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Prices and unit labor costs: a new test of price stickiness☆

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Abstract

This paper investigates the predictions of a simple optimizing model of nominal price rigidity for the dynamics of inflation. Taking as given the paths of nominal labor compensation and labor productivity to approximate the evolution of marginal costs, I determine the path of prices predicted by the solution of the firms' optimal pricing problem. Model parameters are chosen to maximize the fit with the data. I find evidence of a significant degree of price stickiness and substantial support for the forward-looking model of price setting. The results are robust to the use of alternative forecasting models for the path of unit labor costs, alternative measures of marginal costs, and alternative specifications of the model of price staggering. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

This paper investigates the predictions of a simple model of optimal price-setting for the aggregate price level and the dynamics of inflation. The model incorporates

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nominal price rigidity, in the form of delays between price adjustments, as in the model proposed by Calvo (1983). I evaluate the model performance against a 'benchmark' model with flexible prices (the model of pricing assumed in standard real business cycle models), by studying how much the model's deviations from the assumptions of the benchmark model improve the fit with US data.

While much recent evaluation of optimizing models with nominal price rigidity, following the lead of the RBC literature, has been conducted within a similar framework of general equilibrium models,[1] I propose here a different approach. I test the validity of the sticky price hypothesis by testing implications that depend only upon the firm's optimal pricing problem. The advantage of this approach is that it doesn't involve other maintained hypotheses about the structure of the economy—for example, about household preferences or about wage- setting—in addition to the assumed model of pricing and supply behavior by firms. This makes it easier to pin down which aspect of the model specification is responsible for its failure to match the data.

Moreover, rather than specifying the stochastic properties of the ultimate sources of randomness in the economy, I instead take as given the evolution of a number of state variables, and determine what path of prices is predicted by the evolution of these other variables, under the model of price determination considered. In this way I do not need to specify the source of the shock that determines deviations from a steady state equilibrium; the obvious advantage of proceeding in this way is that the results I obtain do not depend on some (more or less) arbitrary identification procedure to extract structural shocks from the residuals of an estimated time series model.

My empirical approach is closely related to the procedure used in a number of papers by Campbell and Shiller (for example, 1987 and 1988) to test present-value models of stock prices. As in the case of the present-value theory of stock prices, the optimizing sticky-price model that I consider here gives rise to a theoretical relationship where the evolution of one variable (the aggregate level of prices) depends on the discounted sum of expected future values of another variable (real marginal cost). I then construct the theoretical path of prices according to the model, taking as given the evolution of nominal labor compensation and labor productivity, and compare it to the data.

In the actual implementation, since prices are not a stationary series, I transform the present-value relationship into one where the price/unit labor cost ratio, which is stationary, depends upon the discounted sum of expected future growth of labor costs, which is also a stationary variable. I then use *VAR* methodology to forecast the evolution of labor costs, and construct the path of the price/unit labor cost ratio predicted by the sticky-price model. This path depends on a number of parameters, which I estimate as those for which the model best fits the data, in terms of matching the level of the actual and predicted series. I also study the implications of the model for the path of inflation. Looking at the predictions for inflation not only provides an

[1] See, for example, King and Watson (1996), Rotemberg (1995), Christiano et al. (1997) and Rotemberg and Woodford (1997).

additional set of statistics to measure the goodness of fit, but allows to compare directly the results of this paper with the literature on the Phillips curve.

The approach to estimation distinguishes this paper from a recent paper on inflation dynamics which is otherwise written in the same spirit, and reaches very similar results. Gali and Gertler (1999) stress, as I do here, the fact that the central implication of the Calvo sticky price model is a prediction about the way that inflation dynamics should depend upon the evolution of marginal cost; this yields a prediction about the relation of inflation and output *only* insofar as standard measures of 'output gap' are good measures of marginal cost. As I do, they also use unit labor costs as a more direct measure of marginal cost. However, they estimate the Phillips curve equation using GMM estimation, and then use the estimated parameters to construct the behavior of the predicted inflation. Such an estimation requires one to find variables that are orthogonal to the one period ahead expected inflation, and therefore can be valid instruments. My procedure directly constructs the path of prices implied by the model for given parameter values, and then chooses an optimal value for those parameters. The advantage of this procedure is that it performs econometric estimation directly on the model solution, allowing an immediate assessment of the goodness of fit of the model. It also forces one to be specific about the stochastic model driving the forcing variables—in the case of this paper, the forecasting VAR. To address the issue of whether the results are sensitive to the way in which the expected future values of the driving variables are determined, I perform a series of robustness checks by varying the specification of the VAR model. Furthermore, I address the issue of whether unit labor cost is an appropriate proxy for marginal cost, and whether the results are sensitive to the particular model of price staggering used.

The rest of the paper is organized as follows. In Section 2, after showing the counterfactual predictions of the standard competitive, flex-price model of pricing used in the RBC literature, denoted the 'benchmark' model, I present the Calvo model of nominal price rigidities, and discuss its theoretical predictions for the paths of prices and inflation. In particular, I show that this model implies an 'expectation augmented Phillips Curve' relationship, where inflation is a function of expected future inflation and current real marginal costs. In Section 3 I present the empirical methodology and discuss the fit of the model under the hypothesis that real marginal costs are well approximated by unit labor costs, and in Section 4 I compare my results to standard New Keynesian Phillips curve estimates. In Section 5 I discuss the robustness of the empirical results to alternative forecasting models of labor costs, to alternative measures of real marginal costs, and to the specification of price staggering. Section 6 concludes.

My results can be summarized as follows. Models of imperfect competitions with nominal price rigidity appear to deliver an extremely close approximation both to the evolution of the price/unit labor cost ratio and to the dynamics of inflation, not only when using a very simple (though familiar) measure of marginal costs, which assumes that they are proportional to unit labor costs, but also under some modifications that take into account potential biases in the measurement of labor productivity or real wages. Among the implications of this finding are not merely evidence of a significant degree of price stickiness in the US, but also important support for a forward-looking model of price setting. Finally, the degree of fit of the simple model suggests that neither variations in marginal costs unrelated to changes in unit labor costs, nor fluctuations in markups for reasons unrelated to price stickiness, are needed to explain the bulk of fluctuations in the US aggregate price level.

2. A model with random intervals between price changes

In the standard model of pricing assumed in the real business cycle literature, perfect competition implies that real wages are equal to the marginal product of labor; with a Cobb–Douglas technology, the marginal product of labor is in turn equal to average labor productivity. As a consequence, the ratio of prices over unit labor costs is constant, and inflation is equal to the rate of change of unit labor costs. These two implications are clearly counterfactual in the US. The historical series of the ratio of prices to unit labor cost (panel a) and inflation (panel b), computed on quarterly data from 1960:2 to 1997:1, are plotted in Fig. 1 as solid lines.[2] The dotted lines trace the corresponding series predicted by the benchmark model. It is clear that, in particular, the benchmark model overstates the variability of inflation quite significantly.

Allowing for nominal price rigidity changes these predictions significantly. I consider a discrete version of the well known 'Calvo' model with random intervals between price changes. The model has a continuum of monopolistic firms, indexed by i, which produce differentiated goods, also indexed by i. The demand curve for product i takes the form:

$$Y_{it} = (P_{it}/F_t)^{-\theta} Y_t,$$

where θ is the Dixit–Stiglitz elasticity of substitution among differentiated goods, and Y_t is the aggregator function defined as $Y_t = [\int_0^1 Y_{it}^{(\theta-1)/\theta}\, di]^{(\theta-1)/\theta}$. Each firm i has a Cobb–Douglas production technology:

$$Y_{it} = (K_{it})^a (\Theta_t H_{it})^{1-a}.$$

Nominal price rigidity is modeled by allowing, in every period, only a fraction $(1-\alpha)$ of the firms to set a new price, independently of the past history of price changes; this price will then be kept fixed until the next time the firm is drawn to change prices again. This set-up implies that the expected time between price changes is $1/(1-\alpha)$; by letting α vary between 0 and 1, the model nests a wide range of assumptions about the degree of price stickiness, from perfect flexibility ($\alpha = 0$) to complete price rigidity (the limit as $\alpha \to 1$).

[2] All the data are for the non farm private business sector. The price series is the implicit deflator of *GDP*, unit labor cost is the ratio of compensation per hour (W) to average labor productivity (APL). The real wage is defined as compensation divided by the *GDP* deflator: this is the real wage relevant to firms, and therefore appropriate for a model of firm behavior. The graphs are in deviation from the mean.

