U.S. Wage and Price Dynamics: A Limited-Information Approach*

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This paper analyzes the dynamics of prices and wages using a limited-information approach to estimation. I estimate a two-equation model for the determination of prices and wages derived from an optimization-based dynamic model, where both goods and labor markets are monopolistically competitive, prices and wages can be reoptimized only at random intervals, and, when not reoptimized, can be partially adjusted to previous-period aggregate inflation. The estimation procedure is a *two-step* minimum-distance estimation, which exploits the restrictions that the model imposes on a time-series representation of the data. In the first step I estimate an *unrestricted* autoregressive representation of the variables of interest. In the second step, I express the model solution in the form of a *constrained* autoregressive representation of the data and define the distance between unconstrained and constrained representations as a function of the structural parameters that characterize the joint dynamics of inflation and labor share. This function summarizes the cross-equation restrictions between the model and the time-series representations of the data: I then estimate the parameters of interest by minimizing a quadratic function of that distance. I find that the estimated dynamics of prices and wages track actual dynamics quite well, and that the estimated parameters are consistent with the observed length of nominal contracts.

JEL Codes: E32, C32, C52.

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1. Introduction

This paper is an empirical analysis of the dynamics of wages and prices implied by a model of monopolistic competition in goods and labor markets, with sluggish adjustment of prices and wages. The objective of the paper is to investigate the link between real and nominal variables predicted by an optimization-based model, without specifying the whole general equilibrium structure.

I build on previous work that has shown that inflation fluctuations are fairly consistent with the predictions of an optimizing model of staggered price setting, if one takes as given the evolution of marginal cost.[1] I take the analysis one step further, endogenizing the determination of nominal wages, to provide an empirical analysis of the joint dynamics of wages and prices and their interaction with aggregate real variables. Allowing sluggish adjustment of both wages and prices, I also seek to shed light on whether the source of the inertia that appears to characterize nominal variables rests more on the price or on the wage-adjustment mechanism.

I analyze a generalized version of the discrete-time model of price and wage setting studied by Erceg, Henderson, and Levin (2000).[2] Specifically, I assume that monopolistically competitive goods-producing firms set their prices to maximize the discounted expected value of their future profits and reoptimize prices only at

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[1]This is argued by Galí and Gertler (1999), Galí, Gertler, and López-Salido (2005), and Sbordone (2002) for the United States; and Galí, Gertler, and López-Salido (2001), Batini, Jackson, and Nickell (2005), and Gagnon and Khan (2005) for European countries and Canada. The robustness of these estimates has been variously discussed: among the criticisms, see Rudd and Whelan (2005), Kurmann (2005), and Lindé (2005).

[2]This way of modeling the wage and price sector is now widely used in empirical DSGE models; see, for example, Amato and Laubach (2003), Christiano, Eichenbaum, and Evans (2005), Altig et al. (2002), and Smets and Wouters (2003, 2005). A comprehensive exposition of such a model can be found in Woodford (2003, ch. 3).

random intervals. Similarly, monopolistically competitive suppliers of differentiated labor services can reoptimize their wages only at random intervals. On the other hand, I assume that both firms and workers, when not allowed to reoptimize, can adjust their prices to past inflation.

Sluggish price and wage adjustments of this kind, following Calvo (1983) modeling, are often introduced in general equilibrium models of business cycle to build in a channel of persistence of monetary policy effects. Estimating the price/wage block within a completely specified general equilibrium model requires further specifications, such as the nature of capital accumulation, the details of fiscal and monetary policy, and the stochastic properties of the shocks. Some papers do so by adopting a full-information approach to estimation using maximum likelihood methods;[3] others rely on the identification of a single shock and estimate the model parameters by matching theoretical and empirical impulse response functions to that shock.[4]

The strategy I propose here aims instead at estimating the dynamics of wages and prices implied by this model without specifying a whole general equilibrium structure. I compare the equilibrium paths of wages and prices derived from the optimizing model to the paths described by an unrestricted vector autoregression model. Under the null hypothesis that the theoretical model is a correct representation of the stochastic process generating the data, the restrictions that the model solution imposes on the parameters of the time-series model should hold exactly. I propose to use these restrictions to construct a two-step distance estimator for the parameters of the structural model.

This approach follows directly from Campbell and Shiller's (1987) analysis, where they suggested testing the present-value model of stock prices by testing the restrictions that it imposes on a bivariate time-series representation of dividends growth and the price/dividend ratio. The model analyzed here also involves two

[3] For small models, the pioneering work using maximum likelihood estimation is Ireland (1997). Smets and Wouters (2003, 2005) have introduced the use of Bayesian techniques in the estimation of medium-scale models.

[4] See, for example, Amato and Laubach (2003), Christiano, Eichenbaum, and Evans (2005), and Altig et al. (2002).

present-value relationships. In the price equation, after solving out inflation expectations, price inflation depends upon the present discounted value of expected future deviations of marginal costs from the price level. Similarly, after solving forward wage expectations in the wage equation, wage growth depends upon the present discounted value of expected future deviations of the marginal rate of substitution from the real wage. The joint model therefore imposes testable restrictions on a multivariate time-series representation of wages and prices.

My estimation approach proceeds as follows. I derive the (approximate) equilibrium conditions for price and wage setting from the optimization-based model and write them in the form of two expectational difference equations in inflation and labor share. I then estimate a multivariate time-series model to describe the evolution of all the variables that matter in the determination of inflation and labor share. Combining the structural equations and the estimated time-series model, I solve for the paths of inflation and labor share as functions of exogenous and predetermined variables. This solution represents a *restricted* autoregressive representation for inflation and labor share, where the parameters are combinations of the structural parameters *and* the parameters of the unrestricted time-series process. I then recover the restrictions imposed by the theoretical model by comparing the coefficients of the restricted and the unrestricted autoregressive representations. These implied restrictions can be interpreted as a measure of the distance between the model and the time-series representation: the structural parameters are estimated as those that minimize a quadratic form of this distance.

The estimator I propose is therefore a two-step distance estimator: the first step involves the estimation of the time-series model, and the second, taking as given those estimated parameters, minimizes the distance function.

Two important issues are involved in the implementation of the proposed empirical strategy. First, the data need a preliminary transformation so that the stationary variables that define the equilibrium conditions of the model have a measurable counterpart. To handle the presence of a stochastic trend in the time series considered, I use a multivariate approach based on the estimated unrestricted vector autoregression representation: the specification of the VAR is therefore central to both steps of the estimation procedure.

The second issue is modeling the marginal rate of substitution, which is the real wage that would prevail in a competitive market, absent wage rigidities; throughout the paper I refer to the marginal rate of substitution as the flexible-wage equilibrium real wage. The expression for this equilibrium wage depends upon the assumptions that one makes about household preferences; without adopting specific functional forms for preferences, I discuss in turn the form that the flexible-wage equilibrium real wage would take under different assumptions.

The rest of the paper is organized as follows. In section 2, I lay out the elements of the optimization model for the determination of the path of price and wage inflation. In section 3, I characterize the model solution; in section 4, I describe the two-step estimator, relating it to similar estimation approaches used in business-cycle literature. Section 5 discusses how to model the flexible-wage equilibrium real wage, while section 6 presents the estimation of the time-series model and discusses the treatment of the trend. Results are presented and discussed in section 7. After a brief discussion of robustness checks in section 8, section 9 concludes.

2. Wage and Price Dynamics with Backward Indexation

The model is based on Erceg, Henderson, and Levin (2000), but allows partial indexation of both wages and prices to lagged inflation.[5] Since the basic structure of this model is quite well known in the literature, the exposition below is kept to a minimum[6] and targeted to illustrate the coefficients to be estimated.

2.1 Staggered Price Setting with Partial Indexation

At any point in time, a fraction $(1 - \alpha_p)$ of the firms choose a price X_{pt} that maximizes the expected discounted sum of the firms' profits

$$E_t \Sigma_j \alpha_p^j Q_{t,t+j} (X_{pt} \Psi_{tj} Y_{t+j}(i) - \mathsf{C}(Y_{t+j}(i)), \tag{1}$$

[5]Full backward indexation was first introduced in Christiano, Eichenbaum, and Evans (2005). The generalized model with partial backward indexation is detailed in Woodford (2003, ch. 3).

[6]Details of some derivations are provided in the appendix.

where $Q_{t,t+j}$ is a nominal discount factor between time t and $t+j$; $Y_t(i)$ is the level of output of firm i; $\mathsf{C}(Y_{t+j}(i))$ is the total cost of production at $t+j$ of the firms that optimally set prices at t; and

$$\Psi_{tj} = \begin{cases} 1 & j = 0 \\ \Pi_{k=0}^{j-1} \pi_{t+k}^{\varrho_p} & j \geq 1 \end{cases}. \tag{2}$$

The coefficient $\varrho_p \,\epsilon\, [0,1]$ indicates the degree of indexation to past inflation of the prices that are not reoptimized.

