t^w + \widehat{\varepsilon}_t^p\right) - \left(\widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l\right)}_{\text{Exogenous}} \end{aligned} \tag{54}$$

In one dimension, the fundamental wedge is decomposed into an *inefficient* component (due to the total markups) and an *efficient* component (due to preference shocks). In another dimension, it is decomposed into an *endogenous* component (due to price and wage rigidities) and an *exogenous* component (due to disturbances). The inefficient component is, of course, the total labor wedge in equation (43), and is in part endogenous and in part exogenous. The efficient component is entirely exogenous and is due to intertemporal preference and labor disutility shocks. The endogenous component is entirely inefficient and is due to wage

[15] Galí, Gertler, and López-Salido (2007) also study the labor wedge in a model similar to Hall (1997) and Shimer (2009), but focus on the wedge as a measure of inefficiency.

[16] See also Galí, Gertler, and López-Salido (2007). In our estimated model, the price markup is typically small (as the real wage moves closely with the marginal product of labor). Thus, the labor wedge is largely determined by the wage markup.

and price rigidities, whereas the exogenous component includes both efficient and inefficient shocks.

Part of the literature has focused on explaining fluctuations in the fundamental wedge. The decomposition in equation (54) shows that these fluctuations can be due to movements in exogenous preference shocks, endogenous markups, or exogenous markup shocks. Our estimated model will give a complete description of the data and therefore all variables in the model, including the fundamental wedge. It is therefore well suited to interpret movements in the labor wedge, hours, and the output gap.

Finally, note that the fundamental wedge itself and its decomposition into the endogenous and exogenous components are independent of whether volatility is generated by efficient shocks to households' preferences or inefficient shocks to the price or wage markups. This is useful because it is not always easy to identify and interpret the shocks in the estimated model, as we discuss next.

3.4 Interpreting the structural shocks

In some cases, the structural interpretation of the estimated shocks is straightforward: shocks to technology are clearly efficient, whereas shocks to monetary policy do not affect the efficient allocation, and are therefore inefficient. In other cases, the interpretation is less clearcut. It is well known that shocks to the disutility from supplying labor (ε_t^l in our model) and shocks to the wage markup (ε_t^w) are observationally equivalent in the log-linearized version of this class of models.[17] These two shocks enter only in the equation relating the real wage to the marginal rate of substitution. In the log-linearized model this equation is given by

$$\begin{aligned} \widehat{w}_t &= \gamma_b \left[\widehat{w}_{t-1} - \widehat{\pi}_t + \gamma_w \widehat{\pi}_{t-1} - \widehat{\varepsilon}_t^z\right] + \gamma_f \left[\widehat{w}_{t+1} + \widehat{\pi}_{t+1} - \gamma_w \widehat{\pi}_t + \widehat{\varepsilon}_{t+1}^z\right] \\ &\quad + \gamma_o \left[\omega \widehat{l}_t - \widehat{\lambda}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l + \widehat{\varepsilon}_t^w\right], \end{aligned} \tag{55}$$

where γ_b, γ_f, and γ_o 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 $\widehat{\varepsilon}_t^l$ and $\widehat{\varepsilon}_t^w$ are observationally equivalent, and if both shocks are present they can only be separately identified if they are assumed to follow different stochastic processes.[18]

For our estimated model, the exact interpretation of these two shocks is not important: each shock could be interpreted either as a labor disutility shock or as a wage markup shock. For questions about efficiency and inefficiency, however, as well as normative issues, the interpretation of the two shocks comes to the forefront: it crucially affects the estimates of the output gap and the labor wedge, as these reflect inefficient fluctuations in output and inefficiencies in the allocation of labor. It also affects the decomposition of the fundamental wedge into its efficient and inefficient components. We will explore below how the interpre-

[17] Similar issues of interpretation also apply to the price markup shock, which can also be interpreted as an efficient relative-price shock to a flexible-price sector in a two-sector model; see de Walque, Smets, and Wouters (2006). The price markup shock is small in our estimated model, however, so its interpretation is quantitatively less important.

[18] The intertemporal preference shock $\widehat{\varepsilon}_t^b$ also enters the consumption Euler equation, and can therefore be identified separately from $\widehat{\varepsilon}_t^l$ and $\widehat{\varepsilon}_t^w$.

tation of these two shocks affects our estimates of the output gap and the labor wedge and the interpretation of macroeconomic fluctuations.

4 Estimation

4.1 Data and estimation technique

We estimate the log-linearized version of the model using quarterly U.S. data from 1960Q1 to 2009Q2 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) hours worked: 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 (rather than the non-farm business sector) and are adjusted for low-frequency movements due to changes in demographics. These data therefore display less low-frequency behavior than unadjusted data. Data definitions and sources are available in Appendix D.

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

$$\mathbf{X}_t = \mathbf{A}(\boldsymbol{\theta})\mathbf{X}_{t-1} + \mathbf{B}(\boldsymbol{\theta})\boldsymbol{\zeta}_t, \qquad \boldsymbol{\zeta}_t \sim i.i.d.\ N(\mathbf{0}, \boldsymbol{\Sigma}_\zeta), \tag{56}$$

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

$$\mathbf{Y}_t = \mathbf{C}(\boldsymbol{\theta}) + \mathbf{D}\mathbf{X}_t + \boldsymbol{\eta}_t, \qquad \boldsymbol{\eta}_t \sim i.i.d.\ N(\mathbf{0}, \boldsymbol{\Sigma}_\eta), \tag{57}$$

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

$$\mathbf{Y}_t = 100\left[\Delta \log Y_t,\ \Delta \log I_t,\ \Delta \log C_t,\ \Delta \log W_t,\ \log L_t,\ \log \pi_t,\ \log R_t\right], \tag{58}$$

and $\boldsymbol{\eta}_t$ is a vector of i.i.d. measurement errors. (We will estimate versions of the model with and without measurement errors.)

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 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;[19] 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 markups 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.

4.2 Labor market shocks in the estimated model

As shown above, the two labor market shocks $\widehat{\varepsilon}_t^l$ and $\widehat{\varepsilon}_t^w$ are observationally equivalent in the log-linearized version of the model. When estimating the model we will separately identify the two shocks by assuming that they follow different stochastic processes: one (denoted $\widehat{\varepsilon}_{1,t}$) follows a stationary AR(1) process, the other (denoted $\widehat{\varepsilon}_{2,t}$) is i.i.d.[20] For the estimated model the exact interpretation of these two shocks is not important: each shock could be interpreted either as a labor disutility shock or as a wage markup shock. For our estimates of the output gap and the labor wedge, however, the interpretation of the two shocks comes to the forefront.

4.3 Priors

Before estimation we assign prior distributions to the parameters to be estimated. These are summarized in Table 1. 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 quarterly growth rate of GDP 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, and 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.

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

[20]Thus, the two shocks follow

$$\begin{aligned} \log \varepsilon_{1,t} &= (1-\rho_1)\log\varepsilon_1 + \rho_1 \log\varepsilon_{1,t-1} + \zeta_{1,t}, \quad \zeta_{1,t} \sim i.i.d.\ N(0,\sigma_1^2), \\ \log\varepsilon_{2,t} &= \log\varepsilon_2 + \zeta_{2,t}, \quad \zeta_{2,t} \sim i.i.d.\ N(0,\sigma_2^2). \end{aligned}$$

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, and 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, and 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 0.15. Finally, for the standard deviations of the shock innovations, we assign Gamma priors. We use Gamma priors 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, whereas we want to allow for the possibility that some shocks have zero variance.

We do not normalize any of the shocks before estimation, and we assign Gamma priors with mean and standard deviation of 5.0 percent to all innovation standard deviations except for the monetary policy and inflation target shocks that have mean and standard deviation equal to 0.15 percent. These priors are meant to imply a reasonable volatility of the structural shocks: the unconditional prior standard deviation of the AR(1) shocks is 5.77 percent, except for the monetary policy shocks that have standard deviations of 0.17 percent, i.e., 17 basis points in quarterly terms. In one respect, however, these priors contrast with the common approach in the literature.

A standard procedure is to normalize some of the shocks (in particular, the price and wage markup shocks) to have a unit impact on some observable variable (for instance, the rate of inflation and the real wage). Then a prior distribution is assigned to the normalized shock. For instance, in our model the AR(1) labor market shock would be normalized by defining $\widetilde{\varepsilon}_{1,t} = \gamma_o \widehat{\varepsilon}_{1,t}$, where γ_o is a convolution of structural parameters. The normalized shock then has a unitary impact on the real wage, see equation (55). One advantage of the normalization is that it makes it easier to assign a prior distribution based on the volatility of the real wage. In addition, the normalization allows for correlation between the shock and the parameters in γ_o, which can be useful.

But this procedure can lead to unreasonable prior distributions for the structural shock—in this case $\widehat{\varepsilon}_{1,t}$—if this shock has a very small direct impact on the real wage. The direct impact of the labor market shocks on the real wage in the log-linearized equation (55) 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. Smets and Wouters (2007) and Justiniano, Primiceri, and Tambalotti (2010) both use a prior mean of 0.10 for the normalized labor market shock. In our model, such a prior would imply a standard deviation of $0.10/0.0026 = 38.5$ percent for the structural innovation, and a standard deviation of 44 percent for the structural shock $\widehat{\varepsilon}_{1,t}$.[21] Such volatility seems unreasonable for any interpretation of the shock, but in particular when the shock is interpreted as a wage markup with a prior mean of 1.15. Chari, Kehoe, and McGrattan (2009) criticize estimated business cycle models in this class for implying an unreasonable posterior volatility of the estimated markup shocks. Under the normalization just described, this volatility originates partly in the prior assigned to the shock. Our approach instead gives a more reasonable prior standard deviation of 5.77 percent, which should imply a more reasonable posterior estimate.

Finally, in some specifications of our estimated model, we allow for measurement errors in real wage growth and inflation. The standard deviations of these measurement errors are assigned Gamma priors 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.

4.4 A model without measurement errors

We first estimate the model under the assumption that the data are observed without error, as in much of the literature, including Smets and Wouters (2007), Justiniano, Primiceri, and Tambalotti (2010), and part of Justiniano and Primiceri (2008). Columns 3–5 of Table 2 report the estimated posterior distribution for this model.[22]

The posterior distributions for the two labor market shocks imply substantial volatility, despite our restrictive prior. The innovation of the AR(1) process is fairly small, but the shock process is very persistent, whereas the i.i.d. shock has a median standard deviation of 33 percent. Apparently, the data strongly favors high volatility in the i.i.d. shock in order to reconcile the joint behavior of hours and wages in the wage equation (55).[23] That is, the prior distribution is not sufficient to avoid the large volatility in the labor market shocks, although volatility is smaller than if we had used standard priors on normalized shocks.

Overall, the volatility of the labor market shocks seems unreasonable in this model, despite our prior assumptions. As these shocks play a lead role in what follows, we want to be careful to make sure that their volatility is consistent with their structural interpretation. One possibility, raised by Justiniano and Primiceri (2008), is that the volatility of the estimated labor market shocks and the price markup shock partly reflects measurement errors rather than structural shocks. Our benchmark model will therefore allow for measurement errors in wage growth and inflation.

4.5 The benchmark model with measurement errors

There are many reasons to allow for measurement errors in aggregate data. First, several authors have pointed out that different data on real wages data have very different time series properties (see, for example, Abraham, Spletzer, and Stewart (1999), or, more recently, Galí, Smets, and Wouters (2010)). Second, Boivin and Giannoni (2006) show that some

[21] The prior assumptions used by Justiniano and Primiceri (2008) would imply even larger volatility of the labor market shock.

[22] The posterior distribution is constructed by generating 150,000 draws using the Random-Walk Metropolis Hastings algorithm (after discarding the first 10,000 draws).

[23] The prior probability of such a large innovation standard deviation is 0.001.

aggregate data series (in particular inflation) have large idiosyncratic components. And more generally, as it is unlikely that model concepts are exactly equivalent to data concepts, it seems reasonable to allow for some discrepancies between the model and the data (see Watson (1993)).

Justiniano and Primiceri (2008) show that the i.i.d. labor market and price markup shocks in their model only have an impact on wages and inflation, resembling measurement errors rather than structural shocks. They also show that interpreting these i.i.d. shocks as measurement error has no consequences for their estimates of potential output and the output gap.

Instead of replacing these shocks with measurement error, we estimate a model that allows for both structural shocks and i.i.d. measurement errors. The shocks and measurement errors can be separatly identified, as volatility in the structural shocks is transmitted to other variables in the model, but volatility in measurement errors is specific to one variable. We can therefore let the data choose the best interpretation. Allowing for both structural shocks and measurement errors, the latter are likely to replace the high-frequency components of the price markup and labor market shocks. The AR(1) properties of the shocks may still remain, however, and may be altered by the introduction of measurement errors.

The estimated posterior distribution is reported in the final three columns of Table 2. The estimated measurement errors are sizable: their median standard deviations are around 0.5 percent for wage growth and 0.2 percent for inflation, compared with the standard deviations of real wage growth and inflation in the data, which are both around 0.6 percent. As expected, the measurement errors reduce the volatility of the price markup and labor market shocks, and the price markup shock and the i.i.d. labor market shock obtain standard deviations close to zero. Thus, much of the high-frequency movements in the price markup and labor market shocks are interpreted as measurement error rather than structural shocks, implying that they have little impact on the other variables in the model. Most other parameter estimates do not change much compared with the model without measurement errors, with the exception of the capital adjustment cost parameter η_k and the standard deviation of the investment shock σ_i, that are both smaller in the model with measurement errors.

Figure 2 shows the estimated paths for the structural shocks in the model with measurement errors (with parameter values fixed at the posterior median). The figure reveals evidence of the "great moderation" starting around the mid-1980s, with lower volatility in many shocks (until the financial crisis hit at the end of the sample). There are clear patterns in the estimated investment shock, the government spending shock, and the inflation target. The investment shock seems to match the patterns in inflation and the nominal interest rate (see Figure 1), the government spending shock matches the behavior of net exports and government expenditure,[24] and the inflation target shock matches the low-frequency movements in inflation. The intertemporal preference shock is fairly large and volatile, whereas the price markup and i.i.d. labor supply shocks are small (due to the inclusion of measurement errors). Most importantly, the AR(1) labor market shock shows large low-frequency fluctuations that

[24]As the data correspond to the U.S. economy as a whole, including the foreign sector, but the model characterizes a closed economy, the government spending shock acts as a residual in the national income identity and picks up movements in both government spending and net exports. This misspecification of the model is part of the critique voiced by Chari, Kehoe, and McGrattan (2009).

resemble the pattern in the labor input (hours worked) in Figure 1.

Table 3 shows the contribution of each shock to the volatility of the seven data series used for estimation, with all series expressed in levels.[25] (The numbers reported are the 5th and 95th percentiles over 1,000 draws from the posterior distribution.) Over all frequencies in panel (a), the non-stationary technology shock is the most important driving force for output, investment, consumption, and the real wage, whereas the persistent labor market shock is most important for fluctuations in hours. Over business cycle frequencies in panel (b), the persistent labor market shock is less important for hours than the technology shock, but it still explains a considerable fraction of the fluctuations in the labor input.[26] The estimated path for the persistent labor market shock and its correspondence with hours worked will play an important role in our interpretation of the estimated output gap and labor wedge below.

5 The output gap and the labor wedge in the estimated model

We now move on to the main results of the paper. In this section we first discuss how our estimated model characterizes potential output, the output gap, and the labor wedge in the U.S. economy, and how sensitive these estimates are to different interpretations of the two labor market shocks. We then interpret movements in the labor wedge. Much of this discussion will focus on how the model characterizes movements in the labor input over the business cycle.