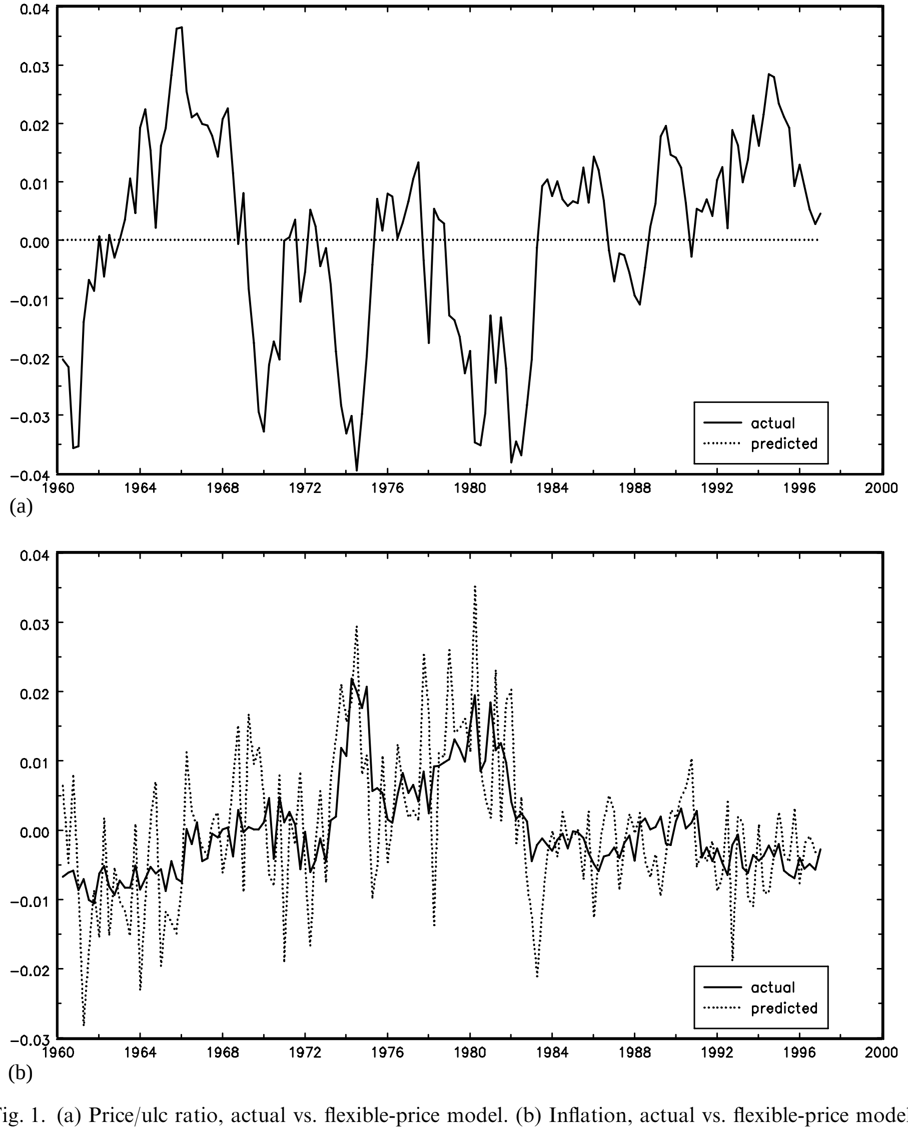


Fig. 1. (a) Price/ulc ratio, actual vs. flexible-price model. (b) Inflation, actual vs. flexible-price model.

The pricing problem of a firm that revises its price in period t is to choose the price, which I will indicate as X_{it}, that maximizes its expected stream of profits

$$\mathrm{E}_t\left\{ \sum_{j=0}^{\infty} R_{t,t+j}\Pi_{it+j} \right\}.$$

Then the first order condition for the optimal price is

$$E_t\left\{\sum_{j=0}^{\infty}\alpha^j R_{t,t+j}\left[(1-\theta)X_t Y_{it+j}+\frac{\theta}{1-a}W_{t+j}H_{it+j}\right]\right\}=0,$$

where, because each firm that is allowed to change prices solves the same problem, I have suppressed the subscript i on X_t (although I need to maintain it for output and hours, to distinguish individual from aggregate quantities). Rewriting this expression as

$$\sum_{j=0}^{\infty}\alpha^j E_t\left\{R_{t,t+j}Y_{it+j}\left[X_t-\frac{\theta}{\theta-1}\left(\frac{1}{1-a}\frac{W_{t+j}H_{it+j}}{Y_{it+j}}\right)\right]\right\}=0$$

and denoting by $S_{t+j,t}$ the marginal cost of producing, at date $t+j$, goods whose price was set at time t, so

$$S_{t+j,t}\equiv\frac{1}{1-a}\frac{W_{t+j}H_{it+j}}{Y_{it+j}},$$

one can substitute the demand constraint for Y_{it+j}, to get:

$$\sum_{j=0}^{\infty}\alpha^j E_t\left\{R_{t,t+j}Y_{t+j}\left(\frac{X_t}{P_{t+j}}\right)^{-\theta}\left[X_t-\frac{\theta}{\theta-1}S_{t+j,t}\right]\right\}=0. \tag{2.1}$$

Finally, dividing this expression by P_t, and defining $x_t=X_t/P_t$ and $s_{t+j,t}\equiv S_{t+j,t}/P_{t+j}$, one can rewrite it as

$$\sum_{j=0}^{\infty}\alpha^j E_t\left\{R_{t,t+j}Y_{it+j}\left(\frac{X_t}{P_{t+j}}\right)^{-\theta}\left[x_t-\frac{\theta}{\theta-1}s_{t+j,t}\prod_{k=1}^{j}\pi_{t+k}\right]\right\}=0. \tag{2.2}$$

This optimal pricing condition, combined with the distribution of aggregate prices at any point in time, allows one to describe the path of aggregate prices and inflation in this model.

The distribution of aggregate prices at time t is a mixture of the distribution of prices of the previous period (since all previous prices have the same probability of being changed), with weight α, and the new price X_t, with weight $(1-\alpha)$

$$P_t=[(1-\alpha)X_t^{1-\theta}+\alpha P_{t-1}^{1-\theta}]^{1/(1-\theta)}. \tag{2.3}$$

The dynamics of the model, in case of small perturbations, can be evaluated by a log-linear approximation around the non-stochastic steady state. Dividing both sides by P_t, and defining $\pi_t\equiv P_t/P_{t-1}$, a log linear approximation of expression (2.3) around $x^*(\equiv 1)$ and $\pi^*(\equiv 1)$, is:[3]

$$0=(1-\alpha)\hat{x}_t-\alpha\hat{\pi}_t$$

or

$$\hat{\pi}_t=\frac{1-\alpha}{\alpha}\hat{x}_t. \tag{2.4}$$

[3] For any variable $y, \hat{y}_t$ denotes the log deviation of y from its steady state value $y^*(\hat{y}_t=\ln(y_t/y^*))$.

Similarly, a log-linear approximation of (2.2) around x^*, π^* and $s^*(\equiv (\theta - 1)/\theta)$ gives:

$$\hat{x}_t = (1 - \alpha R\gamma_y^*) \sum_{j=0}^{\infty} (\alpha R\gamma_y^*)^j \mathrm{E}_t(\hat{s}_{t+j,t} + \sum_{k=1}^{j} \hat{\pi}_{t+k}), \tag{2.5}$$

where R is the steady state value of the stochastic discount factor $R_{t,t+j}$, and γ_y^* is the steady state growth rate of output. Combining expressions (2.4) and (2.5) one can obtain a Phillips curve relationship describing inflation as a function of expected inflation and real marginal costs.

Such a relationship can be obtained under two alternative assumptions about factor markets. If we assume that capital can be instantaneously reallocated across firms, so as to equate the shadow price of capital services at all times, as assumed in papers such as Yun (1996) and Goodfriend and King (1997), then the real marginal cost of the firms that are allowed to charge a new price is the same as the average level of real marginal cost for firms in general (the data on unit labor costs measure the *average* level of costs, of course, not the level specific to firm i). In this case

$$s_{t+j,t} = s_{t+j}^{\text{avg}} \equiv \frac{1}{1-a} \frac{W_{t+j} H_{t+j}}{P_{t+j} Y_{t+j}}.$$

On the contrary, if firms' relative capital stocks do not vary with their relative prices, or relative production levels, then

$$\begin{aligned} s_{t+j,t} &\equiv \frac{1}{1-a} \frac{W_{t+j} H_{it+j}}{P_{t+j} Y_{it+j}} = \left(\frac{1}{1-a} \frac{W_{t+j} H_{t+j}}{P_{t+j} Y_{t+j}} \right) \left[\left(\frac{X_t}{P_{t+j}} \right)^{-\theta} \right]^{1/(1-a)} \\ &= s_{t+j}^{\text{avg}} \cdot \left[\left(\frac{X_t}{P_{t+j}} \right)^{-\theta} \right]^{1/(1-a)}. \end{aligned} \tag{2.6}$$

In this case, the extent to which, at any point in time, firms charge different relative prices determines firms' different levels of sales, and hence their different levels of marginal costs. Therefore, taking a log linear approximation of Eq. (2.6) around the steady state values of $s_{t+j,t}$ and x_t gives

$$\hat{s}_{t+j,t} = \hat{s}_{t+j}^{\text{avg}} - \frac{\theta a}{1-a} (\hat{x}_t - \sum_{k=1}^{j} \hat{\pi}_{t+k}) \tag{2.7}$$

while, in the case of instantaneous capital reallocation, $\hat{s}_{t+j,t} = \hat{s}_{t+j}^{\text{avg}}$.

