A Rational Expectations Model of Optimal Inflation Inertia

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Abstract

This paper presents a monetary model with nominal rigidities and maximizing, rational, forward-looking households, intermediaries and firms. It differs from conventional models in this class in two key respects. First, price (and wage) setters set pricing policies, including an updating rate for future prices, instead of price levels. Second, output fluctuations during the period of a pricing policy are costly to firms.

The paper is motivated by some important shortcomings of conventional models, namely their inability to generate inflation inertia, inflation persistence and recessionary disinflations without introducing either an ad-hoc updating rule or learning. While learning is clearly important, we are interested in the contribution that structural rigidities can make in a forward-looking and optimizing model. The model does generate all of the above effects in response to monetary policy shocks. The channel for these effects in the model is the long-run or inflation updating component of firms' pricing policies. This is distinct from another frequently stressed reason for inflation inertia and persistence, a slow response of marginal cost to shocks, which is also present in our model because all components of marginal cost, not just wages, are sticky. In work in progress, we are estimating the model using Bayesian techniques.

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1 INTRODUCTION

A growing body of research in monetary theory uses the assumption of nominal rigidities embedded in dynamic general equilibrium models with rational expectations. Comprehensive surveys of this literature can be found in Galí (2001) and Lane (2001). The resurgence of this model class is based both on much improved theoretical foundations and on empirical arguments. The time-dependent price adjustment formulations of Taylor (1980), Rotemberg (1982) and Calvo (1983) made it possible to incorporate nominal rigidities into rational expectations models with forward-looking optimizing agents. Empirical support came from evidence showing that monetary policy has significant short-run real effects, such as Christiano, Eichenbaum and Evans (1996, 1998) and Leeper, Sims and Zha (1996).

Many authors[1] argue that models with nominal rigidities can successfully account for most of the effects of monetary policy. But whether these models can fully account for all short-run empirical properties of inflation and output has recently been much debated. Mankiw (2001) notes that they do not generate the empirically observed delayed and gradual response of inflation to monetary policy shocks, a phenomenon that we will refer to as *inflation inertia*. Fuhrer and Moore (1995) show that they also do not generate the observed very prolonged steady state deviations of inflation following a monetary policy shock, a phenomenon that is generally referred to as *inflation persistence*. In short, these are models of stickiness in price levels, but they imply no stickiness in inflation. This in turn implies that disinflationary policies have minimal real costs, or even that anticipated disinflations cause booms (Ball, 1994a). This is also inconsistent with a large body of empirical evidence (see e.g. Gordon 1982, 1997) which shows that disinflationary policies give rise to *recessions*, or more specifically to a U-shaped output response. These empirical regularities are typically presented using VAR impulse responses such as the ones displayed in Figure 1 for the US

[1] See Taylor (1998) and Clarida, Galí and Gertler (1999).

case, showing the response of the nominal interest rate, inflation and output to a one standard deviation monetary policy shock.[2]

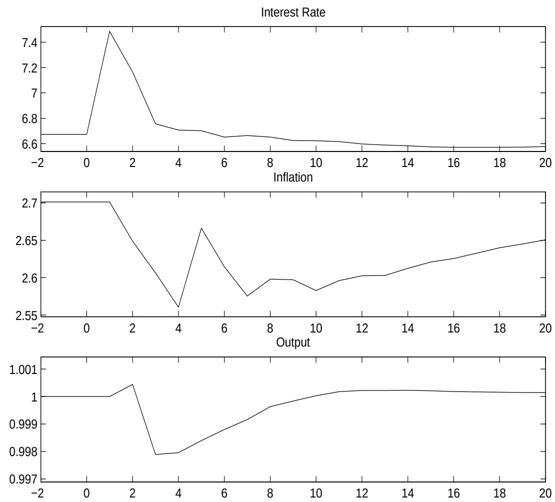

Figure 1 : VAR Impulse Responses to a Monetary Policy Shock

One key ingredient of the model we propose in this paper is a tractable generalization of the Calvo (1983) staggered pricing model first introduced by Calvo, Celasun and Kumhof (2001, 2002). Our model contains the conventional staggered pricing model as a special case. But it is also capable of generating inflation inertia, inflation persistence and recessionary disinflations. Its main difference to conventional treatments is in its specification of firms' price setting behavior. We suggest that, in the realistic case of a positive steady state inflation rate, it is more plausible to assume that firms employ pricing policies instead of setting only a price level. The purpose of such policies is to keep them as close as possible to their steadily increasing flexible price optimum between the times at which price changing opportunities arrive. To keep the model tractable, we specifically assume that once a firm gets the chance to change its pricing policy, it jointly and optimally chooses an initial price level and an

[2] This is a recursive VAR with quarterly data from 1960:2 through 2000:4. The ordering and data are standard: Inflation (CPI growth rate), output (Hodrick-Prescott detrended real per capita GDP) and the interest rate (Fed Funds rate). The results are very similar to Stock and Watson (2001). The initial values shown for the interest rate and inflation are the sample averages.

unconditional rate at which it will update its price in the future, a 'firm-specific inflation rate'.