The demand for goods of producer i is

$$Y_{t+j}(i) = \left(\frac{X_{pt}\Psi_{tj}}{P_{t+j}} \right)^{-\theta_p} Y_{t+j}, \tag{3}$$

where $\theta_p > 1$ denotes the Dixit-Stiglitz elasticity of substitution among differentiated goods, and the aggregate price level is

$$P_t = \left[(1-\alpha_p) X_{pt}^{1-\theta_p} + \alpha_p (\pi_{t-1}^{\varrho_p} P_{t-1})^{1-\theta_p} \right]^{\frac{1}{1-\theta_p}}. \tag{4}$$

The first-order condition for this problem can be expressed as

$$E_t \Sigma_j \alpha_p^j Q_{t,t+j} \left\{ Y_{t+j} P_{t+j}^{\theta_p} {\Psi_{tj}}^{1-\theta_p} \left(X_{pt} - \frac{\theta_p}{\theta_p - 1} S_{t+j,t}(i) \Psi_{tj}^{-1} \right) \right\} = 0,$$

where $S_{t+j,t}(i)$ is nominal marginal cost at $t+j$ of the firms that set optimal price at time t. Dividing this expression by P_t, and using (2), one gets

$$\begin{aligned} & E_t \Sigma_j \alpha_p^j Q_{t,t+j} \left\{ Y_{t+j} P_{t+j}^{\theta_p} {\Psi_{tj}}^{1-\theta_p} \right. \\ & \qquad \left. \times \left(x_{pt} - \frac{\theta_p}{\theta_p - 1} s_{t+j}(i) \left(\Pi_{k=1}^{j} \pi_{t+k} \right) \left(\Pi_{k=0}^{j-1} \pi_{t+k}^{\varrho_p} \right)^{-1} \right) \right\} = 0, \end{aligned}$$

where x_{pt} is the relative price of the firms that set optimal price at t, and $s_{t+j,t}(i)$ is their real marginal cost at time $t+j$. A log-linearization of this expression around a steady state with zero inflation gives

$$\hat{x}_{pt} = (1 - \alpha_p \beta) \Sigma_{j=0}^{\infty} (\alpha_p \beta)^j E_t \left(\hat{s}_{t+j,t} + \Sigma_{k=1}^{j} \hat{\pi}_{t+k} - \varrho_p \Sigma_{k=0}^{j-1} \hat{\pi}_{t+k} \right), \tag{5}$$

where hat variables are log-deviations from steady-state values.[7] Under the hypothesis that capital is not instantaneously reallocated across firms, $s_{t+j,t}$ is, in general, different from the average marginal cost at time $t+j$, s_{t+j}, so that

$$\hat{s}_{t+j,t} = \hat{s}_{t+j} - \theta_p \omega \left(\hat{x}_{pt} - \left(\Sigma_{k=1}^{j} \hat{\pi}_{t+k} - \varrho_p \Sigma_{k=0}^{j-1} \hat{\pi}_{t+k} \right) \right), \qquad (6)$$

where ω is the output elasticity of real marginal cost for the individual firm.[8] Therefore, substituting (6) in (5), one obtains

$$(1+\theta_p\omega)\hat{x}_{pt} = (1-\alpha_p\beta)\Sigma_{j=0}^{\infty}(\alpha_p\beta)^j \times E_t \left(\hat{s}_{t+j} + (1+\theta_p\omega) \left(\Sigma_{k=1}^{j} \hat{\pi}_{t+k} - \varrho_p \Sigma_{k=0}^{j-1} \hat{\pi}_{t+k} \right) \right). \qquad (7)$$

Similarly, dividing (4) by P_t and log-linearizing, one gets

$$\hat{x}_{pt} = \frac{\alpha_p}{1-\alpha_p}(\hat{\pi}_t - \varrho_p \hat{\pi}_{t-1}). \qquad (8)$$

Finally, combining (7) and (8),

$$\hat{\pi}_t - \varrho_p \hat{\pi}_{t-1} = \frac{(1-\alpha_p)(1-\alpha_p\beta)}{\alpha_p(1+\theta_p\omega)} \Sigma_{j=0}^{\infty}(\alpha_p\beta)^j \times E_t \left(\hat{s}_{t+j} + (1+\theta_p\omega) \left(\Sigma_{k=1}^{j} \hat{\pi}_{t+k} - \varrho_p \Sigma_{k=0}^{j-1} \hat{\pi}_{t+k} \right) \right), \qquad (9)$$

which is equivalently written as[9]

$$\hat{\pi}_t - \varrho_p \hat{\pi}_{t-1} = \zeta \hat{s}_t + \beta E_t(\hat{\pi}_{t+1} - \varrho_p \hat{\pi}_t),$$

[7] I denote by β the steady-state value of the discount factor and suppress the index i on variables chosen by the firms that are changing prices, since all those firms solve the same optimization problem.

[8] Note that when the production function takes the Cobb-Douglas form, for example, $\omega = a/(1-a)$, where $(1-a)$ is the output elasticity with respect to labor.

[9] This result is obtained by forwarding (9) one period, multiplying it by β, and subtracting the resulting expression from (9).

where I set $\zeta = \frac{(1-\alpha_p)(1-\alpha_p\beta)}{\alpha_p(1+\theta_p\omega)}$. This equation describes the evolution of inflation as a function of past inflation, expected future inflation, and real marginal costs; compared to the standard Calvo model, where $\varrho_p = 0$, this expression contains a backward-looking component that many have argued is a necessary component to fit the inertia of inflation data. This can be seen by rewriting (9) as:

$$\hat{\pi}_t = \frac{\varrho_p}{1+\varrho_p\beta}\hat{\pi}_{t-1} + \frac{\beta}{1+\varrho_p\beta}E_t\hat{\pi}_{t+1} + \frac{\zeta}{1+\varrho_p\beta}\hat{s}_t. \tag{10}$$

At the other extreme of complete indexation ($\varrho_p = 1$)—considered, for example, in Christiano, Eichenbaum, and Evans (2005)—the model predicts that the *growth rate* of inflation depends upon real marginal costs and the expected future growth rate of inflation. In this case, coefficients on past and future inflation sum to 1, and, for β close to 1, they are approximately the same. For low levels of indexation, instead, the coefficient on past inflation is significantly smaller than the one on future inflation.[10]

2.2 Staggered Wage Setting with Partial Indexation

Similarly to the firms, households are assumed to set their price (for leisure) in a monopolistically competitive way, analogous to the price model. Each household (indexed by i) offers a differentiated type of labor services to the firms and stipulates wage contracts in nominal terms: at the stipulated wage $W_t(i)$ they supply as many hours as are demanded. Unlike Erceg, Henderson, and Levin (2000), however, I allow preferences to be nonseparable in consumption and leisure.[11]

Total labor employed by any firm j is an aggregation of individual differentiated hours $h_t(i)$

$$H_t^j = \left[\int_0^1 h_t(i)^{(\theta_w-1)/\theta_w} di\right]^{\theta_w/(\theta_w-1)}, \tag{11}$$

[10] An equation of similar form is obtained with a slightly different set of assumptions by Galí and Gertler (1999). They assume that part of the firms that reset their price are not forward looking, but adopt instead "rule-of-thumb" price setting.

[11] Although I do not specify at this point the functional form of preferences, I assume here that they are time separable, and the momentary utility is defined on current values of consumption and leisure.

where θ_w is the Dixit-Stiglitz elasticity of substitution among differentiated labor services ($\theta_w > 1$). The wage index is an aggregate of individual wages, defined as

$$W_t = \left[\int_0^1 W_t(i)^{1-\theta_w} di\right]^{1/(1-\theta_w)}.$$

The demand function for labor services of household i from firm j is[12]

$$h_t^j(i) = (W_t(i)/W_t)^{-\theta_w} H_t^j, \tag{12}$$

which, aggregated across firms, gives the total demand of labor hours $h_t(i)$ equal to

$$h_t(i) = (W_t(i)/W_t)^{-\theta_w} H_t, \tag{13}$$

where $H_t = \left[\int_0^1 H_t^j dj\right]$.

At each point in time, only a fraction $(1 - \alpha_w)$ of the households can set a new wage, which I denote by X_{wt}, independently of the past history of wage changes.[13] The expected time between wage changes is therefore $\frac{1}{1-\alpha_w}$. I also assume, as in Erceg, Henderson, and Levin (2000), that households have access to a complete set of state-contingent contracts; in this way, although workers that work different amounts of time have different consumption paths, in equilibrium they have the same marginal utility of consumption.

Finally, for wages that are not reoptimized, I allow indexation to previous-period inflation: specifically, for $\varrho_w \epsilon$ $[0, 1]$, the wage of a household l that cannot reoptimize at t evolves as

$$W_t(l) = \pi_{t-1}^{\varrho_w} W_{t-1}(l).$$

This hypothesis implies that wages reset at time t are expected to grow during the contract period according to

$$X_{wt+j} = X_{wt}\Psi_{tj}^w, \text{ where } \Psi_{tj}^w = \begin{cases} 1 & \text{if } j = 0 \\ \prod_{k=0}^{j-1} \pi_{t+k}^{\varrho_w} & \text{if } j \geq 1 \end{cases}. \tag{14}$$

[12] This demand is obtained by solving firm j's problem of allocating a given wage payment among the differentiated labor services, i.e., the problem of maximizing (11) for a given level of total wages to be paid.

[13] As for the price case, varying α_w between 0 and 1, the model allows various degrees of wage inertia, from perfect wage flexibility ($\alpha_w = 0$) to complete nominal wage rigidity ($\alpha_w \longrightarrow 1$).

