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Does inflation increase after a monetary policy tightening? Answers based on an estimated DSGE model☆

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Abstract

This paper estimates the importance of the cost channel of monetary policy in a New Keynesian model of the business cycle. A model with nominal and real rigidities is extended by assuming that a fraction of firms need to borrow money to pay their wage bill. Hence, a monetary policy tightening increases effective unit labor costs of production, and might imply an increase in inflation. The paper examines the conditions under which the model can generate a positive response of inflation to a monetary contraction, and estimates the model's parameters using Bayesian methods. The paper shows that the estimated demand-side effects of monetary policy dominate the estimated supply side effect, even if restrictions are imposed that make occurrence of a positive inflation response to a monetary contraction more likely.

JEL classification: C11; C15; E31; E32

Keywords: Price puzzle; New keynesian models; Bayesian methods; United states

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1. Introduction

What is the effect of monetary policy on prices? The conventional view suggests that monetary policy tightenings are associated with declines in output and inflation. However, the results coming from using vector autoregressive (VAR) models are far from conclusive: one of the most controversial findings in the empirical literature on monetary policy shocks is the so-called 'price puzzle,' whereby a tightening of monetary policy is associated with an increase, rather than a decrease, of the price level. Two main explanations have been offered for this phenomenon: one implies that the unexpected part of monetary policy shocks is not well measured, while the other suggests that there are 'cost channel' effects of monetary policy.

The first explanation suggests that VAR models cannot properly measure the forward-looking component of monetary policy, and hence, do not properly measure monetary policy shocks. Suppose that the central bank expects higher inflation in the future, due to productivity shocks, oil price shocks, exchange rate developments, and the like. When the central bank increases interest rates, those shocks may have already been built into the economy, so a simultaneous increase in interest rates and prices is observed. Therefore, the price puzzle arises due to a misidentification of the unexpected component of monetary policy shocks. Sims (1992) suggested that once commodity prices are included in a VAR model, the price puzzle disappears. His explanation was that the information set available to policy makers may include variables useful in forecasting inflation that the econometrician has not considered. A more recent paper by Romer and Romer (2004) constructs series of monetary policy shocks after controlling for the endogenous response of the Federal Reserve to its own forecasts of output growth, inflation and unemployment. Among other results, they find that the price puzzle becomes irrelevant.

The second explanation suggests that there is no methodological problem with a price puzzle type of behavior. On the contrary, it is indeed the cost channel of monetary policy that causes prices (or inflation) and nominal interest rates to move in the same direction after a monetary policy shock. When the central bank increases interest rates, some production (financing) costs increase, which will tend to cause an increase in the inflation rate. This 'supply side' effect of monetary policy may coexist with and, in fact, dominate the traditional 'demand-side' effect. Barth and Ramey (2001) reach this conclusion using industry level and aggregate data for the United States, and show that their finding is robust even when commodity prices are introduced in their VAR. More recent work by Christiano et al. (2005) reaches the same conclusion, using aggregate data.

This paper attempts to disentangle these two conflicting explanations by estimating a dynamic stochastic general equilibrium (DSGE) model using a Bayesian approach. The use of DSGE models based on staggered price and wage setting (i.e. New Keynesian models) has become increasingly popular for the analysis of monetary policy, due to their analytical tractability. However, in the baseline model, there is no room for a cost channel of monetary policy: increases in interest rates always cause inflation to decline.[2] In this paper, a New Keynesian model is extended by introducing a 'working capital' or cost channel assumption: a fraction of firms need to borrow funds to pay for their wage bill before selling their product. As a result, the nominal interest rate is a determinant of real marginal costs, and hence, of inflation. By constructing and estimating a model that allows for an increase of inflation after a monetary policy tightening, I examine to what extent this is a feature of the aggregate data, and its relevance in monetary policy making.

The results of the paper can be summarized as follows. First, the estimates of model parameters point at a low elasticity of inflation to changes in the nominal interest rate, with a posterior mean of 0.15. As a result, the posterior probability of observing an increase of inflation after a monetary policy tightening is zero. Second, when the model is estimated assuming that all firms are subject to the 'working capital' assumption, it is still not possible to obtain a positive response of inflation to a monetary policy contraction. In the model, inflation depends on the real marginal cost of production, which includes the real wage, the rental rate of capital, and the nominal interest rate. In order to generate an increase of inflation after a monetary contraction, it is necessary that the immediate positive effect of the nominal interest rate on the real marginal cost is not offset by declines in the real wage and the rental rate of capital. Introducing staggered wage setting with indexation makes the response of the real wage smoother, while allowing for high variability in the capital utilization rate makes the response of the rental rate of capital less volatile. But all these necessary conditions are not picked up when the model is estimated. Finally, when all necessary conditions, in addition to the cost channel, are imposed in the estimation procedure, model fit worsens significantly. In particular, the model has trouble explaining the behavior of nominal variables. Other estimated parameters of the model change such that the demand-side effect of monetary policy always dominates the supply side, and inflation and interest rates move in opposite directions after a monetary policy shock. As a result, policy makers should not be concerned about short-run increases in inflation after policy tightenings.

This paper is closely related to the recent literature of estimation of New Keynesian models with a cost channel of monetary policy. Ravenna and Walsh (2005) estimate a new Phillips Curve which explicitly incorporates a cost channel of monetary policy, and find a large elasticity of inflation to the nominal interest rate. However, their results vary depending on the choice of the weighting matrix in their Generalized Method of Moments estimation procedure, and the choice of instruments. Single equation (or limited information) estimation techniques are most robust and can help reduce potential misspecification problems by leaving some relationships unspecified. However, they cannot capture the linkages between several variables in a larger scale model, they are less efficient, and can suffer from identification problems. Christiano, Eichenbaum, & Evans (2005; CEE henceforth) conduct parameter estimation by minimizing the distance between estimated (VAR-based) and model-based impulse responses of several variables to a monetary policy shock. Since their VAR evidence displays an increase in inflation after a tightening of

[2]See Woodford (2003).

monetary policy, their parameter estimates cause their model to reflect that property.[3]

The work of this paper is complementary to CEE's approach. CEE's focus is to match the VAR-based impulse responses to a monetary policy shock, and they assume a specific value for a subset of parameters of their model that turn out to be key in generating an increase of inflation after a monetary policy tightening in the model. CEE introduce full indexation to lagged inflation in both price and wage setting, a large elasticity of capital utilization with respect to the rental rate of capital, and an elasticity of the real marginal cost of production to the nominal interest rate of one. This paper takes a different approach by estimating the parameters of the model using a likelihood-based method: the estimation procedure tries to fit all the second moments of the data in a model that incorporates more shocks than just monetary policy shocks. The parameter estimates suggest that it is not possible to observe a positive inflation response after a monetary contraction. Assuming parameter values that would generate such effect worsens model fit significantly: the autocorrelations and standard deviations of inflation and interest rates, and the correlation between inflation and interest rates are much higher in the model than in the data.

There are several advantages of using a Bayesian estimation approach in a DSGE framework. First, it is a flexible method that allows the researcher to introduce prior information about the model's parameters. Classical methods make it difficult to accommodate even the most noncontroversial prior information. Second, since it is a likelihood-based method, it takes advantage of the general equilibrium approach: all the theoretical restrictions implied by the model for the likelihood function and the full dimension of the data are taken into account for estimation.[4] The model's accuracy of fit is addressed using the ratio of marginal likelihoods or Bayes factor. The marginal likelihood averages all possible likelihoods across the parameter space, using the prior as a weight, and is a concept of fundamental importance in Bayesian model comparison, because of its role in determining the posterior model probability.[5] A main shortcoming with respect to limited information methods is that the fit of the model is based on a large number of moments, which requires more structure on the model's relationships. In addition, the marginal likelihood depends on the priors chosen by the researcher.

The rest of the paper is organized as follows: in Section 2, I present a model with nominal and real rigidities, which incorporates the cost channel; Section 3 presents the linearized version of the model, while Section 4 shows the response of inflation

[3]On the other hand, Rotemberg and Woodford (1997) and Boivin and Giannoni (2003) follow the same estimation strategy, but since their VAR-based evidence does not display a price puzzle type of behavior, they do not try to explain it when estimating a DSGE model.

[4]An early contribution to estimating DSGE models with Bayesian methods is DeJong et al. (2000). Classical approaches which use full-information maximum likelihood and general equilibrium models, such as Kim (2000) and Ireland (2001), also benefit from this advantage.

[5]See Geweke (1998) for a survey on Markov chain Monte Carlo (MCMC) methods to draw from the posterior distribution. Lubik and Schorfheide (2005), and Rabanal and Rubio-Ramírez (2005) have used these methods to estimate and compare several versions of the New Keynesian model.

and output to a monetary policy shock under CEE's parameterization. Section 5 explains the econometric methodology for parameter estimation and model comparison using Bayesian methods. In Section 6, the main results are discussed, while concluding remarks are left for Section 7.

2. The model

This section presents a now fairly standard New Keynesian model with nominal and real rigidities. The model is used to characterize the joint behavior of output, inflation, interest rate and real wage dynamics for the United States, and is modified to incorporate a cost channel of monetary policy by assuming that a fraction of firms need to borrow cash before paying for their wage bill.

The structure of the goods and labor markets is monopolistic competition as in Blanchard and Kiyotaki (1987). The model consists of: (i) a continuum of identical households, indexed by $j \in [0, 1]$, each supplying a different type of labor that is an imperfect substitute for the other labor types; (ii) a continuum of intermediate goods producers, indexed by $i \in [0, 1]$, each supplying a type of good that is an imperfect substitute for the other goods; and (iii) a continuum of identical final goods producers.

Nominal rigidities in price and wage setting follow the formalism of Calvo (1983), for its simplicity as well as for its successful empirical fit.[6] Sticky wages, as in Erceg et al., (2001), are necessary to match the sluggish behavior of real wages. To further increase real wage persistence, I assume that wage setters follow indexation rules whenever they are not allowed to reoptimize. In addition, as argued by CEE, other nominal and real rigidities are necessary to get the dynamics of inflation right. In order to increase the persistence of inflation, it is assumed that price setters index their price to lagged inflation rates. Variable capital utilization is introduced to avoid excessive variability in the rental rate of capital, which is one of the key determinants of inflation. Finally, in order to properly characterize output dynamics, two additional departures from pure forward looking behavior are needed. First, I introduce habit formation in consumption to obtain a hump-shaped response of consumption. Second, I introduce adjustment costs to investment, as in CEE. The adjustment cost function depends on the growth rate of investment, which helps generate hump-shaped responses of investment to several shocks.[7]

Without the cost channel of monetary policy, this model always generates a decline of inflation after a contractionary monetary policy shock. Because of Calvo pricing, inflation depends on the real marginal cost of production, which in turn depends on the real wage and the rental rate of capital. These two variables always decline after a monetary policy contraction. For the model to display an increase of inflation, it is necessary that the nominal interest rate has an immediate positive impact on the real marginal cost. This is achieved by introducing the cost channel of

[6]See Galí and Gertler (1999), Sbordone (2001), and Eichenbaum and Fischer (2004).