5.1 Potential output, the output gap, and the labor wedge

Panels (a) and (b) of Figure 3 show actual GDP in our sample and the estimated paths for potential GDP (with parameters at their posterior median values) under the two interpretations of the labor market shocks. Panel (a) is from the model where the persistent labor market shock is interpreted as an inefficient wage markup shock (and the i.i.d. shock is an efficient labor disutility shock), whereas panel (b) shows potential GDP when the persistent shock is interpreted as a shock to the disutility of supplying labor (and the i.i.d. shock is a wage markup shock). Panels (c) and (d) show the corresponding output gaps, that is, the percent deviation of actual GDP from potential. (The solid lines are the median estimates over 1,000 draws from the posterior distribution, and the surrounding shaded areas cover the intervals between the 5th and 95th percentiles. These intervals capture both parameter and filter uncertainty.)

[25]The results for the real wage and inflation refer to the volatility in the estimated model, that is, after excluding the volatility due to the measurement errors.

[26]Business cycle fluctuations are defined as cycles of 8 to 32 quarters. In contrast to Justiniano, Primiceri, and Tambalotti (2010), the investment shock is not very important for business cycle fluctuations in our model. It explains around 5 percent of fluctuations in GDP and 8 percent of fluctuations in investment at business cycle frequencies, compared with 50 and 80 percent in their model. To some extent, this is due to the inclusion of measurement errors: in the model without measurement errors, the investment shock explains around 20 and 35 percent of GDP and investment. If we also model price markup shocks as i.i.d. (like Justiniano, Primiceri, and Tambalotti (2010)) rather than AR(1) and include four-quarter inflation and GDP growth in the monetary policy rule (as in Justiniano and Primiceri (2008)), the investment shock explains around 50 percent of GDP fluctuations and 80 percent of investment, as in Justiniano, Primiceri, and Tambalotti (2010).

Under the wage markup shock interpretation in panels (a) and (c)—that is, when the persistent labor market shock is interpreted as a wage markup shock—potential output is similar to a steady trend in output (plus some high-frequency noise), and the output gap resembles persistent fluctuations in output around trend, consistent with the findings of Sala, Söderström, and Trigari (2008) and Justiniano and Primiceri (2008). Thus, output shows persistent inefficient fluctuations around potential, with an important low-frequency component. This output gap is also closely related to the U.S. business cycle as dated by the NBER (the vertical shaded areas are NBER recessions). The output gap tends to increase in expansions and fall in contractions, as actual output grows faster than potential in expansions and more slowly in contractions. The output gap is mostly negative from the 1970s until the early 1980s (and it falls abruptly in the Volcker disinflation period in the early 1980s), it is positive during much of the 1990s and 2000s, and then falls abruptly in the 2008–09 recession, from around 4 percent in the second quarter of 2008 to −4.5 percent two quarters later.[27]

In the model with persistent labor disutility shocks in panels (b) and (d), the differences between actual and potential GDP are smaller: a larger part of the fluctuations in actual GDP is efficient. Therefore, the output gap is smaller than under the alternative interpretation, and it does not display any low-frequency fluctuations. In contrast to the case with persistent wage markup shocks, potential output now sometimes grows faster than actual output in expansions (for instance, in the mid-1980s, early 1990s, and mid-2000s). The output gap is therefore not very closely related to the NBER business cycle; it is instead fairly acyclical, sometimes rising and sometimes falling during expansions, and even rising during the recession in 2008–09.[28]

The probability intervals around the estimated output gaps reveal that parameter and filter uncertainty is important. The output gap is more precisely estimated with persistent wage markup shocks, and the 90 percent interval rarely includes zero. With persistent labor disutility shocks, the interval almost always includes zero, so there is never strong empirical evidence for a positive or a negative output gap. This is because the gap is smaller with persistent labor disutility shocks than with wage markup shocks, but also because the interval is wider. Comparing the gap estimates under the two different interpretations of the labor market shock reveals that uncertainty across the two models is even more important than uncertainty within each model. On several occasions, the output gaps implied by the two models have different sign or move in opposite directions. As these two models are observationally equivalent, they have the same posterior probability. The differences between the

[27]Figure 3 shows the estimated conditional potential output and output gap. The unconditional measures are shown in Figure 4. 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; the unconditional instead depends on the state variables in the hypothetical economy with flexible prices and wages. As a consequence, the conditional output gaps are slightly smaller than the unconditional gaps. The two gaps move very closely together under both interpretations of the shocks, however: the correlation coefficients are around 0.98. The conditional and unconditional measures therefore give a similar picture of fluctuations in the output gap.

[28]The model interprets the 2008–09 recession partly as an increase in the persistent labor market shock; see the estimated shocks in Figure 2. When this shock is interpreted as a wage markup shock, the increase in the wage markup leads to a fall in actual output below potential and a negative output gap. When the shock is a labor disutility shock, in contrast, the fall in labor supply reduces potential output more than actual output, making the output gap positive.

estimated output gaps present a challenge for any policymaker that relies on these estimates to make decisions.

Over business cycle frequencies, inefficient fluctuations in output should be at least partly due to inefficient fluctuations in the labor input. The output gap should therefore be related to inefficiencies in the allocation of labor, as measured by the labor wedge. Recall from Section 3 that the labor wedge in our model is given by

$$\begin{aligned}\widehat{wedge}_t &= \widehat{mrs}_t - \widehat{mpl}_t \\ &= (\alpha+\omega)\widehat{l}_t - \widehat{\lambda}_t - \alpha\widehat{k}_t + \widehat{\varepsilon}^b_t + \widehat{\varepsilon}^l_t, \end{aligned} \tag{59}$$

and that it is related to the output gap through

$$\widehat{y}_t - \widehat{y}^p_t = \frac{Y+F}{Y}\frac{1-\alpha}{\alpha+\omega}\left[\widehat{wedge}_t + \left(\widehat{\lambda}_t - \widehat{\lambda}^p_t\right) + \frac{\alpha(1+\omega)}{1-\alpha}\left(\widehat{k}_t - \widehat{k}^p_t\right)\right]. \tag{60}$$

Panels (c) and (d) of Figure 5 show the labor wedge under the two interpretations of the labor market shocks (for comparison panels (a) and (b) show the output gaps from Figure 3). It is immediately clear that the labor wedge is close to proportional to the output gap in both cases. As we discussed in Section 3, this proportionality is exact in a simple version of the model. Figure 5 reveals that it holds approximately also in the large quantitative model, and is due to the fact that the capital gap ($\widehat{k}_t - \widehat{k}^p_t$) in equation (60) is small (and positively correlated with the output gap) whereas the marginal utility of consumption gap ($\widehat{\lambda}_t - \widehat{\lambda}^p_t$) is roughly proportional to the output gap.[29] The correlation between the labor wedge and the output gap is above 0.99 for the conditional gaps shown in Figure 5.[30] Thus, most inefficiencies in the economy are due to the inefficient allocation of labor. Analyzing the wedge can therefore help us interpret differences in our output gap estimates.[31]

Also the estimates of the labor wedge are thus sensitive to the structural interpretation of the labor market shocks. To interpret movements in the labor wedge it is therefore instructive to study the fundamental wedge, that is, the labor wedge excluding the two preference shocks, as this wedge is independent of the shock interpretation. In the simple version of the model, there is an exact proportionality between the fundamental wedge and hours. Figure 6 shows the fundamental wedge and the direct impact of hours ($(\alpha+\omega)\widehat{l}_t$) in the estimated model, and the fundamental wedge is approximately proportional to hours also in this larger model (the correlation is 0.9). The fundamental wedge is strongly procyclical and is similar to the output gap (and labor wedge) in the model with persistent wage markup shocks. It is also closely related to the labor wedge studied by Hall (1997), Galí, Gertler, and López-Salido (2007), and Shimer (2009). The close correspondence between the fundamental wedge and

[29] Recall that the effective capital gap is given by the gap in capital utilization, as we are using the conditional potential allocation.

[30] The correlation between the labor wedge and the unconditional output gap is above 0.97.

[31] Chari, Kehoe, and McGrattan (2007) identify four different wedges between the data and the equilibrium conditions of a simple prototype version of a real business cycle model: an efficiency wedge, an investment wedge, a government consumption wedge, and a labor wedge. Using a monetary model with sticky prices and wages, Šustek (2010) also identifies an asset price wedge and a monetary policy wedge. In our monetary model, the labor wedge seems to capture all inefficiencies. This does not necessarily imply that the other wedges are not present, only that they do not introduce large additional inefficiencies.

hours means that understanding the fundamental wedge will help us understand movements in the labor input over the business cycle, and, more generally, the fundamental driving forces of macroeconomic fluctuations implied by our estimated model.

5.2 Explaining the labor wedge

Figure 7 shows in more detail the determinants of the labor wedge—the marginal rate of substitution and the marginal product of labor—along with the real wage.[32] Recall from equation (51) in Section 3 that the labor wedge can be written as the negative of the sum of the two markups: the markup of the real wage over the marginal rate of substitution and the markup of prices over marginal cost. Figure 7 shows that the marginal product and the real wage—that do not depend on the interpretation of shocks—are stable and move closely together, implying that the price markup is small. Movements in the marginal rate of substitution, in contrast, are large and volatile. As a consequence, under both interpretations of the labor market shocks, movements in the labor wedge almost entirely reflect movements in the marginal rate of substitution and the markup of the real wage over the MRS. (A similar result is found by Galí, Gertler, and López-Salido (2007) in a smaller theoretical model.)

A long-standing issue in macroeconomics concerns how to reconcile the movements in the labor input and the real wage (see, for instance, Hall (1980)). This is a challenge also for our model, despite the presence of wage rigidities. In the log-linearized model, the relationship between the real wage, the marginal rate of substitution, and hours can be written in two ways. The first is the wage equation

$$\begin{aligned}\widehat{w}_t &= \gamma_b \left[\widehat{w}_{t-1} - \widehat{\pi}_t + \gamma_w \widehat{\pi}_{t-1} - \widehat{\varepsilon}_t^z\right] + \gamma_f \left[\widehat{w}_{t+1} + \widehat{\pi}_{t+1} - \gamma_w \widehat{\pi}_t + \widehat{\varepsilon}_{t+1}^z\right] \\ &\quad + \gamma_o \left[\widehat{mrs}_t + \widehat{\varepsilon}_t^w\right], \end{aligned} \tag{61}$$

where $\widehat{mrs}_t = \omega \widehat{l}_t - \widehat{\lambda}_t + \widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l$. The real wage is driven by the marginal rate of substitution plus the wage markup shock, but wage rigidity and indexation introduce additional leads and lags of the real wage, inflation, and the technology shock. The second way to express this relationship is to write the wage as a markup $\widehat{\mu}_t^w$ over the marginal rate of substitution:

$$\begin{aligned}\widehat{w}_t &= \widehat{\mu}_t^w + \widehat{mrs}_t \\ &= \widetilde{\mu}_t^w + \widehat{\varepsilon}_t^w + \widehat{mrs}_t, \end{aligned} \tag{62}$$

where $\widetilde{\mu}_t^w$ is the endogenous wage markup (the component of the markup that is due to wage rigidities). Under flexible wages, $\gamma_b = \gamma_f = 0$ and $\gamma_o = 1$ in the wage equation (61) and $\widetilde{\mu}_t^w = 0$ in equation (62). The relationship between the real wage and the MRS then reduces to

$$\widehat{w}_t = \widehat{mrs}_t + \widehat{\varepsilon}_t^w, \tag{63}$$

and the wage markup is entirely exogenous. In the presence of wage rigidities, $\gamma_b, \gamma_f > 0$ and $\gamma_o < 1$ (in the estimated model γ_o is very small), and $\widetilde{\mu}_t^w \neq 0$, so the wage markup also has

[32] The MRS, the MPL, and the real wage are all non-stationary. Figure 7 shows these variables detrended by the common productivity trend (the non-stationary technology shock).

an endogenous component.

To illustrate the challenges in explaining the behavior of hours and the real wage, Figure 8 shows the real wage and the MRS excluding the two preference shocks (that is, the figure shows $\omega \widehat{l_t} - \widehat{\lambda}_t$, which is independent of the interpretation of the labor market shocks).[33] The MRS is dominated by movements in hours and is volatile and strongly procyclical, whereas the real wage is more stable and essentially acyclical. In principle, the estimated model can reconcile this pattern in two ways. One way is to introduce wage rigidities, so the MRS has a small direct impact on the real wage (γ_o in equation (61) is small) and the endogenous wage markup in equation (62) is countercyclical. An alternative way is to introduce countercyclical exogenous shocks, either wage markup shocks (that affect the wage markup and stop movements in the MRS from spilling over into the wage) or labor disutility shocks (that stop volatility in hours from spilling over to the MRS).

The macroeconomic literature has discussed which of these explanations—endogenous markups or exogenous shocks—that is most plausible. Shimer (2009) is skeptical to the idea that movements in the labor wedge are due to exogenous shocks to preferences or markups. He also criticizes the Smets and Wouters (2007) model, as it assigns a large role to these shocks in determining real variables, and he instead favors an explanation based on search frictions and real wage rigidities. Galí, Gertler, and López-Salido (2007) focus on endogenous wage markups. They provide some evidence that the fundamental wedge (the wage markup) is endogenous: the wedge is Granger caused by other macroeconomic variables and falls after a contractionary monetary policy shock in an estimated VAR model.

Our model gives a complete description of the labor wedge, including the role of exogenous shocks and endogenous markups. We are therefore able to provide a more precise answer as to the determinants of the labor wedge. This will help not only in explaining the labor wedge and hours, but also in understanding the driving forces behind the output gap.

To study the determinants of the labor wedge, we will exploit the two-way decomposition of the fundamental wedge from Section 3:

$$\begin{aligned} \widetilde{wedge}_t &= \overbrace{-\left(\widetilde{\mu}_t^w + \widetilde{\mu}_t^p\right) - \left(\widehat{\varepsilon}_t^w + \widehat{\varepsilon}_t^p\right)}^{\text{Inefficient}} \overbrace{-\left(\widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l\right)}^{\text{Efficient}} \\ &= \underbrace{-\left(\widetilde{\mu}_t^w + \widetilde{\mu}_t^p\right)}_{\text{Endogenous}} \underbrace{-\left(\widehat{\varepsilon}_t^w + \widehat{\varepsilon}_t^p\right) - \left(\widehat{\varepsilon}_t^b + \widehat{\varepsilon}_t^l\right)}_{\text{Exogenous}}. \end{aligned} \tag{64}$$

This decomposition is illustrated in Figures 9 and 10. It gives several insights.

First, Figure 9 shows the decomposition into the endogenous and exogenous components, the two endogenous markups, and two of the four shocks that affect the fundamental component: the intertemporal preference shock and the persistent labor market shock (the remaining two shocks, the price markup shock and the i.i.d. labor market shock, are essentially zero). The endogenous component in panel (a) is essentially acyclical (its correlation with the fundamental wedge is 0.07), whereas the exogenous component in panel (b) is large and pro-

[33] Again, the MRS and the real wage in Figure 8 are detrended using the common productivity trend. A similar pattern is obtained by comparing data on hours worked and the real wage detrended using the Hodrick-Prescott filter.

cyclical, moving closely with the fundamental wedge (the correlation is 0.8). Panel (c) shows that the endogenous price markup is small compared with the endogenous wage markup, so the endogenous component reflects movements in the endogenous wage markup. And panel (d) reveals that the exogenous component is mainly due to the persistent labor market shock. The overall impression of Figure 9 is that the fundamental wedge and hours are mainly determined by exogenous labor market shocks rather than endogenous movements in price or wage markups, and the endogenous movements in the wage markup are acyclical.