The aggregate wage at any time t is an average of the wage set by the optimizing workers, X_{wt}, and the one set by those who do not optimize:

$$W_t = \left[(1-\alpha_w)(X_{wt})^{1-\theta_w} + \alpha_w(\pi_{t-1}^{\varrho_w} W_{t-1})^{1-\theta_w}\right]^{\frac{1}{1-\theta_w}}. \qquad (15)$$

The wage-setting problem is defined as the choice of the wage X_{wt} that maximizes the expected stream of discounted utility from the new wage; this is defined as the difference between the gain (measured in terms of the marginal utility of consumption) derived from the hours worked at the new wage and the disutility of working the number of hours associated with the new wage. The objective function is then

$$E_t\left\{\Sigma_{j=0}^{\infty}(\beta\alpha_w)^j\left[\frac{\Lambda_{t+j,t}^c}{P_{t+j}}\left(X_{wt}\Psi_{tj}^w h_{t+j,t} - P_{t+j}C_{t+j,t}\right)\right.\right.$$
$$\left.\left. + U(C_{t+j,t}, h_{t+j,t})\right]\right\}, \qquad (16)$$

where $\Lambda_{t+j,t}^c$ is the marginal utility of consumption at $t+j$ of workers that optimize at t, and $h_{t+j,t}$ is hours worked at $t+j$ at the wage set at time t. Given (14), the latter evolves as

$$h_{t+j,t} = \left(\frac{X_{wt}\Psi_{tj}^w}{W_{t+j}}\right)^{-\theta_w} H_{t+j}. \qquad (17)$$

The first-order condition for this problem can be written as

$$E_t\left\{\Sigma_{j=0}^{\infty}(\beta\alpha_w)^j\left(\frac{X_{wt}\Psi_{tj}^w}{W_{t+j}}\right)^{-\theta_w} H_{t+j}\left[\frac{X_{wt}\Psi_{tj}^w}{P_{t+j}} - \frac{\theta_w}{\theta_w - 1}v_{t+j,t}\right]\right\} = 0, \qquad (18)$$

where $v_{t+j,t}$ is the marginal rate of substitution between consumption and leisure at date $t+j$, when the level of hours is $h_{t+j,t}$. A log-linear approximation of this equation is[14]

$$\hat{\pi}_t^w - \varrho_w\hat{\pi}_{t-1} = \gamma(\hat{v}_t - \hat{\omega}_t) + \beta\left(E_t\hat{\pi}_{t+1}^w - \varrho_w\hat{\pi}_t\right), \qquad (19)$$

[14]See the derivation in the first section of the appendix.

where $\gamma = \frac{(1-\alpha_w)(1-\beta\alpha_w)}{\alpha_w(1+\theta_w\chi)}$, and the parameter χ reflects the degree of nonseparability in preferences.[15]

2.3 A Complete Model

The dynamics of wages and prices are then described by the two log-linearized equilibrium conditions (10) and (19). Because the approximations are taken around a point with zero wage and price inflation, $\hat{\pi}_t = \pi_t \equiv \Delta p_t$, and $\hat{\pi}^w_t = \pi^w_t \equiv \Delta w_t$. Furthermore, $\hat{s}_t = w_t - p_t - q_t$, since real wage $(w_t - p_t)$ and labor productivity (q_t) share the same stochastic trend.[16] Similarly, $\hat{v}_t - \hat{\omega}_t = v_t - (w_t - p_t)$, since marginal rate of substitution and real wage also share the same stochastic trend.

Equations (10) and (19) can then be rewritten as

$$\pi_t = \frac{\varrho_p}{1+\varrho_p\beta}\Delta p_{t-1} + \frac{\beta}{1+\varrho_p\beta}E_t\Delta p_{t+1} + \frac{\zeta}{1+\varrho_p\beta}((w_t - q_t) - p_t) + u_{pt} \tag{20}$$

$$\pi^w_t = \varrho_w\Delta p_{t-1} + \beta E_t(\Delta w_{t+1} - \varrho_w\Delta p_t) + \gamma(v_t - (w_t - p_t)) + u_{wt}. \tag{21}$$

These equations show that the dynamics of prices and wages are driven by two *gaps*: the excess of unit labor costs over price (the real marginal cost) and the excess of the "equilibrium" real wage over the actual wage. The two parameters ζ and γ, defined quite symmetrically as $\zeta = \frac{(1-\alpha_p)(1-\alpha_p\beta)}{\alpha_p(1+\theta_p\omega)}$ and $\gamma = \frac{(1-\alpha_w)(1-\beta\alpha_w)}{\alpha_w(1+\theta_w\chi)}$, measure the degree of gradual adjustment of prices and wages to these gaps. These parameters, in turn, depend upon the parameters that determine the frequency of price and wage adjustments—respectively, α_p

[15] $\chi = \frac{-\Lambda^c_h H}{\Lambda^c_c C}\eta_c + \eta_h$, where η_c and η_h are, respectively, the elasticity of the marginal rate of substitution with respect to consumption and with respect to hours, evaluated at the steady state. Λ^c_c and Λ^c_h are derivatives of the marginal utility of consumption Λ^c with respect to consumption and with respect to hours, also evaluated at steady state. Note that when preferences are separable in consumption and leisure, $\Lambda^c_h = 0$.

[16] Note that I am also assuming valid conditions under which marginal cost is proportional to unit labor cost.

and α_w; the degree of substitutability between differentiated goods θ_p and that between differentiated labor services θ_w; the elasticity of firms' marginal costs with respect to their own output ω; and the degree of nonseparability in households' preferences, χ.

I have included an error term in each equation: these terms may pick up unobservable markup variations or allow for other possible misspecifications. I assume that the error terms are mutually uncorrelated, serially uncorrelated: $E(u_{it}u'_{jt-k}) = 0$ for $i, j = p, w$, and $k \neq 0$, and unforecastable, given the information set.

Equations (20) and (21) show the interdependence of wages and prices and their dependence upon the evolution of productivity and the other real variables that determine the evolution of the flexible-wage equilibrium real wage. In a fully specified model, this evolution would be described by similar structural relations. Here, instead, I focus on the restrictions that these equilibrium conditions impose on *any* general model that includes sluggish price and wage adjustment of the form described, independently of the specific form that the other structural relationships may take.

I proceed as follows: I assume that the evolution of the variables that determine the path of wages and prices can be summarized by a covariance stationary m-dimensional process X_t:

$$X_t = \Phi_1 X_{t-1} + \cdots + \Phi_p X_{t-p} + \varepsilon_t \tag{22}$$

(for some lag p to be determined empirically), where $E(\varepsilon_t) = 0$, and $E(\varepsilon_t \varepsilon'_\tau) = \Omega$ for $\tau = t$ and 0 otherwise. This vector includes, in addition to wages and prices, labor productivity q and the determinants of the flexible-wage equilibrium real wage v. Letting $Z_t = [X_t X_{t-1} \dots X_{t-p+1}]'$, (22) can be represented as a first-order autoregressive process:

$$Z_t = AZ_{t-1} + Q\varepsilon_t, \tag{23}$$

where

$$A_{(mp\times mp)} = \begin{bmatrix} \Phi_1 & \Phi_2 & \cdots & \Phi_{p-1} & \Phi_p \\ I & \underline{0} & \cdots & \underline{0} & \underline{0} \\ \underline{0} & \underline{0} & & I & \underline{0} \end{bmatrix}, Q = \begin{bmatrix} I_{m\times m} \\ \underline{0}_{m(p-1)\times m} \end{bmatrix}.$$

The system of equations (20) and (21) places a set of restrictions on the parameters of the process (23). The nature of these restrictions can be recovered as follows: if one considers the joint process of (20), (21), and (23), one can solve for equilibrium processes $\{w_t, p_t\}$, given stochastic processes for $\{v_t, q_t\}$ and initial conditions $\{w_{-1}, p_{-1}\}$. This solution can be expressed as a particular restricted reduced-form representation for the vector Z_t,

$$Z_t = A^R Z_{t-1} + \widetilde{\varepsilon}_t,$$

with $A^R = G(\psi, A)$. ψ is the vector of the structural parameters of interest (defined below), and the function G incorporates the restrictions that the theoretical model imposes on the parameters of the time-series representation. The estimation procedure that I present in the next section is based on minimizing the distance between the restricted and the unrestricted representations of the relevant components of vector Z_t (i.e., the relevant elements of matrices A and A^R).

Before discussing my implementation of this estimation procedure, I will present a further transformation of equations (20) and (21) from equations in price and wage inflation into equations for price inflation and labor share (that is, real wage adjusted for productivity).[17] I will also derive the specific form of the restrictions that define the distance function used for the estimation of the structural parameters.

In what follows, I'll make use of the following identities:

$$q_t = q_{t-1} + \Delta q_t \tag{24}$$

$$w_t - p_t = w_{t-1} - p_{t-1} + \Delta w_t - \Delta p_t \tag{25}$$

and of an expression that defines the theoretical model for the flexible-wage equilibrium real wage:

$$v_t = q_t + \Xi Z_t. \tag{26}$$

The elements of the matrix Ξ depend upon assumptions about the long-run trend driving the time series and the specification of the

[17] As it will become clear later, this transformation is suggested by the properties of the time series of wage and productivity. The transformed structural equations have, therefore, the same form of their corresponding unrestricted representation in the process Z_t.

unrestricted representation (23). The crucial assumption that delivers (26) is that productivity, real wage, output, and consumption are all driven by a single stochastic trend, while hours are trend stationary. The specification of the vector X_t, the choice of the lag length p, and the form of the vector of coefficients Ξ are discussed later.

3. Model Solution

To rewrite equations (20) and (21) as a system in inflation and labor share $s_t \equiv w_t - p_t - q_t$, I first rearrange equation (20) as

$$E_t \Delta p_{t+1} = \frac{1 + \varrho_p \beta}{\beta} \Delta p_t - \frac{\varrho_p}{\beta} \Delta p_{t-1} - \frac{\zeta}{\beta}(w_t - p_t - q_t) + \widetilde{u}_{pt}, \quad (27)$$

where $\widetilde{u}_{pt} = (1 + \varrho_p \beta)\beta^{-1} u_{pt}$. Then I substitute (26) in (21) and rearrange it to get

$$\begin{aligned} E_t \Delta w_{t+1} = {} & \frac{1}{\beta} \Delta w_t + \varrho_w \Delta p_t - \frac{\varrho_w}{\beta} \Delta p_{t-1} \\ & + \frac{\gamma}{\beta}(w_t - p_t - q_t) - \frac{\gamma}{\beta} \Xi Z_t + \widetilde{u}_{wt}, \end{aligned} \quad (28)$$

where $\widetilde{u}_{wt} = \beta^{-1} u_{wt}$. Subtracting (27) and $E_t \Delta q_{t+1}$ from (28), I derive $E_t \Delta s_{t+1} \equiv E_t(\Delta w_{t+1} - \Delta p_{t+1} - \Delta q_{t+1})$ as

$$\begin{aligned} E_t(s_{t+1} - s_t) = {} & \frac{1}{\beta} \Delta w_t + \left(\varrho_w - \varrho_p - \frac{1}{\beta} \right) \Delta p_t + \left(\frac{\varrho_p - \varrho_w}{\beta} \right) \Delta p_{t-1} \\ & + \left(\frac{\gamma + \zeta}{\beta} \right) s_t - \frac{\gamma}{\beta} \Xi Z_t - E_t \Delta q_{t+1} + \nu_t, \end{aligned} \quad (29)$$

where ν_t is a composite error term.[18]