[7]This is opposed to more 'traditional' specifications where adjustment costs are imposed on the growth rate of capital, as in Ireland (2003), or on the investment – capital ratio, as in Lettau (2003).

monetary policy: as a result, the nominal interest rate becomes a component of the real marginal cost of production. In addition, as it will become clear after the calibrated example of Section 4, large degrees of real wage stickiness and smooth rental rates of capital are needed for the model to be able to generate a positive response of inflation to a monetary contraction.

Monetary policy is implemented using an interest rate rule that reacts to deviations of inflation and output from their steady-state values, as in Taylor (1993). As a result, the nominal amount of money plays no role in this model. Hence, following Woodford's (2003) terminology, this is a monetary model in a 'cashless' economy.

Since four observable variables are used in the estimation procedure (output, inflation, interest rate and real wages), four sources of shocks are needed to avoid singularity issues in the likelihood function. The four shocks that the model incorporates are: monetary policy, fiscal, technology, and price markup shocks.

The remainder of this section explains the main components of the model in further detail.

2.1. Intermediate goods producers and the cost channel

The main feature of this model is the presence of a cost channel of monetary policy, which is introduced by assuming that a fraction of intermediate goods producers, indexed as $i \in [0, \gamma]$, have to pay their wage bill every period before they sell their product. These firms borrow at the riskless nominal interest rate. By affecting unit labor costs, this channel can be viewed as a supply side channel of monetary policy, as labeled by Barth and Ramey (2001).

The production function for intermediate goods producers is:

$$Y_t^i = A_t (u_t K_{i,t})^{\alpha} N_{i,t}^{1-\alpha}, \tag{1}$$

where A_t is an economy wide technology factor, $K_{i,t}$ are the units of capital used by firm i, and $N_{i,t}$ is the effective units of labor input used by firm i. $\alpha \in [0, 1]$ is the capital share of output, and firms take the capital utilization rate decision of households (u_t) as given. In order to obtain one effective unit of labor, firms employ all types of labor from households ($N_{i,t}^j$), which are aggregated as follows:

$$N_{i,t} = \left[\int_0^1 \left(N_{i,t}^j \right)^{(\phi-1)/\phi} dj \right]^{\phi/(\phi-1)}. \tag{2}$$

Each firm chooses the optimal labor mix taking all wages as given. Aggregating across firms delivers the following downward sloping demand for each type of labor j:

$$N_t^j = \left(\frac{W_t^i}{W_t} \right)^{-\phi} N_t, \text{ for all } j \in [0, 1], \text{ and } W_t = \left[\int_0^1 \left(W_t^j \right)^{1-\phi} \mathrm{d}j \right]^{1/(1-\phi)}, \tag{3}$$

where N_t and W_t are aggregate labor and wage indices. For a fraction γ of firms the nominal wage bill is $R_t \int_0^1 W_t^j N_{i,t}^j \, \mathrm{d}j$, while for the remaining 1-γ the nominal wage bill is simply $\int_0^1 W_t^j N_{i,t}^j \, dj$. Therefore, for the firms that need to borrow to pay for their wage bill, the nominal interest rate acts as a cost-push shock.

2.2. Final good producers

There is a continuum of final good producers, operating under perfect competition. The technology to produce the aggregate final good is

$$Y_t = \left[\int_0^1 \left(Y_t^i\right)^{(\lambda_t-1)/\lambda_t} \mathrm{d}i\right]^{\lambda_t/(\lambda_t-1)}, \tag{4}$$

where $\lambda_t > 1$ is a time-varying elasticity of substitution between types of goods, Y_t is the final good, and Y_t^i are the intermediate goods. Since the price markup is related to the elasticity of substitution, price markups are also time varying, as in Giannoni (2006).

Profit maximization from the final goods producers delivers the following demand for each type of intermediate good:

$$Y_t^i = \left(\frac{P_t^i}{P_t}\right)^{-\lambda_t} Y_t, \text{ for all } i \in [0,1], \tag{5}$$

where $P_t = \left[\int_0^1 (P_t^i)^{1-\lambda_t} \mathrm{d}i\right]^{1/(1-\lambda_t)}$, the price of the final good, is obtained from the zero profit condition in the final goods sector and P_t^i are the prices of all intermediate goods.

2.3. Households

Households obtain utility from consuming the final good (C_t^j) and disutility from supplying hours of labor (C_t^j), they own the capital stock and make investment and capital utilization decisions.[8] Their lifetime utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(C_t^j - bC_{t-1})^{1-\sigma}}{1-\sigma} - \frac{\left(N_t^j\right)^{1+\eta}}{1+\eta}\right]. \tag{6}$$

E_0 denotes the rational expectations operator using information up to time $t = 0$. $\beta \in [0,1]$ is the discount factor. The utility function displays *external* habit formation. $b \in [0,1]$ denotes the importance of the habit stock, which is last period's aggregate consumption. $\sigma > 0$ captures intertemporal substitution attitudes of households, and $\eta > 0$ is the elasticity of labor supply with respect to the real wage.

Households maximize their utility subject to the following budget constraint:

$$C_t^j + I_t^j + \frac{B_t^j}{P_t R_t} = \frac{W_t^j N_t^j}{P_t} + \frac{B_{t-1}^j}{P_t} + [R_t^k u_t - \Psi(u_t)]K_{t-1}^j + T_t^j + \int_0^1 \Pi_t^j(i)\,\mathrm{d}i, \tag{7}$$

[8] Note that the notation is different for total hours worked by a household (N_t^j) and for total hours employed by a firm ($N_{i,t}$). The same is true for capital.

where I_t^j denotes investment expenditures, W_t^j is the nominal wage, and B_t^j denotes holdings of a riskless bond that costs the inverse of the gross nominal interest rate ($R_t > 1$) and pays one unit of currency next period. T_t^j denotes nominal transfers from (or lump-sum taxes paid to) the government, and K_t^j denotes holdings of the capital stock. The last term on the right hand side of Eq. (7) denotes profits by intermediate goods producers, which are ultimately owned by households. As is customary in this class of models (see Erceg et al., 2001), it is assumed that there exist state-contingent securities that insure households against the variations in household-specific labor income caused by the presence of staggered wages, and the consumption/savings decisions and the labor supply decision can be separated. In order to keep notation simple, the structure of the complete asset markets is not explicitly introduced.

Households rent capital to the firms that produce intermediate goods at a rental rate R_t^k. Capital is predetermined at the beginning of the period, but households can adjust its utilization rate u_t, for which they face a cost $\Psi(u_t)$. The $\Psi(.)$ function is increasing and convex. In the steady state, $\Psi(\bar{u}) = \Psi'(\bar{u}) = 0$,and $\Psi''(\bar{u}) > 0$. The law of motion of capital follows CEE, and allows to obtain a hump-shaped response of investment to exogenous shocks. The adjustment cost function depends on the growth rate of investment:

$$K_t = (1 - \delta)K_{t-1} + \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t. \tag{8}$$

The adjustment cost function $S(.)$, is an increasing, convex function, and in the steady state $\overline{S} = \overline{S}' = 0$ and $\overline{S}'' > 0$.

2.4. Price and wage setting under staggered contracts

Prices and wages are set by intermediate goods producers and households in a staggered way. As in the model of Calvo (1983), agents can only reoptimize prices or wages whenever they receive a stochastic signal to do so. The probability of receiving this signal is independent of the past history of signals and across agents. This assumption greatly simplifies the aggregation of price and wage setting decisions.

Let $\theta_{\rm p}$ denote the probability of not being able to reset prices in a given period. When firms face a Calvo-type restriction, they set prices maximizing the discounted sum of profits taking into account that the price that they set today might not be reset optimally for some time, and taking as given the demand for their type of good. In addition, a fraction $\omega_p \in [0, 1]$ of firms index their price to last period's average inflation rate (P_{t-1}/P_{t-2}), whenever they are not allowed to reoptimize. On average, firms can reoptimize their prices every $1/(1 - \theta_{\rm p})$ periods.

Households face the same restriction to set their wages. Let $\theta_{\rm w}$ denote the probability of not being able to reoptimize for wage setters. Households' labor supply schedule comes from choosing their wage to maximize utility facing a downward sloping demand for their type of labor, taking into account the probabilities of not being able to reoptimize in the near future. Parallel to the price setting case, it is assumed that a fraction $\omega_{\rm w} \in [0, 1]$ of wage setters index their wages to last period's average inflation rate for prices whenever they are not allowed to reoptimize. On average, wages are reoptimized every $1/(1-\theta_{\mathrm{w}})$ periods.

2.5. Monetary and fiscal policy, and market clearing

As in Taylor (1993), it is assumed that the monetary authority conducts monetary policy with an interest rate rule. Fiscal policy is Ricardian, so the government's intertemporal budget constraint is

$$T_t + G_t = \frac{B_t}{R_t} - B_{t-1},$$

where G_t denotes government spending other than transfers. T_t includes net transfers to the household sector as well as transfers to the 'cost channel firms', such that the production of all intermediate goods producers in the steady state is the same.[9]

The market clearing conditions require that in all inputs, intermediate goods and final goods markets supply equals demand. The resource constraint of the economy is

$$Y_t = C_t + I_t + G_t + \Psi(u_t)K_{t-1}. \tag{9}$$

3. The linearized model

This section presents the linearized version of the model, which is obtained by taking a log-linear approximation of households and firms optimal decisions, the monetary policy rule, and the economy-wide resource constraint around the symmetric equilibrium steady state in which all intermediate goods producers set the same price and all households set the same wage, with zero inflation. Lower case variables denote percent (log linear) deviations of each variable from its steady-state value, except for real wages, which are denoted by ω_t.