Second, Figure 10 shows the inefficient and efficient components of the fundamental labor wedge under the two different interpretations of the labor market shocks. When the persistent labor market shock is interpreted as a wage markup shock in panels (a) and (b), the inefficient component (the total wage markup) mainly reflects movements in the wage markup shock and moves closely with the fundamental wedge (the correlation is above 0.9), whereas the efficient component corresponds to the intertemporal preference shock, which is negatively correlated with the fundamental wedge (the correlation is -0.4). With persistent labor disutility shocks in panels (c) and (d), the inefficient component is the same as the endogenous component (that is, the endogenous wage markup), and the efficient component is equal to the exogenous component in Figure 9(b), which is mainly driven by the persistent labor market shock and is closely correlated with the fundamental wedge.

The decomposition reveals an important failure of the model: it does not generate a plausible explanation for movements in the labor input (and the fundamental wedge). Hours are directly explained by exogenous shocks, either to the wage markup or to the disutility of supplying labor. Wage rigidities are substantial (the estimated wage stickiness parameter θ_w is large), but generate a wage markup that is essentially acyclical. The total wage markup is countercyclical when the persistent labor market shock is interpreted as a wage markup shock, but this is entirely due to exogenous markup shocks. Galí, Gertler, and López-Salido (2007) also find that the total wage markup is countercyclical, and present evidence that the wage markup is at least partially endogenous. Our results are not entirely inconsistent with their findings, as the wage markup is partly endogenous also in our model. The countercyclical wage markup is, however, generated by exogenous shocks rather than endogenous wage rigidities.[34]

We can now go back to interpret the output gap and the labor wedge in Figure 5. With persistent wage markup shocks the output gap and the labor wedge are similar to the fundamental wedge, and are thus procyclical and partly endogenous, partly exogenous. But the endogenous part is acyclical, and the procyclicality is due to the exogenous shock. With persistent labor disutility shocks, the output gap and the labor wedge are entirely endogenous, but acyclical. Figure 11 shows the contribution of the labor market shock to hours and the two output gaps in our sample. The labor input is again largely explained by the labor

[34]The overall correlation between the endogenous wage markup and the fundamental wedge (and hours) depends on the relative importance of the different shocks. The variance decomposition in Table 3 shows that movements in hours worked are mainly driven by two shocks: technology shocks and persistent labor market shocks. The same is true for the endogenous wage markup and the fundamental wedge (these results are available upon request). Technology shocks generate a perfect negative correlation between the endogenous wage markup and the fundamental wedge, whereas persistent labor market shocks generate a positive correlation (around 0.2). (There is a perfect negative correlation also after shocks to investment, government spending, the inflation target, and monetary policy, but these shocks are quantitatively less important.) The large importance given to the persistent labor market shock within the sample (see Figure 11) implies that the unconditional correlation is close to zero.

market shock, but also movements in the two different output gaps (and therefore also in the labor wedges) are due to this shock. All inefficiencies are thus driven almost exclusively by the persistent labor market shock. When the shock is interpreted as an inefficient disturbance to the wage markup, fluctuations in the output gap are mainly exogenous. When the shock is interpreted as movements in the disutility of supplying labor, the output gap is determined by the inefficient effects of the efficient labor market shock, working through acyclical movements in the endogenous wage markup.

6 Robustness analysis

The previous section demonstrated our main results: the estimated model implies that hours worked are almost entirely exogenous and the endogenous wage markup is acyclical. Thus, the endogenous inefficient fluctuations in output and the labor input are also essentially acyclical. We also showed that the output gap is closely correlated with the labor wedge, and the fundamental wedge is closely related to hours worked. This section analyzes the robustness of these results by studying four different specifications of our empirical model. We first study the model without measurement errors that we estimated in Section 4 but rejected as it implied an unreasonably large volatility of the labor market shocks. Second, we study a version of the model where wages are more flexible. Third, we estimate a model where the monetary policy rule is specified in terms of the output gap. Finally, we study an estimated model where we remove the low-frequency movements in hours worked prior to estimation. We will show that our main results go through also in these alternative specifications.

6.1 The model without measurement errors

We begin by considering the model without measurement errors that we estimated in Section 4. We here consider two versions of the model: one with only one labor market shock, modelled as an AR(1) process, and one with two labor market shocks, one AR(1) and one i.i.d.[35]

Figure 12 summarizes the main features of the model with one labor market shock; Figure 13 shows the model with two shocks. (Table 4 shows the estimated posterior modes of the parameters in both models.) As noted above, the models without measurement errors imply very volatile labor market shocks. In the one-shock model in Figure 12, the persistent labor market shock is very volatile, but its low-frequency component is similar to hours worked. The output gap with persistent wage markup shocks is very similar to the gap in the benchmark model, whereas the gap with persistent labor disutility shocks is very volatile and resembles a noisy version of the gap in the benchmark model. The two output gaps correlate closely with the labor wedges, and the wedges are in turn almost entirely explained by the marginal rate of substitution. (Thus, the gap and the wedge are driven mainly by movements in the wage markup.) The fundamental wedge is closely related to hours worked, and

[35]In our benchmark model with measurement errors and two labor market shocks studied in Section 5, the i.i.d. shock was found to be very small. Therefore, the two-shock model studied above is almost identical to a model with only one labor market shock.

although the volatile shocks make it difficult to identify any patterns, the fundamental wedge seems more closely related to the exogenous component than to the endogenous component.

In the two-shock model in Figure 13, the persistent labor market shock is similar to the low-frequency movements in hours worked and is slightly less volatile than in the benchmark model. The output gap with persistent wage markup shocks is like a noisy version of the gap in the benchmark model; the gap with persistent labor disutility shocks is less volatile and also similar to the benchmark model. Again, the output gaps are proportional to the labor wedges, which are mainly driven by the marginal rate of substitution and the wage markup. And the fundamental wedge is similar to hours worked and seems more closely related to the exogenous than the endogenous component.

6.2 The importance of wage rigidities

We next study the importance of wage rigidities by using a version of the benchmark model where we reduce the wage stickiness parameter θ_w to 0.1 while keeping all other parameters unchanged at their posterior medians. The estimated posterior median of $\theta_w = 0.75$ implies that wages are reoptimized on average every four quarters, whereas with $\theta_w = 0.1$ the average duration of the optimized wage contracts is 1.1 quarters.

Figure 14 summarizes the results. When wages are more flexible, the persistent labor market shock exhibits more high-frequency volatility. This is because movements in the marginal rate of substitution have a larger direct impact on the real wage, so it is more important for the shock to offset these movements. The output gap with persistent wage markup shocks is very similar to the gap in the benchmark model, and also to the estimated persistent labor market shock in panel (*b*). The gap with persistent labor disutility shocks is smaller than in the benchmark model, as the efficient shock removes more of the volatility in hours. The output gaps are proportional to the labor wedges, that are closely related to the marginal rate of substitution, in particular in the model with persistent wage markup shocks. Thus, even with more flexible wages, the wage markup is more important than the price markup. Finally, the exogenous component explains almost all movements in the fundamental wedge and hours, and the endogenous component is very small.

6.3 A model with the output gap in the monetary policy rule

The benchmark model assumes that monetary policy responds to the growth rate of output. We now consider a model where the monetary policy rule is specified in terms of the output gap.[36] In principle, the wage markup shock is no longer observationally equivalent to the labor disutility shock in this model, as the two shocks have different implications for the output gap and therefore for monetary policy. The estimated coefficient on the output gap in the monetary policy rule is, however, very small (see Table 4), implying that the interpretation of the shock has almost no consequences for the estimated models.[37] This is also demonstrated

[36]For simplicity, we use the unconditional output gap in the policy rule. As this gap is very similar to the conditional gap, using the latter should imply very similar results. To facilitate comparison with the benchmark model, Figures 15 and 16 show the conditional output gap.

[37]As in the benchmark model, the i.i.d. labor market shock and the price markup shock obtain very small variances. The models with one and two shocks are thus essentially identical.

in Figures 15 and 16 that show the results for the two models: the only difference between the models is for the estimated output gap, labor wedge, and MRS. All features of these models are also very similar to the benchmark model: the output gap is closely related to the labor wedge, the fundamental wedge is closely related to hours, and is mainly exogenous, and the endogenous component of the fundamental wedge (the endogenous wage markup) is acyclical.

6.4 Using detrended hours

As the interpretation of fluctuations in hours worked is an important part of our story, we study a model where the low-frequency component in hours was removed before estimation. In particular, we used the Hodrick-Prescott filter to remove the very low-frequency movements (applying a smoothing parameter of 10,000). The results are summarized in Figure 17, and parameter estimates are shown in Table 4.[38]

Hours worked are now very cyclical, and the persistent labor market shock reflects movements in detrended hours. The output gap with persistent wage markup shocks is also closely related to detrended hours, whereas the gap with persistent labor disutility shocks is similar to the benchmark model. The relationship between the output gap, the labor wedge, and the marginal rate of substitution remains very strong, and the fundamental wedge is similar to hours. Hours worked and the fundamental wedge are more closely related to the exogenous component than to the endogenous component. Thus, the main results go through also without the low-frequency movements in hours.

7 Summary and concluding remarks

Modern monetary business cycle models that combine neoclassical and Keynesian features and generate a good fit to aggregate data are potentially useful to understand the extent to which business cycle fluctuations are efficient. We use a standard model in this class to estimate two measures of inefficiency: the output gap and the labor wedge. We first show that these two measures are essentially identical, but the estimates are highly sensitive to the structural interpretation of the model, in particular, to the interpretation of labor market shocks. We find that the gap and the wedge are strongly procyclical when persistent labor market shocks are interpreted as shocks to the wage markup, but essentially acyclical when the shocks are interpreted as labor disutility shocks.

The close correspondence between the output gap and the labor wedge suggests that most inefficiencies in output are related to the inefficient allocation of labor, and that studying the determinants of the labor wedge can give further insights into the sources of business cycle inefficiencies. For this purpose we construct a “fundamental wedge” that is independent of the interpretation of labor market shocks, and is closely related to the labor wedge studied in the literature. We show that this wedge moves closely with the labor input over the business cycle. Explaining this wedge therefore means explaining movements in hours, and, more generally, the driving forces of business cycle fluctuations in our estimated model. By decomposing the

[38] We have also estimated a model with hours in first differences. The results from that model are virtually identical to the benchmark model.

fundamental wedge we demonstrate a key challenge for the model: to reconcile the procyclical behavior of hours worked with the largely acyclical real wage. In principle this pattern can be explained by endogenous wage markups or exogenous shocks. Our decomposition shows that hours are largely driven by the direct effects of exogenous shocks, rather than countercyclical markups due to price and wage rigidities. The endogenous movements in the wage markup are instead acyclical. Whenever the wage markup is found to be countercyclical, this is due to large countercyclical markup shocks rather than the endogenous effects of wage rigidities.

We conclude that the model fails in two important respects: it does not give clear guidance concerning the efficiency of business cycle fluctuations, and it provides an unsatisfactory explanation of labor market and business cycle dynamics. These findings cast doubt on the usefulness of this class of models for business cycle analysis.

In future work we plan to go deeper into the issues identified in this paper. One way forward is to study models that are able to properly identify the different labor market shocks. This is the route taken by Galí, Smets, and Wouters (2010), who reinterpret the standard model to incorporate a measure of unemployment that is directly related to the wage markup. But labor market dynamics seems largely exogenous also in their estimated model. Another possibility is to use more general specifications of preferences and technology. For instance, preferences that are non-separable in consumption and leisure can also help identify the two labor market shocks, as labor disutility shocks then affect households' consumption decision. Again, however, such extensions are unlikely to solve to the more fundamental problem with the model.

A more promising alternative is a model with search and matching frictions in the labor market and nominal price and wage rigidities, along the lines of Gertler, Sala, and Trigari (2008). A version of that model with an intensive and an extensive margin of labor solves the identification problem, although through mechanisms very different from Galí, Smets, and Wouters (2010). Furthermore, the intensive margin could be efficient while wage rigidities create inefficiencies in the extensive margin through inefficient job creation. But the extensive margin is not subject to the critique of sticky-wage models raised by Barro (1977): once firms and workers have met, their decision to stay together or separate is efficient as long as the wage stays within the bargaining set. This model therefore has the potential of giving a different and more satisfactory account of the dynamics and efficiency of labor market fluctuations.

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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)):

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

Tobin's Q (equation (10)):

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

Capital utilization (equation (11)):

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

Production function (equation (16)):

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

Labor demand (equation (18)):

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

Capital renting (equation (19)):

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

Price setting (equation (24)):

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

Aggregate price index (equation (26)):

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

Wage setting (equation (32)):

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

Aggregate wage (equation (35)):

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

Government spending (equation (36)):

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

Monetary policy rule (equation (38)):

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

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:

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

Consumption Euler equation:

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

Investment:

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

Tobin's Q:

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

Capital utilization:

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

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:

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

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

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

where

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

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

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

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:[39]

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:

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

Marginal utility of consumption:

$$\begin{aligned}\left(1-\frac{h}{\gamma_z}\right)\left(1-\frac{\beta h}{\gamma_z}\right)\widehat{\lambda}^f_t &= \frac{h}{\gamma_z}\left[\widehat{c}^f_{t-1} - \widehat{\varepsilon}^z_t\right] - \left(1+\frac{\beta h^2}{\gamma_z^2}\right)\widehat{c}^f_t \\ &+ \frac{\beta h}{\gamma_z}\mathrm{E}_t\left[\widehat{c}^f_{t+1} + \widehat{\varepsilon}^z_{t+1}\right] + \left(1-\frac{h}{\gamma_z}\right)\left[\widehat{\varepsilon}^b_t - \frac{\beta h}{\gamma_z}\mathrm{E}_t\widehat{\varepsilon}^b_{t+1}\right];\end{aligned} \tag{A46}$$

Consumption Euler equation:

$$\widehat{\lambda}^f_t = \mathrm{E}_t\widehat{\lambda}^f_{t+1} + \widehat{r}^f_t - \mathrm{E}_t\widehat{\varepsilon}^z_{t+1}; \tag{A47}$$

[39] 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.

Investment:

$$\widehat{i}_t = \frac{1}{1+\beta}\left[\widehat{i}^f_{t-1} - \widehat{\varepsilon}^z_t\right] + \frac{1}{\eta_k \gamma_z^2 (1+\beta)}\left[\widehat{q}^f_t + \widehat{\varepsilon}^i_t\right] + \frac{\beta}{1+\beta}\mathrm{E}_t\left[\widehat{i}^f_{t+1} + \widehat{\varepsilon}^z_{t+1}\right]; \tag{A48}$$

Tobin's Q:

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

Capital utilization

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

Production function

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

Labor demand

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

Capital renting

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

Labor supply:

$$\widehat{w}^f_t \quad = \quad \omega\widehat{l}^f_t - \widehat{\lambda}^f_t + \widehat{\varepsilon}^b_t; \tag{A54}$$

Government spending:

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

Resource constraint:

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

B Efficient and potential output

This appendix demonstrates that the efficient and potential levels of output only differ by a constant due to the steady-state price and wage markups, and that their dynamics is not affected by the steady-state markups. Therefore, fluctuations in the efficient level of output are reflected fully in movements in potential output.