As I explain below, productivity growth Δq_t is an element of the vector X_t so that, by (23),

$$E_t \Delta q_{t+1} = e_q' A Z_t, \quad (30)$$

[18] $\nu_t = 1/\beta(u_{wt} - (1 + \varrho_p \beta) u_{pt})$.

where the selection vector e'_q has a 1 in correspondence to productivity growth and 0 elsewhere. Combining the terms in s_t and using (30), equation (29) becomes

$$E_t s_{t+1} = (\varrho_w - \varrho_p)\Delta p_t + \left(\frac{1+\beta+\gamma+\zeta}{\beta}\right) s_t + \left(\frac{\varrho_p - \varrho_w}{\beta}\right) \Delta p_{t-1} - \frac{1}{\beta} s_{t-1} - \left(\frac{\gamma}{\beta}\Xi - \frac{1}{\beta} e'_q + e'_q A\right) Z_t + \nu_t. \tag{31}$$

I now define a vector y_t as

$$y_t = [\pi_t \; s_t \; \pi_{t-1} \; s_{t-1}\,]' \tag{32}$$

and let $Y_{t+1} = [y_{t+1} \; Z_{t+1}]'$. The system of equations composed of (27), (31), and (23) can then be written as

$$E_t Y_{t+1} = M Y_t + N u_t, \tag{33}$$

where $u_t = [u_{pt} \; u_{wt}]'$, and the matrices M (of dim. $(4 + mp)$) and N are partitioned as follows:

$$M = \begin{bmatrix} M_{yy} & M_{yZ} \\ 0 & A \end{bmatrix}, \quad N = \begin{bmatrix} N_1 \\ \underline{0} \end{bmatrix}.$$

The (4×4) block M_{yy} describes the interaction of the structural variables; the $(4\times mp)$ block M_{yZ} describes the dependence of structural variables upon the exogenous block.[19] If the matrix M has exactly two unstable eigenvalues, the system of equations (33) has a unique solution, which can be expressed in autoregressive form as

$$Y_t = G Y_{t-1} + F \upsilon_t, \tag{34}$$

where the matrices G and F depend upon the vector of structural parameters ψ and the parameters of the unrestricted VAR process, the elements of A; the error term is $\upsilon_t = (u'_t, \varepsilon'_t)'$. The solution for

[19] The matrix N_1 is $\begin{pmatrix} \beta^{-1}(1+\varrho_p\beta) & 0 \\ -\beta^{-1}(1+\varrho_p\beta) & \beta^{-1} \end{pmatrix}$.

the endogenous variables π_t and s_t is the upper block of (34), which can be expressed as

$$\pi_t \equiv y_{1t} = g^\pi(\psi, A)Y_{t-1} + f^\pi \upsilon_t = g_y^\pi y_{t-1} + g_Z^\pi Z_{t-1} + f^\pi \upsilon_t \quad (35)$$

$$s_t \equiv y_{2t} = g^s(\psi, A)Y_{t-1} + f^s \upsilon_t = g_y^s y_{t-1} + g_Z^s Z_{t-1} + f^s \upsilon_t, \quad (36)$$

where g^i and f^i (for $i = \pi, s$) denote the row of the matrices G and F corresponding to variable i.

4. Approach to Estimation

Since both inflation and labor share are elements of the unrestricted process (22), they can be expressed as elements of Z_t, with appropriate definitions of selection vectors e'_π and e'_s:

$$\pi_t = e'_\pi Z_t \quad \text{and} \quad s_t = e'_s Z_t. \quad (37)$$

Similarly, the components of vector y_{t-1}, which includes lagged inflation and labor share, can be expressed in terms of elements of the vector Z_{t-1}, by way of an appropriate selection matrix $\Upsilon : y_{t-1} = \Upsilon Z_{t-1}$. Using this definition, and substituting (37) in (35) and (36), I get

$$e'_\pi Z_t - g_y^\pi \Upsilon Z_{t-1} - g_Z^\pi Z_{t-1} = f^\pi \upsilon_t \quad (38)$$

$$e'_s Z_t - g_y^s \Upsilon Z_{t-1} - g_Z^s Z_{t-1} = f^s \upsilon_t. \quad (39)$$

Finally, projecting both sides of (38) and (39) onto the information set Z_{t-1} and observing that, by assumption, $E(\upsilon_t|Z_{t-1}) = 0$, and also $E(Z_t|Z_{t-1}) = AZ_{t-1}$, I obtain

$$e'_\pi A Z_{t-1} - g_y^\pi \Upsilon Z_{t-1} - g_Z^\pi Z_{t-1} = \underline{0}$$

$$e'_s A Z_{t-1} - g_y^s \Upsilon Z_{t-1} - g_Z^s Z_{t-1} = \underline{0}.$$

Since these equalities must hold for every t, it follows that

$$e'_\pi A - g_y^\pi \Upsilon - g_Z^\pi = \underline{0} \quad (40)$$

$$e'_s A - g_y^s \Upsilon - g_Z^s = \underline{0}. \quad (41)$$

Expressions (40) and (41) form a set of $2 \times mp$ restrictions on the parameters of the unrestricted process (23), which must hold if the model is true. The structural parameters can then be estimated as those values that most likely make these restrictions hold.

The estimation strategy proceeds in two steps. First, I estimate an unrestricted VAR in all the variables of interest, to obtain a consistent estimate $\hat{A}$ of the autoregressive matrix A. In the second step, taking as given the estimated matrix $\hat{A}$, and stacking the restrictions (40) and (41) in a vector function $\digamma(\psi, A) = 0$, I choose the structural parameters ψ to make the empirical value of the function $\digamma$ as close as possible to its theoretical value of zero; namely, I choose

$$\hat{\psi} = \arg\min \digamma(\psi, \hat{A})' W^{-1} \digamma(\psi, \hat{A}) \tag{42}$$

for an appropriate choice of the weighting matrix W.[20]

The proposed estimator can be interpreted as a minimum-distance estimator, in application of the approach that Campbell and Shiller (1987) proposed for the empirical evaluation of present-value models. I have in fact interpreted the restrictions that define the function $\digamma$ as measuring the "distance" between the restricted and unrestricted representations of the data.[21] This estimator is close in spirit to another distance estimator used in the business-cycle literature, based on matching empirical and theoretical impulse response functions to specific structural shocks.[22] That estimator, as the one proposed here, uses an auxiliary VAR model in the first stage to characterize the dynamics of the data; then it minimizes the distance between the dynamic response to identified exogenous shocks estimated in the data and the response predicted by the theoretical model. Unlike the estimator based on matching impulse response

[20]As weighting matrix, I use a diagonal matrix with the variance of the estimated parameters A along the diagonal. This choice downweights the parameters that are estimated with greater uncertainty.

[21]In my previous applications of a similar two-step minimum-distance estimation, the objective function had the form of an (unweighted) distance between "model" and data (Sbordone 2002).

[22]Rotemberg and Woodford (1997) were the first to propose to estimate the structural parameters of a small monetary model by matching the model's predicted responses to a monetary policy shock to the responses estimated in an identified VAR model. This type of estimator has since been applied in several monetary models of business cycle by, among others, Amato and Laubach (2003), Boivin and Giannoni (2005), and Christiano, Eichenbaum, and Evans (2005). It has been applied to match the responses to both technology and monetary shocks by Altig et al. (2002) and Edge, Laubach, and Williams (2003).

functions, the one proposed here doesn't rely on further identification restrictions—those necessary to recover the structural shocks from the VAR innovations. Instead, it exploits the specific restrictions that the VAR specification imposes on the solution of the structural model and tries to match the dynamic evolution of the endogenous variables implied by the theoretical model with their evolution as described by the data.

Finally, although the distance restrictions are not moments conditions, this estimator is similar to a GMM estimator whose instruments are the variables of the time-series representation. However, such an estimator is usually applied to orthogonality conditions that proxy the future values of the endogenous variables, as opposed to solving the expectational equations.[23]

5. Modeling the Flexible-Wage Equilibrium Real Wage

A crucial step in implementing the empirical strategy discussed is the specification of the flexible-wage equilibrium real wage. Relationship (26) expresses the theoretical link between the flexible-wage equilibrium real wage (which I denoted by v_t) and real variables in Z_t that are not determined by the two structural equations. Therefore, the expression for the parameter vector Ξ incorporates hypotheses about the determinants of the cyclical components of the marginal rate of substitution, together with hypotheses about the evolution of its trend component.

The real wage v_t is the equilibrium wage that solves the household optimization problem under flexible wages: it is therefore equal to the ratio of the marginal disutility of working Λ_t^h and the marginal utility of consumption Λ_t^c. If there is no time dependence in the momentary utility function, these marginal utilities depend only upon current values of consumption and hours,[24] and a log-linearized expression for v_t is

$$\hat{v}_t = \eta_c \hat{c}_t + \eta_h \hat{h}_t, \tag{43}$$

[23] See my discussion of this point in Sbordone (2005).

[24] With time dependence, for example, if one allows habit persistence in consumption, the marginal rate of substitution depends also on past and future expected values of consumption and hours.

where the coefficients η_i are elasticities. Since "hat" variables are deviations from steady state, which are defined after appropriate transformations of the variables to remove their (possibly stochastic) trends, their natural empirical counterparts are cyclical components defined as deviations from estimated trends. Their derivation is explained in the next section.

6. The Time-Series Model

The second crucial step of the empirical methodology that I described is the specification of the *unrestricted* joint dynamics of the variables that appear as endogenous and forcing variables in the structural equations (20) and (21). These variables are inflation, labor share, labor productivity, and, following the discussion of the previous section, consumption and hours of work, which determine the evolution of the flexible-wage equilibrium real wage.