Since the focus of the paper is to study how the presence of the cost channel affects inflation dynamics, I first discuss the implications of introducing the cost channel assumption in an otherwise standard medium-scale New Keynesian model. The remaining equations of the model, which are fairly standard given the assumptions on real rigidities, are then discussed in a more brief way.

Staggered price setting with backward looking indexation delivers the following equation for the dynamics of price inflation, where E_t denotes the expectation operator with information up to time t, and Δ denotes the first difference operator:

$$\Delta p_t = \gamma_{\mathrm{b}}\Delta p_{t-1} + \gamma_{\mathrm{f}} E_t \Delta p_{t+1} + \kappa_{\mathrm{p}} mc_t + \kappa_{\mathrm{p}}\varepsilon_t^{\mathrm{p}}, \tag{10}$$

where the backward and forward looking components are respectively $\gamma_{\mathrm{b}} = \omega_{\mathrm{p}}/(1+\beta\omega_{\mathrm{p}})$ and $\gamma_{\mathrm{f}} = \beta/(1+\beta\omega_{\mathrm{p}})$, and $\kappa_{\mathrm{p}} = (1-\theta_{\mathrm{p}}\beta)(1-\theta_{\mathrm{p}})/[(1+\beta\omega_{\mathrm{p}})\theta_{\mathrm{p}}]$. The price

[9] In the steady state the gross nominal interest rate is greater than one. Hence, firms subject to the cost channel would have higher steady-state marginal costs of production and lower production levels. For convenience, I introduce this subsidy and make production levels for all intermediate goods producers to be the same in the steady state.

mark-up shock is defined as $\varepsilon_t^{\mathrm{p}} = \log[\lambda_t/(\lambda_t - 1)] - \log[\bar{\lambda}/(\bar{\lambda} - 1)]$, where $\bar{\lambda}$ is the steady-state value of λ_t.

A higher degree of indexation ω_{p} will increase the persistence in the response of inflation to any given shock. A higher degree of nominal rigidity, which would be reflected in a higher probability that prices cannot be reoptimized in a given period, will imply smaller responses of inflation to the real marginal cost of production, because there is a negative relationship between the slope of the Phillips Curve parameter, κ_{p}, and θ_{p}. The two parameters ω_{p} and θ_{p} do not affect the sign of the response of inflation to monetary shocks, but do affect the amplitude and persistence of that response.

As shown by Galí and Gertler (1999) and Sbordone (2001), the model-based driving force of inflation is the real marginal cost of production. In a standard model without the cost channel, the real marginal cost depends on real wages and the rental rate of capital, because both labor and capital are used in the production function, and on technology shocks. When the cost channel is introduced, the nominal interest rate also becomes a direct determinant of real marginal costs, and of inflation. The expression for the real marginal cost is the following:

$$mc_t = \alpha r_t^k + (1 - \alpha)(\omega_t + \gamma r_t) - a_t. \tag{11}$$

In a model with no cost channel, as in Smets and Wouters (2003), $\gamma = 0$. In this case, after an increase in interest rates caused by a monetary policy shock, the real marginal costs of production always declines: real wages fall because of a decline in labor demand, and the rental rate of capital declines because of a drop in investment. This would be the traditional effect of monetary policy, also labeled as the demand-side effect by Barth and Ramey (2001). On the other hand, when there is a cost channel, $\gamma > 0$. This introduces a supply side effect of monetary policy, because the nominal interest rate acts as a cost-push shock: the real marginal cost of production increases with the cost of borrowing. In order to observe real marginal costs, and hence inflation, increase after a monetary policy tightening, it is necessary that the impact of the supply side effect of monetary policy is not offset by the demand-side effect. For this to happen, a smooth response of the rental rate of capital and real wages is needed. The following two equations explain how to achieve muted responses of these two variables.

The relationship between the rental rate of capital and the capital utilization rate is

$$u_t = \psi r_t^k, \tag{12}$$

where $\psi = \Psi'(1)/\Psi''(1)$, assuming that the utilization rate is one in the steady state. Therefore, high values of ψ will imply highly volatile utilization rates and smooth rental rates of capital. Conversely, if the utilization rate is not variable (i.e. fixed), then $\psi = 0$, and the rental rate of capital will be highly volatile. From now on, these two terms will be used interchangeably.

Higher real wage rigidities, which would take the form of higher probabilities of not being able to reoptimize any given period, θ_{w}, and higher degrees of wage indexation, ω_{w}, will smooth the response of real wages. Staggered wage setting with backward looking indexation leads to the following dynamics for the real wage:

$$(1+\beta)\omega_t = \omega_{t-1} + \beta E_t\omega_{t+1} + \omega_{\mathrm{w}}\Delta p_{t-1} - (1+\beta\omega_{\mathrm{w}})\Delta p_t + \beta E_t\Delta p_{t+1} - \kappa_{\mathrm{w}}\left(\omega_t - \frac{\sigma}{(1-b)}(c_t - bc_{t-1}) - \eta n_t\right) \tag{13}$$

where $\kappa_{\mathrm{w}} = (1-\theta_{\mathrm{w}}\beta)(1-\theta_{\mathrm{w}})/\{[1+\phi(\eta-1)]\theta_{\mathrm{w}}\}$. If wages were fully flexible, the usual intratemporal condition that real wages equal the marginal rate of substitution between consumption and hours applies. However, with staggered contracts, agents know that they might not be able to reoptimize their wage in the near future. Hence, they take into account current and future expected deviations between the desired marginal rate of substitution and the actual real wage, using the corresponding probability as a weight.

The last equation that is affected by the presence of the cost channel is the optimal capital-labor ratio. From the firm's optimal decisions, in equilibrium, the marginal cost of using an extra unit of capital and labor is equalized. Because of the presence of the cost channel, the nominal interest rate affects the marginal cost of using an extra unit of labor:

$$l_t - u_t - k_{t-1} = r_t^k - (\omega_t + \gamma r_t). \tag{14}$$

This equation makes explicit the impact of the cost channel of monetary policy on output. Since the capital stock is fixed, and the utilization rate is chosen by households, an increase in nominal interest rates will affect labor costs, which ceteris paribus, will reduce labor demand and output.

The remaining equations are fairly standard in this class of models (see CEE for more details) so they are only presented here. The consumption Euler equation with external habit formation is

$$(1+b)c_t = bc_{t-1} + E_tc_{t+1} - (1-b)\sigma^{-1}(r_t - E_t\Delta p_{t+1}). \tag{15}$$

The evolution of the shadow price of investment in terms of consumption goods (Tobin's Q) is related to the rental rate of capital and the real interest rate as follows:

$$q_t = \beta(1-\delta)E_tq_{t+1} + [1-\beta(1-\delta)]E_tr_{t+1}^k - (r_t - E_t\Delta p_{t+1}), \tag{16}$$

while the evolution of capital and investment in linear terms is

$$k_t = (1-\delta)k_{t-1} + \delta i_t, \text{ and } i_t = \frac{1}{(1+\beta)}(\beta E_ti_{t+1} + i_{t-1} + \varphi q_t), \tag{17}$$

where $\varphi = 1/\bar{S}''$. Note that while the specification of the law of motion of capital is standard, the investment equation, with backward and forward looking components, comes from the particular form chosen for the investment adjustment cost function, and helps in generating hump-shaped responses of investment to various shocks.

The production function is

$$y_t = a_t + \alpha(u_t + k_{t-1}) + (1-\alpha)n_t. \tag{18}$$

The Taylor rule reacts to deviations of inflation and output to their steady-state values:

$$r_t = \rho_{\mathrm{r}}r_{t-1} + (1-\rho_{\mathrm{r}})\gamma_{\mathrm{p}}\Delta p_t + (1-\rho_{\mathrm{r}})\gamma_y y_t + \varepsilon_t^z, \tag{19}$$

where $\gamma_p > 1$ and $\gamma_y > 0$ denote the long run responses of the nominal interest rate to inflation and output fluctuations. In addition, an interest rate smoothing component ($\rho_{\rm r}$) is included, following the empirical evidence in Clarida et al. (2000). The Taylor rule includes a shock ε_t^z, which is interpreted as a monetary policy shock. The central bank uses the Taylor rule as a main guide for conducting monetary policy, but also observes more variables and indicators than the econometrician does (e.g., exchange rates, asset prices, government deficits, consumer confidence) and uses that information to 'fine tune' the desired nominal interest rate.

The resource constraint is

$$y_t = (1 - \bar{I} - \bar{G})c_t + \bar{I}i_t + \bar{G}g_t + \alpha\bar{\lambda}/(\bar{\lambda} - 1)u_t, \tag{20}$$

where the steady-state investment–output ratio is $\bar{I} = \delta\alpha\bar{\lambda}/\{(\bar{\lambda} - 1)[1/\beta - (1 - \delta)]\}$, and $\bar{G}$ is the steady-state government consumption–output ratio.

The technology (a_t) and government spending (g_t) shocks evolve as AR(1) processes, with AR coefficients $\rho_a, \rho_g \in [0, 1]$, while the monetary and price markup shocks are iid. All innovations ($\varepsilon_t^a, \varepsilon_t^g, \varepsilon_t^p, \varepsilon_t^z$) follow zero mean Normal distributions.

There are three reasons why the monetary and price markup shocks are assumed to be serially uncorrelated. The first one is that this choice reduces the number of parameters to be estimated. The second reason is that both the Taylor rule and the New Keynesian Phillips Curve equations already include lagged terms, which should be enough to induce persistence in these variables, without having to rely on autoregressive shocks. More importantly, Galí and Rabanal (2004) show that backward looking behavior in the inflation equation becomes irrelevant once autoregressive price markup shocks are introduced. Hence, this choice would imply a 'worse' fit of inflation dynamics to other shocks, like monetary policy shocks.

4. Generating a positive response of inflation after a monetary contraction in the model: A calibrated example

This section provides a calibrated example on how to generate a positive response of inflation after a contractionary monetary policy shock in the model. The purpose of this exercise is to clarify what forces influence the response of inflation after a monetary policy contraction, and shows that the presence of the cost channel for all firms is not sufficient to generate a positive response of inflation. In order to generate a positive response of inflation to a monetary policy tightening, it is also necessary to introduce large real wage stickiness and large variability in the utilization rate of capital. This illustration will be helpful to frame the choice of priors for estimation, and the discussion of several robustness exercises below.