We motivate this specification by appealing to costs of reoptimization, such as costs of information gathering, decision making, negotiation and communication. The empirical evidence presented by Zbaracki, Ritson, Levy, Dutta and Bergen (2004) emphasizes the importance of reoptimization costs relative to menu costs (Akerlof and Yellen, 1985), the most common motivation for nominal rigidities. Christiano, Eichenbaum and Evans (2001) describe price setting behavior under reoptimization costs as follows: '...in the presence of these costs firms fully optimize prices only periodically, and follow simple rules for changing their prices at other times.' In the existing literature there are two dominant approaches to specifying such a simple rule. In one (Woodford, 2002) firms choose only a price level without updating. In the other (Yun, 1996) firms still choose only a price level but update their prices at the steady state inflation rate at all times. But under both of these approaches only the aggregate price level is sticky while inflation is flexible. Credible disinflations therefore do not cause recessions.

By contrast, when firms employ pricing policies of the kind we propose, an unexpected and permanent decline in the steady state inflation rate targeted by monetary policy entails a slow inflation response and output losses, even if the change in policy is perfectly credible. Less persistent monetary policy shocks also give rise to much more inertia than observed in conventional specifications. There are two main reasons for the slow inflation response. The first is the continuing effect of historic pricing decisions. The economy initially contains a large number of firms that have chosen their price updating rates under the previous policy, and the weighted average of such updating rates is an important component of aggregate inflation. Intuitively, because it is costly for firms to be continuously informed about monetary conditions, it takes time for their periodic inflationary updating to fully reflect the stance of monetary policy on inflation. The second reason for the slow inflation response is the behavior of new price setters. The spread between firms' initially chosen price and the aggregate price level, or 'front loading', is the second component of aggregate inflation. Because firms have the option of updating their prices, front loading will respond very little to the policy change, contributing further to the sluggishness of the inflation response. This effect is very much reinforced in our model by the assumption that it is costly for firms to experience highly time-varying output levels throughout the duration of a pricing policy. A small quadratic cost of excessive output volatility is enough to make firms adjust mostly their inflation updating rate instead of their initial price level. This has the advantage of avoiding another difficulty of the Calvo-Yun model pointed out by Bakshi et al. (2003), namely that if steady state inflation is significant firms in that model will choose price paths that generate very large fluctuations in demand and therefore output. Finally, the real interest rate increase induced by the slow inflation response gives rise to a recession.

The motivation for our pricing specification[3] is similar to that of Mankiw and Reis (2002). These authors present a model where price setters are assumed to be able to reset their price every period, but receive information only at random intervals. This is equivalent to assuming that firms choose a price path, and it generates predictions that qualitatively match important features of the data. The drawback is that the model's microeconomic foundations are not fully laid out, which makes it harder to explore its quantitative predictions and their sensitivity to the values of structural parameters.[4]

The literature related to inflation inertia also encompasses models of backward-looking behavior, imperfect credibility, learning and supply side rigidities. Until quite recently the literature mostly relied on specifications that were not explicitly built on forward-looking optimizing behavior. Fuhrer and Moore (1995) present a relative real wage model, while Ghezzi (2001) and Clarida, Galí and Gertler (1999) modify the Calvo (1983) model to allow

[3] See Calvo, Celasun and Kumhof (2001) for the original statement.

[4] Burstein (2002) provides a general equilibrium model with microeconomic foundations that is related to Mankiw and Reis (2002). However, it is a nonlinear model and complex to solve. We will argue below that concentrating on linear pricing policies is both reasonable and advantageous for quantitative model evaluation.

for a share of price setters to be backward looking, in the sense of using a rule of thumb that depends on lagged inflation. A well-known explanation for inflation inertia during disinflations is lack of credibility, see the papers by Ball (1995) and Calvo and Vegh (1993). However, in many countries where disinflations were costly the monetary authority enjoyed a high degree of credibility, as argued by Ball (1994b). This is therefore only a suitable explanation for a limited number of cases. Models of learning about monetary policy have recently become popular, and clearly such models do give rise to inflation inertia because the contain an element of backward-looking behavior. Two examples are Woodford (2001) and Erceg and Levin (2003). Christiano, Eichenbaum and Evans (2001) generate inflation and output inertia in a rational expectations model by introducing a number of nominal and real supply side rigidities. Their most successful model variant does however still rely on a backward-looking price and wage indexation scheme.

The future plan for this research agenda is as follows. The rational expectations model is completely laid out in this paper, and we show by way of an example that it generates a very high degree of inflation persistence even with a modest degree of price stickiness. We plan to nest this model with a Kalman-filter type learning mechanism, given that learning is currently the most popular explanation for inflation inertia. Our plan is to compare the relative roles of learning and of forward-looking optimizing behavior constrained by structural rigidities, by estimating the model using Bayesian techniques. The model's structure on the real side is very similar to Juillard et al. (2004), apart from price setting where there are big differences. We will therefore follow a similar estimation strategy.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 contains a preliminary comparison of the performance of the two models. Section 4 concludes.