Substituting (2.7) into (2.5), using the relationship between $\hat{\pi}_t$ and $\hat{x}_t$ of Eq. (2.4), and further simplifying[4] one gets

$$\hat{\pi}_t = \left(\frac{(1 - \alpha R\gamma_y^*)(1-\alpha)}{\alpha} \right) \left(\frac{1-a}{1-a+a\theta} \right) \hat{s}_t^{\text{avg}} + R\gamma_y^* \mathrm{E}_t \hat{\pi}_{t+1}$$

[4] The steps of this derivation are detailed in the appendix of Sbordone (1998). γ_y^* is the steady state value of the variable $\gamma_{yt} \equiv y_t / y_{t-1}$.

which can be written as

$$\hat{\pi}_t = \frac{1}{\alpha_0}\hat{s}_t^{\text{avg}} + \alpha_1 \mathrm{E}_t \hat{\pi}_{t+1} \tag{2.8}$$

where I set

$$\alpha_0 \equiv \left(\frac{\alpha}{(1-\alpha R\gamma_y^*)(1-\alpha)}\right)\left(\frac{1-a+a\theta}{1-a}\right) \quad \text{and} \quad \alpha_1 \equiv R\gamma_y^*.$$

Note that in the case in which $\hat{s}_{t+j,t} = \hat{s}_{\text{t+j}}^{\text{avg}}$, the parameter α_0 in expression (2.8) simplifies to

$$\alpha_0 = \frac{\alpha}{(1-\alpha R\gamma_y^*)(1-\alpha)}.$$

Average marginal costs, because of the assumption of a Cobb–Douglas production technology, can in turn be approximated by average unit labor costs, so that

$$\hat{s}_t^{\text{avg}} = \widehat{ulc}_t$$

and the inflation dynamics described by Eq. (2.8) can be rewritten as

$$\Delta p_t = \alpha_1 \mathrm{E}_t \Delta p_{t+1} + \frac{1}{\alpha_0}(ulc_t - p_t - \kappa), \tag{2.9}$$

where lowercase letters denote natural logs of the corresponding upper case letters, and κ is the steady state value of unit labor costs [$\kappa = ln((1-a)(\theta-1)/\theta)$]. From this equation one can easily derive the implied path of aggregate prices. Writing the above equation as an expression for unit labor costs:

$$ulc_t - p_t = \kappa + \alpha_0[\Delta p_t - \alpha_1 \mathrm{E}_t \Delta p_{t+1}]$$

and solving this expression for the optimal price path, one solves for prices as a weighted average of past prices and expected future unit labor costs[5]

$$p_t = \lambda_1 p_{t-1} + (1-\lambda_1)\left[(1-\lambda_2^{-1})\sum_{j=0}^{\infty}\lambda_2^{-j}\mathrm{E}_t(ulc_{t+j} - \kappa)\right], \tag{2.10}$$

where λ_1 and λ_2 are the real roots of the characteristic polynomial of the difference equation in p_t, $P(\lambda) = \alpha_1\lambda^2 - (1 + \alpha_1 + \alpha_0^{-1})\lambda + 1 = 0$, with $0<\lambda_1<1<\lambda_2$.

Finally, denoting by F_t the forward-looking component term which is in square brackets ($F_t \equiv (1-\lambda_2^{-1})\sum_{j=0}^{\infty}\lambda_2^{-j}\mathrm{E}_t(ulc_{t+j} - \kappa)$), Eq. (2.10) can be conveniently rewritten as

$$p_t = (1-\lambda_1)\sum_{j=0}^{\infty}\lambda_1^j F_{t-j}. \tag{2.11}$$

This equation forms the basis for the computation of the theoretical path of prices. The estimated value of α_0 will then be interpreted in terms of the average expected time between price changes $(1/(1-\alpha))$.

[5] See again the appendix of Sbordone (1998).

3. Empirical results

3.1. The fit of the model

To evaluate the empirical predictions of this sticky price model, I construct the predicted path of the price level according to the model solution (2.11), and choose the parameter estimates that minimize the discrepancy between this predicted path and the actual path. This methodology involves two steps: first, the choice of a forecasting model to compute expectations of future unit labor cost, and then the estimation of the parameters that best fit the model to the data.

To compute expected future unit labor costs, I assume that all information at time t about current and future values of unit labor costs can be summarized by a vector of variables Z_t, which include unit labor costs, and also that $\{Z_t\}$ is a stationary Markov process: $Z_{t+1} = \Gamma Z_t + \varepsilon_{Zt+1}$. Then, to estimate the parameters of this auto regressive process, I use the VAR methodology.

In the 'baseline' specification (the one used in the main results reported below)[6] the forecasting model is a two-variable VAR model in unit labor costs and the price/cost ratio. Unit labor cost is modeled as an $I(1)$ process, while the price/unit labor cost ratio is assumed stationary.[7] The vector VAR model therefore includes the rate of change of unit labor costs, and the (log of the) ratio of prices to unit labor costs. Two lags of the dependent variables are included.[8] Denoting by X_t the vector of dependent variables, $X_t = [\Delta ulc_t\, (p_t - ulc_t)]'$, the vector Z_t is defined as $Z_t = [X_t\, X_{t-1}]'$. This baseline VAR specification is parsimonious, but captures about 40% of unit labor costs volatility.[9]

Next, I define as criterion function for the empirical fit of the model the variance of the distance between the predicted path of prices (the model) and the actual path of prices (the data): such distance measures the error that one commits when approximating the data with the model prediction. I therefore select for the model parameters the values that minimize this criterion function.[10]

Specifically, let ε_t^p be defined as:

$$\varepsilon_t^p = [p_t - ulc_t]^{\text{model}} - [p_t - ulc_t]^{\text{data}} = p_t^{\text{model}} - p_t^{\text{data}}, \tag{3.1}$$

where $[p_t - ulc_t]^{\text{model}} = f(\underline{\Psi})$, and $\underline{\Psi}$ is the vector of unknown parameters. The elements of $\underline{\Psi}$ are estimated by:

$$\hat{\underline{\Psi}} = \arg\min var(\varepsilon_t^p).$$

[6] I discuss in Section 5 the sensitivity of the results to the specification of the forecasting VAR.

[7] Standard unit roots and cointegration tests motivate these assumptions.

[8] This implies that the VAR is estimated over the period 1960:2–1997:1, with the 1959:4 and 1960:1 observations taken as initial conditions. The same time span is used for estimating the structural model.

[9] It is worth noting at this point that this specification mimics very closely the test of the present-value theory of stock prices proposed by Campbell and Shiller (1988), where they use a bivariate VAR model in the price/dividend ratio and dividend growth to model the evolution of dividends.

[10] Such approach to the estimation is in the spirit of the methodology proposed by Watson (1993) to evaluate the goodness of fit of calibrated models, and later extended by Diebold et al. (1998).

With the estimated parameter values, the model is then evaluated by measuring the ability of the predicted series of price/unit labor cost ratio and inflation to match the actual behavior of the series, and their serial correlation properties.

The predicted price process, according to Eq. (2.10), depends upon the parameters λ_1 and λ_2, roots of the polynomial $P(\lambda) = 0$, and therefore depends upon the structural parameters α_0 and α_1. Of these two parameters, $\alpha_1 = \gamma_y^* R$, and its value can be confidently set equal to 1, if one approximates the steady state value of output growth with its average over the sample period considered,[11] and assumes, quite reasonably, a discount factor R almost equal to 1. The important parameter is α_0, which measures the degree of price stickiness.[12] In the results presented here, I therefore set $\alpha_1 = 1$,[13] and estimate α_0 by searching over the space of positive values of α_0 for the value that minimizes the variance of the distance between the ratio of prices to unit labor costs implied by the model, and the corresponding ratio computed in the data.

In the implementation, I actually use a transformation of Eq. (2.11) to compute the theoretical price path. Such transformation is convenient, because it uses the forecast of the *rate of change* of unit labor cost, Δulc_{t+j}, which is easily computed from the estimated *VAR*. Using the fact that

$$\mathrm{E}_t \sum_{j=0}^{\infty} \lambda_2^{-j} ulc_{t+j} = \frac{1}{(1-\lambda_2^{-1})}(ulc_t + \mathrm{E}_t \sum_{j=1}^{\infty} \lambda_2^{-j} \Delta ulc_{t+j}).$$

Eq. (2.10) becomes

$$p_t = \lambda_1 p_{t-1} + (1-\lambda_1) ulc_t + (1-\lambda_1) \sum_{j=1}^{\infty} \lambda_2^{-j} \mathrm{E}_t(\Delta ulc_{t+j}) - (1-\lambda_1)\kappa$$

which can be written as

$$p_t - ulc_t = \lambda_1 (p_{t-1} - ulc_{t-1}) - \Delta ulc_t + (1-\lambda_1) \sum_{j=0}^{\infty} \lambda_2^{-j} \mathrm{E}_t(\Delta ulc_{t+j}) - (1-\lambda_1)\kappa. \tag{3.2}$$

I compute theoretical p/ulc ratios according to this equation. Given α_1, for each value of α_0 I solve for the roots λ_1 and λ_2, compute the forecast term $\sum_{j=0}^{\infty} \lambda_2^{-j} \mathrm{E}_t(\Delta ulc_{t+j})$,[14] and the predicted price/unit labor cost ratio. The 'optimal' value for α_0 is the value that minimizes the variance of the distance ε_t^p, defined in (3.1).

[11] This approximation gives $\gamma_y^* = 1.0084$.

[12] A widely used alternative approach to model nominal price rigidity is to assume that firms face convex costs of adjusting prices, as in the model of Rotemberg '82. It is worth pointing out, therefore, that such a model generates an equation like (2.8) as well, where the parameter α_0 measures the curvature of the adjustment cost function.

[13] I consider later the consequences of treating α_1 as a free parameter as well.

[14] Since unity labor cost growth is the first element of the vector Z_t, and $E_t Z_{t+j} = \Gamma^j Z_t$, this weighted sum is the first element of the vector $[I - \lambda_2^{-1}\Gamma]^{-1} Z_t$.

This approach to estimation is quite different from that used by Gali and Gertler (1999). Here expectations of future prices are not proxied by a vector of instrumental variables, but instead solved out in terms of the forcing variables predicted by the model. Moreover, the specific implementation is such that the behavior of nominal prices is estimated taking as given the evolution of nominal labor costs.