The first order of problems is choosing a transformation of the data consistent with the hypotheses built into the model. The time series of productivity, real wage, consumption, and output all contain a unit root, but it appears that the consumption-output ratio and the ratio of real wage to labor productivity are stationary. Hours, in turn, appear stationary around a deterministic trend. One can then assume that there is only one common stochastic trend to drive the long-run behavior of the series considered.

The hypothesis of a single stochastic trend in the data is consistent with the assumption built into the model that the economy is driven by a single source of nonstationarity.[25] As in the model, stationary variables used in estimation are then defined as deviation from this single stochastic trend. I handle the nonstationarity in the same multivariate context that I use for the time-series representation and apply the Beveridge-Nelson (1981) detrending method. The vector X_t of (22) is specified as

$$X_t = [\Delta q_t \quad h_t \quad cy_t \quad \pi_t \quad s_t]', \tag{44}$$

[25]This is a stochastic process Θ_t, which I model as a logarithmic random walk. In the model, nonstationary variables such as consumption and real wage are transformed by dividing through this process.

where Δq_t is labor productivity growth, h_t is an index of hours, cy_t is the consumption output ratio, s_t is the share of labor in total output, and inflation is the rate of growth of the implicit GDP deflator.[26]

I use the fact that any difference stationary series can be decomposed in a random-walk component (the stochastic trend) and a stationary component. I identify the single common stochastic trend in vector X_t with the random-walk component of labor productivity, which is in turn defined as the current value of productivity plus all expected future productivity growth.[27] Formally, letting q_t denote labor productivity, its trend is defined as

$$q_t^T = \lim_{k\to\infty} E_t(q_{t+k} - k\mu_q) = q_t + \sum_{j=1}^{\infty} E_t(\Delta q_{t+j} - \mu_q), \tag{45}$$

where $\mu_q = E(\Delta q)$. The stationary, or cyclical, component of productivity is then defined as the deviation of the series from its stochastic trend. The assumption of stationary labor share in the VAR in turn implies that the trend in real wage is the same as the trend in productivity, and the stationarity of the consumption-output ratio, together with the stationarity of hours (which corresponds to the ratio of output to productivity), implies that consumption shares the same trend as productivity.

The cyclical variables that appear in the theoretical model can be constructed as deviations from their respective trends.[28] From the joint representation of the series in (23), the s-step-ahead forecasts that define the trend are easily computed, for each variable i in vector X, as

$$E_t X_{i,t+s} = e_i' E_t Z_{t+s} = e_i' A^s Z_t. \tag{46}$$

[26]Unless otherwise indicated, lowercase letters denote natural logs.

[27]The rationale is that, if productivity growth is expected to be higher than average in the future, then labor productivity today is below trend; vice versa, if productivity growth is expected to be below average, then productivity today is above trend.

[28]The theoretical model has implications only for the co-movement of the stationary components of real wage, consumption, and hours. The specific detrending procedure followed here intends to reflect closely the assumption about the nature of the trend assumed in the theoretical model.

These forecasts underlie the derivation of the vector of parameters Ξ in the expression for the real wage v_t in (26).[29] The specification of Ξ completes the specification of the system (33) used for the estimation of the structural parameters ψ.

Using (46), the trend in productivity defined in (45) is

$$q_t^T = q_t + e_q'[I - A]^{-1} A Z_t. \tag{47}$$

The cyclical component of consumption is derived using the fact that the output-productivity ratio and the consumption-output ratio are stationary so that output, productivity, and consumption share the same stochastic trend. Writing $c_t = (c_t - y_t) + (y_t - q_t) + q_t$, I obtain that

$$c_t^{cyc} = c_t - c_t^T = e_{cy}' Z_t + e_h' Z_t - e_q'[I - A]^{-1} A Z_t, \tag{48}$$

where I have also used the fact that hours are stationary, so that cyclical hours h_t^{cyc} are simply the appropriate component of vector Z_t.

7. Results

7.1 VAR Specification

In the estimation I use quarterly data from 1952:Q1 to 2002:Q1, with data for 1951:Q2–1951:Q4 as initial values. Productivity, output, wages, prices, and hours are for the nonfarm business sector of the economy.[30] Nominal wage is hourly compensation, and real wage is nominal wage divided by the implicit GDP deflator. Consumption is the aggregate of nondurables and services.[31] I fit a VAR with three lags[32] to the vector X_t defined in (44) and estimate the common trend as the trend in productivity defined in (47). As discussed above, productivity, real wage, and consumption share the

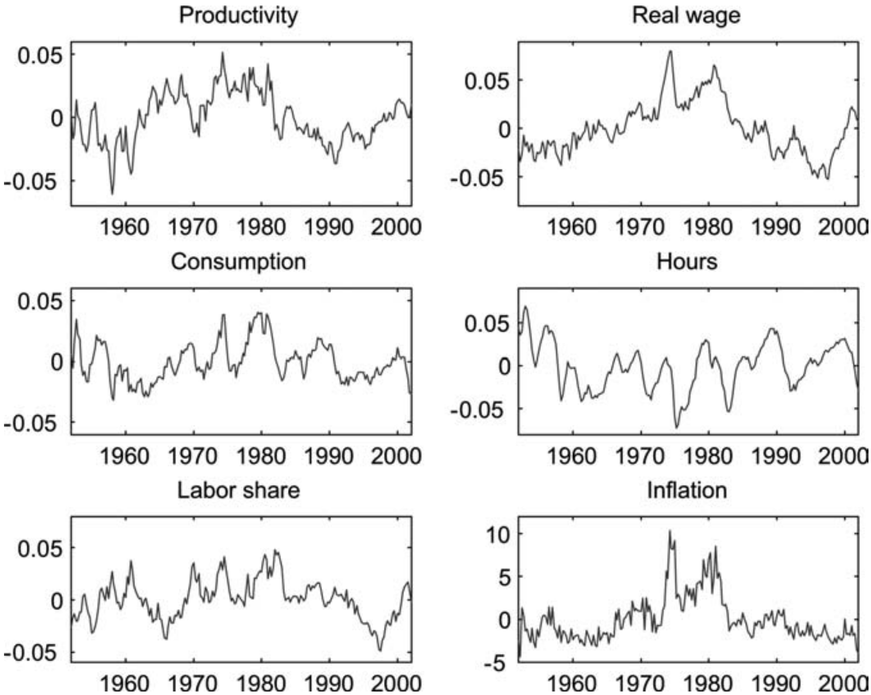
[29] The derivation of Ξ as a function of the exogenous variables in vector Z is detailed in the "Empirical Implementation" section of the appendix.

[30] The time series are downloaded from the Federal Reserve Economic Data (FRED) database at the Federal Reserve Bank of St. Louis.

[31] All variables are in deviation from the mean, and hours are linearly detrended. I also remove, prior to estimation, a moderate deterministic trend that appears in the consumption-output ratio and the labor share.

[32] The optimal lag length is chosen with the Akaike criterion.

Figure 1. Real Variables: Cyclical Components (Inflation: Deviation from Mean, Annualized)



same stochastic trend, while hours have a deterministic trend. Subtracting the appropriate trends from the actual real series, I derive the series' cyclical components, which I plot in figure 1. For inflation, the figure plots its deviation from a constant mean, annualized.

My objective is to compare the cyclical pattern of inflation and real wage to the pattern predicted by the theoretical model. As written, the model has implications for the dynamic behavior of inflation and labor share: given the behavior of productivity, the predicted path of real wages is then recovered from the estimated path of the labor share.

7.2 Estimation of Structural Parameters

Recall that the parameter vector is

$$\psi = (\beta, \varrho_p, \varrho_w, \eta_c, \eta_h, \zeta, \gamma)',$$

Table 1. Parameter Estimates—Baseline VAR (1952:Q1–2002:Q1)

β	ϱ_p	ϱ_w	η_c	η_h	ζ	γ
.967	.226	.058	2.41	−.891	.0255	.040
(.007)	(.041)	(.039)	(.537)	(.312)	(.007)	(.014)
Related Statistics						
$corr(\pi, \pi^m)$	.905					
$corr(s, s^m)$	.798				$Q = 38.42$	
$corr(\omega, \omega^m)$	.908				[p-value: .139]	

where β is a discount factor; ϱ_p and ϱ_w are indexation parameters, respectively, for price and wage setting; η_c and η_h are elasticities of the marginal rate of substitution with respect to consumption and hours of work; and ζ and γ are measures of the inertia in the price and wage settings. The last two parameters are nonlinear combinations of other structural parameters that are not separately identified: the frequency of price and wage adjustments and the structure of technology and preferences. However, calibrating some of these parameters, we can draw some inference on which values of the frequency of price and wage adjustments are consistent with the estimated values of ζ and γ.

Table 1 reports parameter estimates, standard errors (in parentheses),[33] and correlation of the theoretical paths of inflation, labor share, and real wage (denoted with superscript m) with their observed counterparts.

[33]To compute standard errors, I use the empirical distribution of the parameter matrix A to generate N samples A_i $(i = 1, \ldots, N)$: for each of these, I estimate a vector of structural parameters $\hat{\psi}_i$. I then compute the sample variance of $\hat{\psi}$ and report the square root of its main diagonal elements as standard errors. For each estimated vector $\hat{\psi}_i$, I also compute the value of the distance function $\mathcal{F}_i$ and its covariance matrix $\Sigma_{\mathcal{F}}$; the Wald statistic reported in the table is $Q = \mathcal{F}(\hat{\psi})'\Sigma_{\mathcal{F}}\mathcal{F}(\hat{\psi})$, where $\mathcal{F}(\hat{\psi})$ is the value of the distance evaluated at the optimal value of ψ. It can be read as a test of the model restrictions.