The baseline parameterization follows CEE closely. CEE impose the following features in the model: First, there is full indexation to last period's inflation rate for both price and wage setters ($\omega_{\rm p} = \omega_{\rm w} = 1$). Second, the cost channel affects all firms ($\gamma = 1$), and there is a high elasticity of capital utilization with respect to the rental rate of capital ($\psi = 100$). Third, the following values are set: $\sigma = 1$, $\phi = 21$, $\eta = 1$, and $\beta = 0.9926$. Afterwards, CEE estimate the rest of the parameters by minimizing the distance between VAR-based and model-based impulse responses. Their estimate for the average price markup is 20 percent. The habit formation parameter is estimated to be $b = 0.65$, and the coefficient that measures the elasticity of 'Tobin's Q' to investment growth is $\varphi^{-1} = 2.48$. For the Taylor rule, CEE assume the following values: $\rho_r = 0.8$, $\gamma_p = 1.5$, and $\gamma_y = 0.1$.[10] Finally, I assume that prices are optimally reset every two- quarters and wages are reset every four quarters ($\theta_\mathrm{p} = 0.5$ and $\theta_\mathrm{w} = 0.75$), which is slightly different than CEE's estimates.[11]

Fig. 1 displays the response of inflation, output and nominal interest rates to a monetary policy shock that takes the form of an increase of 25 basis points in the nominal interest rate. Under the baseline parameterization (solid line), inflation initially increases and then turns negative after six-quarters. This behavior is the result of several effects happening at the same time. On the one hand, large real wage rigidities and a large degree of variable capital utilization are needed to make the initial response of real wages and the rental rate of capital close to zero, i.e. the demand-side effect is quantitatively small on impact. The calibrated parameters help achieve the muted initial response of those two variables. On the other hand, because all firms are subject to the cost channel ($\gamma = 1$), there is a large initial impact of the nominal interest rate on real marginal costs, i.e. the supply side effect is large. As a result, inflation increases after a monetary policy tightening. Over time, the real wage declines because consumption and hours fall following the monetary contraction, and the rental rate of capital falls because of the drop in investment. These demand-side effects eventually dominate the supply side effect, and inflation becomes negative after six quarters.

In order to understand how each rigidity affects the response of inflation to a monetary policy shock, each key feature of the model is shut down one at a time. First, the effect of price rigidities is discussed. The response of the three variables is labeled 'Flex. Prices' with dash-dotted lines in Fig. 1. More price flexibility or less backward looking behavior in price setting cause a larger inflation increase after a monetary contraction, because inflation becomes more responsive to the real marginal cost. As the model approaches full price flexibility ($\theta_\mathrm{p} = 0.0001$) without indexation ($\omega_\mathrm{p} = 0$), the response of inflation becomes much more positive than under the baseline case. Therefore, the degree of price stickiness and backward looking behavior affects the amplitude of the response of inflation, but not its sign.

Second, the effect of wage rigidities and variable capital utilization is discussed. Increasing wage flexibility or eliminating variable capital utilization will cause inflation to fall after a monetary contraction, despite the fact that the full cost channel effect is always in place ($\gamma = 1$). If either the real wage or the rental rate of capital are allowed to display a large response to monetary shocks, their behavior will offset the effect that interest rates have on inflation, and the demand-side effect will dominate the supply side effect. As Fig. 1 shows, under the limiting case where

[10]In their baseline scenario, CEE assume that their monetary policy rule is VAR-based. However, they also conduct a robustness exercise using a Taylor rule, and find that the reaction of inflation to a monetary policy shock remains basically unchanged.

[11]Using CEE's point estimates ($\theta_\mathrm{p} = 0.6$ and $\theta_\mathrm{w} = 0.64$) does not change the qualitative results.

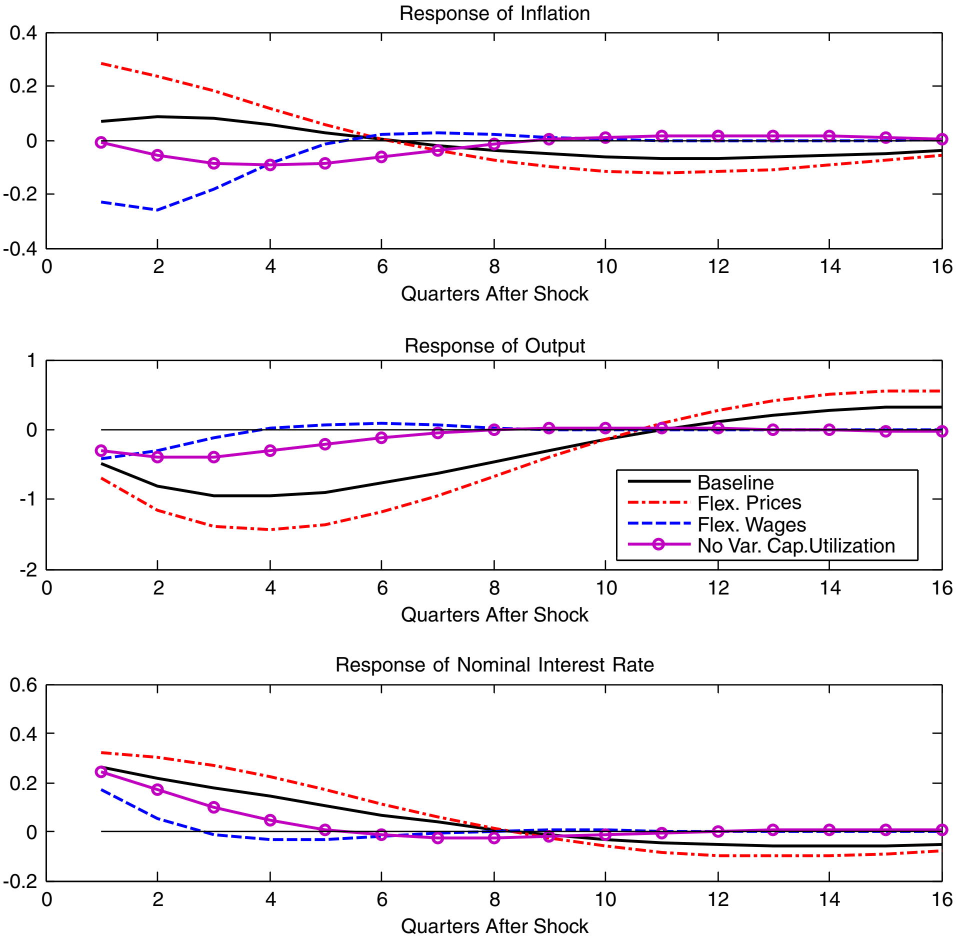

Fig. 1. Impulse responses to a monetary policy shock in the model (in percent deviation from steady-state values).

wages are flexible (dashed line, labeled 'Flex. Wages') and there is no wage indexation, inflation declines after a monetary contraction, obtaining the more traditional, demand-side driven result. Similarly, not allowing for variable capital utilization (solid line with circles, labeled 'No Var. Cap. Utilization') also causes inflation to decline after an increase in interest rates, because of the associated drop in the rental rate of capital.

Therefore, it is important to note that the presence of the cost channel is not enough to generate a positive response of inflation after a monetary policy contraction. In addition to having a large elasticity of the nominal interest rate on the real marginal costs of production, high real wage stickiness and variable capital utilization rates (which implies low volatility in the rental rate of capital) are needed.

In what follows, the remainder of the paper examines to what extent all these necessary features are in fact present in the data, by estimating the parameters of the model using Bayesian methods.

5. Econometric methodology

This section explains how to implement the Bayesian approach, using data for the United States and how to use the Bayes factor to assess the importance of cost channel effects.[12] Applying a Bayesian approach to parameter estimation implies obtaining the posterior distribution of the parameters conditional on the data. From Bayes rule, the posterior distribution is proportional to the product of the likelihood function and the prior:

$$p(\upsilon|\{d_t\}_{t=1}^{T}) \propto L(\{d_t\}_{t=1}^{T}|\upsilon)\Pi(\upsilon),$$

where υ is the vector of parameters that describe the model, $\{d_t\}_{t=1}^{T}$ is the vector of endogenous variables, T is the sample size, $L(\{d_t\}_{t=1}^{T}|\upsilon)$ is the conditional likelihood function of the data on the model and the parameters, and $\Pi(\upsilon)$ is the prior distribution of the parameters.[13] Since there is no analytical expression for the posterior, numerical methods are needed to simulate the posterior distribution, to obtain the relevant moments of the posterior distribution of the parameters, as well as to compute the marginal likelihood and the Bayes factor.

5.1. The data

The Federal Funds rate is used as the relevant nominal interest rate. This series was obtained through the Federal Reserve Bank of Saint Louis database (FRED). The measure of output is the 'Nonfarm Business Sector Output,' as published by the Bureau of Labor Statistics (BLS). The measure of prices is the associated price deflator. Finally, the measure of nominal wages is the 'Hourly Compensation for the Nonfarm Business Sector,' also obtained through the BLS. The choice of variables is done for comparability with previous studies on inflation dynamics. The inflation rate is the quarterly growth rate of the price level, and the nominal interest rate is expressed in quarterly terms. The sample period is the first-quarter of 1959 to the fourth-quarter of 2004, at a quarterly frequency. Real variables (output and the real wage) are detrended using a quadratic trend, while nominal variables (interest rates and inflation) are treated as deviations from their sample mean.

[12] A previous version of the paper (Rabanal, 2003) included estimates for the euro area in a model without capital, using the data set of Fagan et al. (2001). I am grateful to the Econometric Modeling Unit at the European Central Bank, and especially to Alistair Deppe, for providing me with the euro area data. Since the results are qualitatively very similar to the ones presented here for the U.S., they are not shown but are available upon request. Smets and Wouters (2003) estimate a very similar model for the euro area but they do not allow for or estimate the 'cost channel' effect.

[13] The denominator of the Bayes formula, which would be the marginal likelihood of the data for each model, is not included since it is constant with respect to the value of the parameters.

Fig. 2 presents the estimated impulse response of inflation, output and interest rates to a monetary policy shock using a VAR. This is done both as an illustration of the price puzzle, and to verify that the data set used in this paper displays such a puzzle when the monetary policy shock is identified with a VAR. The data is introduced the same way as when estimating the DSGE model, as described in the previous paragraph. The VAR is estimated with four lags, and the monetary policy shock is identified with the Cholesky decomposition of the variance–covariance matrix of the reduced-form residuals.