First, to show that the dynamics is unaffected by the steady-state markups, we use the log-linearized equations for the allocation with flexible prices and wages in Appendix A.4. The steady-state markups can only affect the log-linearized model through the steady-state ratios of consumption, investment, government spending, and capital to output, which affect the dynamics of the model through government spending in equation (A55) and the resource constraint (A56). The ratio of government spending to output (g/y) is calibrated to 0.2 before estimation and so is fixed. The consumption/output ratio c/y is calculated as a residual using equation (A27), given g/y and i/y. The investment/output ratio i/y is determined by equation (A26) as a function of the investment/capital ratio i/k and the capital/output ratio k/y, where i/k is given directly through equation (A25) as

$$\frac{i}{k} = \left[1 - \frac{1-\delta}{\gamma_z}\right]\gamma_z. \tag{B1}$$

Finally, equation (A24) implies that the capital/output ratio is given by

$$\frac{k}{y} = \frac{\alpha}{r^k}, \tag{B2}$$

and so is independent of the steady-state markups. Thus, the dynamics of the model does not depend on the steady-state markups.[40]

Second, we show that the efficient level of output is higher than the potential level at all times. Equations (A3) and (A13) imply that in steady state the marginal utility of consumption and the real wage are given by

$$\lambda = \frac{1}{c}\frac{\gamma_z - \beta h}{\gamma_z - h}, \tag{B3}$$

$$w = \frac{\varepsilon^w \varepsilon^l L^\omega}{\lambda}. \tag{B4}$$

Combining with (A19)–(A21) and solving for the steady-state level of hours gives

$$L = \left[(1-\alpha)\frac{\gamma_z - \beta h}{\gamma_z - h}\frac{1}{\varepsilon^p \varepsilon^w \varepsilon^l}\left(\frac{\alpha}{r^k \varepsilon^p}\right)^{\alpha/(1-\alpha)}\frac{1}{(c/y)y}\right]^{1/\omega}. \tag{B5}$$

Equation (A20) and (A24) imply that the output-labor ratio is given by

$$\frac{y}{L} = \left(\frac{\alpha}{r^k}\right)^{\alpha/(1-\alpha)}\left(\frac{1}{\varepsilon^p}\right)^{1/(1-\alpha)}. \tag{B6}$$

[40] This result hinges on the assumption that fixed costs in production make profits zero in steady state, so the output/labor ratio in (A24) is proportional to the capital/labor ratio. Without the fixed cost, the output/labor ratio would move less than one-for-one with the capital/labor ratio. Then k/y and therefore i/y and c/y would be affected by the steady-state markups.

Using this in equation (B5) implies that the steady-state level of output is

$$y = \Phi \left(\frac{1}{\varepsilon^p}\right)^{1/(1-\alpha)} \left(\frac{1}{\varepsilon^w}\right)^{1/(1+\omega)}, \tag{B7}$$

where

$$\Phi \equiv \left(\frac{\alpha}{r^k}\right)^{(\alpha/(1-\alpha))(\omega/(1+\omega))} \left[(1-\alpha)\frac{\gamma_z - \beta h}{\gamma_z - h}\left(\frac{\alpha}{r^k}\right)^{\alpha/(1-\alpha)} \frac{1}{\varepsilon^l}\frac{1}{c/y}\right]^{1/\omega}, \tag{B8}$$

which is independent of the steady-state markups. The efficient level of output in steady state is then given by

$$y^e = \Phi, \tag{B9}$$

and the potential level is

$$y^p = y^e \left(\frac{1}{\varepsilon^p}\right)^{1/(1-\alpha)} \left(\frac{1}{\varepsilon^w}\right)^{1/(1+\omega)}, \tag{B10}$$

or, in logs,

$$\log y^p = \log y^e - \frac{1}{1-\alpha}\log \varepsilon^p - \frac{1}{1+\omega}\log \varepsilon^w \le y^e, \tag{B11}$$

since $\varepsilon^p, \varepsilon^w \ge 1$.

Thus, as the steady-state markups affect only the steady-state levels of output, not the dynamics, the efficient and potential levels of output differ by a constant at all times:

$$y_t^p = y_t^e - C, \tag{B12}$$

where the constant C is determined by the steady-state price and wage markups.

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, whereas 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

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

When 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 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.

Hours worked 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.

Table 1: Prior parameter distributions

Parameter	Notation	Prior distribution	Mean	Standard deviation
(*a*) *Structural parameters*				
Steady-state growth rate	γ_z	Normal	1.004	0.001
Utilization rate elasticity	ψ_ν	Beta	0.5	0.1
Capital adjustment cost elasticity	η_k	Normal	4.0	1.5
Habit parameter	h	Beta	0.5	0.1
Labor supply elasticity	ω	Gamma	2.0	0.75
Calvo wage parameter	θ_w	Beta	0.75	0.1
Calvo price parameter	θ_p	Beta	0.66	0.1
Wage indexing parameter	γ_w	Uniform[a]	0	1
Price indexing parameter	γ_p	Uniform[a]	0	1
Steady-state wage markup	ε^w	Normal	1.15	0.05
Steady-state price markup	ε^p	Normal	1.15	0.05
Policy response to inflation	r_π	Normal	1.7	0.3
Policy response to output	r_y	Gamma	0.125	0.1
Policy inertia	ρ_s	Beta	0.75	0.1
(*b*) *Autoregressive shock parameters*				
Productivity growth rate	ρ_z	Beta	0.5	0.15
Preferences	ρ_b	Beta	0.5	0.15
Investment	ρ_i	Beta	0.5	0.15
Price markup	ρ_p	Beta	0.5	0.15
Government spending	ρ_g	Beta	0.5	0.15
Inflation target	ρ_*	Beta	0.5	0.15
AR(1) labor market shock	ρ_1	Beta	0.5	0.15
(*c*) *Innovation standard deviations*				
Productivity growth rate	σ_z	Gamma	5.0	5.0
Preferences	σ_b	Gamma	5.0	5.0
Investment	σ_i	Gamma	5.0	5.0
Price markup	σ_p	Gamma	5.0	5.0
Government spending	σ_g	Gamma	5.0	5.0
Inflation target	σ_*	Gamma	0.15	0.15
Monetary policy	σ_r	Gamma	0.15	0.15
AR(1) labor market shock	σ_1	Gamma	5.0	5.0
i.i.d. labor market shock	σ_2	Gamma	5.0	5.0
(*d*) *Measurement error standard deviations*				
Wage growth	$\sigma_{\eta w}$	Gamma	0.612	0.612
Inflation	$\sigma_{\eta\pi}$	Gamma	0.596	0.596

This table reports the prior distribution of the parameters in the estimated models. [a] For the uniform distribution, the two numbers are the lower and upper bounds.

Table 2: Posterior parameter estimates

		Without measurement errors			With measurement errors		
		Median	5%	95%	Median	5%	95%
(*a*) *Structural parameters*							
Steady-state growth rate	γ_z	1.0029	1.0025	1.0033	1.0032	1.0031	1.0034
Utilization rate elasticity	ψ_ν	0.91	0.87	0.94	0.86	0.83	0.88
Capital adj. cost elasticity	η_k	0.73	0.53	0.99	0.05	0.03	0.07
Habit parameter	h	0.83	0.80	0.85	0.90	0.89	0.91
Labor supply elasticity	ω	1.48	1.29	1.66	2.24	2.04	2.42
Calvo wage parameter	θ_w	0.63	0.60	0.66	0.75	0.71	0.77
Calvo price parameter	θ_p	0.69	0.66	0.72	0.80	0.79	0.82
Wage indexing parameter	γ_w	0.94	0.83	0.99	0.97	0.92	1.00
Price indexing parameter	γ_p	0.03	0.00	0.11	0.01	0.00	0.05
Steady-state wage markup	ε^w	1.17	1.15	1.19	1.15	1.13	1.17
Steady-state price markup	ε^p	1.27	1.26	1.28	1.21	1.20	1.22
Mon. pol. response to inflation	r_π	2.19	2.08	2.29	2.85	2.76	2.94
Mon. pol. response to output	r_y	0.41	0.36	0.46	0.29	0.27	0.32
Mon. pol. inertia	ρ_s	0.72	0.68	0.76	0.30	0.27	0.32
(*b*) *Autoregressive shock parameters*							
Technology	ρ_z	0.15	0.11	0.20	0.31	0.24	0.37
Preference	ρ_b	0.43	0.37	0.50	0.43	0.41	0.46
Investment	ρ_i	0.86	0.82	0.89	0.93	0.91	0.95
Government spending	ρ_g	0.98	0.97	0.99	0.98	0.97	0.99
Price markup	ρ_p	0.92	0.90	0.95	0.50	0.47	0.52
Inflation target	ρ_*	0.77	0.74	0.80	0.95	0.93	0.96
AR(1) labor market shock	ρ_1	0.98	0.97	0.99	0.96	0.95	0.98
(*c*) *Innovation standard deviations*							
Technology	σ_z	1.23	1.12	1.35	1.18	1.09	1.29
Preference	σ_b	2.71	2.30	3.17	5.02	4.57	5.52
Investment	σ_i	2.36	1.98	2.82	1.59	1.33	1.92
Government spending	σ_g	0.54	0.50	0.58	0.54	0.50	0.59
Price markup	σ_p	0.87	0.77	0.99	0.14	0.01	0.37
Inflation target	σ_*	0.18	0.15	0.22	0.08	0.07	0.10
Monetary policy	σ_r	0.19	0.17	0.21	0.15	0.13	0.17
AR(1) labor market shock	σ_1	2.51	1.95	3.20	6.02	4.92	7.25
i.i.d. labor market shock	σ_2	33.27	30.70	35.25	0.46	0.04	1.38
(*d*) *Measurement error standard deviations*							
Wage growth	$\sigma_{\eta w}$				0.51	0.47	0.55
Inflation	$\sigma_{\eta \pi}$				0.21	0.19	0.23

This table reports the estimated posterior distribution of parameters in two versions of the model, with and without measurement errors. The posterior distribution was constructed by generating 150,000 draws using the Random-Walk Metropolis Hastings algorithm (after discarding the first 10,000 draws).

Table 3: Variance decomposition in the estimated model

Shock	Output	Investment	Consumption	Real wage	Hours	Inflation	Interest rate
(*a*) *All frequencies*							
Technology	[0.55 , 0.76]	[0.51 , 0.68]	[0.42 , 0.63]	[0.77 , 0.87]	[0.09 , 0.36]	[0.04 , 0.11]	[0.04 , 0.08]
Preference	[0.00 , 0.00]	[0.04 , 0.07]	[0.10 , 0.16]	[0.00 , 0.01]	[0.00 , 0.00]	[0.00 , 0.00]	[0.01 , 0.01]
Investment	[0.04 , 0.07]	[0.08 , 0.16]	[0.04 , 0.11]	[0.04 , 0.08]	[0.02 , 0.07]	[0.13 , 0.28]	[0.54 , 0.72]
Govt spending	[0.00 , 0.00]	[0.02 , 0.03]	[0.04 , 0.09]	[0.00 , 0.01]	[0.01 , 0.07]	[0.00 , 0.01]	[0.02 , 0.03]
Price markup	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]
Inflation target	[0.01 , 0.03]	[0.01 , 0.04]	[0.002 , 0.01]	[0.01 , 0.02]	[0.01 , 0.04]	[0.60 , 0.79]	[0.17 , 0.33]
Monetary policy	[0.00 , 0.01]	[0.01 , 0.01]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.01]	[0.00 , 0.01]	[0.00 , 0.00]
AR(1) labor market	[0.16 , 0.37]	[0.11 , 0.25]	[0.13 , 0.31]	[0.06 , 0.14]	[0.51 , 0.84]	[0.01 , 0.02]	[0.02 , 0.05]
i.i.d. labor market	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]
(*b*) *Business cycle frequencies*							
Technology	[0.74 , 0.86]	[0.64 , 0.76]	[0.18 , 0.31]	[0.67 , 0.81]	[0.47 , 0.66]	[0.18 , 0.31]	[0.06 , 0.10]
Preference	[0.00 , 0.00]	[0.05 , 0.09]	[0.56 , 0.68]	[0.00 , 0.01]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]
Investment	[0.03 , 0.06]	[0.06 , 0.10]	[0.02 , 0.05]	[0.02 , 0.04]	[0.07 , 0.13]	[0.16 , 0.29]	[0.64 , 0.78]
Govt spending	[0.00 , 0.01]	[0.03 , 0.05]	[0.03 , 0.05]	[0.00 , 0.01]	[0.00 , 0.01]	[0.00 , 0.00]	[0.00 , 0.01]
Price markup	[0.00 , 0.01]	[0.00 , 0.01]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.02]	[0.00 , 0.00]	[0.00 , 0.00]
Inflation target	[0.02 , 0.06]	[0.02 , 0.06]	[0.00 , 0.00]	[0.02 , 0.05]	[0.04 , 0.12]	[0.39 , 0.61]	[0.13 , 0.27]
Monetary policy	[0.01 , 0.03]	[0.02 , 0.03]	[0.00 , 0.00]	[0.00 , 0.00]	[0.03 , 0.06]	[0.01 , 0.02]	[0.00 , 0.00]
AR(1) labor market	[0.05 , 0.14]	[0.03 , 0.08]	[0.04 , 0.10]	[0.12 , 0.25]	[0.12 , 0.29]	[0.01 , 0.03]	[0.00 , 0.01]
i.i.d. labor market	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]	[0.00 , 0.00]

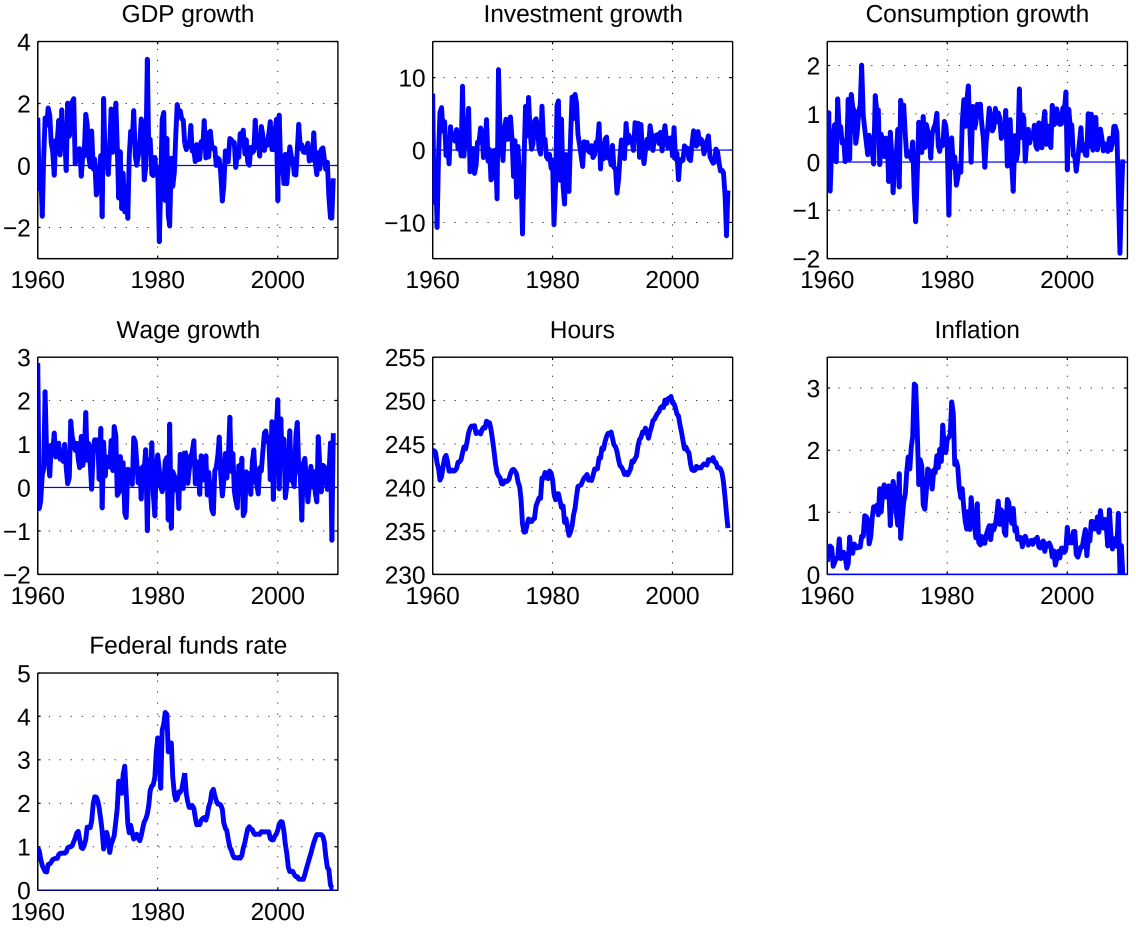
This table reports the contribution of each shock to the variance of observable variables in the estimated model with measurement errors. All variables are in levels. The variance shares for different frequencies are constructed using a spectral decomposition of the total variance for each shock. Business cycle frequencies are defined as cycles of 8 to 32 quarters; for the non-stationary variables (output, investment, consumption, and the real wage), all frequencies include cycles shorter than 128 quarters. Entries are the 5th and 95th percentiles over 1,000 draws from the posterior parameter distribution.