The first block of Table 1 summarizes the 'goodness of fit' of this baseline sticky price model, for several values of the inertia parameter α_0. The last two columns report the gain of the model with respect to the benchmark flexible-price model, measured by the reduction in the variance of the distance between the price/unit labor cost in the model and the data (ε_t^p), and the reduction in the inflation distance (ε_t^π). The optimal value of α_0 is 18.3; as the statistics in the table show, however, even values of α_0 much smaller than that improve significantly upon the fit of the flexible price model ($\alpha_0 = 0$): for example, for $\alpha_0 = 2$, the goodness of fit of this model is about 40% higher than that of the benchmark flexible-price model. The dramatic increase in the approximation of the model can be also seen in graph (a) of Fig. 3, which plots the variance of the distance ε_t^p against the inertia parameter α_0.

At the optimal value of α_0 the model obtains a reduction of 88% of the variance of the distance between the predicted and the actual price/unit labor cost, compared with the benchmark model. As for inflation, in the sticky price model inflation volatility is reduced, compared to the volatility of unit labor cost growth, by about 60%, and the variance of the distance between predicted and actual inflation is reduced by about 94%, compared to the benchmark model (see again Table 1). In other words, the discrepancy between actual inflation and the theoretical inflation

Table 1
Measures of fit as function of expected time between price changes

VAR forecasting model	α_0^*	expected time ($a = 0.25, \theta = 6$)	% red. $V(\varepsilon_t^p)$ vs. benchmark	%red. $V(\varepsilon_t^\pi)$ vs. benchmark
Unit labor cost, alternative forecasting models				
a. $[\Delta ulc_t\ (p_t - ulc_t)]'$	2	$4\frac{1}{2}$ months	38.5	68.6
(baseline)	6	6 months	67.1	85.3
	12	$7\frac{1}{2}$ months	83.7	91.7
	18.3	9 months	87.8	93.8
	(3.9)			
b. $[\Delta ulc_t\ (p_t - ulc_t)\ h_t^{dt}]'$	14.6	$8\frac{1}{4}$ months	72.5	88.9
	(2.2)			
c. $[\Delta ulc_t\ \Delta y_t\ h_t^{dt}]'$	9.6	$7\frac{1}{4}$ months	55.1	77.5
	(2.6)			
Alternative models of marginal cost, VAR forecasting system: $[\Delta ulc_t\ p_t - ulc_t\ h_t^{dt}]'$				
d. Labor adj. cost	17.3	$8\frac{1}{2}$ months	58.7	78.2
$\delta_0 = 4, \delta_1 = 1$	(4.64)			
e. Overhead labor	15.2	$8\frac{1}{2}$ months	58.1	85.1
$\beta = -0.3$	(2.97)			

*Standard errors for estimates of optimal α_0 are in parentheses.

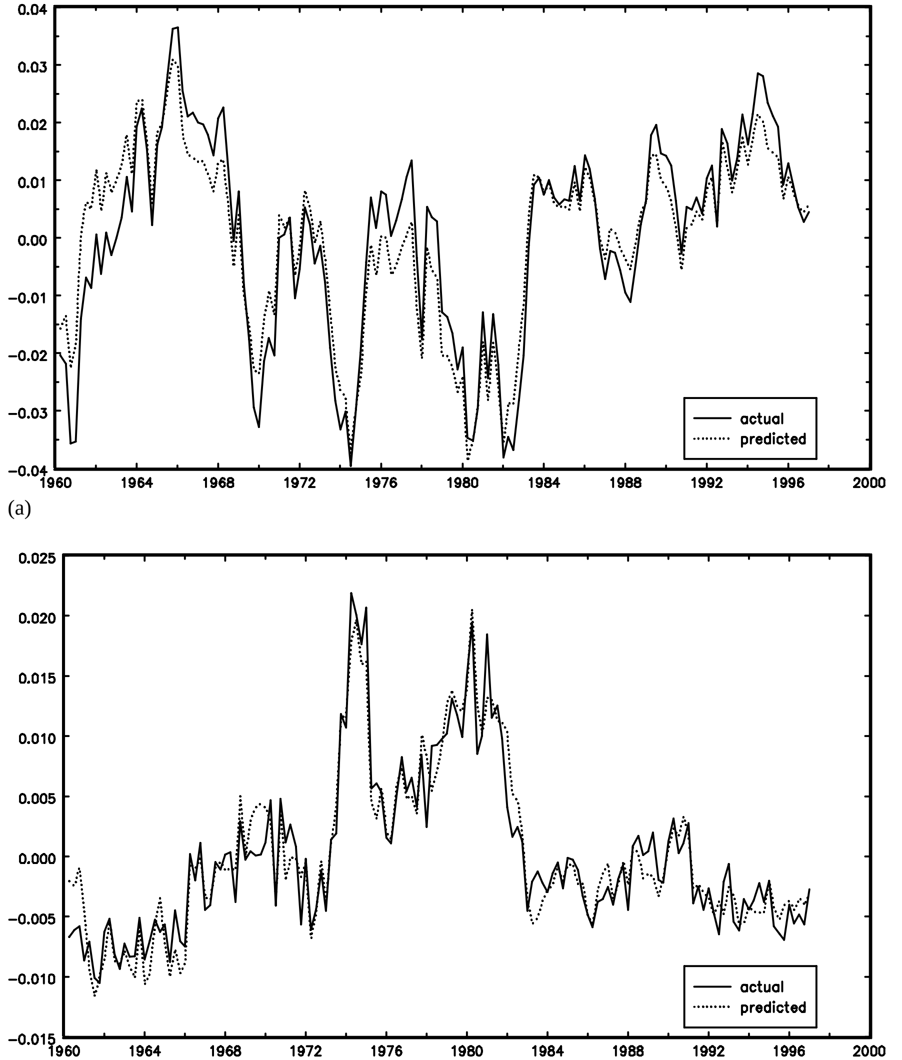


Fig. 2. (a) Price/ulc ratio, actual vs. sticky-price model. (b) Inflation, actual vs. sticky-price model.

predicted by the sticky price model is reduced to a mere 6% of what it would have been in the absence of nominal rigidities.

The series of price/unit labor cost and inflation predicted by (3.2) for the optimal value of α_0 are plotted in Fig. 2, as dotted lines, versus the actual series (solid line). Comparing this figure to Fig. 1 one can appreciate the extent of the improvement over the benchmark model. Another relevant dimension of the model fit is illustrated in panel (b) of Fig. 3, which graphs the auto correlation of predicted and actual inflation. The auto correlations of the predicted series are close to the sample

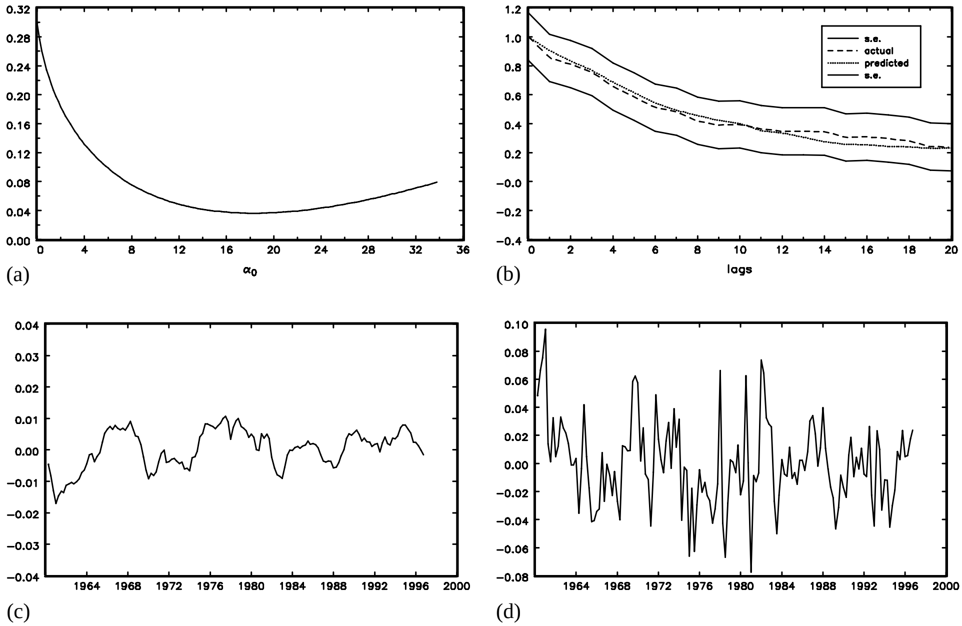


Fig. 3. (a) Variance of distance ε_t^p. (b) Inflation autocorrelations. (c) Estimated residuals ε_t^p. (d) Implied desired mark-up fluctuations.

correlations, and well within the confidence bands, which implies that the model can account quite well for the persistence properties of inflation.[15]

Fig. 3(c) plots the estimated residual. The dynamics of these residuals is driven in part by what can be interpreted as variations in the desired mark-up (the mark-up that would be charged under flexible prices). The estimate of the model is in fact obtained under the assumption that such a desired mark-up is constant (this can be seen from Eq. (2.9), where κ is assumed constant). But if indeed the desired mark-up is not constant, one may use Eq. (2.9) to compute an estimate of its range of variation: as Fig. 3(d) shows, this is of the order of $\pm 8\%$. These variations put a lower bound on the average desired mark-up, if the desired mark-up is always to be positive; the calculation above shows that the data are consistent with the order of mark-up margins typically assumed in the literature.

