The Multiplier for Price Stickiness*

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Abstract

We propose a DSGE model that accounts well for the positive serial correlation of U.S. inflation and persistence in aggregate quantities in response to monetary policy shocks. Our model is fully consistent with the optimizing behavior of monopolistically competitive households and firms and does not require the use of ad hoc backward-looking terms. It exploits strong interactions between a roundabout production structure, nominal rigidities and monetary policy inertia giving rise to a multiplier for price stickiness (MPS) in the spirit of Basu (American Economic Review, 1995). While helping to deliver strong inflation inertia, the MPS also plays a critical role generating persistent and hump-shaped responses of aggregate quantities to a monetary policy shock even with a high frequency of price adjustment. Monetary policy and investment-specific shocks are identified as plausible sources of the strong positive comovement between hours and output observed during the postwar business cycle, but not neutral technology shocks.

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1 Introduction

A major puzzle emerging in the recent business cycle literature is that once imposing the rigor and discipline of quantitative general equilibrium in rational expectations models with staggered nominal contracts (Taylor, 1980), one finds this class of models can hardly explain the inertial behavior of inflation (Nelson, 1998; Galí and Gertler, 1999; Cogley and Sbordone, 2008) and persistence in aggregate quantities in response to monetary policy shocks (Chari, Kehoe and McGrattan, 2000; Estrella and Fuhrer, 2002) unless ad hoc backward-looking components are called to the rescue. These mechanisms include rule-of-thumb behavior of price-setters (Galí and Gertler, 1999) and the backward indexation of wages and prices (Christiano, Eichenbaum and Evans, 2005), both enhancing the persistence of nominal and real variables in response to monetary policy shocks.

However, these assumptions have been criticized because they lack a convincing microfoundation (Woodford, 2007; Cogley and Sbordone, 2008; Chari, Kehoe and McGrattan, 2009) and are inconsistent with micro level evidence on the frequency of wage and price adjustments (Bils and Klenow, 2004; Nakamura and Steinsson, 2008; Barattieri, Basu and Gottschalk, 2010).

The present paper proposes an alternative theory of short-run inflation dynamics and persistence in aggregate quantities that does not require the use of arbitrary backward-looking terms. In our framework, the decisions of households and firms are cast entirely within explicit individual optimization problems. Our work complements ongoing research that seeks to identify new sources of inflation and output persistence in dynamic stochastic general equilibrium (DSGE) settings.

Our model exploits strong interactions between the increased roundaboutness of goods produced in modern industrialized economies, nominal rigidities and endogenous monetary policy, especially the degree of policy inertia (see also Long and Plosser, 1983; Basu, 1995; Bergin and Feenstra, 2000; Huang, Liu and Phaneuf, 2004; Dotsey and King, 2006; Nakamura and Steinsson, 2010). Basu (1995) offers evidence showing that the interplay between intermediate goods and a state-dependent price rigidity can possibly act as a multiplier for price stickiness (hereafter MPS). Working from an aggregate-demand driven model with small (menu) costs of changing prices and no capital accumulation, he shows that when prices are costly to change, firms using intermediate goods to produce inherit increased price sluggishness through the rigid intermediate input price that becomes a component of their marginal cost.

The questions which are central to our paper are threefold. First, how important
is the MPS once evaluated from a business cycle model that meets the current standards of DSGE modeling? Second, can it help produce a high serial correlation of inflation when the model is asked to comply to micro level evidence on wage and price adjustments (Bils and Klenow, 2004; Nakamura and Steinsson, 2008; Barattieri, Basu and Gottschalk, 2010)? Third, how does the MPS contribute to the transmission of monetary policy shocks?

To address these questions, we propose a DSGE model featuring input-output linkages between firms and other key structural features of the new generation of small-scale monetary business cycle models (Huang, Liu and Phaneuf, 2004; Christiano, Eichenbaum and Evans, 2005; Smets and Wouters, 2007; Justiniano and Primiceri, 2008). These include habit formation in consumption, investment adjustment costs, variable capital utilization and fixed costs in production. The model also embeds Calvo-style staggered wage and price contracts. Monetary policy is represented by a Taylor-type of rule which says that the monetary authority systematically reacts to deviations of inflation and output from targets (Taylor, 1993), while trying to smooth short-term movements in nominal interest rates (Clarida, Galí and Gertler, 2000).

After the model has been laid out in section 2 and calibration issues have been discussed in section 3, we examine in section 4 a model in which sticky prices interact with a roundabout production structure and endogenous monetary. This allows us to directly assess Basu’s contention that the interplay between an input-output production structure and nominal price rigidity gives rise to a MPS. With a plausible calibration of parameters, we find that the MPS is quantitatively important. It helps generate a positive serial correlation of inflation which parallels that found in the relative real wage contracting model of Fuhrer and Moore (1995). But in contrast to Fuhrer and Moore, we obtain this finding using a model which is fully consistent with the optimizing behavior of households and firms.