Table 4: Posterior mode estimates for all models

	Benchmark	No errors		Output gap in policy rule		Detrended hours
				$\widehat{\varepsilon}_t^w$ AR(1)	$\widehat{\varepsilon}_t^l$ AR(1)	
(a) Structural parameters						
γ_z	1.0031	1.0032	1.0030	1.0027	1.0027	1.0031
ψ_ν	0.87	0.90	0.90	0.91	0.91	0.86
η_k	0.05	0.94	0.70	0.42	0.40	0.04
h	0.91	0.74	0.84	0.89	0.89	0.91
ω	2.34	2.24	1.53	2.33	2.38	3.26
θ_w	0.72	0.71	0.63	0.64	0.63	0.69
θ_p	0.80	0.74	0.69	0.85	0.85	0.80
γ_w	1.00	1.00	1.00	1.00	1.00	1.00
γ_p	0.00	0.00	0.00	0.18	0.19	0.00
ε^w	1.16	1.16	1.17	1.17	1.17	1.16
ε^p	1.21	1.30	1.27	1.24	1.23	1.22
r_π	2.87	2.28	2.23	2.33	2.39	2.89
r_y	0.29	0.37	0.40	0.04	0.03	0.29
ρ_s	0.31	0.74	0.74	0.41	0.40	0.29
(b) Autoregressive shock parameters						
ρ_z	0.30	0.18	0.15	0.27	0.27	0.31
ρ_b	0.42	0.85	0.42	0.50	0.51	0.43
ρ_i	0.93	0.88	0.86	0.92	0.92	0.93
ρ_g	0.98	0.98	0.98	0.98	0.98	0.98
ρ_p	0.50	0.89	0.92	0.50	0.50	0.50
ρ_*	0.94	0.94	0.77	0.93	0.94	0.95
ρ_1	0.97	0.35	0.99	0.98	0.97	0.82
(c) Innovation standard deviations						
σ_z	1.18	1.24	1.21	1.21	1.20	1.19
σ_b	5.50	2.44	2.81	4.54	4.60	5.68
σ_i	1.54	2.71	2.33	2.01	1.97	1.52
σ_g	0.53	0.54	0.53	0.53	0.53	0.54
σ_p	0.00	1.05	0.86	0.00	0.00	0.00
σ_*	0.08	0.09	0.18	0.10	0.10	0.08
σ_r	0.15	0.21	0.19	0.14	0.14	0.15
σ_1	5.62	70.65	2.36	4.05	4.34	10.95
σ_2	0.00		34.23	0.00	0.00	0.00
(d) Measurement error standard deviations						
$\sigma_{\eta w}$	0.51			0.52	0.52	0.51
$\sigma_{\eta \pi}$	0.21			0.20	0.20	0.21

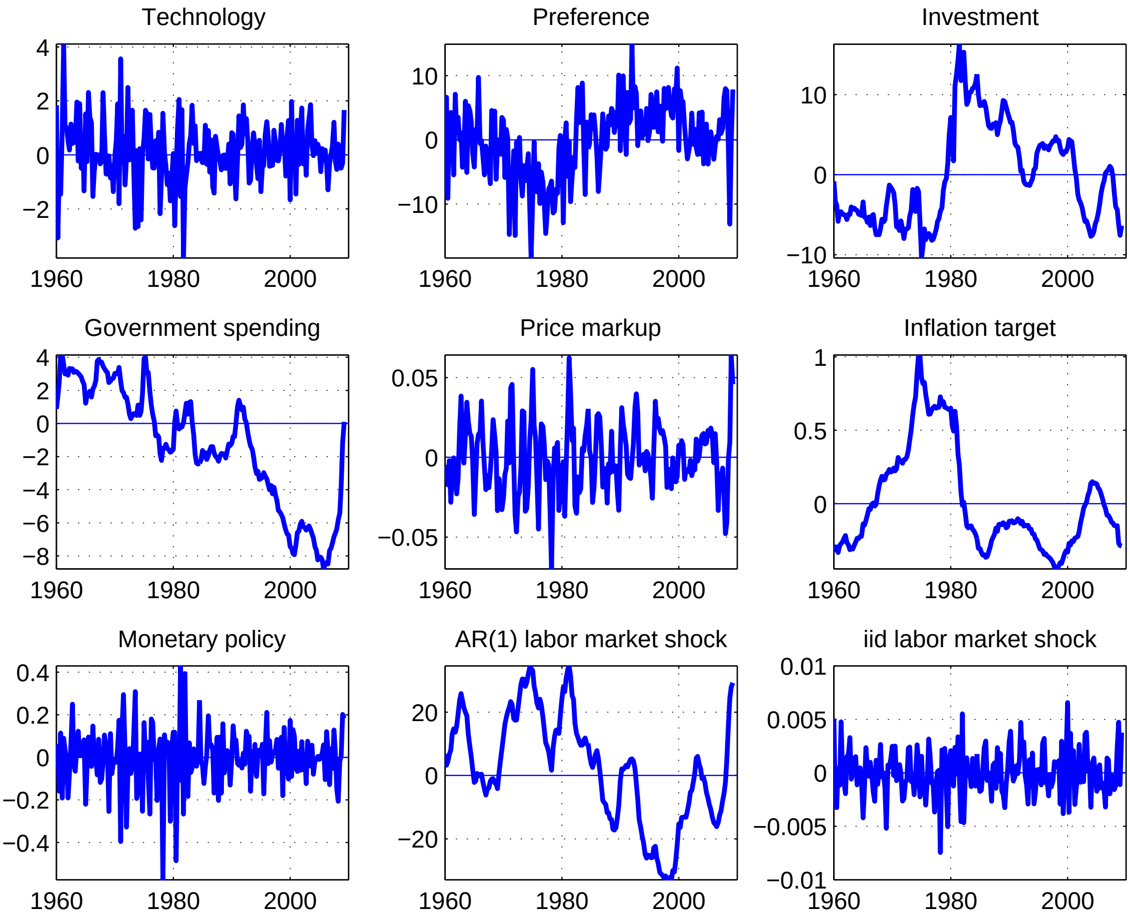
This table reports the estimated posterior mode of parameters in all models discussed in the paper: the benchmark model with measurement errors, the model without measurement errors (with one and two labor market shocks), the two models with the output gap in the monetary policy rule, and the model with detrended hours.

Figure 1: Data



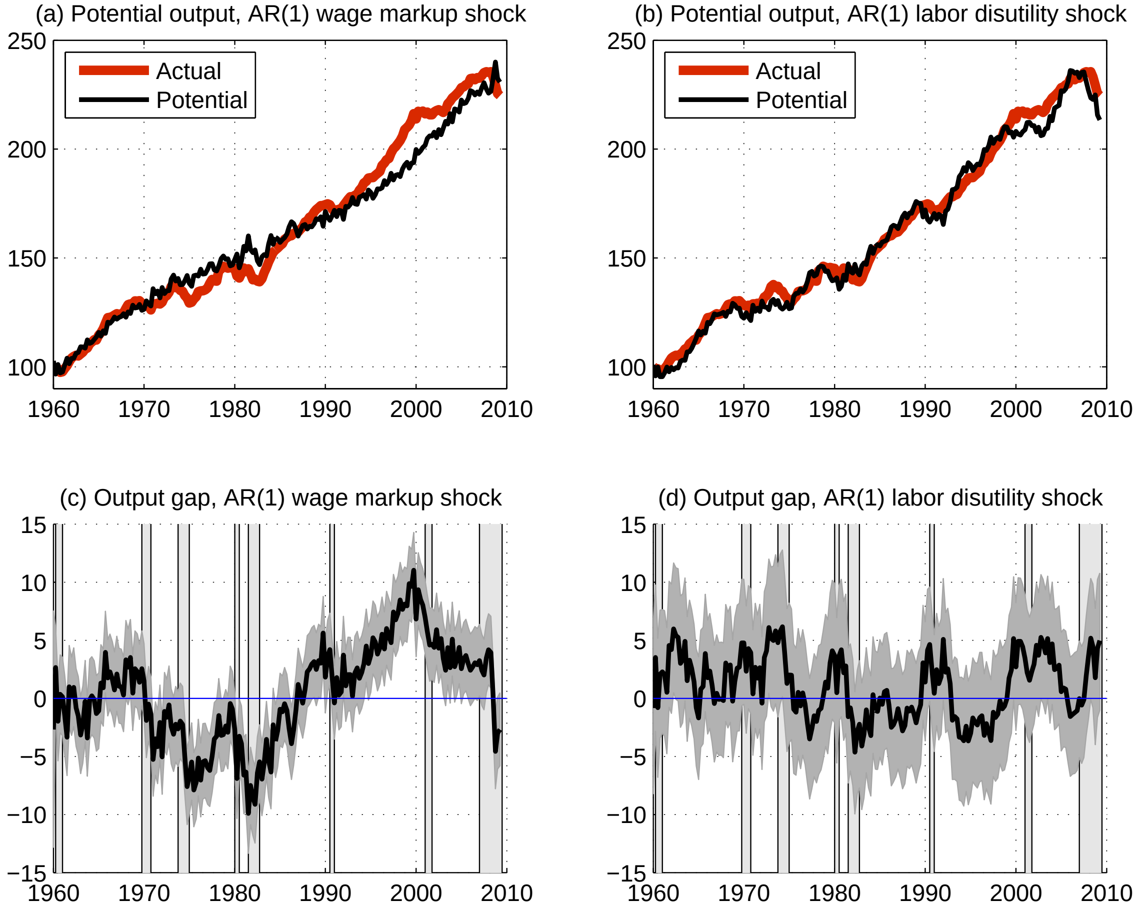
This figure shows the data series used for estimation. Data sources and details are reported in Appendix D.

Figure 2: Estimated shocks



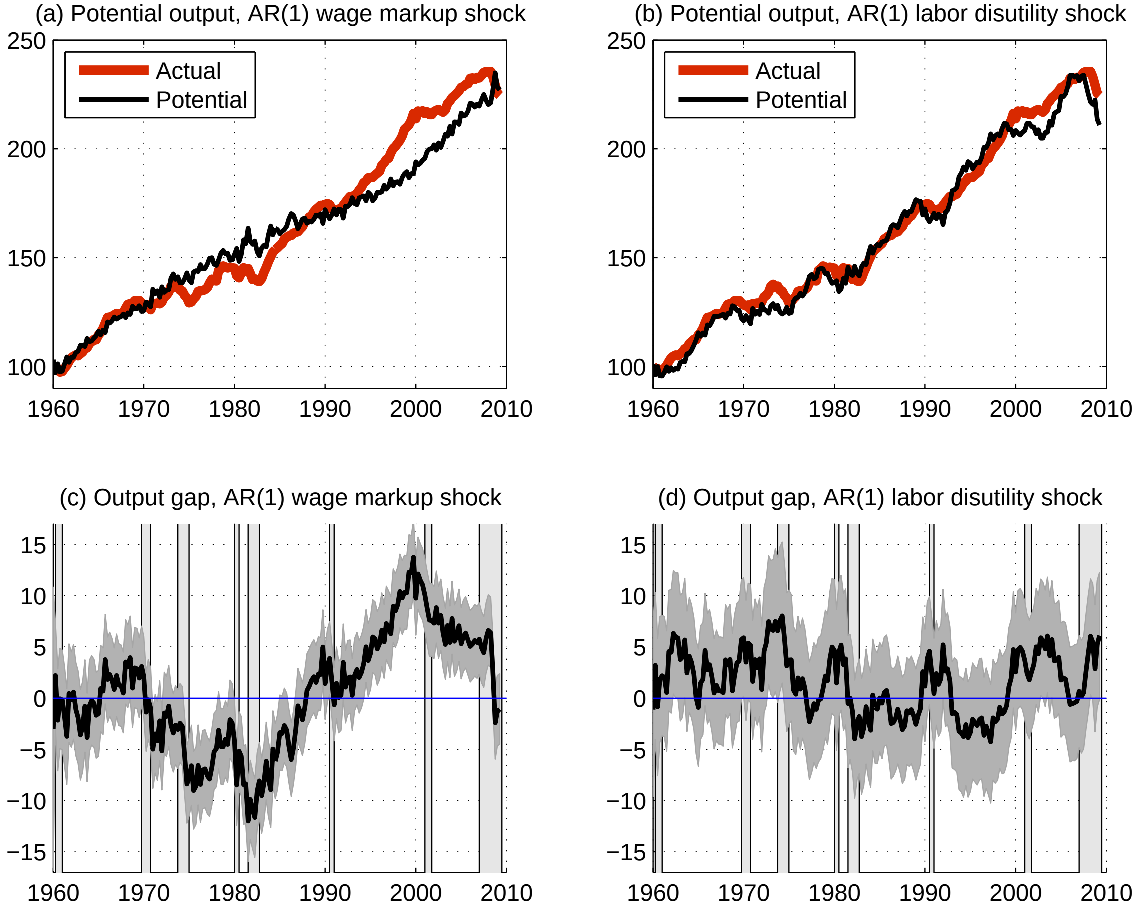
This figure shows the estimated paths for the structural shocks in the model with measurement errors. Parameters are set to their posterior median values.