2 THE MODEL

The economy consists of a continuum of measure one of identical price-taking infinitely-lived households indexed by $i \in [0,1]$, a continuum of monopolistically competitive infinitely-lived firms indexed by $j \in [0,1]$, a continuum of monopolistically competitive infinitely-lived financial intermediaries indexed by $z \in [0,1]$ and a government.

2.1 Households

Household i maximizes lifetime utility, which depends on his per capita consumption C_t^i, leisure $1 - L_t^i$ (where 1 is the fixed time endowment and L_t is total labor supply), and real money balances M_t^i/P_t (where M_t is nominal money and P_t is the aggregate price index):

$$Max \quad E_0 \sum_{t=0}^{\infty} \beta^t \left\{ S_t^c \frac{(H_t^i)^{1-\frac{1}{\gamma}}}{1-\frac{1}{\gamma}} + S_t^L \psi \frac{(1-L_t^i)^{1-\frac{1}{\gamma}}}{1-\frac{1}{\gamma}} + \frac{a}{1-\epsilon} \left(\frac{M_t^i}{P_t} \right)^{1-\epsilon} \right\} . \tag{1}$$

Throughout, shocks are denoted by S_t^x, where x is the sector subject to the shock. Households exhibit habit persistence with respect to C_t^i, with habit parameter ν:

$$H_t^i = C_t^i - \nu C_{t-1}^i \quad . \tag{2}$$

Consumption C_t^i is a CES aggregator over individual varieties $c_t^i(j)$, with time-varying elasticity of substitution $\sigma_t > 1$,

$$C_t^i = \left(\int_0^1 c_t^i(j)^{\frac{\sigma_t - 1}{\sigma_t}} dj \right)^{\frac{\sigma_t}{\sigma_t - 1}} \quad , \tag{3}$$

and the aggregate price index P_t is the consumption based price index associated with this consumption aggregator,

$$P_t = \left(\int_0^1 P_t(j)^{1-\sigma_t} dj \right)^{\frac{1}{1-\sigma_t}} \quad . \tag{4}$$

Capital accumulation follows time-to-build technologies, with a six-period lag between the investment decision I_t^i and the point at which the investment decision leads to an addition to the productive capital stock:

$$K_{t+1}^i = (1-\Delta) K_t^i + I_{t-5}^i \quad . \tag{5}$$

Furthermore, changes in the level of investment spending are subject to a quadratic adjustment cost paid out of household income. Each investment decision represents a commitment to a spending plan over six periods, starting in the period of the decision and ending one period before capital becomes productive. The shares of the investment project that have to be disbursed in each period are given by $\omega_j, \;\; j = 0, ..., 5$, with $\Sigma_{j=0}^{5}\omega_j = 1$. Actual investment spending J_t^i is therefore given by

$$J_t^i = \omega_0 I_t^i + \omega_1 I_{t-1}^i + \omega_2 I_{t-2}^i + \omega_3 I_{t-3}^i + \omega_4 I_{t-4}^i + \omega_5 I_{t-5}^i \;\; . \tag{6}$$

In addition to money households hold one period nominal government bonds B_t with gross nominal return i_t.[5] Their income consists of nominal wage income $W_t^i L_t^i$, nominal returns to capital $R_t^k K_t^i$, lump-sum profit redistributions from firms $\int_0^1 \Pi_t(j)dj$, and lump-sum transfers from the government $P_t\tau_t$. Expenditure consists of consumption spending $P_t C_t^i$, investment spending $P_t J_t^i$, and quadratic adjustment costs on the capital stock. The budget constraint is therefore

$$\begin{aligned} B_t^i &= i_{t-1}B_{t-1}^i + M_{t-1}^i - M_t^i + W_t^i L_t^i + R_t^k K_t^i + \int_0^1 \Pi_t(j)dj + P_t\tau_t^i \\ &\quad -P_t C_t^i - P_t J_t^i - P_t \frac{\theta}{2} K_t^i \left(\frac{I_t^i}{K_t^i} - \Delta S_t^I \right)^2 \;\; . \end{aligned} \tag{7}$$

We assume complete contingent claims markets for labor income, and identical initial endowments of capital, bonds and money. Then all optimality conditions will be the same across households, except for labor supply. We therefore drop the superscript i. The first-order conditions for $c_t(j)$, B_t, C_t, I_t and K_{t+1}, are as follows:

$$c_t(j) = C_t \left(\frac{P_{t+k}(j)}{P_{t+k}} \right)^{-\sigma_t} \tag{8}$$

$$\lambda_t = \beta i_t E_t \left(\frac{\lambda_{t+1}}{\pi_{t+1}} \right) \tag{9}$$

$$S_t^c H_t^{-\frac{1}{\gamma}} - \beta\nu E_t S_{t+1}^c H_{t+1}^{-\frac{1}{\gamma}} = \lambda_t \tag{10}$$