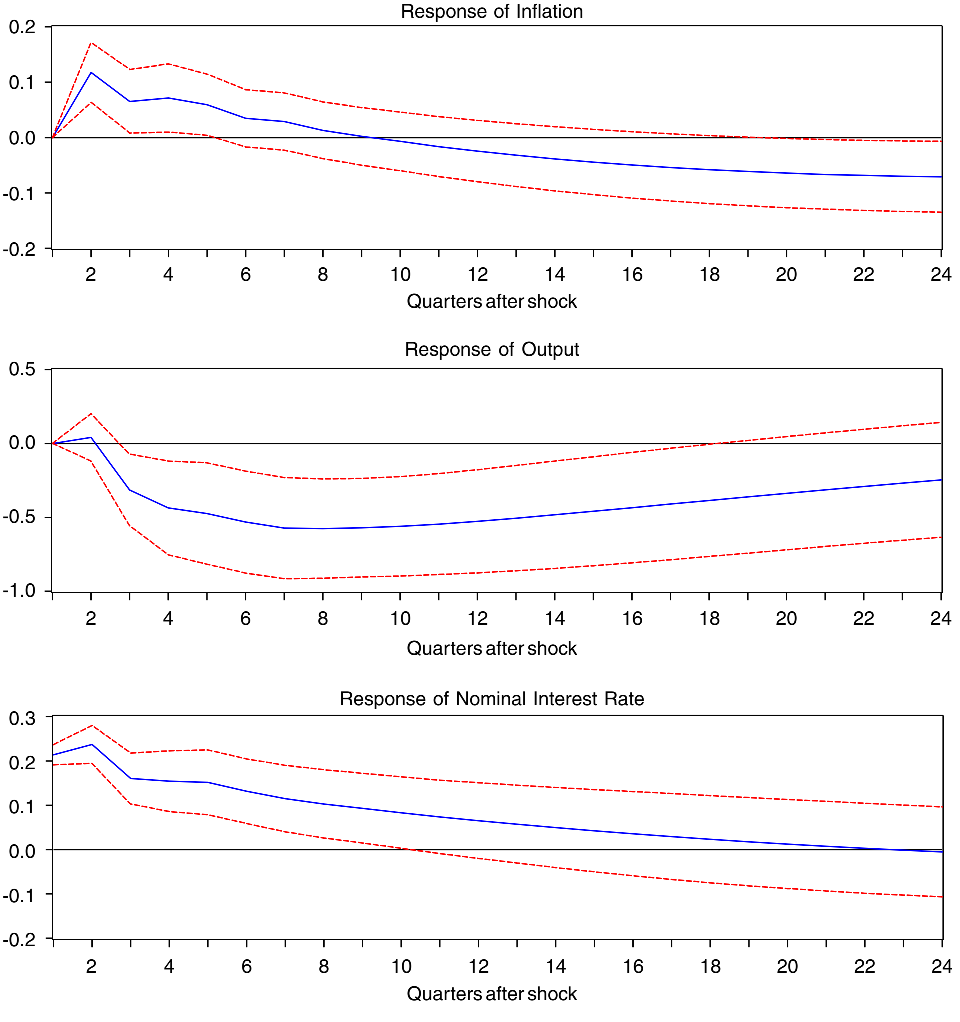

Fig. 2. Estimated impulse responses to a monetary policy shock using a VAR (± 2 standard deviation bands).

Following CEE, it is assumed that monetary policy reacts to contemporaneous values of all other macroeconomic variables, but all other variables are not contemporaneously affected by monetary policy. Therefore, the nominal interest rate is placed last in the ordering of the variables in the VAR. After an increase of one standard deviation in the interest rate (about 21 basis points), inflation increases after one-quarter, because of the built-in lag in the transmission of monetary policy. Afterwards, it declines in a nonmonotonic way, and crosses the zero line after seven-quarters. The qualitative result of an increase in inflation after a monetary contraction is not affected by the ordering of the variables. Therefore, an estimation methodology that minimizes the distance between VAR-based and model-based impulse response to monetary policy shocks, such as CEE, will deliver parameter values that explain this behavior of inflation. In this paper, I study to what extent all the features that are needed to explain the price puzzle are in fact present in the data, in a model with more shocks than just monetary policy shocks, and using likelihood-based methods.

5.2. *Prior distributions*

This section describes the prior distribution $\Pi(\upsilon)$, which gives an important weight to values of the parameters that would generate an increase of inflation after a monetary contraction. Table 1 presents the prior distributions of the parameters. First, I comment on the priors over those parameters that relate to the rigidities which make possible an increase of inflation after a monetary contraction in the model. The coefficient on the cost channel has a prior uniform distribution between zero and one. I adopt a Gamma distribution for the elasticity of the capital utilization with respect to the rental rate which has the same prior mean as in CEE: 100. It also has a large enough standard deviation to allow for a wide range of parameters. The probabilities of the Calvo lotteries are Beta distributions, in order to

Table 1
Prior distributions

Parameter	Distribution	Mean	Standard dev.
γ	Uniform(0,1)	0.50	0.29
θ_{p}, θ_{w}	Beta	0.60	0.20
ω_{p}, ω_{w}	Uniform(0,1)	0.50	0.29
ψ	Gamma	100	14.14
σ	Gamma	2.00	1.41
b	Normal	0.70	0.05
φ	Gamma	2.00	1.41
γ_p	Normal	1.50	0.13
γ_y	Normal	0.50	0.13
ρ_r	Uniform	0.50	0.29
ρ_a, ρ_g	Normal	0.80	0.05
$\sigma_a, \sigma_g, \sigma_z, \sigma_p$	Gamma	0.01	0.005

keep them bounded between zero and one. These priors imply an average duration between optimal changes of both prices and wages of between two and three quarters, as suggested by CEE. The priors on the indexation to last period's inflation rate for both price and wage setters are uniform distributions in the [0,1] interval.

The prior for σ is a Gamma distribution in order to stay in positive values. In theoretical papers, as well as in CEE, this parameter is usually calibrated at a value of one to be consistent with the existence of a balanced growth path, but empirical values in the literature are found to be between 2 and 4.[14] The mean of the prior is 2 and the standard deviation is large enough to incorporate enough uncertainty about this parameter. The habit formation in consumption parameter is a Normal distribution centered at 0.7, a value close to that suggested by Boldrin et al. (2001), with a standard deviation of 0.05. The prior distribution is truncated at six standard deviations from the mean, so it can effectively take values between 0.4 and 1. Finally, the elasticity of the growth rate of investment with respect to Tobin's Q is also a Gamma distribution with a mean prior of 2 and a relatively large standard deviation, 1.41.

The prior distributions of the coefficients of the Taylor rule are Normal distributions, centered at Taylor's original values. The parameter space is censored to the region where the model has a unique, stable solution. The interest rate smoothing parameter is allowed to take any value between zero and one, with a uniform prior. The priors of the coefficients on the autoregressive parameters are set to Normal distributions with mean 0.8 and standard deviation 0.05. They are both truncated such that parameter values above 0.95 are ruled out. I opt for these truncated prior distributions to favor the 'endogenous' propagation mechanism through the various rigidities in the model, rather than have the model match the persistence in the data due to highly persistent shocks. Finally, the priors on the standard deviations of the shocks are Gamma distributions to stay in positive reals, with mean of 1 percent and standard deviation of 0.5 percent.

Some parameters in the estimation are fixed, because of two main reasons. First, some parameters are not identified in the price and wage setting equations. Since the focus is on the estimation of price and wage Calvo lottery parameters, the cost channel elasticity, and the backward-looking parameters in inflation and real wages, the parameters that relate to the price and wage markup, and the labor supply elasticity are not identified. The values for the elasticities of substitution between types of goods and labor are set, following CEE, to $\bar{\lambda} = 6$ and $\phi = 21$. The value for the inverse elasticity of labor supply is set to $\eta = 1$. This value is consistent with the estimates of Rabanal and Rubio-Ramírez (2005) for a model with staggered price and wage contracts, as well as with CEE's parameterizations.[15] Second, the value for some parameters is available from the first moments of the data, or can be difficult to

[14] See Basu and Kimball (2000).

[15] These parameters choices affect the average duration of prices and wages. However, they do not affect significantly the dynamics of the model, because by fixing these parameters to some other value, the estimates of the Calvo lotteries will tend to adjust accordingly to roughly obtain the same numerical values for κ_{p} and κ_{w}.

estimate without actual data on those series. The depreciation rate for capital is set to a quarterly value of $\delta = 0.025$. The capital share of output is set to $\alpha = 0.36$, the discount factor to $\beta = 0.99$, and the government consumption-output ratio is set to 0.2. All these values are fairly standard in the literature.

5.3. The law of motion and the likelihood function

Let x_t be the vector of all endogenous variables, $s_t = \{a_t, g_t, \varepsilon_t^z, \varepsilon_t^p\}'$ the vector of random exogenous driving processes, $\varepsilon_t = \{\varepsilon_t^a, \varepsilon_t^g, \varepsilon_t^z, \varepsilon_t^p\}'$ the vector of innovations, and $d_t = \{\Delta p_t, y_t, r_t, \omega_t\}'$ the vector of observable variables. Then, the solution to the system of Eqs. (10)–(21) can be written in state-space representation, following Uhlig (1999):

$$\begin{aligned} \begin{bmatrix} x_t \\ s_t \end{bmatrix} &= A(\upsilon) \begin{bmatrix} x_{t-1} \\ s_{t-1} \end{bmatrix} + B(\upsilon)\varepsilon_t, \quad E(\varepsilon_t \varepsilon_t^{'}) = \Sigma(\upsilon), \\ d_t &= D(\upsilon) \begin{bmatrix} x_t \\ s_t \end{bmatrix}. \end{aligned} \tag{21}$$

The likelihood function of the observable data conditional on the parameters $L(\{d_t\}_{t=1}^T|\upsilon)$ is evaluated by applying the Kalman filter.