Figure 3: Estimated conditional potential output and output gap



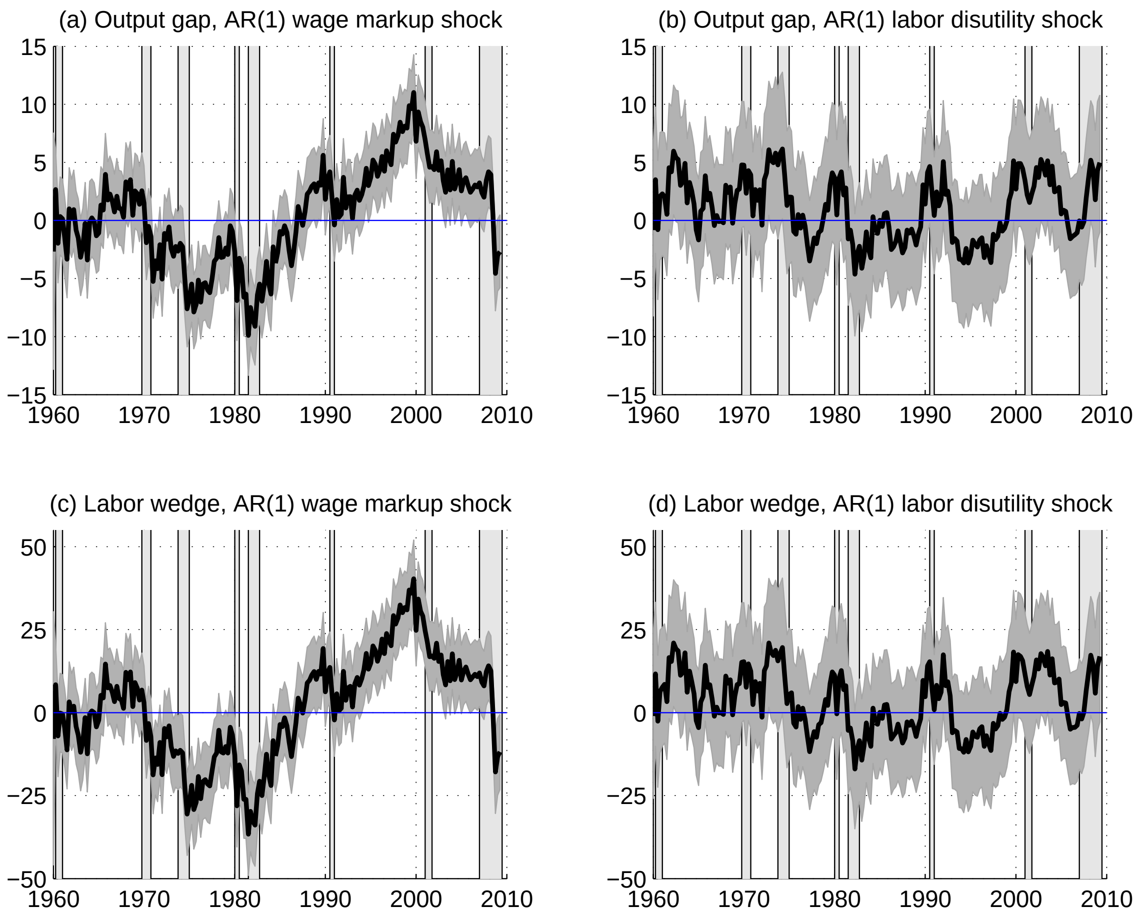
This figure shows the estimated paths for the conditional potential GDP in the U.S. and the output gap (the percent deviation of actual GDP from potential GDP) in the model with measurement errors under different interpretations of the labor market shocks. For potential GDP, parameters are set to their posterior median values. For the output gap, the solid lines show the median estimate and the shaded intervals represent 90 percent probability intervals over 1,000 draws from the estimated posterior distributions of parameters. The vertical shaded bands represent recessions dated by the National Bureau of Economic Research.

Figure 4: Estimated unconditional potential output and output gap



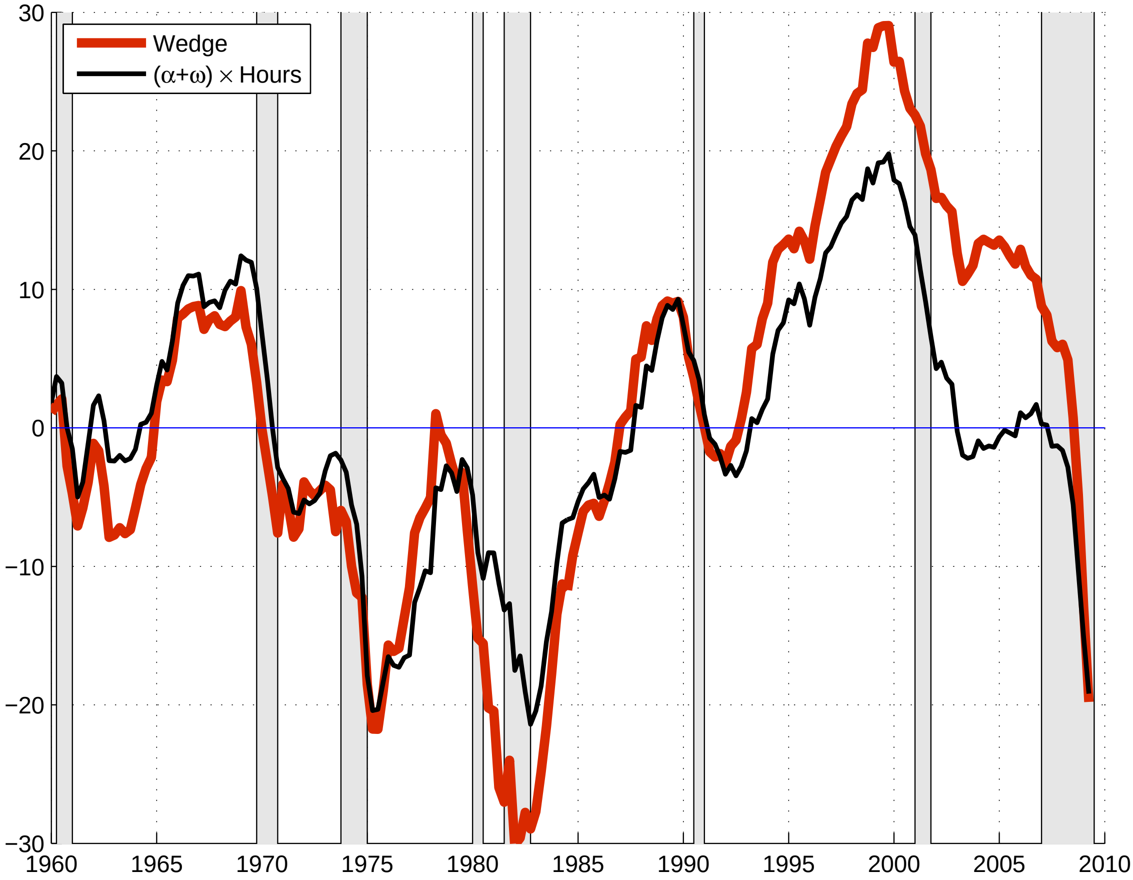
This figure shows the estimated paths for the unconditional potential GDP in the U.S. and the output gap (the percent deviation of actual GDP from potential GDP) in the model with measurement errors under different interpretations of the labor market shocks. For potential GDP, parameters are set to their posterior median values. For the output gap, the solid lines show the median estimate and the shaded intervals represent 90 percent probability intervals over 1,000 draws from the estimated posterior distributions of parameters. The vertical shaded bands represent recessions dated by the National Bureau of Economic Research.

Figure 5: Estimated output gap and labor wedge



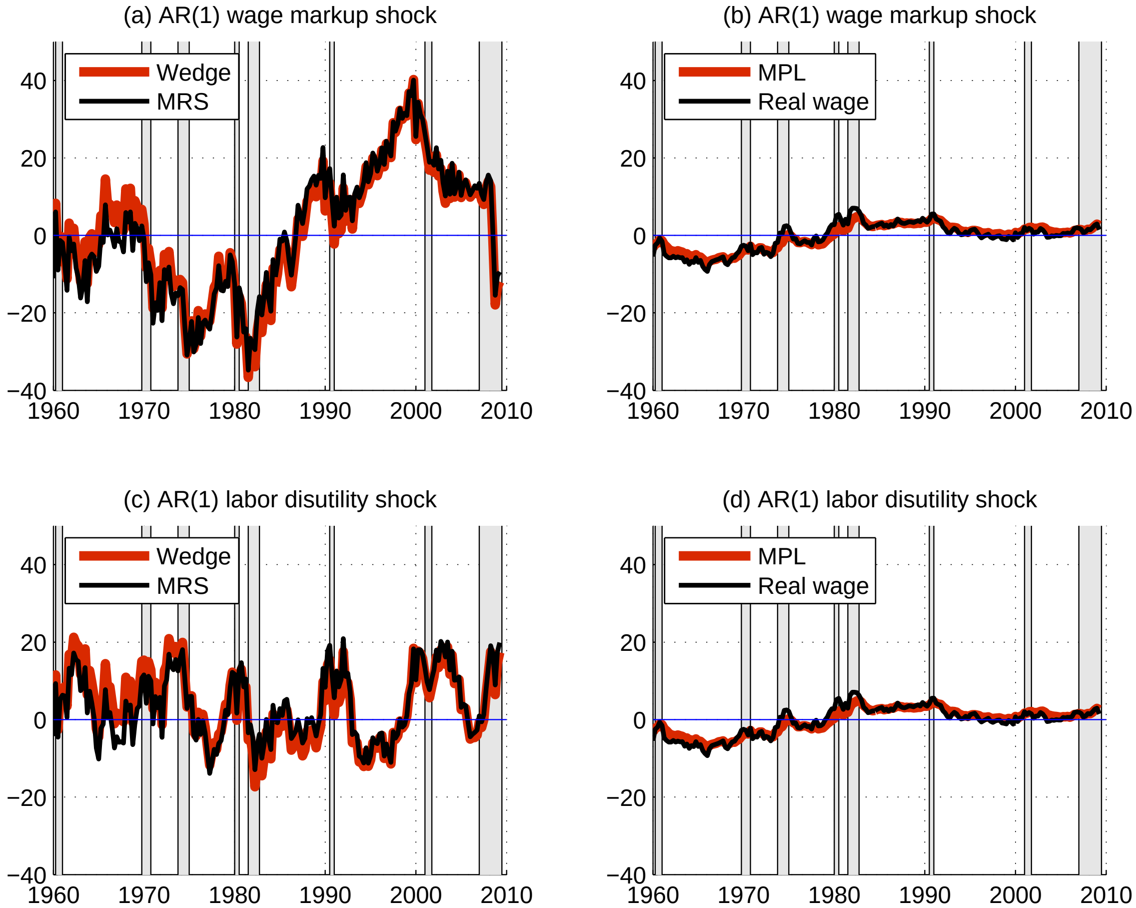
This figure shows the estimated paths for the U.S. output gap (the percent deviation of actual GDP from potential GDP) and labor wedge (the wedge between households' marginal rate of substitution and firms' marginal product of labor) in the model with measurement errors under different interpretations of the labor market shocks. The solid lines show the median estimate and the shaded intervals represent 90 percent probability intervals over 1,000 draws from the estimated posterior distributions of parameters. The vertical shaded bands represent recessions dated by the National Bureau of Economic Research.

Figure 6: The fundamental wedge and hours



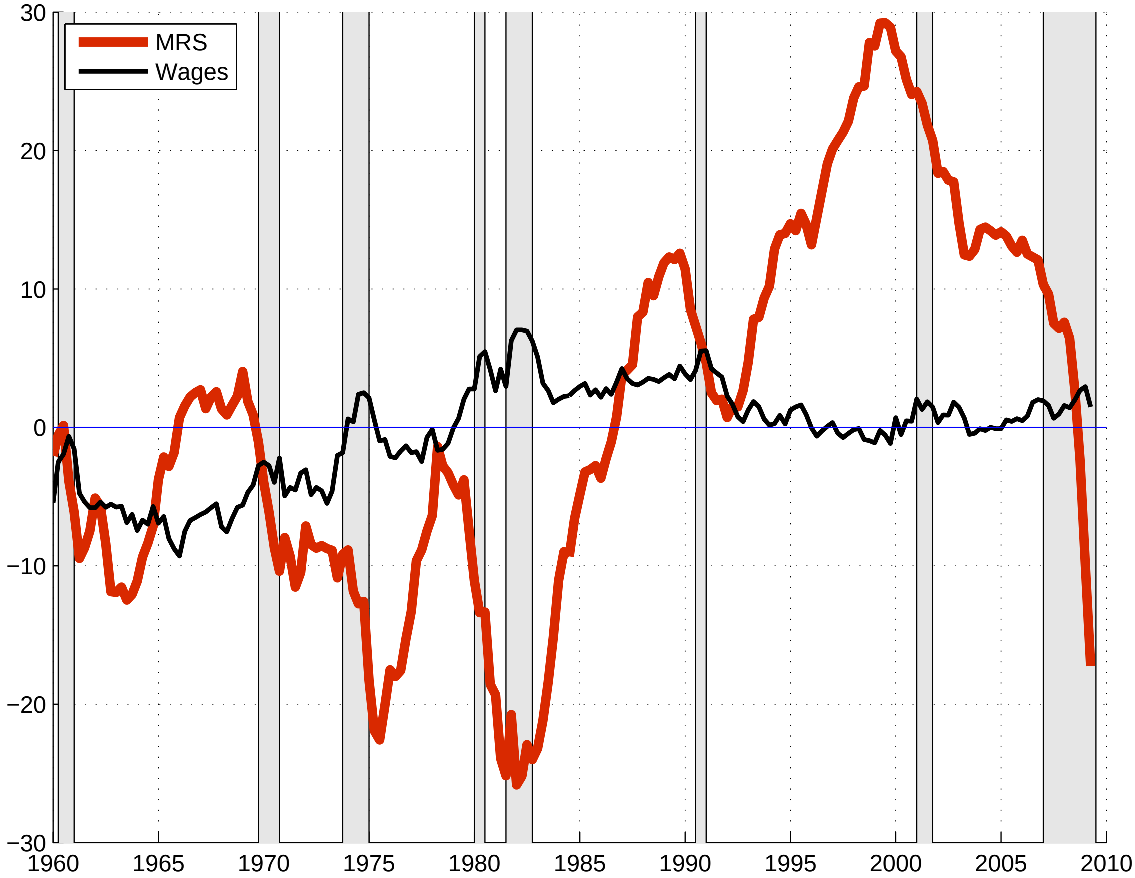
This figure shows the estimated paths for the "fundamental" labor wedge (the labor wedge excluding exogenous shocks) and the direct impact of hours worked in the model with measurement errors. Parameters are set to their posterior median values. The shaded areas represent recessions dated by the National Bureau of Economic Research.

Figure 7: The labor wedge and its components



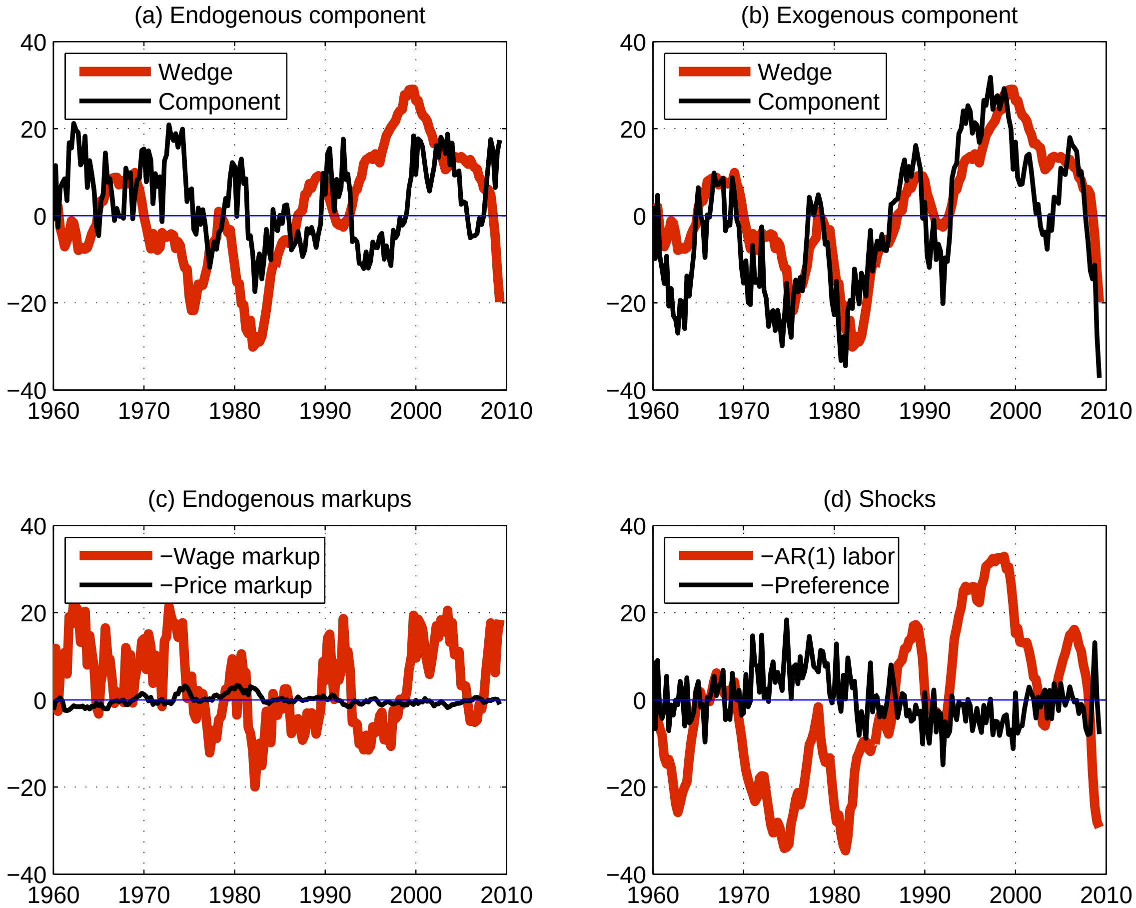
This figure shows the estimated paths for the labor wedge (the wedge between the marginal rate of substitution and the marginal product of labor), the marginal rate of substitution, the marginal product of labor, and the real wage in the model with measurement errors under different assumptions about the labor market shocks. The marginal rate of substitution, the marginal product of labor, and the real wage are measured as deviations from model trend. Parameters are set to their posterior median values. The shaded areas represent recessions dated by the National Bureau of Economic Research.