[5] All interest and inflation rates will be expressed in gross terms.

$$E_t\left\{\omega_0\lambda_t+\omega_1\beta\lambda_{t+1}+\omega_2\beta^2\lambda_{t+2}+\omega_3\beta^3\lambda_{t+3}+\omega_4\beta^4\lambda_{t+4}+\omega_5\beta^5\lambda_{t+5}\right\} \tag{11}$$
$$= \beta^5E_t\left\{\lambda_{t+5}q_{t+5}\right\}-\lambda_t\theta\left(\frac{I_t}{K_t}-\Delta S_t^I\right)$$

$$\lambda_t q_t=\beta E_t\lambda_{t+1}\left[q_{t+1}(1-\Delta)+r_{t+1}^k-\frac{\theta}{2}\left(\frac{I_{t+1}}{K_{t+1}}-\Delta S_t^I\right)^2+\theta\left(\frac{I_{t+1}}{K_{t+1}}-\Delta S_{t+1}^I\right)\frac{I_{t+1}}{K_{t+1}}\right] \tag{12}$$

We will return to the household's wage setting problem at a later point, as we will be able to exploit analogies with the firms' price setting. Linearized first-order conditions are presented in a separate Technical Appendix (available on request).

2.2 Firms

2.2.1 Cost Minimization

Each firm $j\in[0,1]$ sells a distinct product variety. Heterogeneity in price setting decisions and therefore in demand for individual products arises because each firm receives its price changing opportunities at different, random points in time. Following Calvo (1983) it is assumed that these opportunities follow a geometric distribution, so that the probability $(1-\delta)$ of a firm's receiving a new opportunity is independent of how long ago it was last able to change its price. It is also independent across firms, so that it is straightforward to determine the aggregate distribution of prices.

The production function for variety j is given by

$$y_t(j)=S_t^y l_t(j)^{1-\alpha}k_t(j)^{\alpha}\ , \tag{13}$$

with corresponding real marginal cost

$$mc_t=Aw_t^{1-\alpha}\left(u_t\right)^{\alpha}/S_t^y\ , \tag{14}$$

where $A=\alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}$. Let $L_t^i=\int_0^1 L_t^i(j)dj$ and $L_t=\int_0^1 l_t(j)dj$, where firm j's demand for aggregate labor is given by $l_t(j)=\left(\int_0^1 L_t^i(j)^{\frac{\sigma_t^w-1}{\sigma_t^w}}di\right)^{\frac{\sigma_t^w}{\sigma_t^w-1}}$, a CES labor production function with time varying elasticity of substitution σ_t^w. Capital, as we will see, is supplied by a continuum of intermediaries indexed by $z \in [0,1]$, and we have $k_t^z = \int_0^1 k_t^z(j)dj$ and $k_t = \int_0^1 k_t(j)dj$, where firm j's demand for aggregate capital is given by $k_t(j) = \left(\int_0^1 k_t^z(j)^{\frac{\sigma^k-1}{\sigma^k}} dz\right)^{\frac{\sigma^k}{\sigma^k-1}}$, a CES capital production function with constant elasticity of substitution σ^k. Finally, aggregate output is given by $Y_t = \left(\int_0^1 y_t(j)^{\frac{\sigma_t-1}{\sigma_t}} dj\right)^{\frac{\sigma_t}{\sigma_t-1}}$, and we define the auxiliary variable $\tilde{Y}_t = \int_0^1 y_t(j)dj$. It is straightforward to show that the steady state values and the log-deviations from steady state of the last two variables are equal. Then, given that factor markets are competitive so that all firms face identical costs of hiring capital and labor, we can derive the following aggregate input demand conditions:

$$L_t = (1-\alpha)\frac{mc_t}{w_t}\tilde{Y}_t \quad , \tag{15}$$

$$k_t = \alpha\frac{mc_t}{u_t}\tilde{Y}_t \tag{16}$$

2.2.2 Profit Maximization

Each firm maximizes the present discounted value of real profits. The first two determinants of profit are real revenue $P_{t+k}(j)y_{t+k}(j)/P_{t+k}$ and real marginal cost $mc_{t+k}y_{t+k}(j)$. The two key differences between our model and other models of nominal rigidities in rational expectations settings concern first the manner in which firms set their prices when they receive an opportunity to do so, and second the cost of setting prices far away from prevailing average market prices P_t. Let us first turn to the latter. As shown by Bakshi et al. (2003), conventional price-setting in a Calvo-Yun type model implies that firms optimally choose prices that imply a very large variability in demand and therefore output. It is clear that such variability is very costly to firms for a variety of reasons, including difficulties in customer and supplier relationships. We therefore assume that firms face a small quadratic cost of deviating from the output level of its average competitor, meaning the firm that charges the current market average price. Such costs make no difference in Calvo-Yun type models because of the rigidity of the assumed pricing policy available to firms, namely the fact that firms can only choose a new price level once and thereafter need to either keep their price level constant or update it at the steady state inflation rate. However, in conjunction with our more flexible assumptions about pricing, quadratic costs lead to a dramatically improved performance of the model in terms of its ability to generate inflation persistence in response to shocks.