We also show that the MPS is an important channel of monetary transmission, playing a critical role in producing persistent and hump-shaped responses of output, consumption, investment and hours to a monetary policy shock. The persistent and hump-shaped responses of aggregate quantities implied by the MPS not only represent an answer to the so-called persistence problem unveiled by Chari, Kehoe and McGrattan (2000), but are broadly consistent with the consensus view emerging from the empirical literature on the effects of monetary policy shocks (Barro, 1978; Mishkin, 1982; Galí, 1992; Bernanke and Mihov, 1998; Christiano, Eichenbaum and Evans, 1999, 2005; Romer and Romer, 2004; Normandin and Phaneuf, 2004). To the
best of our knowledge, this is the first time a DSGE model is able to produce persistent, hump-shaped impulse responses of aggregate quantities to a monetary policy shock without having to use \textit{ad hoc} backward-looking elements.

How does the MPS generate these findings? The evidence reported in Christiano, Eichenbaum and Evans (2005) suggests that a model featuring sticky prices and flexible wage decisions will predict a strong reaction of inflation to a monetary policy shock and a weak and short-lived response of output that does not display the typical hump-shaped pattern. This leads them to conclude that staggered price contracts do not contribute much to inflation and output persistence at the onset of a monetary policy shock. But unlike our model, theirs does not feature a roundabout production structure. By contrast, we find that once input-output linkages and sticky prices are combined, the autocorrelations of inflation are much higher and the responses of aggregate quantities to a monetary policy shock are much stronger, persistent and hump-shaped.

Our findings can be briefly explained as follows. In the standard new keynesian sticky-price model, inflation equals a discounted stream of expected future marginal costs. Without input-output linkages, the marginal cost records two flexible components: the rental rate on capital services and the wage index. With prices that are quite flexible, inflation is weakly persistent. With roundabout production, the marginal cost includes a third component in the form of the rigid intermediate input price, whose importance increases with the share of materials input. Both the marginal cost and inflation become less sensitive to the monetary policy shock, leading to higher autocorrelations of inflation, as well as persistent and hump-shaped responses of aggregate quantities. These findings therefore strongly suggest that the MPS is important quantitatively.

Endogenous monetary policy, and in particular the degree of policy inertia, plays a significant role shaping the MPS: the higher is the interest-rate smoothing parameter in the policy rule, the larger, more persistent and hump-shaped are the responses of aggregate quantities to a monetary policy shock. Since this parameter is high according to recent studies, policy inertia is an important element strengthening the MPS.\footnote{For instance, Smets and Wouters (2007) report an estimate for the interest-rate smoothing parameter of 0.81 for postwar U.S., and Justiniano and Primiceri (2008), an estimate of 0.85. Gali and Gertler (2007) argue that this parameter is well above 0.6 empirically and can be as high as 0.9.}

But despite several interesting implications, the model with a roundabout production and sticky prices is affected by two shortcomings. First and following Lucas and
Rapping (1969), employment fluctuations should be associated with much smaller variations in the real wage. In the same vein, some evidence says that the real wage weakly increases in the wake of an expansionary monetary policy shock (Christiano, Eichenbaum and Evans, 1997, 2005). In contrast, the sticky-price model with materials input predicts a sharp increase in the real wage following a negative innovation to the nominal interest rate. Second, while movements in materials input ought to be roughly proportionate to value-added and hours worked over the business cycle (Dotsey and King, 2006), the model predicts materials input fluctuates significantly more than hours worked and value-added.

To overcome these shortcomings, we add sticky wages to the model (see section 5). While leaving other main findings intact, sticky wages dampen the increase in real wage and magnify movements in both hours and output relative to materials input. With materials input, sticky wages and sticky prices, the marginal cost has three components, two of which—the intermediate input price and the wage index—that are rigid. The marginal cost becomes less responsive to the monetary policy shock. Price sluggishness increases and the responses of aggregate quantities are stronger.