3.2. Assessing the degree of price stickiness

From the estimate of the inertia parameter α_0 one can derive an estimate of the expected time between price changes. Consider Eq. (2.8): in the case in which all

[15] The model accounts also reasonably well for the autocorrelation properties of the price/ulc ratio, and the autocovariance function of both series (Figures are not included).

firms face the same real marginal cost,

$$\alpha_0 = \frac{\alpha}{(1-\alpha)(1-\alpha R\gamma_y^*)} = \frac{\alpha}{(1-\alpha)(1-\alpha\alpha_1)}.$$

Using the fact that the value of α_1 was set to 1, this expression reduces to $\alpha_0 = \alpha/(1-\alpha)^2$. In this case, (which, given the estimated long run growth of output, implies a discount rate $R = 0.996$), the estimated value of α_0 is consistent with an average expected time between price changes $(1/(1-\alpha))$ of about 14 months. As argued before, however, a more realistic case is one in which there is a wedge between the real marginal cost of the firms that change prices, and the average real marginal cost; in such a case the expression for α_0 is

$$\alpha_0 = \frac{\alpha}{(1-\alpha)(1-\alpha R\gamma_y^*)}\left(\frac{1-a+a\theta}{1-a}\right),$$

and the value that its estimate implies for the average interval between price changes depends on the values of the share of capital a and of the Dixit-Stiglitz elasticity θ. Note that the value of θ in turn implies a specific steady state value of markup μ^*, since $\mu^* = \theta/(\theta-1)$.

The average time between price adjustments, using benchmark values for a and θ, is reported in the third column of Table 1, for each estimated value of α_0. The table shows that the estimated value of α_0 is consistent with $a = 0.25$, $\theta = 6$ (which implies an average value of markup of 1.2), and a third of the firms changing prices at any point in time ($\alpha = 0.66$); in this case the average time between price changes is about 9 months. Increasing the average value of markup (i.e. lowering θ), for any given value of the capital share a, increases modestly the estimated value of α: for example, an average markup of 1.6, for $a = 0.25$, brings the fraction α to 72%, and the estimated average time between price changes to slightly less than 11 months. Conversely, for any given value of θ, increasing the assumed capital share reduces the fraction α: for example, for $\theta = 6$, increasing the capital share to $\frac{1}{3}$ makes the estimated value of the cost of adjusting prices consistent with 63% of the firms keeping prices constant from one period to the other, which implies an average expected time between price changes again of little above 8 months. In fact, one observes that an increase in the degree of monopolistic competition makes the estimated cost of adjusting prices consistent with longer intervals between price changes.

Summing up, varying the parameter calibration within the range discussed suggests an estimated price inertia between $2\frac{1}{2}$ and $3\frac{1}{2}$ quarters. These numbers are in line with survey evidence on the frequency of price adjustment: for example, in a survey of about 200 manufacturing firms, Blinder et al. (1998) report that 65% of the firms claim between one and two price changes over the year; also, the median time between price changes is reported to be 9 months.[16]

[16] Blinder et al. (1998), Table 4.1, p. 84.

4. A further test of the model restrictions: do the forward-looking terms matter?

A crucial feature of this model is the importance assigned to forward-looking determinants of price-setting behavior. This feature represents an important departure from the older literature on price/cost margins. A typical price equation from the 1960s (see, e.g., Eckstein and Fromm, 1968) posits prices as a function of unit labor costs, but includes only the current and lagged values of these costs as explanatory variables. Other variables typically enter the regression to account for other cost or demand factors. Here expectations of *future* unit labor costs enter instead, and with a substantial weight. And interestingly, other variables, such as material prices or the ratio of unfilled orders to sales, are not needed in order to account for a very large fraction of the overall variation in the price level. A possible interpretation, consistent with the theoretical framework proposed here, is that these other variables entered significantly in traditional price equations because they were *proxies* for the omitted expectational terms. In that case, treating these estimated equations as structural for purposes of policy analysis would be vulnerable to the Lucas critique (Lucas, 1976).

But some recent studies have questioned the importance of the forward-looking component in pricing behavior, focusing on some empirical drawbacks of the inflation equation derived by sticky price models. Typically, the inflation dynamics is estimated in the form of a relationship between inflation and output gap, which is obtained by combining the inflation equation derived from a model with price rigidities (Eq. (2.8)) with a postulated proportionality between real marginal cost and output, of the form

$$\hat{s}_t^{\text{avg}} = \eta \hat{y}_t^{\text{gap}} \tag{4.1}$$

where y_t^{gap} is some measure of the output gap, and $\eta > 0$. Substituting (4.1) in Eq. (2.8) one gets an expectations augmented Phillips Curve:

$$\hat{\pi}_t = \alpha_1 \mathrm{E}_t \hat{\pi}_{t+1} + \gamma \hat{y}_t^{\text{gap}} \tag{4.2}$$

where $\gamma \equiv \eta/\alpha_0$. This is the formulation estimated, for example, in Roberts (1995).

Empirical estimates of this curve are often taken to represent tests of nominal rigidities, or tests of the role of forward looking behavior in the price setting mechanism. For example, Fuhrer (1997) argues for the un-importance of forward-looking behavior in price specifications, because of the negligible role of future inflation in an estimated inflation- output gap relationship. Furher's Phillips curve is specified in a way that is intended to nest the 'New Keynesian' Phillips Curve specification (4.2), the more complex variant proposed by Fuhrer and Moore (1995), and purely backward-looking Phillips Curve specifications. Roberts (1997, 1998) instead argues that the New Keynesian Phillips Curve fits reasonably well when survey measures of inflation expectations are used to estimate it, but that it does not fit well under the hypothesis of rational expectations. He thus proposes a model with an important backward-looking component in the inflation expectations, which amounts to weakening the weight put on the forward-looking terms in his aggregate supply relation.

Here I propose instead to address the question of whether the forward-looking term in the pricing equation matters, abstracting from any assumption about how marginal costs are related to the level of economic activity.[17]

From the definition of F_t in Eq. (2.11), one sees that the expected evolution of unit labor costs in the future matters only insofar as the parameter $\lambda_2^{-1} \neq 0$. Moreover, the model implies that the parameters λ_1 and λ_2 are combinations of the structural parameters α_0 and α_1. To test these implications, I reestimate the price equation without imposing the constraints on λ_1 and λ_2.

Unconstrained parameter estimates
$\hat{\lambda}_2^{-1} = 0.946$ (0.006)
$\hat{\lambda}_1 = 0.838$ (0.003)

The results of this unconstrained estimation indicate that both parameters are statistically significant; moreover, although a formal test rejects the hypothesis that the product of λ_1 and λ_2 is exactly equal to 1, as implied by my assumption that the parameter α_1 is equal to 1,[18] a significant reduction of the distance between model and data, for any value of λ_1, occurs only for values of λ_2^{-1} sufficiently close to it. This claim can be easily verified from Fig. 4, which plots the variance reduction against the values of λ_1 and λ_2^{-1}. An alternative way to evaluate the importance of the forward-looking component is by looking at the predictions of the sticky-price model under the hypothesis that the forward-looking term is zero. Fig. 5 plots the price/unit labor cost ratio predicted by Eq. (2.11), where the term in F_t is set to zero, as well as the implied inflation series. As it can be evinced from the figure, the fit is quite worse: the square distance between the price level predicted under this restriction and the actual data is actually higher than that between the benchmark model and the data. The introduction of the forward looking component help to reduce the model-data distance by 92%.

These results suggest that the forward looking component in the price equation is quite important. They also suggest that the inflation dynamics implied by this forward-looking model, according to which inflation is a function of expected future inflation and real marginal costs, does indeed describe very closely the dynamics of the data. As a consequence, it may not be necessary to hypothesize forms of departure from full rationality (as Roberts, 1997, 1998 does), or to introduce additional inertia in the inflation process (as in Fuhrer, 1997). I would therefore

[17] The approach of Gali and Gertler (1999) is in the same spirit. Although they use a methodology different from mine, they stress the same point, that the relation predicted by the theoretical model of price setting with nominal rigidities, which should be investigated empirically, is one linking inflation to the stream of future real marginal costs.

[18] The optimal value of α_1 is in fact 1.1 (s.e. = 0.006), which is significantly different from 1, and the corresponding optimal value of α_0 is 46.5. Although this pair of values improves further the fit of the model (the variance of the distance between the theoretical and the actual price/unit labor cost ratio is now reduced by 95%), it is hard to interpret a value of of $\alpha_1 > 1$, because it would imply a discount factor R also bigger than 1.