Specifically, we assume that when a firm j gets an opportunity to decide on its pricing policy, it chooses both its current price level V_t^j and the rate v_t^j at which it will update its price from today onwards until the time it is next allowed to change its policy.[6] At any time $t+k$ when the time t policy is still in force, its price is therefore[7]

$$P_{t+k}(j) = V_t^j (v_t^j)^k \quad . \tag{17}$$

Firms discount profits expected in period $t+k$ by the k-period ahead real intertemporal marginal rate of substitution and by δ^k, the probability that their period t pricing policy will still be in force k periods from t. They take into account households' demand for their output (8). Their profit maximization problem is therefore

$$\underset{V_t, v_t}{Max} E_t \sum_{k=0}^{\infty} (\delta\beta)^k \lambda_{t+k} \left[\left(\frac{V_t (v_t)^k}{P_{t+k}} \right)^{1-\sigma_t} Y_{t+k} \right. \tag{18}$$

$$\left. -mc_{t+k} \left(\frac{V_t (v_t)^k}{P_{t+k}} \right)^{-\sigma_t} Y_{t+k} - \frac{\phi}{2} \frac{\left(y_{t+k}(j) - Y_{t+k}\right)^2}{Y_{t+k}} \right] \quad .$$

Note that the firm specific superscript j can be dropped because all firms that get a price changing opportunity at time t will behave identically. We define the front-loading term for price setting, the ratio of a new price setter's first period price to the market average price, as $p_t \equiv V_t/P_t$, cumulative aggregate inflation as $\Pi_{t,k} \equiv \prod_{j=1}^{k} \pi_{t+j}$ for $k \geq 1$ $(\equiv 1$ for $k=0)$,

[6] We emphasize that our modelling of nominal rigidities builds in less ad-hoc behavior than the Calvo-Yun model, because it imposes fewer exogenous constraints on the firm's profit maximization problem.

[7] As for the possibility of more general price paths, we would argue that it is natural to focus on equilibria characterized by a constant steady state growth rate of the nominal anchor. The model can then be solved by linearizing around that steady state, in which case it is sufficient to allow firms to specify their pricing policies up to the growth rate of their price path. This permits the use of conventional solution methods, which makes quantitative analysis much more straightforward.

and the mark-up term as $\mu_t = \frac{\sigma_t}{\sigma_t - 1}$. Then the firm's first order conditions for the choice of its initial price level V_t and its inflation updating rate v_t are

$$p_t = \mu_t \frac{E_t \sum_{k=0}^{\infty} (\delta\beta)^k \lambda_{t+k} y_{t+k}(j) \left(mc_{t+k} + \phi \left(\frac{y_{t+k}(j) - Y_{t+k}}{Y_{t+k}} \right) \right)}{E_t \sum_{k=0}^{\infty} (\delta\beta)^k \lambda_{t+k} y_{t+k}(j) \left(\frac{(v_t)^k}{\Pi_{t,k}} \right)} \quad , \tag{19}$$

$$p_t = \mu_t \frac{E_t \sum_{k=0}^{\infty} (\delta\beta)^k k \lambda_{t+k} y_{t+k}(j) \left(mc_{t+k} + \phi \left(\frac{y_{t+k}(j) - Y_{t+k}}{Y_{t+k}} \right) \right)}{E_t \sum_{k=0}^{\infty} (\delta\beta)^k k \lambda_{t+k} y_{t+k}(j) \left(\frac{(v_t)^k}{\Pi_{t,k}} \right)} \quad . \tag{20}$$

The intuition for this result becomes much clearer once the conditions are linearized. As this is algebraically very involved, the details are presented in the Technical Appendix. We discuss the key equations here. They replace the traditional one-equation representation of aggregate inflation through a New Keynesian Phillips curve with a three-equation system in $\hat{\pi}_t$, $\hat{v}_t$ and an inertial variable $\hat{\psi}_t$ defined as

$$\hat{\psi}_t = (1 - \delta) \sum_{k=0}^{\infty} \delta^k \hat{v}_{t-1-k} \quad . \tag{21}$$

This is, in deviation form, the weighted average of all those past firm-specific inflation rates that are still in force between periods $t-1$ and t, and which therefore enter into period t aggregate inflation. Then we can write

$$\hat{\pi}_t = \frac{1 - \delta}{\delta} \hat{p}_t + \hat{\psi}_t \quad . \tag{22}$$

This is a key equation, because its two components reflect the two main sources of inflation inertia. Following a monetary policy shock, the continuing effects of price updating decisions made under the old monetary policy are represented by $\hat{\psi}_t$, and this is the main source of inertia in aggregate inflation. In addition, if a monetary policy shock is very persistent then new price setters respond mainly through changes in their updating rates. In that case front-loading $\hat{p}_t$ responds very little, thereby generating further inertia.