Most of the estimated parameters are statistically significant. The parameters of the inflation model are consistent with several of the empirical results in the New Keynesian Phillips curve (NKPC) literature. First, there is a modest role for a backward-looking component in inflation dynamics: the indexation parameter ϱ_p is significantly different from zero, but the implied weight on the backward-looking component $(\varrho_p/(1 + \beta\varrho_p) \simeq .18)$ is quantitatively much smaller than the weight on the forward-looking component $(\beta/(1+\beta\varrho_p) \simeq .79)$. Secondly, the size of the coefficient on the labor share, as it will be discussed below, is consistent with other estimates of price inertia in the literature.

In the labor share equation, the parameter of wage indexation ϱ_w is much smaller than 1, the value imposed in Christiano, Eichenbaum, and Evans (2005), and more in the range estimated by Smets and Wouters (2003) for the euro area. Finally, the value of the statistic Q indicates that the restrictions that the model imposes on the parameters of A cannot be rejected.

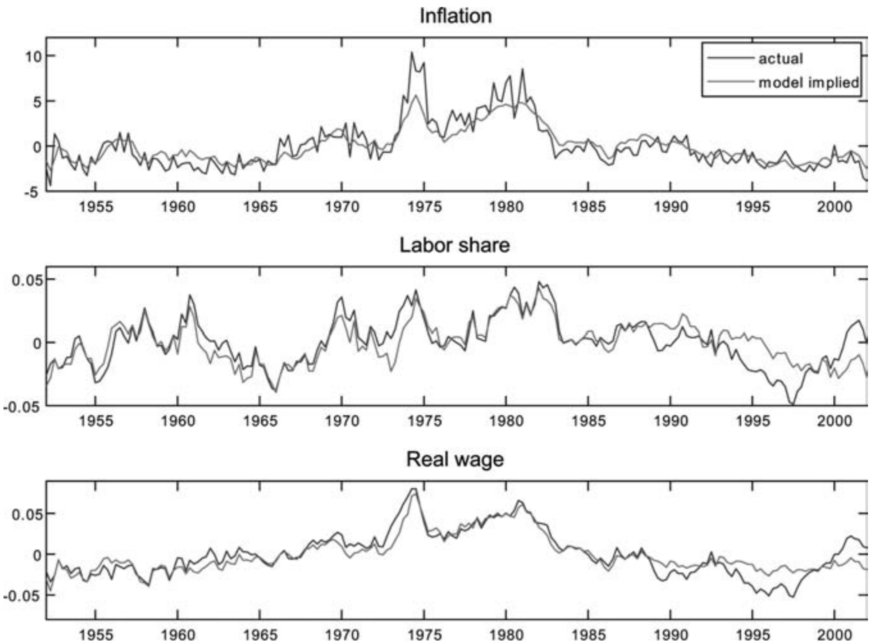
Figure 2 compares actual inflation, labor share, and real wage (namely, the cyclical components of these series as portrayed in figure 1) to the paths of inflation, labor share, and real wage constructed recursively from the model solution evaluated at the estimated parameters—labeled “model implied” in the figure.[34] These paths seem to capture well the underlying dynamics of the actual series: on these accounts, the model of wage and price inflation described seems to fit the data quite well.

Furthermore, the model is able to match the dynamic correlation between inflation and output. As noted in the literature,[35] output leads inflation in the data: the cyclical component of output, variously measured, is positively correlated with future inflation, with the highest value at about three quarters ahead. Purely forward-looking NKPCs driven by the output gap, when this is measured as deviation from a deterministic trend, are unable to reproduce such a result: output gap typically lags inflation in such a

[34] The “model implied” paths of inflation and labor share are directly computed from expressions (35) and (36); the path of real wage is recovered from that of the labor share by adding productivity.

[35] See, for example, the discussion of “reverse dynamic” cross-correlation in Taylor (1999).

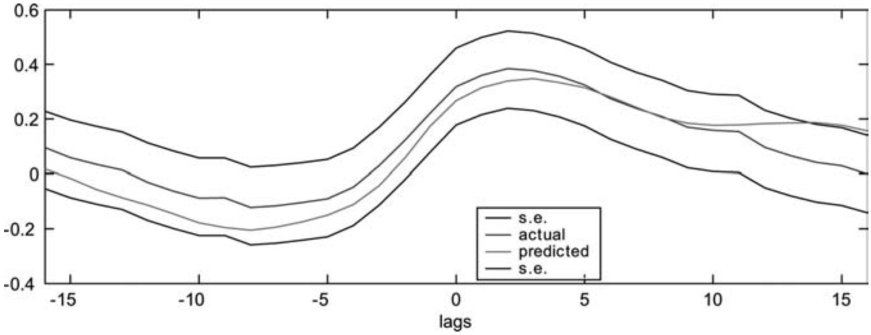
Figure 2. Inflation, Labor Share, and Real Wage: Actual versus Model Implied



model.[36] Output-inflation correlations are shown in figure 3. The figure compares the dynamic correlation of output gap and actual inflation (the line labeled "actual") with the dynamic correlation of output gap and the inflation series generated by the estimated model (the line labeled "predicted"). The output-gap measure used to compute these correlations is, consistently with the estimated time-series model, the deviation of output from the estimated stochastic trend. As the figure shows, output leads inflation both in the model and in the data, and actual and predicted dynamic correlations peak at about the same time. This provides further evidence that the model succeeds in capturing the main dynamics of inflation.

[36]See evidence presented in Sbordone (2001) or Galí and Gertler (1999). More recently, Guerrieri (2006) argued that the Fuhrer and Moore (1995) relative price contract is better able to reproduce this dynamic correlation than a standard n-period Taylor (1980) contract.

Figure 3. Dynamic Cross-Correlations: Output Gap (t) versus Inflation (t + k)



7.3 Implied Degree of Nominal Rigidities

The parameters that measure the degree of price and wage inertia are significantly different from zero, but they do not give a direct estimate of the frequency of price and wage adjustments. In the Calvo model, the frequency of price and wage adjustment is driven by the probability of changing prices or wages at any point in time, measured respectively by α_p and α_w. In order to infer those parameters from the estimated values of ζ and γ, some further hypotheses are needed. From the definition of $\zeta = \frac{(1-\alpha_p)(1-\alpha_p\beta)}{\alpha_p(1+\theta_p\omega)}$, to draw inference on α_p, one has to make some assumption about the degree of substitution among differentiated goods θ_p and the elasticity of real marginal cost to output for the individual firm, ω. On the upper part of table 2, I report the implied degree of inertia (measured as the average time between price changes, measured in months) under two different assumptions about these two parameters. For the parameter ω I consider two benchmark values, .33 and .54;[37] for θ_p, which is related to the steady-state markup μ^* by $\mu^* = \theta_p/(\theta_p - 1)$, I consider values that imply a low (20 percent) and a high (60 percent) steady-state markup, two benchmark

[37] As mentioned before, in the case of a Cobb-Douglas technology, $\omega = a/(1-a)$, where a is the output elasticity with respect to capital. The two values assumed for ω correspond, therefore, to an output elasticity with respect to capital of .25 and .35, respectively.

Table 2. Implied Degrees of Nominal Rigidity

Average Time between Price Changes (Months)			
	Low Markup ($\mu^{p*} = 1.2$)	High Markup ($\mu^{p*} = 1.6$)	
$\omega = .33$	12.4	15.1	
$\omega = .54$	10.7	13.6	
Average Time between Wage Changes (Months)			
	Low Wage Markup ($\mu^{w*} = 1.1$)	Mid Wage Markup ($\mu^{w*} = 1.3$)	High Wage Markup ($\mu^{w*} = 1.5$)
Low Nonsep.	13.4	12.3	16.1
Mid Nonsep.	8.6	11.4	12.5
High Nonsep.	5.8	7.6	8.4

values often used in the literature.[38] As the table shows, the average duration of prices ranges from a little more than three quarters to about five quarters, depending on these assumptions.

The bottom part of the table shows the implied degree of wage inertia, computed in a similar manner. Here the inertia is summarized by $\gamma = \frac{(1-\alpha_w)(1-\beta\alpha_w)}{\alpha_w(1+\theta_w\chi)}$; in order to make inference on α_w, some assumption must be made about the value of the parameters θ_w and, therefore, about the value of the steady-state wage markup and about the degree of nonseparability between consumption and leisure in preferences, which determines the size of the parameter χ. In the table I consider different values for the steady-state markup and different degrees of nonseparability.[39] For low degrees of nonseparability, the average duration of wage contracts is similar to those of prices, while it is shorter for highly nonseparable preferences.

That preferences should be nonseparable in consumption and leisure is an implication of the negative sign of the elasticity of the

[38]Values of μ^* above 1.5 are, for example, estimated by Hall (1988) on a large number of U.S. manufacturing industries.

[39]I show in the appendix (in the section titled "Inference on Wage Rigidity") that the degree of nonseparability can be parameterized by calibrating the value of the intertemporal elasticity of substitution in consumption and the share of labor income in consumption.

marginal rate of substitution with respect to hours.[40] While most of the business-cycle literature adopts a separable preference specification, empirical evidence on significant nonseparability in preferences has been found, most recently, by Basu and Kimball (2000). Moreover, within the class of preferences that are consistent with balanced growth, a negative elasticity of the marginal rate of substitution with respect to hours can be obtained in a generalized indivisible labor model, as shown in King and Rebelo (1999). The interpretation of the large elasticity η_c is more problematic and requires further investigation. As we will see below, however, a modification in the specification of the time-series model reduces its size. Another possibility to be explored, which is left to future research, is that this parameter is overestimated for an omitted variable problem in the wage equation, as would be the case if preferences were time dependent.

8. Some Robustness Analysis

The inference presented on the structural parameters relies on the inference in the first step of the procedure: the estimation of the time-series model. I made a number of assumptions to model the VAR: the choice of variables was suggested by the need to limit its dimension, but the inclusion of additional variables could potentially improve the forecast of the driving forces of the structural equations. I modeled only one stochastic trend in the data, to mimic the trend assumption of the theoretical model; but the data may be consistent with other assumptions about the number of common stochastic trends. Finally, the VAR structure has been modeled as time invariant, while many recent analyses suggest that changes in policy regime have determined drifts over time in the reduced-form representation of the relation between nominal and real variables.[41]

While some of these issues are pursued in separate research,[42] in table 3 I present the results of alternative estimates to shed

[40] This can be shown by expressing the two elasticities of the marginal rate of substitution η_c and η_h in terms of the Frish elasticities of consumption and labor supply (see Sbordone 2001).