5.4. Drawing from the posterior and computing the bayes factors

It is not possible to obtain an analytical expression for the posterior distribution. Since both the prior distribution and the likelihood function can be numerically evaluated, a numerical algorithm is applied to obtain a draw from the posterior distribution. A random walk Markov Chain of size 500,000 is obtained from the posterior distribution using the Metropolis-Hastings algorithm.[16]

In order to compare the performance of different models in a set M, the marginal likelihood of each model $m \in M$ is computed as follows:

$$L(\{d_t\}_{t=1}^T|m) = \int_{\upsilon \in \Upsilon} L(\{d_t\}_{t=1}^T|\upsilon, m)\Pi(\upsilon, m)\,\mathrm{d}\upsilon.$$

The marginal likelihood averages all possible likelihoods across the parameter space, using the prior as a weight. Multiple integration is required to compute the marginal likelihood, making the exact calculation impossible.[17] It is important to stress that the marginal likelihood already takes into account that the size of the parameter

[16]See Rabanal (2003) for computational details on the Metropolis – Hastings algorithm. At every step, the new proposed draw has a variance–covariance matrix proportional to the inverse Hessian of an initial guess of the mode of the posterior. The Hessian is updated every 50,000 draws, and the constant of proportionality is adjusted such that the acceptance rate of the algorithm lies between 25 and 35 percent. An initial burn-in period of 100,000 draws is discarded.

[17]The modified harmonic mean estimator is used. See Fernández-Villaverde and Rubio-Ramírez (2004).

space for different models can be different. Hence, more complicated models will not necessarily rank better than simpler models, if the extra parameterization is unimportant. This is so because the marginal likelihood visits all the regions of the parameter space, and takes the average of both relatively large and small values of the likelihood function.[18]

For two different models (A and B), the posterior odds ratio is

$$\frac{P(A|\{d_t\}_{t=1}^T)}{P(B|\{d_t\}_{t=1}^T)} = \frac{Pr(A)L(\{d_t\}_{t=1}^T|\text{model} = A)}{Pr(B)L(\{d_t\}_{t=1}^T|\text{model} = B)}.$$

If there are $m \in M$ competing models, and one does not have strong views on which model is the true one (i.e. $\Pr(A) = \Pr(B) = 1/M$) the posterior odds ratio equals the ratio of marginal likelihoods, also known as the Bayes factor. The Bayes factor is therefore of fundamental importance in Bayesian model comparison, because of its role in determining the posterior model probability.

6. Results

This section presents the results from the baseline estimation, as well as several robustness exercises, analysis of second moments, and subsample analysis. The main result is that the posterior probability of observing an inflation increase after a tightening of monetary policy is zero. Under the baseline estimation, the fraction of firms subject to the cost channel is too low to generate an increase of inflation. Other features of the estimation include a high degree of price stickiness, a low degree of wage stickiness, and a low degree of wage indexation. All these features would prevent observing a positive response of inflation to a monetary policy tightening even when a full cost channel ($\gamma = 1$) is assumed. Finally, it is shown that setting key parameters of the model to values similar to those in Section 4 deteriorates the model fit to the data. In this case, the correlation coefficient between these two nominal variables is much higher in the model than in the data. In addition, the restricted model does a poor job in matching inflation and nominal interest rate persistence and volatility.

6.1. Baseline estimation

Fig. 3 shows the posterior distribution for selected parameters of the model using data for the United States, while Table 2 contains the mean and standard deviation of the posterior distribution of all the model's parameters. For the sake of brevity, I will only comment on the key parameters of the estimation, in order to focus the discussion on their implications for the reaction of inflation to a monetary policy shock. The remaining parameter estimates are quite similar to other studies that have

[18] In terms of performing maximum likelihood, it is true that the additional parameterization, even if unimportant, cannot deliver a smaller maximum value.

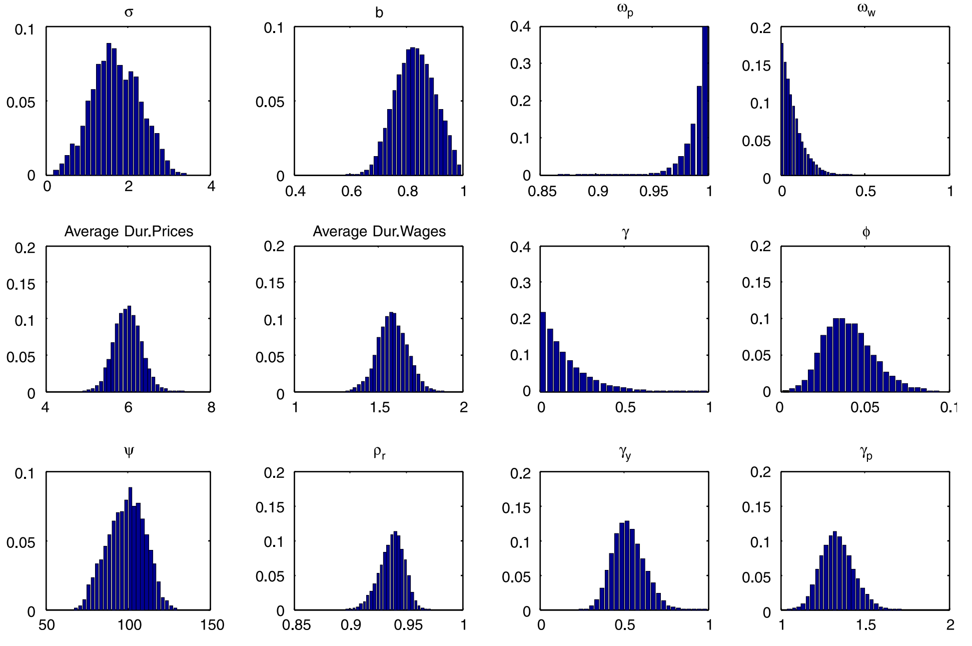

Fig. 3. Posterior distributions.

estimated several versions of the New Keynesian model using U.S. data and Bayesian methods.[19]

The baseline point estimates are presented under the 'I. Baseline' column. The most important coefficient in this estimation is the elasticity of the real marginal cost with respect to the nominal interest rate, γ, which has a mean posterior of just 0.15, with a relatively large standard deviation of 0.13. The posterior distribution suggests that all the mass is concentrated below one-half. Hence, the assumption by CEE that all firms are subject to a 'cost channel' constraint does not seem to be present in the data, given that the prior allowed for any value between zero and one with equal probability.[20]

The proportion of firms that cannot reoptimize prices in a given period is estimated at 0.83, which delivers a mean posterior average duration between optimal price changes of six-quarters. This value is somewhat higher than CEE (their estimate is in the range of two-to-three quarters).[21] The result for the average duration of wage contracts is surprisingly low, with a probability of keeping wages

[19]See Rabanal and Rubio-Ramírez (2005) and Galí and Rabanal (2004).

[20]Ravenna and Walsh (2005) estimate values for the cost channel parameter that range between 1.23 and 11.83, using a GMM approach to estimate Eq. (10). Their results depend on the set of instruments used, as well as on the choice of the weighting matrix.

[21]Eichenbaum and Fischer (2004) suggest that introducing additional real rigidities helps in lowering the implied average duration between price reoptimizations. Altig et al. (2005) reach the same conclusion by introducing firm-specific capital.

Table 2
Posterior distributions

Parameter	I.Baseline		II.Full cost channel		III.More restricted		IV. Fixed cap. Utilization		V. Sample 1959–1979		VI.Sample 1983–2003	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
γ	0.15	0.13	1.00	—	1.00	—	0.15	0.14	0.25	0.21	0.56	0.28
θ_{p}	0.83	0.01	0.84	0.01	0.50	—	0.86	0.02	0.80	0.02	0.84	0.01
θ_{w}	0.37	0.03	0.35	0.04	0.75	—	0.24	0.07	0.12	0.07	0.17	0.05
ω_{p}	0.99	0.01	0.99	0.01	1.00	—	0.89	0.16	0.88	0.14	0.99	0.01
ω_{w}	0.07	0.06	0.07	0.06	1.00	—	0.13	0.12	0.48	0.23	0.18	0.17
ψ	99.03	11.31	108.05	11.07	92.36	3.92	0.00	—	109.22	16.53	102.72	13.42
σ	1.71	0.58	3.32	1.62	1.97	0.58	0.34	0.16	3.09	1.47	5.65	1.78
b	0.83	0.07	0.78	0.07	0.71	0.05	0.96	0.02	0.73	0.05	0.73	0.06
φ	0.04	0.01	0.05	0.02	5.99	0.92	0.03	0.02	0.32	0.23	0.04	0.01
γ_p	1.34	0.10	1.42	0.09	1.04	0.00	1.14	0.13	1.09	0.08	1.49	0.11
γ_y	0.53	0.10	0.48	0.09	0.08	0.01	0.25	0.10	0.23	0.10	0.46	0.09
ρ_r	0.94	0.01	0.93	0.01	0.73	0.03	0.87	0.03	0.94	0.01	0.94	0.01
ρ_a	0.94	0.004	0.95	0.004	0.95	0.001	0.78	0.05	0.84	0.05	0.94	0.01
ρ_g	0.89	0.02	0.88	0.02	0.95	0.001	0.90	0.02	0.86	0.02	0.88	0.02
σ_a	0.010	0.001	0.010	0.001	0.049	0.003	0.016	0.003	0.016	0.005	0.008	0.001
σ_g	0.043	0.003	0.042	0.003	0.039	0.005	0.058	0.003	0.043	0.005	0.031	0.003
σ_z	0.0024	0.0001	0.0024	0.0001	0.0027	0.0002	0.0025	0.0001	0.0023	0.0002	0.0015	0.0001
σ_p	0.159	0.013	0.171	0.014	0.073	0.004	0.216	0.0223	0.120	0.013	0.126	0.013
Log(L)	2581.2		2571.6		2132.5		2558.4		—		—	

fixed of 0.37, which implies an average duration of 1.58 quarters between optimal wage changes. For reasonable wage markups, it is not possible to obtain posterior mean average wage durations of more than three quarters. The proportion of firms that index their price to last period's inflation rate whenever they are not allowed to reoptimize is almost one (0.99), which validates the parameter value that CEE impose in their estimation strategy. On the contrary, wage indexation is on the low side, with a posterior mean of 0.07. As will be discussed below, these estimates will be crucial to explain the lack of a positive comovement between inflation and interest rates after a monetary policy shock.

Another key parameter that affects the response of inflation is the elasticity of the capital utilization rate with respect to the rental rate of capital, ψ. This parameter has a posterior mean and standard deviation very similar to the prior, suggesting that there is not much information in the data about this parameter. The parameter ϕ, that measures the elasticity of the growth rate of investment to Tobin's Q, has a posterior mean of just 0.04, much smaller than estimates of other papers and the prior mean.