Figure 8: The marginal rate of substitution excluding shocks and the real wage



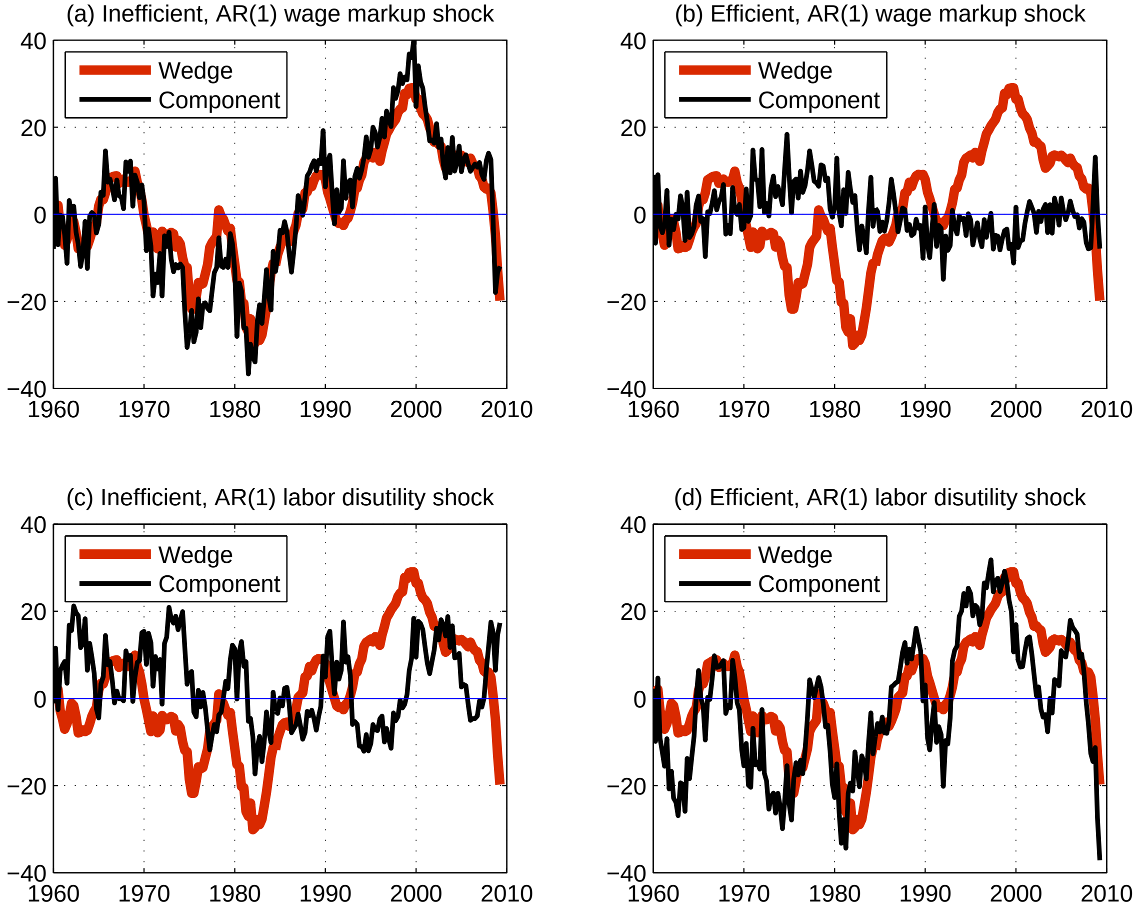
This figure shows the estimated paths for the marginal rate of substitution between consumption and leisure, excluding the exogenous preference shocks, and the real wage in the model with measurement errors. Both variables are measured as deviation from model trend. Parameters are set to their posterior median values. The shaded areas represent recessions dated by the National Bureau of Economic Research.

Figure 9: Decomposing the fundamental wedge into its endogenous and exogenous components



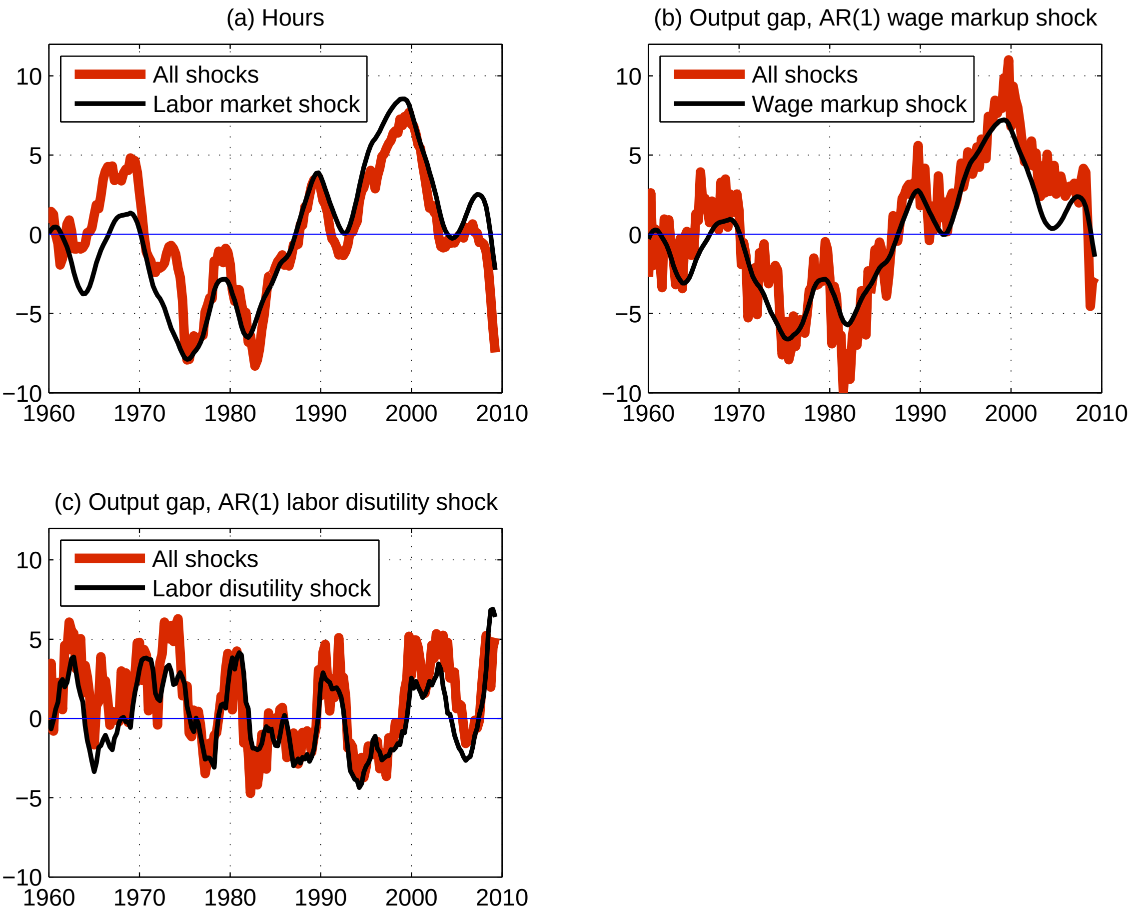
This figure shows the estimated paths for the fundamental wedge, its endogenous and exogenous components, the endogenous price and wage markups, and two estimated shocks (the persistent labor market shock and the intertemporal preference shock) in the model with measurement errors. Parameters are set to their posterior median values.

Figure 10: Decomposing the fundamental wedge into its inefficient and efficient components



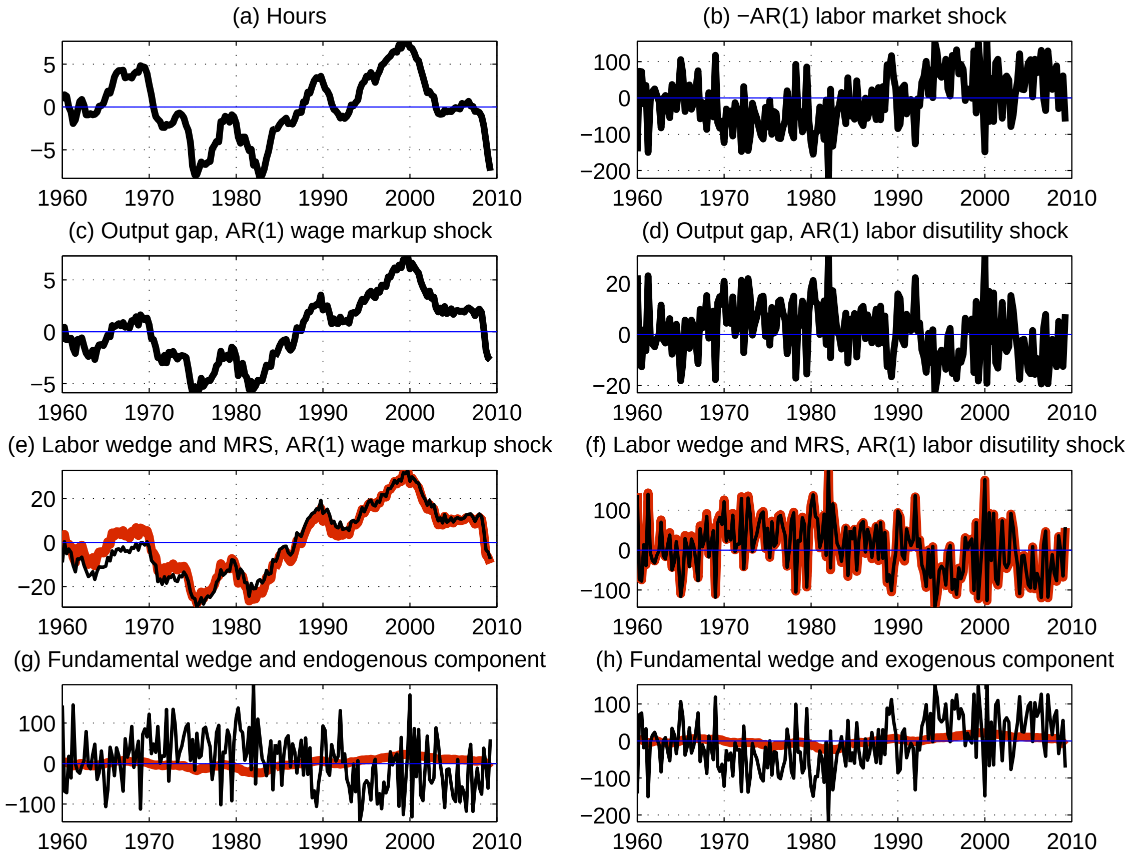
This figure shows the estimated paths for the fundamental wedge and its inefficient and efficient components in the model with measurement errors under different assumptions about the labor market shocks. Parameters are set to their posterior median values.

Figure 11: Contribution of persistent labor market shock to hours and the output gap



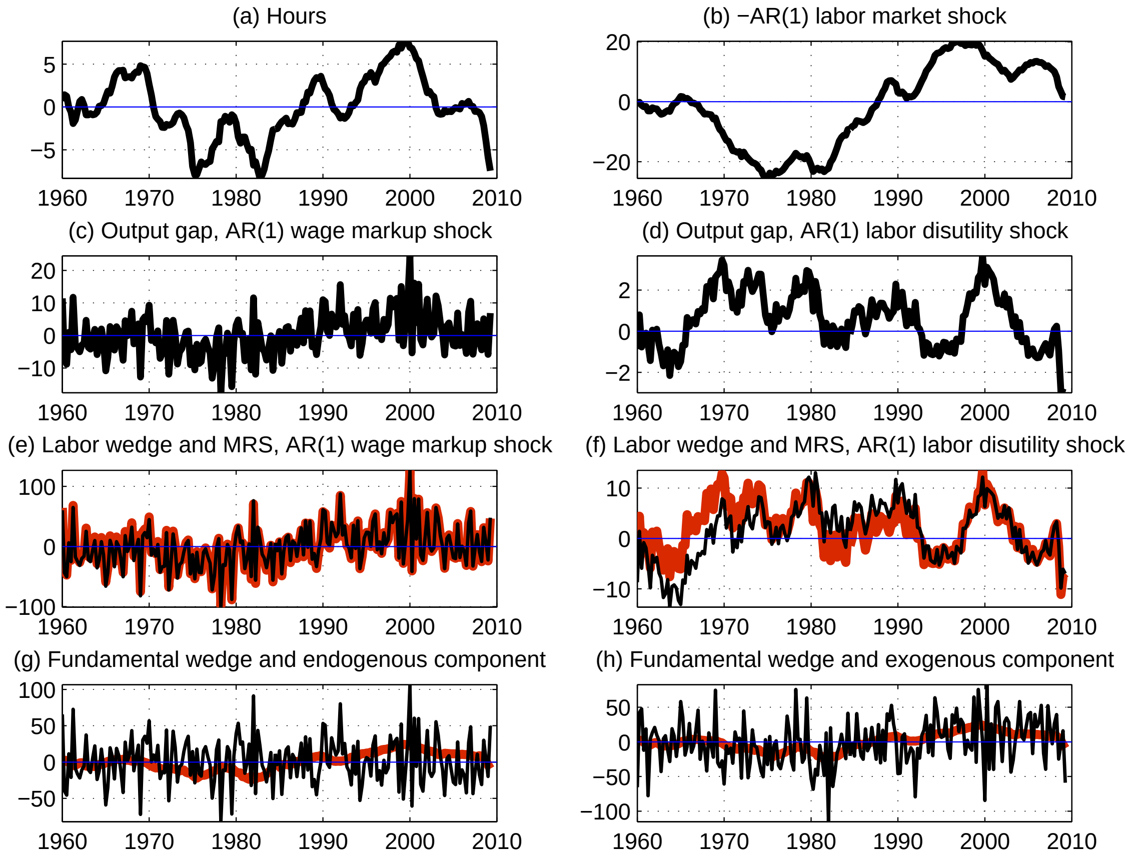
This figure shows the contribution of the AR(1) labor market shock to hours worked and the two different conditional output gaps in the model with measurement errors. The output gap in panel (b) is from the model with an AR(1) wage markup shock and an i.i.d. labor disutility shock in Figure 5(a), the output gap in panel (c) is from the model with an AR(1) labor disutility shock and an i.i.d. wage markup shock in Figure 5(b). Parameters are set to their posterior median values.