[41] See, for example, Boivin and Giannoni (2005) and Cogley and Sargent (2001, 2005).

[42] Cogley and Sbordone (2005) extend the two-step estimation procedure to the case of a small-scale first-stage VAR with drifting parameters.

Table 3. Parameter Estimates—Augmented VAR (1954:Q3–2002:Q1)*

	β	ϱ_p	ϱ_w	η_c	η_h	ζ	γ
	.967 .(0027)	.154 (.027)	.001 (.071)	2.74 (.581)	−.71 (.319)	.018 (.009)	.033 (.034)
Related Statistics							
$corr(\pi, \pi^m)$	.897						
$corr(s, s^m)$	.782						$Q = 36.44$
$corr(\omega, \omega^m)$	.903						[p-value: .194]
Average Time between Price Changes (Months)							
	Low Markup			High Markup			
$\omega = .54$	13.0			16.3			
Average Time between Wage Changes (Months)							
	Low Markup			High Markup			
Low Nonsep.	6.63			9.81			
High Nonsep.	5.70			8.26			

*The shorter sample is due to the federal funds rate data being available only from 1954:Q3.

some light on how sensitive the results presented so far are to the inclusion of additional variables in the time-series model. Specifically, I augment the baseline VAR with the federal funds rate: although the corresponding equation in the VAR is not meant to represent a policy rule, the introduction of the federal funds rate can be thought of as representing the reduced-form effect of monetary policy on inflation and the real variables of the system. The drawback of including an additional variable in the VAR, though, is an increase in uncertainty when the relative parameters are not tightly estimated.

Table 3 reports the second-stage parameter estimates and the implied nominal rigidity. The results are qualitatively similar to the previous ones, but the lower estimates of the inertia parameters imply a higher degree of nominal rigidity, especially for prices.

9. Conclusion

In this paper I estimate the joint dynamics of U.S. prices and wages using a partial-information approach. I derive the implied price and wage inflations from an optimization-based model of staggered price and wage contracts with random duration and then implement a two-step minimum-distance estimation of the structural parameters. In the first step, I estimate an unrestricted time-series representation for the variables of interest and derive the restrictions that the model solution imposes on this representation. In the second step, I use these restrictions to define a distance function to be minimized for the estimation of the structural parameters. This methodology allows me to investigate the dynamics of prices and wages without having to make all the additional assumptions required to close the model and to characterize its entire stochastic structure.

I find that a generalized version of the Calvo mechanism of random intervals between price and wage adjustments fits the data quite well, that there is some backward-looking component in inflation, and that the average duration of both contracts is around a year. The robustness of these results to the specification of the first stage of the proposed estimation procedure is to be further explored.

Appendix

Derivation of Equation (19)[43]

Under the hypothesis that there is a single stochastic trend driving long-run growth, say Θ_t, with $\gamma_{\Theta_t} = \Theta_t/\Theta_{t-1}$ an i.i.d. process, one can define stationary variables $x_{wt} \equiv \frac{X_{wt}}{W_t}$, $\pi_t^w \equiv \frac{W_t}{W_{t-1}}$, $\widetilde{\omega}_t = \frac{W_t}{\Theta_t P_t}$, and $\widetilde{v}_t = \frac{v_t}{\Theta_t}$. Then, using the fact that $\frac{X_{wt}}{W_{t+j}} = \frac{X_{wt}}{W_t}\frac{W_t}{W_{t+j}}$ and $\frac{X_{wt}}{P_{t+j}} = \frac{X_{wt}}{W_{t+j}}\frac{W_{t+j}}{P_{t+j}}$, equation (18) can be written as

$$E_t \left\{ \Sigma_{j=0}^{\infty} (\beta\alpha_w)^j \left(x_{wt} \Psi_{tj}^w \Pi_{k=1}^j (\pi_{t+k}^w)^{-1} \right)^{-\theta_w} \right.$$
$$\left. \times\ H_{t+j} \left[x_{wt} \Psi_{tj}^w \widetilde{\omega}_{t+j} \Pi_{k=1}^j (\pi_{t+k}^w)^{-1} - \frac{\theta_w}{\theta_w - 1} \widetilde{v}_{t+j,t} \right] \right\} = 0,$$

[43] This derivation follows Sbordone (2001).

so that a log-linearization around steady-state values $x_w^*, \pi^*, \pi^{w*}, \omega^*$, v^* gives

$$\Sigma_{j=0}^{\infty}(\beta\alpha_w)^j \left(\hat{x}_{wt} + \varrho_w \Sigma_{k=0}^{j-1}\hat{\pi}_{t+k} - \Sigma_{k=1}^{j}\hat{\pi}_{t+k}^{w} + \hat{\omega}_{t+j}\right)$$
$$= \Sigma_{j=0}^{\infty}(\beta\alpha_w)^j \; E_t(\hat{v}_{t+j,t}),$$

or

$$\hat{x}_{wt} = (1-\beta\alpha_w)\Sigma_{j=0}^{\infty}(\beta\alpha_w)^j \; E_t \times \left(\hat{v}_{t+j,t} - \hat{\omega}_{t+j} - \varrho_w \Sigma_{k=0}^{j-1}\hat{\pi}_{t+k} + \Sigma_{k=1}^{j}\hat{\pi}_{t+k}^{w}\right). \qquad (49)$$

To express $\hat{v}_{t+j,t}$ in terms of the average marginal rate of substitution, I write

$$v_{t+j,t} \equiv \frac{\Lambda^h}{\Lambda^c}(c_{t+j,t}, h_{t+j,t}) = \frac{\frac{\Lambda^h}{\Lambda^c}(c_{t+j,t}, h_{t+j,t})}{\frac{\Lambda^h}{\Lambda^c}(c_{t+j}, h_{t+j})}\left(\frac{\Lambda^h}{\Lambda^c}(c_{t+j}, h_{t+j})\right), \qquad (50)$$

where $c_t = C_t/\Theta_t$, and Λ^h denotes the marginal disutility of work. Therefore, a log-linearization of (50) gives

$$\hat{v}_{t+j,t} = \eta_c(\hat{c}_{t+j,t} - \hat{c}_{t+j}) + \eta_h(\hat{h}_{t+j,t} - \hat{h}_{t+j}) + \hat{v}_{t+j}, \qquad (51)$$

where η_x $(x = c, h)$ indicates the elasticity of the marginal rate of substitution between leisure and consumption with respect to x, evaluated at the steady state. By the assumption that changes in consumption occur in a way that maintains the marginal utility of consumption equal across households, $\hat{c}_{t+j,t}$ and $\hat{c}_{t+j}$ are, respectively, functions of $\hat{h}_{t+j,t}$ and $\hat{h}_{t+j}$. Moreover, from (17) it follows that

$$\hat{h}_{t+j,t} - \hat{h}_{t+j} = -\theta_w\left(\hat{x}_{wt} + \varrho_w \Sigma_{k=0}^{j-1}\hat{\pi}_{t+k} - \Sigma_{k=1}^{j}\hat{\pi}_{t+k}^{w}\right).$$

Substituting this result in (51), I get

$$\hat{v}_{t+j,t} = -\chi\theta_w\left(\hat{x}_{wt} + \varrho_w \Sigma_{k=0}^{j-1}\hat{\pi}_{t+k} - \Sigma_{k=1}^{j}\hat{\pi}_{t+k}^{w}\right) + \hat{v}_{t+j}, \qquad (52)$$

where I defined $\chi = \frac{-\Lambda_h^c}{\Lambda_c^c}\eta_c + \eta_h$, and where Λ_i^c indicates the derivative of the marginal utility of consumption with respect to argument i.

In (15), dividing both sides by W_t and log-linearizing, I obtain

$$\hat{x}_{wt} = \frac{\alpha_w}{1-\alpha_w}(\hat{\pi}_t^w - \varrho_w \hat{\pi}_{t-1}). \tag{53}$$

Substituting (53) and (52) into (49), I obtain

$$\begin{aligned}(\hat{\pi}_t^w - \varrho_w \hat{\pi}_{t-1}) = \gamma \Sigma_{j=0}^{\infty} (\beta\alpha_w)^j \ E_t\Big(\hat{v}_{t+j} - \hat{\omega}_{t+j} \\ + (1+\chi\theta_w)\left(\Sigma_{k=1}^{j} \hat{\pi}_{t+k}^w - \varrho_w \Sigma_{k=0}^{j-1} \hat{\pi}_{t+k}\right)\Big), \end{aligned} \tag{54}$$

where $\gamma = \frac{(1-\alpha_w)(1-\beta\alpha_w)}{\alpha_w(1+\theta_w\chi)}$.

Finally, forwarding (54) one period, premultiplying it by $\beta\alpha_w$, and subtracting the resulting expression from (54), I obtain the wage equation (19) in the text.

Empirical Implementation

To compute the solution, I cast the model in the following canonical form:

$$Y_{t+1} = MY_t + \Psi u_{t+1} + \Pi \eta_{yt+1}, \tag{55}$$

where $\eta_{y,t+1} = y_{t+1} - E_t y_{t+1}$ are expectational errors.