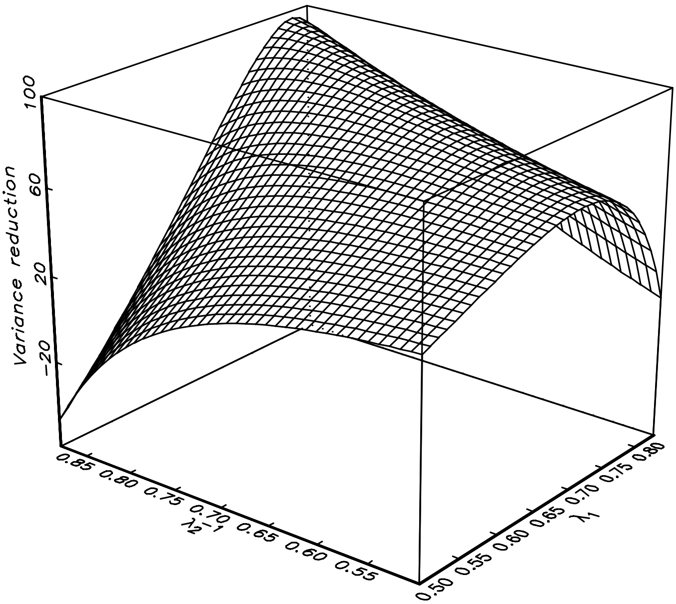


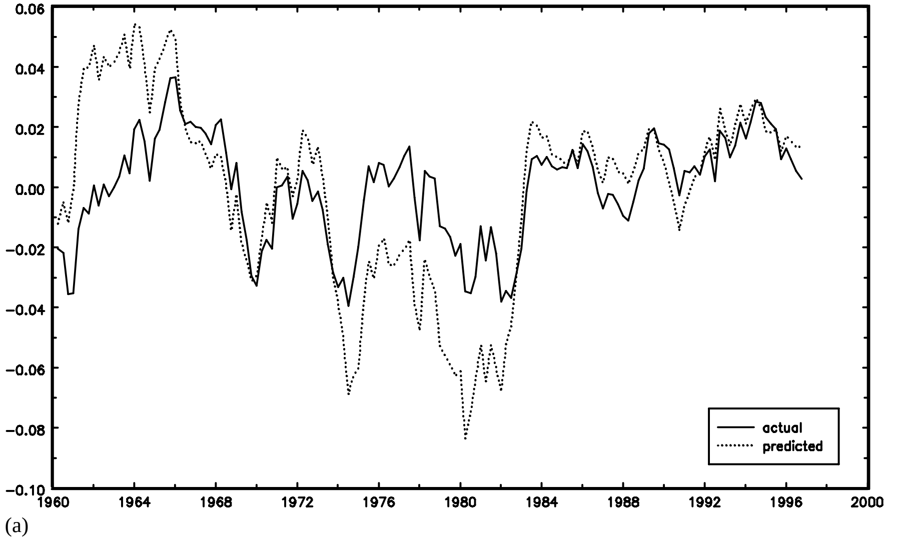
Fig. 4. Variance reduction of *p*/*ulc* distance with respect to benchmark.

argue that the mis-specification of the New-Keynesian Phillips Curve derives from the fact that the output gap measure used in standard NKPC estimates is not a good proxy for real marginal cost.

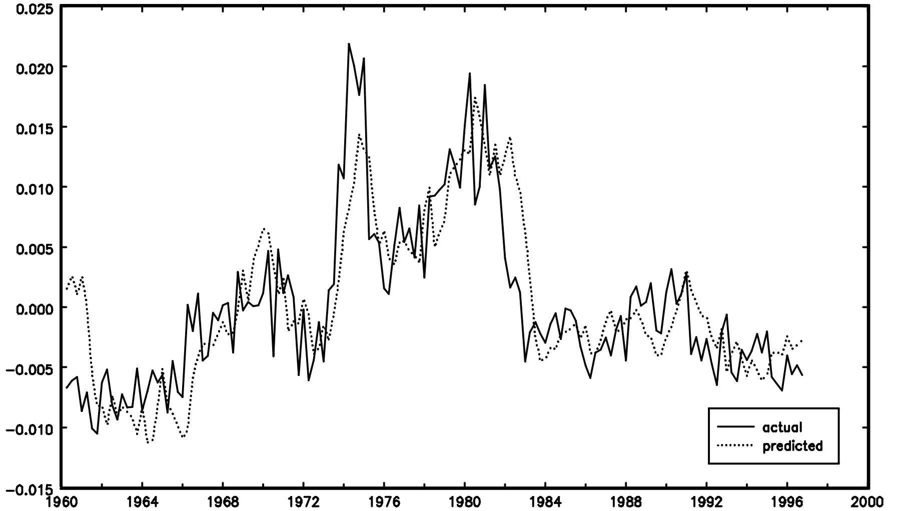
Evidence that unit labor cost is a better proxy than output gap for real marginal cost is provided by an analysis of the dynamic cross-correlations of inflation and unit labor costs. Estrella and Fuhrer (1998) criticize the NKPC model for its inability to account for the correlation between inflation and output gap that one observes in the data. Specifically, they contrast the virtual zero correlation between inflation and lagged output gap predicted by that model with the positive correlation between inflation and lagged output gap estimated in the data. A model with a backward looking Phillips curve instead, they further show, generates the same correlation between inflation and lagged output gap that is observed in the data.

But while the actual dynamic behavior of output gap and inflation may be inconsistent with the New-Keynesian Phillips curve, it is not inconsistent with the prediction of the sticky price model, where marginal cost is proxied by unit labor cost.

This point is made clear by Fig. 6. The top panel plots the dynamic correlation of output gap, measured as deviation of output from a quadratic trend, and actual inflation (solid line) vs. the dynamic correlation of output gap and inflation predicted by the sticky price model estimated here (dotted line). It is clear that, once inflation is predicted with the appropriate variable, the model delivers both the positive comovement of output with future inflation and the negative comovement with past inflation that characterize the data. The reason is found in the next graph (Fig. 6b),



(a)



(b)

Fig. 5. (a) Price/ulc ratio without forward-looking component. (b) Inflation without forward-looking component.

which shows the dynamic correlations of real unit labor cost and actual inflation (solid line) vs. the correlations of real unit labor cost and inflation predicted by the sticky price model. Unit labor cost has a strong contemporaneous correlation with inflation, and is also positively correlated with past inflation.[19] Although the model

[19] This point is also made by Gali and Gertler (1999).

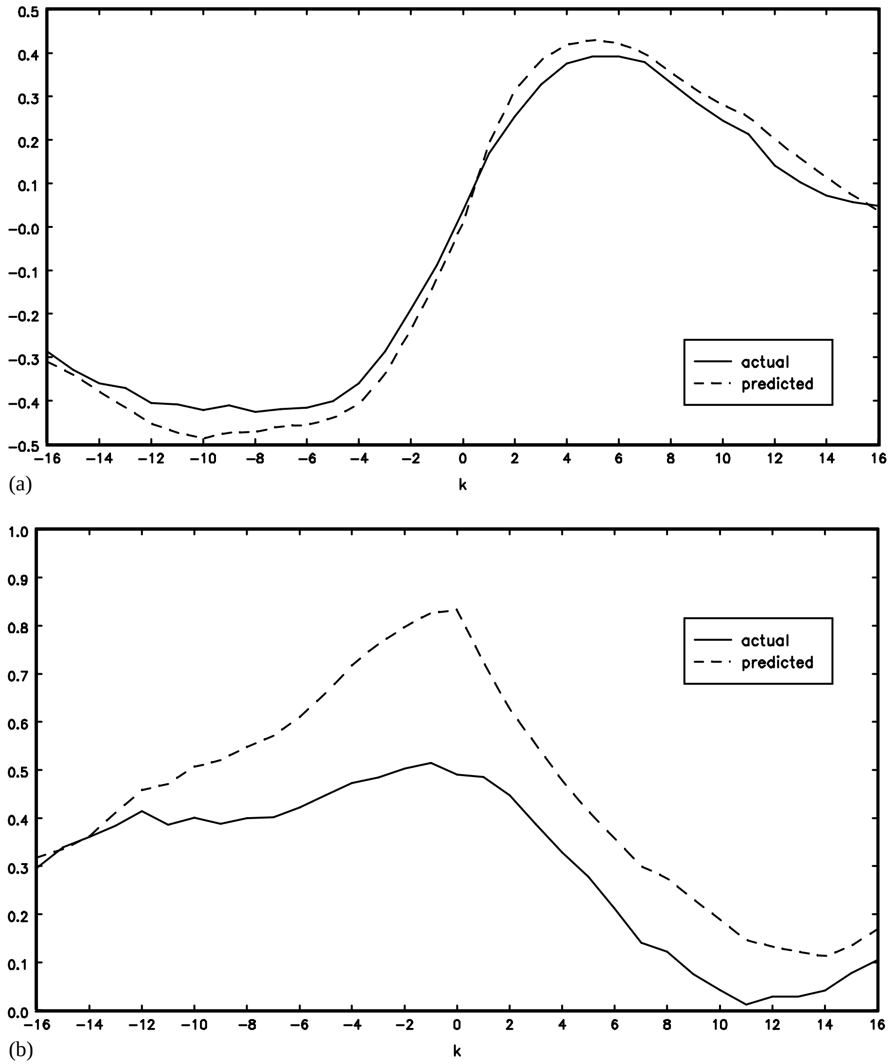


Fig. 6. (a) Cross-correlations: output gap(t), *infl.*$(t+k)$. (b) Cross-correlations: $ulc(t)$, *infl.*$(t+k)$.

predicts correlations between inflation and unit labor costs slightly higher than those estimated in the data, it nonetheless correctly predicts the lead-lag relationship that characterizes the data.

I take these results as evidence that the rational expectations model of price setting with nominal rigidities does indeed provide a quite good approximation to the actual dynamic of inflation. What is at fault in the New-Keynesian Phillips Curve specification is not the forward-looking model of price setting but the assumed proportionality between marginal costs and measures of the output gap.