But if monetary policy shocks are not very persistent, it turns out that inflation dynamics can nevertheless be dominated by the front-loading term - in effect, firms choose to behave like Calvo-Yun price setters even though they can also choose their price updating rate.

However this behavior, as we discussed, implies very large fluctuations in demand and therefore output. The introduction of only a very small quadratic adjustment cost of such fluctuations is then enough to make firms behave very differently. Consider the example of a temporary disinflationary shock, starting from a significantly positive steady state inflation rate. A Calvo-Yun type price setter would respond to such a shock by setting his initial price well below the market price and would then let it grow (as he is assumed not to have a choice in that matter) at the steady state inflation rate so that eventually his price would be well above the market average. The fluctuations in his demand would be dramatic given the elasticities of substitution typically assumed in this type of model. Costs of deviating from market average output would make almost no difference to this argument. Now consider a firm that is given more flexibility in price setting by also having the option of adjusting its price updating rate. During a temporary disinflation it could lower that updating rate, which would allow it to stay much closer to market average prices both on impact and during the entire duration of the price contract. Doing so would avoid the extreme and costly output fluctuations it would otherwise experience. In an economy populated by such firms the term $\hat{\psi}_t$ is the dominant driving force of aggregate inflation. For the reasons mentioned above, inflation will therefore by much more inertial.

Household nominal wage setting follows the same pattern as just discussed, the only major difference being that mc_t is replaced by mrs_t/w_t.

2.3 Financial Intermediaries

We assume that all capital is intermediated by a continuum of intermediaries indexed by $z \in [0, 1]$. They are competitive in their input market, renting capital K_t from households at rental rate r_t^k. On the other hand, they are monopolistically competitive in their output market, lending capital varieties k_t^z to firms at rental rates u_t^z. This gives rise to sluggish user costs of capital, which play a similar role in the model to sticky wages in labor markets. Taken together, sticky wages and sticky user costs make marginal cost react sluggishly to shocks, and this can translate to sluggish responses in inflation. In preliminary calibrations of the model this channel however seems less powerful than firms' price setting behavior combined with quadratic costs of output volatility. The final word on the two transmission channels will come in the Bayesian estimation. If sticky user cost is not important in the data, they will hopefully tell us so.

Every firm j must use composite capital, a CES aggregate of the varieties supplied by different intermediaries denoted by $k_t(j) = \left(\int_0^1 \left(k_t^z(j)\right)^{\frac{\sigma^k-1}{\sigma^k}} dz\right)^{\frac{\sigma^k}{\sigma^k-1}}$. Firms' costs minimization yields demands

$$k_t^z = k_t \left(\frac{u_t^z}{u_t}\right)^{-\sigma^k} \quad , \tag{23}$$

where the overall user cost to firms is given by

$$u_t = \left(\int_0^1 \left(u_t^z\right)^{1-\sigma^k} dz\right)^{\frac{1}{1-\sigma^k}} \quad . \tag{24}$$

The profit maximization problem of the intermediary is similar to (18). We define the gross intermediation spread as $s_t = u_t/r_t^k$, the gross rate of change of user cost as $\pi_t^k = u_t/u_{t-1}$, with cumulative rate of change $\Pi_{t,i}^k$ similar to firms above, and we define the mark-up as $\mu_k = \sigma^k/(\sigma^k - 1)$ (assumed not time-varying). Then the first-order conditions are

$$p_t^k E_t \sum_{i=0}^{\infty} \left(\delta^k \beta\right)^i \lambda_{t+i} k_{t+i}^z = \mu_k E_t \sum_{i=0}^{\infty} \left(\delta^k \beta\right)^i \lambda_{t+i} k_{t+i}^z \left[\left(\frac{\Pi_{t,i}^k}{\left(v_t^k\right)^i}\right) \frac{1}{s_t} + \phi^k \left(\frac{k_{t+i}^z - k_{t+i}}{k_{t+i}}\right)\right] \quad ,$$

$$p_t^k E_t \sum_{i=0}^{\infty} \left(\delta^k \beta\right)^i i\lambda_{t+i} k_{t+i}^z = \mu_k E_t \sum_{i=0}^{\infty} \left(\delta^k \beta\right)^i i\lambda_{t+i} k_{t+i}^z \left[\left(\frac{\Pi_{t,i}^k}{\left(v_t^k\right)^i}\right) \frac{1}{s_t} + \phi^k \left(\frac{k_{t+i}^z - k_{t+i}}{k_{t+i}}\right)\right] \quad .$$

The linearized FOC for this problem are exactly analogous to those for firm price setting, with two modifications. First, the term $\widehat{mc}_t$ is replaced with $-\hat{s}_t$, and second the mark-up μ_k is assumed to not be time-varying.