Figure 12: Robustness analysis: The model without measurement errors with one labor market shock



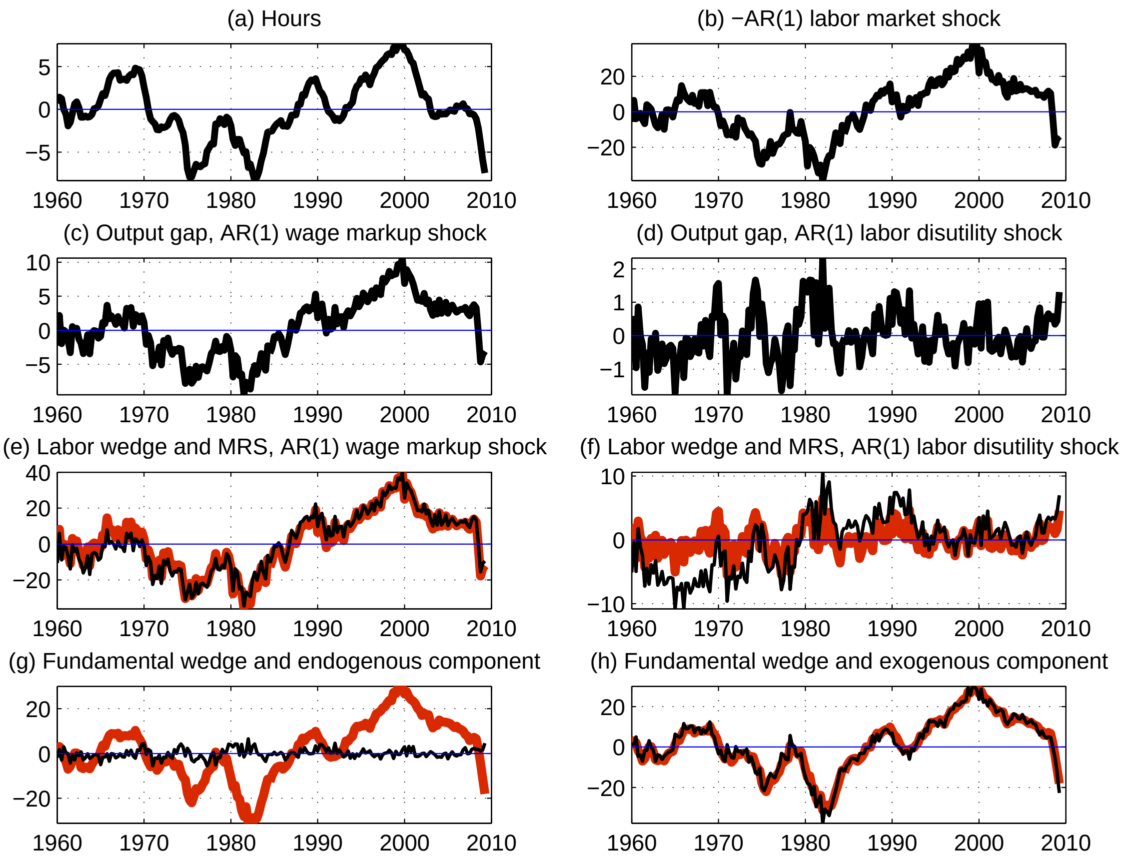
This figure shows hours worked and the AR(1) labor market shock; the output gap, the labor wedge, and households' marginal rate of substitution under two different interpretations of the labor market shocks; and the fundamental wedge and its endogenous and exogenous components in the estimated model without measurement errors with one labor market shock. In panels (e) and (f), the thick red (or grey) line is the labor wedge and the thin line is the MRS; in panels (g) and (h), the thick red (or grey) line is the fundamental wedge and the thin line is the endogenous or exogenous component. Parameters are set to their posterior mode values.

Figure 13: Robustness analysis: The model without measurement errors with two labor market shocks



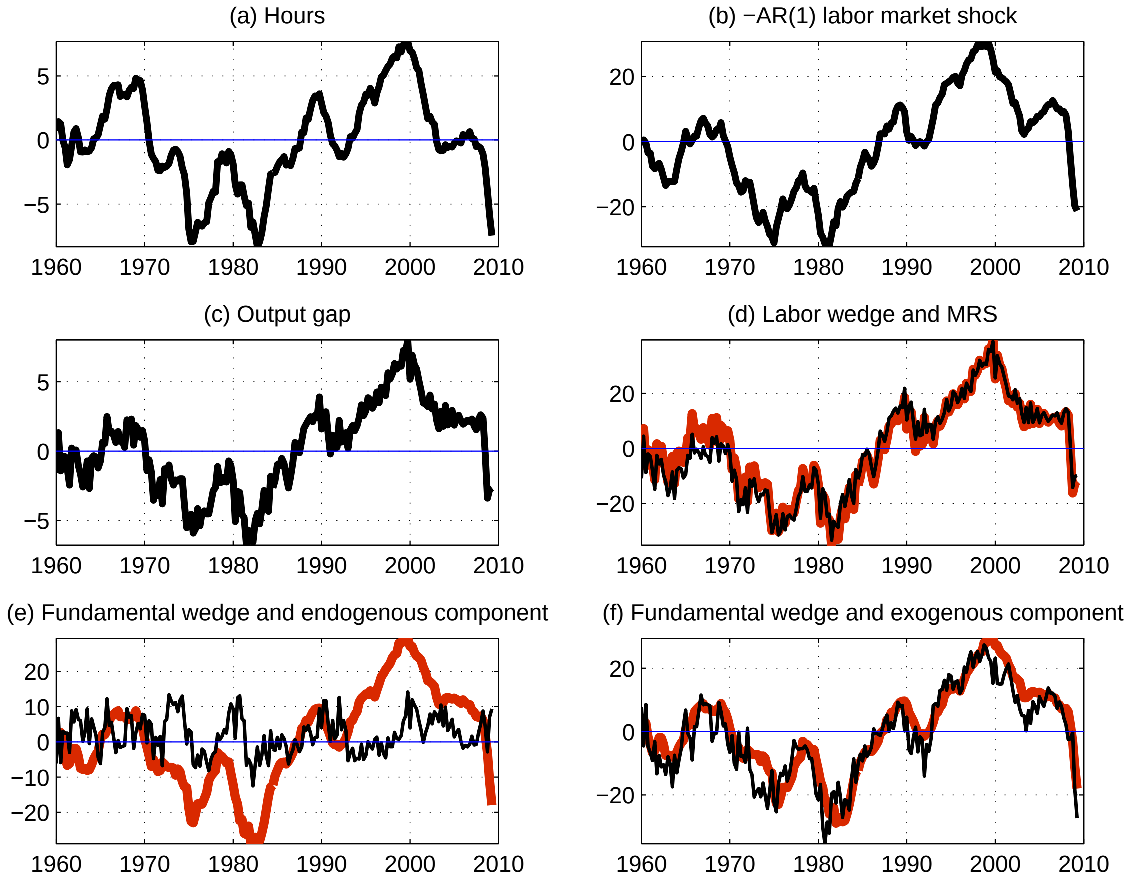
This figure shows hours worked and the AR(1) labor market shock; the output gap, the labor wedge, and households' marginal rate of substitution under two different interpretations of the labor market shocks; and the fundamental wedge and its endogenous and exogenous components in the estimated model without measurement errors with two labor market shocks. In panels (e) and (f), the thick red (or grey) line is the labor wedge and the thin line is the MRS; in panels (g) and (h), the thick red (or grey) line is the fundamental wedge and the thin line is the endogenous or exogenous component. Parameters are set to their posterior mode values.

Figure 14: Robustness analysis: A model with more flexible wages



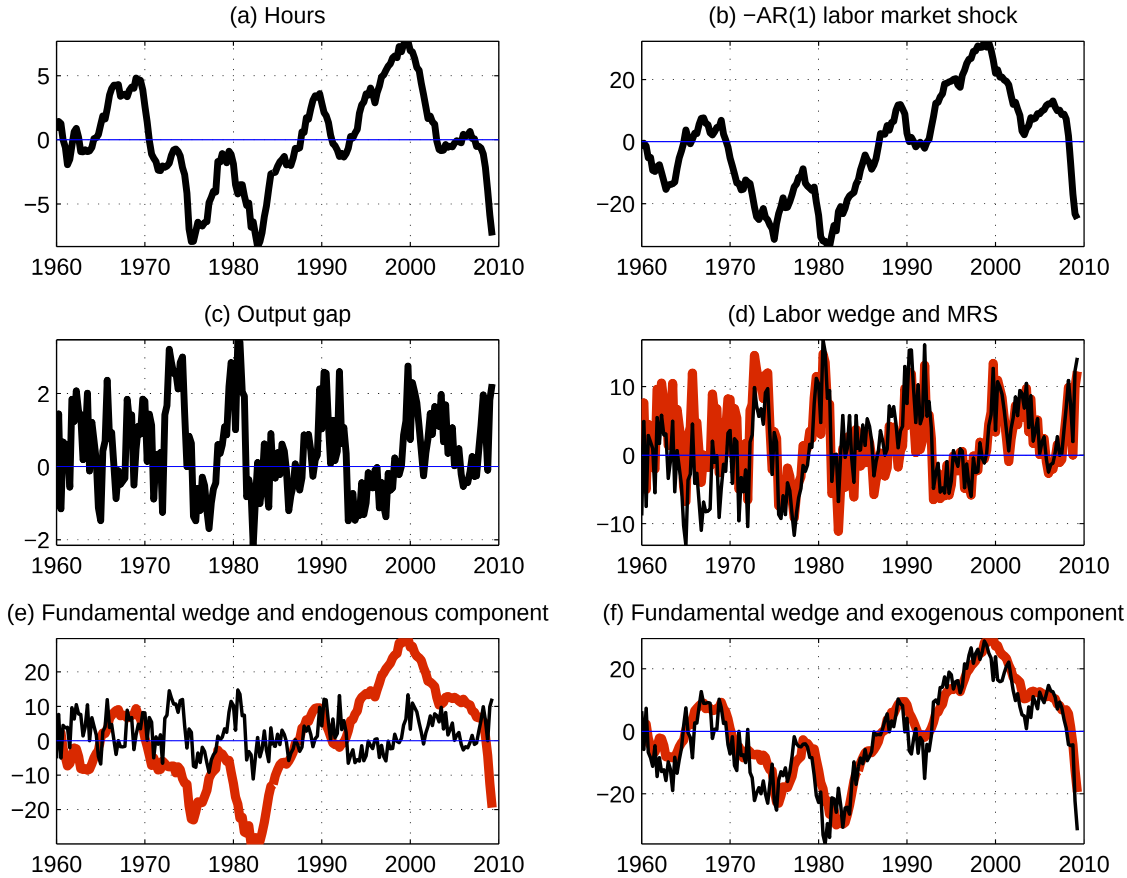
This figure shows hours worked and the AR(1) labor market shock; the output gap, the labor wedge, and households' marginal rate of substitution under two different interpretations of the labor market shocks; and the fundamental wedge and its endogenous and exogenous components in a model with more flexible wages than in the estimated model ($\theta_w = 0.1$). In panels (e) and (f), the thick red (or grey) line is the labor wedge and the thin line is the MRS; in panels (g) and (h), the thick red (or grey) line is the fundamental wedge and the thin line is the endogenous or exogenous component. Parameters are set to their posterior mode values.

Figure 15: Robustness analysis: A model with the output gap in the monetary policy rule and AR(1) wage markup shocks



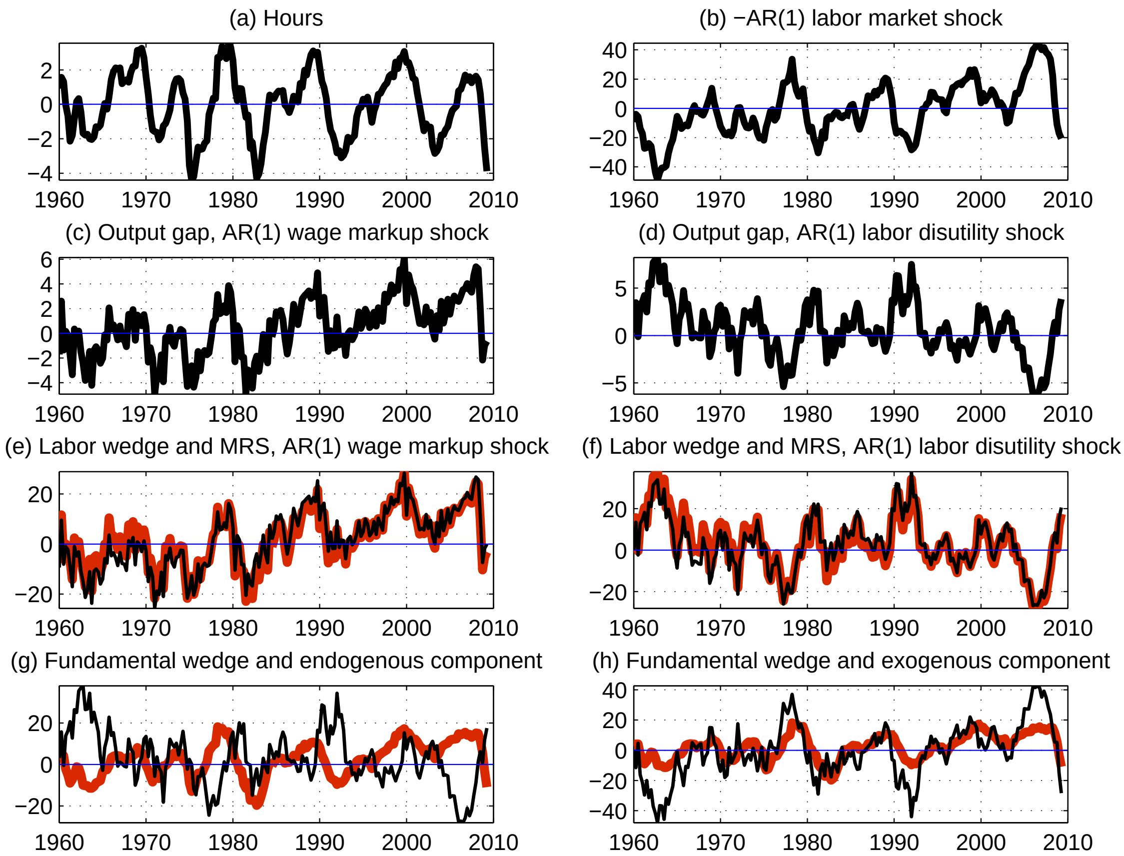
This figure shows hours worked and the AR(1) labor market shock; the output gap, the labor wedge, and households' marginal rate of substitution; and the fundamental wedge and its endogenous and exogenous components in an estimated model with the output gap in the monetary policy rule and AR(1) wage markup shocks. In panel (d), the thick red (or grey) line is the labor wedge and the thin line is the MRS; in panels (e) and (f), the thick red (or grey) line is the fundamental wedge and the thin line is the endogenous or exogenous component. Parameters are set to their posterior mode values.

Figure 16: Robustness analysis: A model with the output gap in the monetary policy rule and AR(1) labor disutility shocks



This figure shows hours worked and the AR(1) labor market shock; the output gap, the labor wedge, and households' marginal rate of substitution; and the fundamental wedge and its endogenous and exogenous components in an estimated model with the output gap in the monetary policy rule and AR(1) labor disutility shocks. In panel (d), the thick red (or grey) line is the labor wedge and the thin line is the MRS; in panels (e) and (f), the thick red (or grey) line is the fundamental wedge and the thin line is the endogenous or exogenous component. Parameters are set to their posterior mode values.

Figure 17: Robustness analysis: A model with detrended hours



This figure shows hours worked and the AR(1) labor market shock; the output gap, the labor wedge, and households' marginal rate of substitution under two different interpretations of the labor market shocks; and the fundamental wedge and its endogenous and exogenous components in an estimated model where hours were detrended using the Hodrick-Prescott filter (with a smoothing parameter of 10,000) prior to estimation. In panels (e) and (f), the thick red (or grey) line is the labor wedge and the thin line is the MRS; in panels (g) and (h), the thick red (or grey) line is the fundamental wedge and the thin line is the endogenous or exogenous component. Parameters are set to their posterior mode values.