Fig. 4 shows the posterior impulse response functions to a monetary policy shock that takes the form of a tightening by one estimated standard deviation, which is close to 25 basis points, together with 3 standard deviation posterior bands.[22] The most important feature is that the posterior probability of observing an increase in inflation after an increase in interest rates is zero. This result is not surprising given the low estimated elasticity of inflation with respect to the nominal interest rate: the estimated parameters favor a specification where the demand-side effect of monetary policy dominates the supply side effect. Fig. 4 also presents the impulse responses to the other three shocks of the model. The behavior in most cases is the typical of New Keynesian models. However, it is important to note that the response of output to a technology shock represents an unattractive feature: the impulse response is initially negative, it takes about seven quarters for it to become positive, and it peaks after 15 quarters. The estimated large variability in the capital utilization rate and investment rigidities are behind this result.[23]

6.2. Robustness

This subsection presents robustness exercises to understand why the parameters coming from the estimation procedure do not imply an increase of inflation after a monetary policy shock. Different versions of the model are reestimated by setting some key parameters to values that would help in generating an increase in inflation after a monetary policy tightening, based on the calibration of Section 4. The impact of these restrictions on the estimated parameters and on the impulse–response functions is discussed, and the different versions of the model are compared by making use of the Bayes factor.

[22]The impulse responses are based on simulating the model using the 500,000 draws from the Metropolis – Hastings algorithm.

[23]In fact, Basu et al. (2004) suggest that this might be indeed the case: after a technology shock output declines in the short run, and increases thereafter.

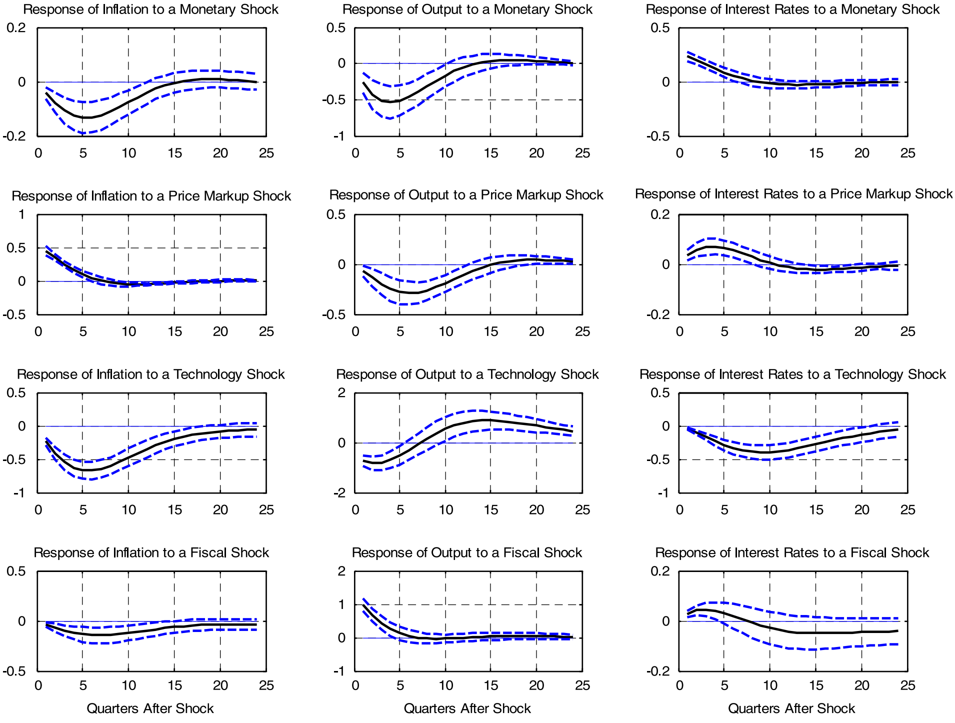

Fig. 4. Impulse responses with baseline estimates (in percent deviation from steady-state values).

The 'II. Full Cost Channel' column of Table 2 shows the result of the estimation where the restriction that $\gamma = 1$ is imposed. In this case, as in CEE, all firms are subject to the cost channel of monetary policy. Interestingly, most parameter estimates do not change much, except for σ, that increases to 3.32, and the estimated degree of habit formation, that decreases to 0.78. More importantly, imposing the restriction that $\gamma = 1$ does not affect the impulse responses to a monetary policy shock (Fig. 5, left column). In fact, the numerical differences between the 'Baseline' and the 'Full Cost Channel' models are very small. Once again, this confirms that assuming that all firms are subject to the cost channel is not sufficient to observe an increase of inflation after a monetary policy contraction, and that additional features need to be introduced in the model.

The last row of Table 2 presents the log marginal likelihoods of the 'Baseline' model and the 'Full Cost Channel' model. The log difference (i.e. the log Bayes factor) between these two models is about 9.4. A higher marginal likelihood is obtained with the original priors because, in that case, the γ parameter is allowed to visit the region close to zero, where the likelihood function achieves higher values.[24]

[24]This statement is based on the shape of the posterior distribution of the baseline estimation (Fig. 3). Since most posterior mass is concentrated below $\frac{1}{2}$, and the prior is a uniform, the likelihood function achieves higher values in the region where γ is low.

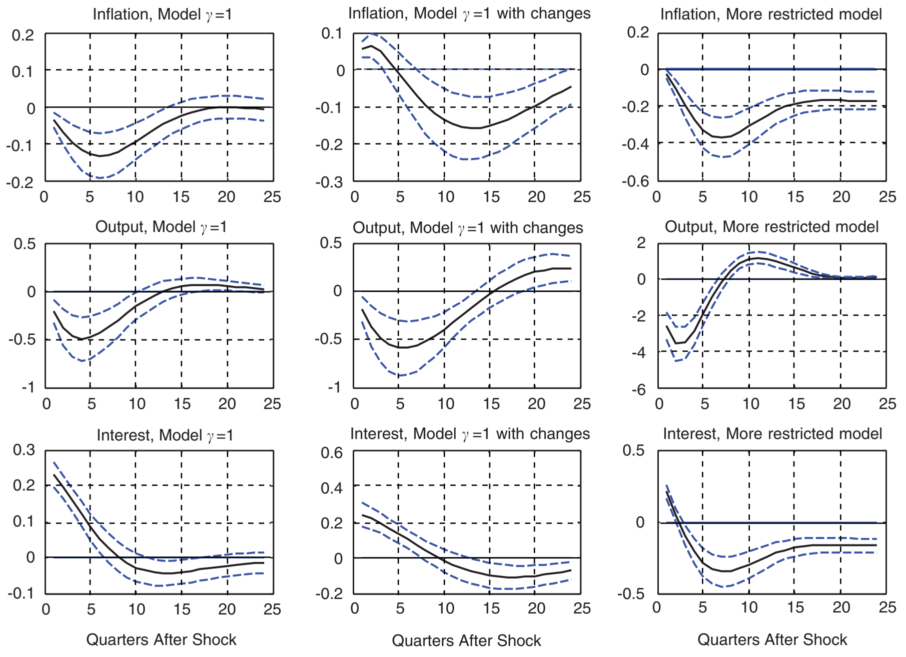

Fig. 5. Impulse responses to a monetary policy shock with restricted models (in percent deviation from steady-state values).

The ratio of marginal likelihoods means that a prior that favors the model with full cost channel by a factor of 12088 is needed in order to accept the restriction that $\gamma = 1$ after observing the data.[25]

Then, the question to ask is, why does the 'Full Cost Channel' model fail to display an increase of inflation after a contractionary monetary policy shock? While the parameter estimates favor a high variability of the capital utilization rate, the estimation procedure fails to pick up the following three ingredients:

1. lower price stickiness,
2. higher wage stickiness,
3. and full wage indexation to last period's inflation rate,

all of which are necessary to generate an increase of inflation after a monetary policy shock, as was shown in the calibration exercise of Section 4. The reason why price stickiness is mentioned here is the following: a high degree of price stickiness does not affect the sign of the response of inflation to shocks, but the amplitude of

[25]Using the Bayesian model comparison language, as in Kass and Raftery (1995), with such a difference between two models there is "very strong" evidence for the baseline model vis-à-vis the model with full cost channel.

that response. However, a high degree of price stickiness, like the one estimated here, implies a very small response of inflation to monetary policy shocks when all the other necessary features are in place. Hence, the problem is not one of sign, but one of size: it could be difficult to tell if the impulse response is different from zero.

To understand how the 'Full Cost Channel' model would behave if these three conditions are imposed, I compute what the impulse responses would look like by using the estimates of the 'Full Cost Channel' model, but substituting for the following parameter values: $\omega_{\mathrm{p}} = \omega_{\mathrm{w}} = 1$ (full price and wage indexation), $\theta_{\mathrm{p}} = 0.5$ (implying that prices are optimally reset every two periods), and $\theta_{\mathrm{w}} = 0.75$ (implying that wages are optimally reset every four periods).[26] Once the substitution is made, the increase in inflation after a monetary tightening is again possible, as shown in the center column of Fig. 5.

This exercise provides an additional illustration of the conditions under which the model with a full cost channel would generate an increase of inflation after a monetary policy tightening, but does not come from an optimization–based likelihood method. The natural next step consists in estimating the model by holding fixed all the parameters that would generate an increase in inflation to a monetary policy shock to 'desirable' values: these values are the ones in the price and wage setting equations just described in the previous paragraph. The result of the estimation is presented in the 'III. More Restricted' column of Table 2. In this case, other parameters change in important dimensions. First, the elasticity of investment to Tobin's Q increases from 0.04 to 5.99, thereby making investment highly responsive to any change in economic conditions. The estimated parameters of the Taylor rule decrease significantly, while the estimate of the standard deviation of the technology shock increases by a factor of five, and the standard deviation of the price markup shock declines significantly. The marginal likelihood declines to 2132.5, clearly suggesting a much worse fit of the model to the data. By any standards, a log Bayes factor of more than 400 between two models is far too large to accept the restrictions imposed in the 'More Restricted' model.

The most interesting result is that the estimated impulse responses (right column of Fig. 5) show no increase of inflation after a monetary policy tightening, despite the fact that most of the relevant parameters have been fixed to cause such an increase. In addition, the output decline is about six times as large as in the other cases. Since the price and wage stickiness and indexation mechanisms are imposed, and the variable capital utilization estimate does not change significantly, the estimation favors a strong reaction of investment to economic conditions. As a result, the model manages to cause a decline in inflation by making investment highly responsive to Tobin's Q: a contractionary monetary policy shock causes a large drop in investment, which in turn causes a drop in the rental rate of capital, and therefore inflation declines.