2.4 Government

The government's fiscal policy is assumed to be Ricardian. In particular, we assume that the government budget is balanced period by period through lump-sum taxes/transfers, and that the initial stock of government bonds is zero. The budget constraint is therefore simply:

$$\tau_t = \frac{M_t - M_{t-1}}{P_t} \quad , \tag{25}$$

We assume that the central bank pursues the following interest rate rule for its policy instrument i_t:

$$i_t = (i_{t-1})^{\xi} \left(\beta^{-1} \bar{\pi} \left(\frac{E_t(\pi_{t+1})}{\bar{\pi}} \right)^{\rho} \left(\frac{y_t}{\bar{y}} \right)^{\theta} \right)^{1-\xi} S_t^{int} \quad . \tag{26}$$

The first two components on the right-hand side equal the steady state gross nominal interest rate. The inflation target $\bar{\pi}$ is an integral part of the specification of monetary policy, and permanent monetary policy shocks will be modeled as permanent changes in $\bar{\pi}$. The central bank interest rate response to expected deviations of inflation from its steady state value has the response coefficient ρ. The response coefficient θ applies to the output gap. Finally, S_t^{int} is a zero mean autocorrelated monetary policy shock[8] with law of motion

A *government policy* is defined as a set of stochastic processes $\{i_s, \tau_s\}_{s=t}^{\infty}$ such that, given stochastic processes $\{M_s, P_s, y_s, S_s^{int}\}_{s=t}^{\infty}$, the conditions (25) and (26) hold for all $s \geq t$.

2.5 Equilibrium

An *allocation* is given by $\{B_s, M_s, c_s, L_s, k_s, y_s, c_s(j), l_s(j), k_s(j), y_s(j), j \in [0,1]\}_{s=t}^{\infty}$, a list of stochastic processes. A *price system* is a list of stochastic processes $\left\{P_s, W_s, R_s^k, U_s, P_s(j), V_s^j, v_s^j, j \in [0,1]\right\}_{s=t}^{\infty}$. *Shock processes* are a list of stochastic processes $\left\{S_s^c, S_s^L, S_s^I, S_s^y, S_s^g, S_s^{int}, \mu_s, \mu_s^w\right\}_{s=t}^{\infty}$. Then equilibrium is defined as follows:

An equilibrium is an allocation, a price system, a government policy and shock processes such that

*(a) given the government policy, the price system and shock processes, the allocation solves the household's problem of maximizing (*1*) subject to (*7*),*

(b) given the government policy, shock processes, the restrictions on price setting, and

[8] Such shocks, apart from capturing deliberate decisions to deviate temporarily and possibly persistently from a systematic rule, may also represent the effects on interest rates of autocorrelated inflation forecast errors. We thank Charles Goodhart for emphasizing this point to us.

the sequences $\{P_s, MC_s, Y_s\}_{s=0}^{\infty}$, *the sequences* $\{V_s^j, v_s^j, j \in [0,1]\}_{s=0}^{\infty}$ *solve firms' problem of maximizing (*18*),*

(c) the goods market clears for all goods and at all times,

(d) the labor market clears at all times,

(e) the market for capital clears at all times,

(f) the bond market clears at all times.

3 MACROECONOMIC DYNAMICS

We calibrate parameter values for the quarterly frequency. We assume a degree of price stickiness of only $\delta = 0.5$ for prices, and similarly for wages and user costs of capital. This implies an average contract length of two quarters. The parameter determining the quadratic cost of output volatility is in all cases set to be small at 0.1. The intertemporal elasticity of substitution γ is assumed to equal 0.5.[9] The proportion of time spent working in steady state $\bar{L} = 1/3$ is based on the evidence cited in Kydland (1995). The value for the habit parameter $\nu = 0.72$ is close to Boldrin, Christiano and Fisher (2001). We follow the literature in assuming $\beta = 0.99$. Our parameter choices for the monetary policy rule are $\rho = 1.5$ and $\theta = 0.5$ for inflation and output, and an interest rate smoothing parameter of $\xi = 0.5$. As for the shock processes, we choose the AR1-coefficient of monetary policy shocks to be equal to 0.8.

We solve the model by DYNARE, and use impulse responses to display the dynamic response of the economy to a 50 basis points monetary policy shock. The results are shown in Figure 2. Inflation exhibits both a very gradual initial response, inertia, and a very prolonged deviation from its (new) steady state, persistence. This is first because of the continuing effect of pricing decisions taken under the old, higher inflation monetary regime, and second because front-loading responds very little. The latter is due to the quadratic cost of output

[9] See e.g. Hansen and Singleton (1996).

volatility. The inflation deviation from steady state and the high response coefficient to such deviations in the monetary policy rule imply that nominal interest rates initially stay very high, and more importantly that there is a steep rise in the real interest rate. This causes consumption, output and therefore labor demand to drop, i.e. we observe the recession that is associated with disinflations in the data. This in turn lowers real marginal cost, which exerts downward pressure on prices so that inflation begins to fall. At the same time the recession induces lower nominal interest rates through the monetary policy rule. The combination of these two effects starts to lower real interest rates, and once this process is complete the recession ends and inflation drops to its new target. An output sacrifice is therefore unavoidable in bringing down inflation.