5. Robustness analysis

The empirical analysis that I presented is conditional upon two assumptions. One is that unit labor cost is well forecast by a two-variable VAR, and the other is that real unit labor cost itself is a good approximation to real marginal cost. In this section, I address the issue of how sensitive my results are to alternative specifications of the forecasting model, and to the particular measure of marginal cost that I used. Furthermore, I show that the results are not specific to the particular model of staggered prices adopted, the Calvo specification, but hold as well in another well known model of staggered prices, the one with fixed-length contracts introduced by Taylor (1980).

5.1. Robustness to the specification of the forecasting system

As I argued before, the choice of the 'baseline' forecasting model can be motivated in a manner similar to the Campbell-Shiller methodology to test other present value relationships.

However, one doesn't necessarily have to exclude from the information set other variables that are known at time t, if they may in fact help forecasting the unit labor cost, beyond the contribution of past price/unit labor cost ratios. Alternatively, one may argue that data on the price level should not be used in the construction of unit labor costs, so that the predicted price level and inflation series are constructed with no reference at all to the actual price level data.

To look at these issues I conduct the structural estimation under two alternative *VAR* models. The first augments the baseline *VAR* by including hours of work. The second eliminates altogether prices from the forecasting equations, and includes instead output and hours. While there is reason to believe that, as proxies of the level of economic activity, both hours and output growth could help in forecasting unit labor costs, these alternative specifications do not particularly improve upon the baseline specification in terms of their ability to account for the variability of unit labor costs. However, they are worth exploring because they are still able to explain about 40% of the variability of unit labor costs.[20]

The results are presented in the second block of Table 1. I report the optimal value of α_0, the corresponding expected time between price changes, and the measures of fit obtained, respectively, under a $VAR(2)$ where the vector of dependent variables is $X_t = [\Delta ulc_t\, (p_t - ulc_t)\, h_t^{dt}]'$ (row b), and a $VAR(2)$ where the vector of dependent variables is $X_t = [\Delta ulc_t\, \Delta y_t\, h_t^{dt}]'$(row c).[21]

As the table shows, while the point estimates are somewhat different, the quality of the results does not change. Both specifications lead to a price equation that

[20] I also explored a simple univariate autoregressive model to forecast unit labor cost; since its fit is significantly worse than any *VAR* model that I tried, I do not report the results here.

[21] Hours are total hours of work in the non-farm business sector. The hypothesis of a stochastic trend is strongly rejected for hours (which show instead a significant deterministic trend), but not rejected for *GDP*. The *VAR* includes therefore the deviation of hours from a linear trend (h^{dt}) and the rate of growth of output.

still fits the data quite well, although it improves upon the fit of the benchmark model to a lower degree (the first model reduces the theoretical error in the price/cost ratio by about 70%, and the one in inflation by about 90%, the second respectively by about 55% and 80%). Interestingly, however, the best fit is obtained with a moderately lower degree of price stickiness. Moreover, in both specifications, the hypothesis that $\alpha_1 = 1$ is not rejected by the data.

Of course, if the theoretical model is correct, one would expect that the price/unit labor cost ratio should be a good variable in the forecasting regression for future changes in the unit labor cost, so it is not surprising that a VAR that excludes the price/unit labor cost ratio yields somewhat worse results.

5.2. Robustness to alternative measures of marginal cost

The second maintained hypothesis in the estimates presented is that unit labor costs is a good proxy for marginal costs. This hypothesis is justified by the assumption that the production technology is Cobb–Douglas, and the exclusion of any other friction that could break the proportionality between marginal and average labor costs. Although these assumptions are very frequently made in the business cycle literature, several authors have pointed out that there are various reasons why unit labor costs may not be proportional to marginal cost (see Rotemberg-Woodford, 1999, for an extensive discussion). While I pursue elsewhere a more extensive study of the empirical importance of a number of departures from the baseline model presented above (see Sbordone, 1999), here I present results for two models, which illustrate two different classes of factors that might cause average and marginal cost to vary differently.

The first is a model with variable labor effort due to the existence of costs in adjusting labor. In this model marginal cost is not proportional to average labor cost because of a 'real wage bias': the marginal cost of hours is not equal to the wage. The second model considers the existence of overhead labor. In this case marginal cost is not proportional to average labor cost because of a 'productivity bias': the growth rate of the effective variable input is larger than the growth rate of total labor hours, which is used to compute unit labor costs.

5.2.1. Adjustment costs for labor

The model with labor adjustment costs follows Sbordone (1996), where optimizing firms resort to effort variations because they face adjustment costs for increasing hours of work. The sticky price model is therefore modified by adding to the basic wage level a cost of adjusting hours $W_t H_{it} \lambda(H_{it}/H_{it-1})$, where the nominal wage W_t is still determined on a competitive market, and $\lambda(.)$ is a convex function representing the cost associated with rapid increases in hours. The first-order condition for optimal pricing, evaluated at a symmetric equilibrium,[22] now gives the average real

[22] Details of the calculations can be found in the appendix of Sbordone (1998).

marginal cost as

$$s_t^{\text{avg}} = \frac{1}{(1-a)}\frac{W_t H_t \Omega_t}{P_t Y_t} = \frac{1}{(1-a)}\frac{ULC_t}{P_t}\Omega_t, \tag{5.1}$$

where Ω_t is

$$\Omega_t = 1 + \lambda(\gamma_{Ht}) + \gamma_{Ht}\lambda'(\gamma_{Ht}) - \mathrm{E}_t R_{t,t+1}\gamma_{wt+1}\gamma_{Ht+1}^2\lambda'(\gamma_{Ht+1}) \tag{5.2}$$

and $\gamma_{Ht} = H_t/H_{t-1}$. Taking logarithms of both sides, expression (5.1) gives

$$\ln s_t = ulc_t - p_t + \ln\Omega_t - \ln(1-a).$$

There is now a time-varying wedge between real marginal cost and real average cost represented by the function Ω_t. To evaluate this function, I take a log-linear approximation of expression (5.2) around the steady state value Ω^* to obtain[23]

$$\hat{\Omega}_t = (\gamma_H^*)^2\lambda''(\gamma_H^*)[\hat{\gamma}_{Ht} - R\gamma_w^*\gamma_H^*\mathrm{E}_t\hat{\gamma}_{Ht+1}] = \delta_0[\hat{\gamma}_{Ht} - \delta_1\mathrm{E}_t\hat{\gamma}_{Ht+1}], \tag{5.3}$$

where $\delta_0 = (\gamma_H^*)^2\lambda''(\gamma_H^*)$ is a measure of the curvature of the adjustment cost function and $\delta_1 = R\gamma_w^*\gamma_H^*$. I use expression (5.3) to obtain an appropriate measure of the real marginal cost to correct Eq. (2.9). On the basis of available estimates of the adjustment cost parameter in individual sectors of the manufacturing industries, I calibrate $\delta_0 = 4$.[24] I also set $\delta_1 = 1$; this value is obtained by measuring the steady state growth level of hours and wage by their average rate of growth over the sample period, and by assuming a discount rate approximately equal to 1. With the modified measure of marginal cost, I proceed to evaluate the sticky-price model as before. In this case, though, the forecast of marginal cost involves forecasting both unit labor cost and the function Ω_t, which depends on the evolution of hours growth. Therefore, in this exercise, the forecasting model is the 3-variable *VAR* in unit labor cost growth, price/unit labor cost ratio, and detrended hours discussed in the previous section. Row d. of Table 1 reports the results of the estimation of the sticky-price model modified with the introduction of labor adjustment cost. This estimate should be compared to the one reported on row b. of the table, where the baseline model is estimated conditional upon the same forecasting *VAR* used here. The estimated value of the stickiness parameter α_0 is slightly higher, and corresponds to an increase of about a quarter of a month in the approximate interval between price changes. The fit of the model, as measured by its gain compared to the benchmark flexible price model, is still fairly good: the theoretical error in the price/cost ratio is reduced by about 60% and that in inflation by more than 80%.

Increasing the size of the adjustment cost leads to a slow decline in the variance reduction statistics, and seems to require a moderately higher degree of nominal

[23] Note that $\Omega^* = 1$, by the assumptions that the cost of adjusting hours has a minimum of zero at the steady state level of hours growth, i.e., that $\lambda(\gamma_H^*) = \lambda'(\gamma_H^*) = 0$.

[24] In Sbordone (1996), using annual data for the two-digit industries in the manufacturing sector, I estimate adjustment cost parameters, on average, of about 0.25.

rigidity to maintain a good fit.[25] Overall, I would conclude that, for a reasonable size of labor adjustment costs, the resulting discrepancy between marginal and average labor cost doesn't seem to affect the fit of the sticky-price model in a significant way.

5.2.2. Overhead labor

If we allow for 'overhead labor', defined as the hours that need to be hired regardless of the level of production, the baseline sticky price model needs to be modified to include in the production function the amount of hours in excess of the overhead labor $\bar{H} \geqslant 0$. The production function is therefore modified as

$$Y_t = K_t^a (\Theta_t (H_t - \bar{H}))^{1-a}$$

so that real marginal cost is

$$\ln s_t^{\text{avg}} = ulc_t - p_t - \ln \frac{H_t}{H_t - \bar{H}} - \ln(1 - a)$$

The appropriate correction to unit labor costs needed to better approximate marginal costs involves adding to the inflation Eq. (2.9) the term $-\beta \hat{h}_t^{dt}$, where the coefficient β represents the elasticity of the factor $H/(H - \bar{H})$ with respect to H (and it is therefore negative), and $\hat{h}_t^{dt}$ represents log-deviation of (detrended) hours from their steady state level. Following Rotemberg-Woodford (1999), I set $\beta = -0.3$: the empirical evaluation of the sticky price model, under this corrected measure of marginal cost, is in row e. of Table 1. The table shows that the estimate of α_0 is only marginally higher than that of the baseline case, so that the implied expected time between price changes remains basically the same; moreover, as in the previous model, in this case as well the imposed constraint of $\alpha_1 = 1$ is not rejected. The ability of the model to fit inflation data remains pretty good: the variance of the discrepancy between the actual inflation and the inflation predicted by the model is reduced to only 15% of what it would be predicted by a flexible price model.