[26] I use the random draw of size 500,000, and simulate the model for each draw performing the substitution of the four parameters: price and wage indexation, and price and wage Calvo lotteries.

6.3. Second moments

To understand why the 'Full Cost Channel' and the 'More Restricted' versions of the model cannot fit the data, Table 3 presents some selected second moments of the data and those implied by the different estimated versions of the model. The moments are computed at the posterior mode in each case. It is important to stress that likelihood-based methods try to fit all second moments of the data, so this selection is just illustrative of where the models fail.

Since the focus of the paper is the relationship between inflation and interest rates, a key second moment to look at is the correlation between interest rates and

Table 3
Selected second moments in the data and in the models

	SD (Δp)	SD (r)	SD (y)	SD (ω)	Corr ($\Delta p,r$)
Data	**0.71**	**0.83**	**3.63**	**3.25**	**0.67**
Baseline	2.69	2.15	3.97	4.48	0.85
Full cost channel	3.93	3.65	5.53	5.82	0.95
More restricted	64.46	63.99	144.90	51.29	0.99
Fixed cap. utilization	1.33	1.00	2.32	2.53	0.59
Autocorrelations (Lag)					
Δp	1	2	3	4	5
Data	**0.81**	**0.79**	**0.75**	**0.66**	**0.58**
Baseline	0.97	0.93	0.88	0.83	0.78
Full cost channel	0.99	0.97	0.94	0.91	0.88
More restricted	0.99	0.99	0.98	0.98	0.97
Fixed cap. utilization	0.90	0.77	0.63	0.49	0.36
i	1	2	3	4	5
Data	**0.95**	**0.87**	**0.81**	**0.75**	**0.68**
Baseline	0.99	0.98	0.96	0.94	0.91
Full cost channel	0.99	0.99	0.98	0.97	0.95
More restricted	0.99	0.99	0.99	0.98	0.97
Fixed cap. utilization	0.95	0.89	0.82	0.74	0.66
y	1	2	3	4	5
Data	**0.95**	**0.87**	**0.76**	**0.66**	**0.55**
Baseline	0.94	0.86	0.76	0.66	0.57
Full cost channel	0.96	0.91	0.85	0.79	0.72
More restricted	0.97	0.89	0.77	0.63	0.49
Fixed cap. utilization	0.87	0.74	0.62	0.51	0.41
ω	1	2	3	4	5
Data	**0.96**	**0.92**	**0.87**	**0.82**	**0.78**
Baseline	0.97	0.90	0.80	0.69	0.57
Full cost channel	0.98	0.93	0.86	0.80	0.72
More restricted	0.99	0.98	0.97	0.96	0.94
Fixed cap. utilization	0.92	0.76	0.56	0.35	0.16

inflation. The 'Baseline' model predicts a correlation between inflation and nominal interest rates of 0.85, higher than the one observed in the data (0.67). When the full cost channel is imposed, this correlation increases to 0.95, while the More Restricted model implies that the correlation is virtually one (to be exact, it is 0.9976). This result can be explained as follows: the Taylor rule already imposes a significant positive comovement between inflation and the nominal interest rate. The assumption that all firms are subject to the cost channel, and the introduction of additional real rigidities that are aimed at generating a positive response of inflation to nominal interest rates, makes that positive comovement even stronger. As a result, the correlation between inflation and nominal interest rates is much higher than in the data. This would also explain why the estimated coefficient of the reaction of inflation to the Taylor rule in the 'More Restricted' model is smaller, since it would be a channel through which the estimation procedure tries to reduce the correlation between these two variables.

Another important dimension where the Full Cost Channel and the More Restricted models do a poor job is in matching the autocorrelation of nominal interest rates and inflation. In both cases, the correlogram of inflation and interest rates decays much slower than in the data. For instance, the More Restricted model delivers an autocorrelation of both inflation and interest rates of 0.97 at the fifth lag, while in the data it is 0.58 for inflation and 0.68 for the nominal interest rate. Again, imposing a tight relationship between interest rates and inflation via the cost channel and other rigidities, causes the Full Cost Channel and the More Restricted models to overpredict the persistence of the two nominal variables. On the other hand, the Baseline model provides a somewhat better fit than the other two models in this dimension, but it also overpredicts persistence. However, in terms of matching persistence of real variables, the Full Cost Channel model provides an almost perfect fit to the real wage autocorrelation function, while the More Restricted and the Baseline models perform very well in matching the persistence of output.

Next, I proceed to explain how the models fit the standard deviation of the four observed variables. The Baseline model does a good job in matching the volatility of output, but it overpredicts the standard deviation of real wages, which is 4.48 in the model and 3.25 percent in the data. However, the volatility of nominal variables is overpredicted by a factor of three. Introducing a full cost channel implies higher standard deviations of all four variables, moving further away from the actual values in the data. The More Restricted model performs extremely poorly in this dimension: it delivers standard deviations of the observed variables that are between 15 and 90 times larger than in the data. This again shows the great amplification effect of real rigidities: they can be useful in a model with only monetary shocks, but they introduce too much volatility when other shocks are considered.

Since the three models (Baseline, Full Cost Channel, and More Restricted) perform poorly in explaining the behavior of nominal varibles, a natural question to ask is what feature is behind this result. A main feature of increased persistence in the model is the large variability in the capital utilization rate. When the model is reestimated by assuming that variable capital utilization is switched off ($\psi = 0$), the fit to nominal variables improves: the correlation between inflation and nominal interest rates, becomes 0.59, much closer to the data.[27] In addition, this version of the model provides a very good fit to the correlograms of the two nominal variables. On the other hand, the main shortcoming of the model without variable capital utilization is that it cannot explain the persistence of real variables. In particular, it provides a poor fit to the persistence of real wages: the autocorrelation at the fifth lag is 0.78 in the data, while in the model it is only 0.16.

The main conclusions of this subsection are two. First, all models score successes and failures when trying to fit a large set of second moments. Hence, the tool that allows the researcher to discriminate among models is the marginal likelihood, because it provides a summary statistic of overall model fit. Under this criterion, the Baseline model provides the best fit. Second, and most important, the Full Cost Channel and the More Restricted model cannot explain the behavior of nominal variables. By forcing the models to display an increase of inflation after a monetary policy contraction, the models get the dynamics of inflation and nominal interest rates, and their correlation, wrong.

6.4. Subsample analysis

To conclude this section, subsample estimates, using the periods 1959–1979 and 1983–onwards, are presented in the last two columns of Table 2.[28] The point estimates of γ are smaller in the earlier period than in the later (0.25 versus 0.56).[29] While there are important differences in some parameters, (for instance, in the Taylor rule and the wage indexation parameter), the main qualitative features remain for both subperiods. In the two cases, the estimated parameters imply too high price stickiness, too low wage stickiness and no period-by-period full wage indexation. Therefore, based on the whole analysis of this section, even after imposing that $\gamma = 1$ and other desirable parameter values, an increase in inflation after a monetary policy shock is very unlikely to happen in both subperiods.

Hence, based on all the exercises performed in this section, I conclude that it is not possible in the context of an estimated monetary DSGE model to observe an increase in inflation after a contractionary monetary policy shock.

7. Concluding remarks

The results of the present paper are based on a likelihood-based estimated structural model, and support the view that inflation and interest rates move in opposite directions after a monetary policy shock. Therefore, the results contradict the view that the supply side effect of monetary policy dominates the more

[27] Parameter estimates are shown in the "IV. Fixed Cap. Utilization" column of Table 2.

[28] The marginal likelihood is not computed in this case because the data sets are different. The Bayes factor is useful to compare models when the same data set is used, but not to compare models across subsample periods.

[29] In an early paper, Seelig (1974) rejected that changes in the nominal interest rate play a significant role in the determination of inflation during the 1955–1969 period, using industry level data.

traditional demand-side effect. As in any other research paper, the results are conditional on the choice of a model, econometric strategy, and a particular data set. However, the paper has shown that by imposing several structural relationships aimed at generating an increase of inflation to a monetary policy shock, the overall model fit to the data worsens. In particular, when some parameters of the model are fixed to values that would allow for an increase of inflation after a monetary policy shock, the model cannot fit the behavior of nominal variables: it implies too high inflation and nominal interest rate persistence and volatility, and a correlation of one between inflation and interest rates, which is at odds with the data. In addition, the more restricted models deliver a too high volatility of all variables.

The results of the paper contradict those of Ravenna and Walsh (2005) and CEE, who suggest that the presence of the cost channel is more important, and that it is possible, in the context of this model, to observe an increase of inflation to a monetary policy shock. In those papers, the econometric methodology was based in matching a smaller set of moments. But when the set of moments to be explained is expanded, their results disappear. Why? In other to fit the additional observed moments, the estimated parameters move away from the choices that would generate a positive response of inflation to a contractionary monetary policy shock. Interestingly, Altig et al. (2005) estimate the parameters of a New Keynesian model similar to the one presented here (and in CEE) by minimizing the distance between model-based and VAR-based impulse responses to monetary, investment specific and neutral technology shocks. Among other results, their estimate of ψ falls from 100 when trying to match the response to only monetary policy shocks, to 0.5 when trying to match the response to the three shocks at the time. In the latter case, their estimated model-based impulse responses no longer display an increase of inflation after a contractionary monetary policy shock.[30]

The methodology presented in the present paper delivers different results about the behavior of inflation after a monetary policy shock than a strand of the VAR literature, in particular the results obtained by Barth and Ramey (2001) for the 1960–1979 period. Therefore, if a price puzzle type of behavior arises in a VAR, it is likely to come from misspecification. The interesting question to study in future research would be if VARs can properly identify the effects of monetary policy shocks using simulated data.[31]

Finally, it is important to highlight that the estimate of average duration of wage contracts is surprisingly low. It could well be that the Calvo (1983) model for wage setting does not seem to explain wage dynamics as well as it explains inflation dynamics. Competing models of wage setting should be further studied in a DSGE setup. In addition, it would be worthwhile estimating a dynamic general equilibrium model using Bayesian methods and industry-level data, and examine the sectoral properties of inflation dynamics. This would allow to study which sectors are

[30]See Fig. 1 in Altig et al. (2005).

[31]Some interesting work on this direction has been performed by Castelnuovo and Surico (2006), who show that when the monetary policy rule is such that the solution to the model displays indeterminacy, VARs cannot properly identify the effects of a monetary policy shock.

affected by the cost channel, and whether there are washing out effects once the step from industry-level to aggregate data is done.

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