Because following the fairly persistent monetary policy shock aggregate inflation is expected to be lower than its initial value for some time, firms have an incentive to change the long-run component of their pricing policies, thereby delaying the instantaneous response of inflation. This reason for inertia is different from the one that is commonly stressed in the literature, which relies on a slow response of marginal cost to shocks. Of course the latter is also present in our model, and our final estimation will pay attention to the contribution that this makes. But preliminary results from simulating the model without our price setting behavior indicate that sticky pricing policies are essential.

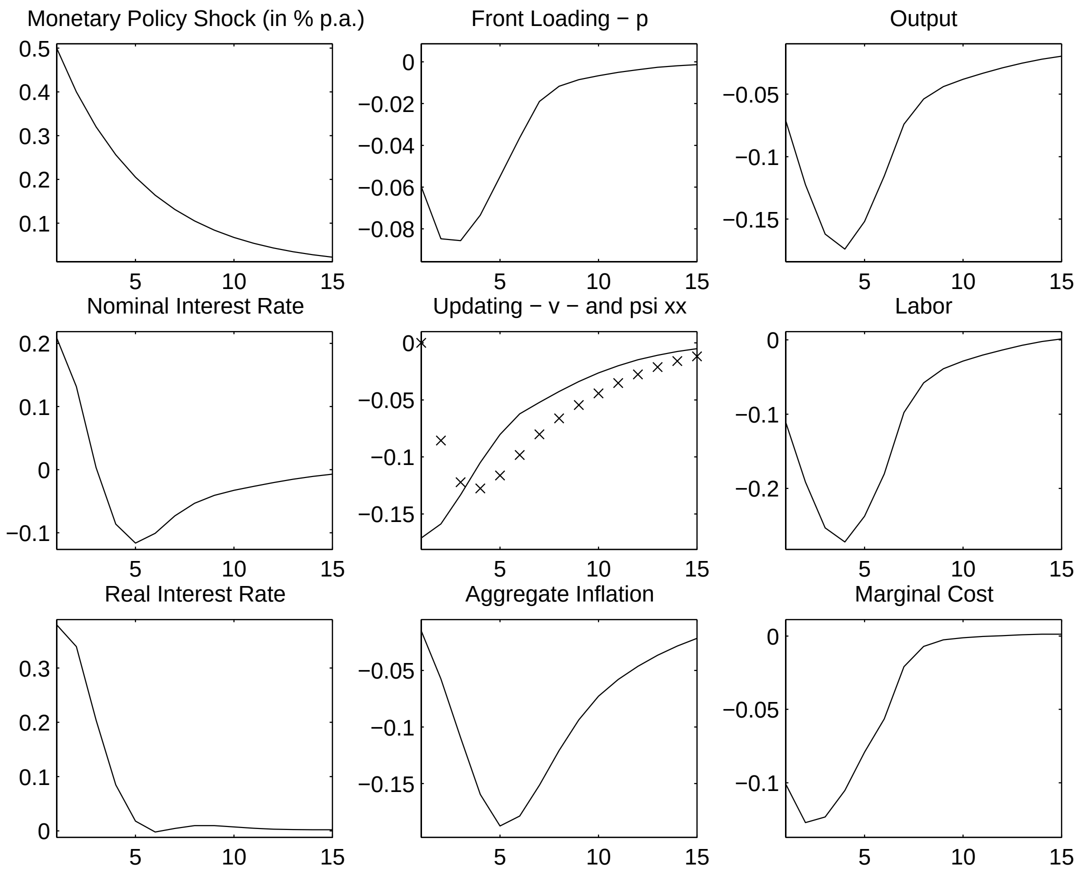

Figure 2: Impulse Responses to a Monetary Policy Shock

4 CONCLUSION

This paper presents a monetary model with nominal rigidities and maximizing, rational, forward-looking households, intermediaries and firms. It differs from conventional models in this class in two key respects. First, firms set pricing policies, including an updating rate for future prices, instead of price levels. Second, output fluctuations during the period of a pricing policy are costly to firms.

The paper is motivated by some important shortcomings of conventional models, namely their inability to generate inflation inertia, inflation persistence and recessionary disinflations without introducing either an ad-hoc updating rule or learning. While learning is clearly important, we are interested in the contribution that structural rigidities can make in a forward-looking and optimizing model. The model does generate all of the above effects in response to monetary policy shocks. The channel for these effects in the model is the long-run or inflation updating component of firms' pricing policies. This is distinct from another frequently stressed reason for inflation inertia and persistence, a slow response of marginal cost to shocks, which is also present in our model because all components of marginal cost, not just wages, are sticky.

We are currently nesting the above model with a Kalman-filter learning mechanism, and are in the process of estimating that model. Our aim is to establish the relative importance of learning versus structural rigidities in a fully-optimizing rational expectations model. Also, within the rational expectations model, we will analyze the relative contributions of sticky marginal costs and the type of pricing policies we propose.

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