The definitions of the vector Y_t and of the matrix M are as in the text, and the matrices Ψ and Π are

$$\Psi = \begin{bmatrix} N_1 & 0 \\ \underline{0} & 0 \\ \underline{0} & Q \end{bmatrix} \text{ and } \Pi = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \underline{0} & \underline{0} \end{bmatrix}.$$

Furthermore,

$$M_{yy} = \begin{bmatrix} \frac{1+\varrho_p\beta}{\beta} & -\frac{\zeta}{\beta} & -\frac{\varrho_p}{\beta} & 0 \\ \varrho_w - \varrho_p & \frac{1+\beta+\gamma+\zeta}{\beta} & \frac{\varrho_p - \varrho_w}{\beta} & -\frac{1}{\beta} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

$$M_{yZ} = \begin{bmatrix} \underline{0} \\ -\left(\frac{\gamma}{\beta}\Xi - \frac{1}{\beta}e_q' + e_q' A\right) \\ \underline{0} \\ \underline{0} \end{bmatrix}.$$

As indicated in the text, the vector Ξ depends on the chosen specification of preferences and on the assumptions about trend.

Since $v_t = v_t^T + v_t^{cyc} = q_t^T + v_t^{cyc}$, from the definition of the trend in productivity (47), it follows that

$$v_t = q_t + e_q'[I-A]^{-1}A + \eta_c c_t^{cyc} + \eta_h h_t^{cyc},$$

and the vector Ξ is therefore defined as

$$\begin{aligned}\Xi &= e_q'[I-A]^{-1}A + \eta_c\left(e_{cy}' + e_h' - e_q'[I-A]^{-1}A\right) + \eta_h e_h' \\ &= (1-\eta_c)e_q'[I-A]^{-1}A + \left[\eta_c(e_{cy}' + e_h') + \eta_h e_h'\right].\end{aligned}$$

The parameters of interest in this expression are the elasticities η_c and η_h, which are estimated together with the adjustment parameters of the wage and price equations.

Inference on Wage Rigidity

To translate the estimate of the "inertia" parameter γ into an estimate of the degree of wage rigidity, I need to parameterize χ, which is

$$\chi = \frac{-\Lambda_h^c H}{\Lambda_c^c C}\eta_c + \eta_h. \tag{56}$$

I first consider a slight transformation of this expression:[44]

$$\chi = \frac{-\Lambda_h^c \Lambda^c}{\Lambda_c^c \Lambda^h}\left(\frac{\Lambda^h H}{\Lambda^c C}\right)\eta_c + \eta_h \tag{57}$$

and then write the expression for η_c as

$$\begin{aligned}\eta_c &= -\frac{\Lambda_c^c C}{\Lambda^c} + \frac{\Lambda_h^c C}{\Lambda^h} = \sigma + \frac{\Lambda_h^c C}{\Lambda^h} \\ &= \sigma + \frac{\Lambda_h^c}{\Lambda_c^c}\left(\frac{\Lambda_c^c C}{\Lambda^c}\right)\frac{\Lambda^c}{\Lambda^h} = \sigma\left(1 - \frac{\Lambda_h^c}{\Lambda_c^c}\frac{\Lambda^c}{\Lambda^h}\right),\end{aligned} \tag{58}$$

[44] A more detailed discussion of this parameterization is in Sbordone (2001).

where, with conventional notation, I indicate with σ the inverse of the intertemporal elasticity of substitution in consumption. Expression (58) implies that

$$\frac{\Lambda_h^c}{\Lambda_c^c}\frac{\Lambda^c}{\Lambda^h} = \frac{\sigma - \eta_c}{\sigma};$$

substituting this result in (57), I obtain

$$\chi = \left(\frac{\sigma - \eta_c}{\sigma} * \tau\right)\eta_c + \eta_h.$$

Therefore, given the estimated η_c and η_h, one can determine the value of χ for any value that one wishes to assign to σ and to the ratio wH/C, which I have denoted by τ. The computations in table 2 are based on three different assumptions about the value of the intertemporal elasticity of substitution in consumption (corresponding to $\sigma = 4, 5$, or 10) and the value of $\tau = 1$. Every value of σ implies, in turn, a different degree of nonseparability in preferences.

References

Altig, D., L. J. Christiano, M. Eichenbaum, and J. Lindé. 2002. "Technology Shocks and Aggregate Fluctuations." Unpublished.

Amato, J. D., and T. Laubach. 2003. "Estimation and Control of an Optimization-Based Model with Sticky Prices and Wages." *Journal of Economic Dynamics and Control* 27 (7): 1181–1215.

Basu, S., and M. S. Kimball. 2000. "Long-Run Labor Supply and the Elasticity of Intertemporal Substitution for Consumption." Unpublished, University of Michigan.

Batini, N., B. Jackson, and S. Nickell. 2005. "An Open-Economy New Keynesian Phillips Curve for the U.K." *Journal of Monetary Economics* 52 (6): 1061–72.

Beveridge, S., and C. R. Nelson. 1981. "A New Approach to Decomposition of Economic Time Series into Permanent and Transitory Components with Particular Attention to Measurement of the 'Business Cycle'." *Journal of Monetary Economics* 7 (2): 151–74.

Boivin, J., and M. Giannoni. 2005. "Has Monetary Policy Become More Effective?" Forthcoming in *Review of Economics and Statistics.*

Calvo, G. A. 1983. “Staggered Prices in a Utility-Maximizing Framework.” *Journal of Monetary Economics* 12 (3): 383–98.

Campbell, J. Y., and R. J. Shiller. 1987. “Cointegration and Tests of Present Value Models.” *Journal of Political Economy* 95 (5): 1062–88.

Christiano, L., M. Eichenbaum, and C. Evans. 2005. “Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy.” *Journal of Political Economy* 113 (1): 1–45.

Cogley, T., and T. J. Sargent. 2001. “Evolving Post-World War II U.S. Inflation Dynamics.” In *NBER Macroeconomics Annual*, ed. B. S. Bernanke and K. S. Rogoff, 331–73.

———. 2005. “Drifts and Volatilities: Monetary Policies and Outcomes in the Post WWII U.S.” *Review of Economic Dynamics* 8 (2): 262–302.

Cogley, T., and A. M. Sbordone. 2005. “A Search for a Structural Phillips Curve.” Staff Report No. 203, Federal Reserve Bank of New York.

Edge, R., T. Laubach, and J. Williams. 2003. “Productivity Slowdowns and Speedups: A Dynamic General Equilibrium Approach.” Unpublished, Board of Governors of the Federal Reserve System.

Erceg, C. J., D. W. Henderson, and A. T. Levin. 2000. “Optimal Monetary Policy with Staggered Wage and Price Contracts.” *Journal of Monetary Economics* 46 (2): 281–313.

Fuhrer, J., and G. Moore. 1995. “Inflation Persistence.” *Quarterly Journal of Economics* 110 (1): 127–59.

Gagnon, E., and H. Khan. 2005. “New Phillips Curve under Alternative Technologies for Canada, the United States, and the Euro Area.” *European Economic Review* 49 (6): 1571–1602.

Galí, J., and M. Gertler. 1999. “Inflation Dynamics: A Structural Econometric Analysis.” *Journal of Monetary Economics* 44 (2): 195–222.

Galí, J., M. Gertler, and J. D. López-Salido. 2001. “European Inflation Dynamics.” *European Economic Review* 45 (7): 1237–70.

———. 2005. “Robustness of the Estimates of the Hybrid New Keynesian Phillips Curve.” *Journal of Monetary Economics*. 52 (6): 1107–18.

Guerrieri, L. 2006. “The Inflation Persistence of Staggered Contracts.” *Journal of Money, Credit, and Banking* 38 (2): 483–94.

Hall, R. 1988. "The Relation Between Price and Marginal Cost in U.S. Industry." *Journal of Political Economy* 96 (5): 921–47.

Ireland, P. 1997. "A Small, Structural, Quarterly Model for Monetary Policy Evaluation." *Carnegie-Rochester Conference Series on Public Policy* 47:83–108.

King, R. J., and S. T. Rebelo. 1999. "Resuscitating Real Business Cycles." In *Handbook of Macroeconomics,* Vol. 1B, ed. J. B. Taylor and M. Woodford, 927–1007. Elsevier Science.

Kurmann, A. 2005. "Quantifying the Uncertainty about the Fit of a New Keynesian Pricing Model." *Journal of Monetary Economics* 52 (6): 1119–34.

Lindé, J. 2005. "Estimating New-Keynesian Phillips Curves: A Full Information Maximum Likelihood Approach." *Journal of Monetary Economics* 52 (6): 1135–49.

Rotemberg, J., and M. Woodford. 1997. "An Optimization-Based Econometric Framework for the Evaluation of Monetary Policy." In *NBER Macroeconomics Annual*, ed. B. S. Bernanke and J. J. Rotemberg, 297–346.

Rudd, J., and K. Whelan. 2005. "New Tests of the New-Keynesian Phillips Curve." *Journal of Monetary Economics* 52 (6): 1167–81.

Sbordone, A. M. 2001. "An Optimizing Model of U.S. Wage and Price Dynamics." Working Paper Series 2001-10, Rutgers University.

———. 2002. "Prices and Unit Labor Costs: A New Test of Price Stickiness." *Journal of Monetary Economics* 49 (2): 265–92.

———. 2005. "Do Expected Future Marginal Costs Drive Inflation Dynamics?" *Journal of Monetary Economics* 52 (6): 1183–97.

Sims, C. A. 2001. "Comments on Papers by Jordi Galí and by Stefania Albanesi, V.V. Chari and Lawrence J. Christiano." Unpublished, Princeton University.

Smets, F., and R. Wouters. 2003. "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area." *Journal of the European Economic Association* 1 (5): 1123–75.

———. 2005. "Comparing Shocks and Frictions in US and Euro Area Business Cycles: A Bayesian DSGE Approach." *Journal of Applied Econometrics* 20 (2): 161–83.

Taylor, J. B. 1980. "Aggregate Dynamics and Staggered Contracts." *Journal of Political Economy* 88 (1): 1–23.

———. 1999. "Staggered Price and Wage Setting in Macroeconomics." In *Handbook of Macroeconomics*, Vol. 1B, ed. J. B. Taylor and M. Woodford, 1009–50. Elsevier Science.

Woodford, M. 2003. *Interest and Prices: Foundations of a Theory of Monetary Policy.* Princeton, NJ: Princeton University Press.