How sensitive are these results to variations in the value of the calibrated parameter β? An increase in the absolute value of β (a larger departure from the baseline sticky-price model) mildly rises the estimated degree of nominal rigidity and slightly reduces the 'gain' of the model with respect to the benchmark flex-price model; but, as in the previous case, the qualitative implications of the sticky price model still hold.[26]

Overall, these results suggest that modifications to unit labor costs of the sort sometimes proposed as better measures of marginal costs do not significantly alter the main results. While the preliminary investigation presented in this section does suggest that allowing for modifications in the measurement of productivity or wages may require a slightly higher degree of nominal rigidity to fit the data, this higher

[25] For example, doubling the size of the adjustment cost parameter ($\delta_0 = 8$) increases α_0 to 21.9 (which corresponds to an expected time between price changes of slightly less than 10 months), maintaining the ability of the model to reduce the variance of ε_t^p by about 50% and that of the inflation distance by about 70%.

[26] For example, a value of the elasticity $\beta = -0.5$ increases α_0 to 16.5, maintaining the ability of the model to reduce the variance of ε_t^p by about 50% and that of the inflation distance by about 80%.

rigidity is still within ranges that, on the basis of survey evidence, we should believe perfectly plausible: intervals between price adjustments that are no longer than a year. Finally, it is worth noting that neither of the alternative measures of marginal cost considered here improves the fit of the model; insofar as the behavior of prices is used to infer the character of marginal cost, we find no evidence that either of these proposed modifications provide a better measure of marginal cost.

5.3. Robustness to the specification of the price staggering model

Finally, I explore in this section whether the fit of the sticky-price model depends on the particular specification chosen for modeling the price inertia.[27]

The Calvo model is sometimes asserted not to be a reasonable specification of price staggering (Wolman, 1999), since it implies that there is always a positive, although small, fraction of firms that charge prices set arbitrarily far in the past. Although a thorough analysis of which price specification is more appropriate is beyond the scope of this paper,[28] it is relatively easy to investigate, using the framework of this paper, the implications for the dynamics of prices of an alternative specification in which all prices are changed within a finite time. I consider here a model in which price commitments last for a fixed length of time, as in the wage contracting model of Taylor (1980). I suppose that every firm sets its price for a fixed number of periods N, so that at any point in time a fraction $1/N$ charges a price that was set n periods before ($n = 1, \ldots N-1$). Unlike the Calvo model, where in every period each firm has a probability $(1-\alpha)$ of changing prices, in this set-up firms have 0 probability of changing prices between periods 1 and $N-1$. Viewed in this way, the two models lie at opposite ends of a spectrum of possible specifications, in which the probability of price change may rise more or less sharply with the length of time since the previous revision.

With a Taylor specification the first order condition of the optimization problem of the firm that changes prices at t (the analog of Eq. (2.2)) is

$$\sum_{j=0}^{N-1} \mathrm{E}_t \left\{ R_{t,t+j} Y_{t+j} \left(\frac{X_t}{P_{t+j}} \right)^{-\theta} \left[x_t - \frac{\theta}{\theta-1} s_{t+j,t} \prod_{k=1}^{j} \pi_{t+k} \right] \right\} = 0 \tag{5.4}$$

and the aggregate price level is defined (analogously to (2.3)) as

$$P_t = \left[\frac{1}{N} \sum_{j=0}^{N-1} X_{t-j}^{1-\theta} \right]^{1/(1-\theta)}$$

[27] The result of the paper implies that a pricing specification that models stickiness through a convex cost of adjusting prices also fits the data well, since the Rotemberg (1982) model implies the same equation for inflation dynamics as the Calvo model (the log-linear approximation in (2.8)).

[28] An empirical investigation of the pricing behavior specification is done by Jadresic (1999), who analyzes the fit of staggered price models with a flexible distribution of the duration of prices. Unlike the present paper, though, Jadresic focuses on fitting the behavior of an inflation-output relationship.

Log-linearizing as before, this last relation becomes

$$\log P_t = \frac{1}{N}\sum_{j=0}^{N-1} \log X_{t-j}$$

Considering, for simplicity, the case in which all firms have a common marginal cost of supplying goods (with previous notation, $s_{t+j,t} = s_{t+j}^{\mathrm{avg}}$), and again assuming that marginal cost is well approximated by unit labor cost, the log-linear approximation of Eq. (5.4) can be solved, yielding

$$\log X_t = \frac{1}{N}\sum_{j=0}^{N-1} \mathrm{E}_t(ulc_{t+j} - \kappa)$$

The predicted path of the price/unit labor cost ratio, for any assumed interval N, can therefore be computed as

$$p_t - ulc_t = -\sum_{j=0}^{N-1} \frac{N-j}{N} \Delta ulc_{t+1-j} + \frac{1}{N^2}\left\{ \sum_{j=0}^{N-1} j \sum_{j=0}^{N-1} \mathrm{E}_{t-k} \Delta ulc_{t+j-k} \right\}$$

On the basis of the goodness of fit criterion chosen for the Calvo model, one would here choose the interval N that minimizes the distance between the actual and the predicted price/unit labor cost ratio. Searching over values of N between 2 and 6, I find that the best fit is for $N = 4$, in which case the mean squared prediction error is 0.17×10^{-4}. Fig. 7 plots actual and predicted p/ulc ratios for this value of N: as the

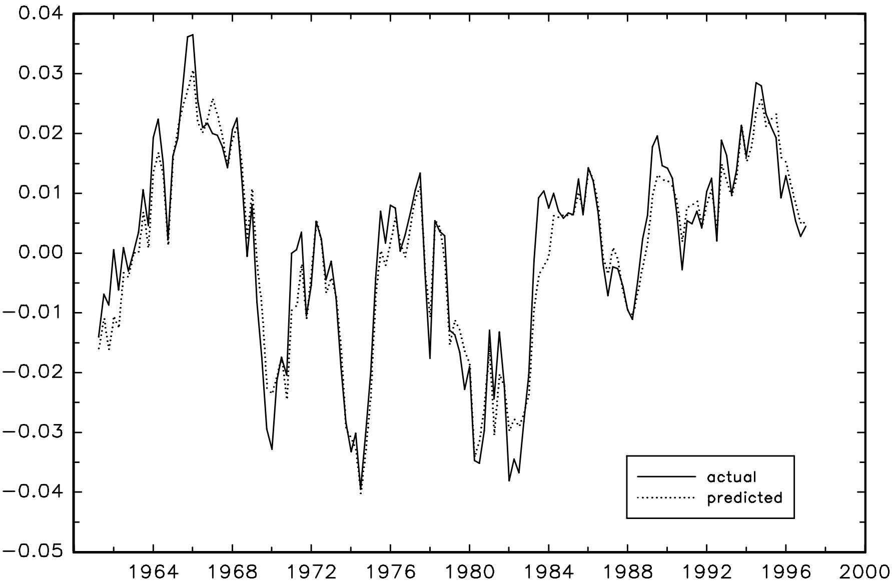


Fig. 7. *P/ulc*, actual vs. fixed-length price commitment model ($N = 4$).

graph shows, the Taylor model fits as well as does the Calvo model considered earlier. Furthermore, the degree of stickiness of prices needed to fit the data is similar in this case. As discussed before, the estimated average time between price changes is about 14 months; this is a time interval very close to the best-fitting case of 4 quarters.

The question of which precise model of price staggering is most accurate is left as a topic for future research. Here we note simply that, on the criterion proposed here, it does not seem to matter much whether the intervals between price changes are random or uniform, as long as one assumes the right average frequency of price adjustments.

6. Conclusion

This paper derives the implications of a simple model with nominal rigidities about the path of aggregate prices and inflation dynamics; it shows that such a model delivers a good approximation to both the price/unit labor cost ratio and the inflation process. In particular, the predicted behavior of aggregate prices, which is driven by the anticipated behavior of unit labor costs, describes quite well the actual behavior of prices.

This result is potentially interesting for two brands of the literature. On one hand, it shows that nominal rigidities are a reasonable component of a complete macroeconomic model. The failure of existing general equilibrium models which incorporate nominal rigidities to account for all features of observed time series (see King and Watson, 1996; Christiano et al., 1997) may not be due to a misspecified pricing equation, but rather to other features of these models (that they share with standard real business cycle models).

Secondly, the result is relevant for the literature on estimation of aggregate supply curves. It suggests to redirect both theoretical and empirical effort towards understanding the determinants of marginal costs and the relationship between marginal cost and output, rather than to further refinements of models of price adjustment. If one believes the results of this paper, to explain price behavior one should not necessarily look for other shocks (like energy price shock, for example), that alter the price-labor cost relationship, nor postulate additional stickiness in the inflation rate (as opposed to the price level), as in the FRB-US model (see Brayton and Tinsley, 1996) and the model of Fuhrer and Moore (1995). What one most needs, instead, is an empirically successful model of the dynamics of unit labor costs.[29]

[29] This issue is taken up in Sbordone (2000), which tests optimizing models of wage behavior.

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