A few other substantive findings can be summarized as follows. When decreasing the median waiting time between price adjustments to only 4.3 months as microeconomic evidence by Bils and Klenow (2004) seems to suggest, we find that a monetary policy shock still is followed by persistent and hump-shaped responses in aggregate quantities. Also, if we assume that the frequency of wage adjustment is much lower than the frequency of price adjustment as microeconomic evidence by Barattieri, Basu and Gottschalk (2010) seems to suggest, we still find that the real wage is weakly procyclical at the onset of a monetary policy shock. When accounting later in the paper (section 6) for neutral technology and investment-specific technology shocks, we find that the later type of shock generates persistent and hump-shaped responses of aggregate quantities, a weakly procyclical real wage, and roughly proportionate movements in materials input, value-added and hours. In contrast, neutral technology shocks give rise to a short-run decline in hours while increasing output. We conclude that monetary policy and investment-specific technology shocks are plausible forces that may have shaped the strong positive comovement between hours and output observed during the postwar period, but not neutral technology shocks.
2 The Model

The economy is populated by a large number of households, each endowed with a differentiated labor skill indexed by \( i \in [0, 1] \) and by a large number of firms, each producing a differentiated good indexed by \( j \in [0, 1] \). A government conducts monetary policy.

2.1 The Model

Denote by \( L_t \) a composite of differentiated labor skills \( L_t(i) \) for \( i \in [0, 1] \) such that \( L_t = \left[ \int_0^1 L_t(i)^{(\sigma-1)/\sigma} di \right]^{\sigma/(\sigma-1)} \), and by \( X_t \) a composite of differentiated goods \( X_t(j) \) for \( j \in [0, 1] \) such that \( X_t = \left[ \int_0^1 X_t(j)^{(\theta-1)/\theta} dj \right]^{\theta/(\theta-1)} \), where \( \sigma \in (1, \infty) \) and \( \theta \in (1, \infty) \) are the elasticity of substitution between the skills and between the goods, respectively. Both the composite skill and the composite good are produced in a perfectly competitive aggregate sector.

The demand functions for labor skill of type \( i \) and for good of type \( j \) resulting from optimizing behavior in the aggregation sector are respectively given by

\[
L_t^d(i) = \left[ \frac{W_t(i)}{W_t} \right]^{-\sigma} L_t,
\]

\[
X_t^d(j) = \left[ \frac{P_t(j)}{P_t} \right]^{-\theta} X_t,
\]

where \( W_t \) is the wage rate of the composite skill which is related to the wage rates \( W_t(i) \) for \( i \in [0, 1] \) of the differentiated skills by \( W_t = \left[ \int_0^1 W_t(i)^{(1-\sigma)/\sigma} di \right]^{1/(1-\sigma)} \), and \( P_t \) is the price of the composite good related to the prices \( P_t(j) \) for \( j \in [0, 1] \) of the differentiated goods by \( P_t = \left[ \int_0^1 P_t(j)^{(1-\theta)/\theta} dj \right]^{1/(1-\theta)} \).

While the composite skill serves only as an input for the production of each differentiated good, the composite good serves either as a final consumption or investment good, or as an intermediate production input. The production of good \( j \) requires the use of intermediate goods, effective capital services and labor as inputs. The production function for a good of type \( j \) is given by

\[
X_t(j) = \begin{cases} 
\Gamma_t(j)^{\phi}[\widehat{K}_t(j)^{\alpha}L_t(j)^{1-\alpha}]^{1-\phi} - F, & \text{if } \Gamma_t(j)^{\phi}[\widehat{K}_t(j)^{\alpha}L_t(j)^{1-\alpha}]^{1-\phi} \geq F \\
0, & \text{otherwise},
\end{cases}
\]

where \( \Gamma_t(j) \) is the input of intermediate goods, \( \widehat{K}_t(j) \) and \( L_t(j) \) are the inputs of capital services and the composite skill, and \( F \) is a fixed cost which is identical across
firms and ensures that profits are zero in the steady state. We rule out entry into
and exit out of the production of good $j$. The parameter $\phi \in (0, 1)$ measures the
elasticity of output with respect to intermediate input, and the parameters $\alpha \in (0, 1)$
and $(1 - \alpha)$ are the elasticities of value-added with respect to the capital services and
labor inputs.

Each firm acts as a price-taker in the input markets and as a monopolistic com-
petition in the product market. A firm can choose the price of its product, taking the
demand schedule in (1) as given. Prices are set according to the mechanism spelled
out in Calvo (1983). In each period, a firm faces a constant probability $1 - \xi_p$ of
reoptimizing its price, with the ability to reoptimize being independent across firms
and time. A firm that can reoptimize its price will do so before the realization of the
policy shock at time $t$.

A firm $j$ setting a new price at date $t$ chooses $P_t(j)$ to maximize its profits

$$E_t \sum_{\tau = t}^{\infty} (\xi_p)^{\tau-t} D_{t,\tau} [P_t(j) X^d_{\tau}(j) - V(X^d_{\tau}(j))],$$

(3)

where $E$ is an expectations operator, and $D_{t,\tau}$ is the price of a dollar at time $\tau$ in
units of dollars at time $t$ and $V(X^d_{\tau}(j))$ is the cost of producing $X^d_{\tau}(j)$, equal to
$V_\tau[X^d_{\tau}(j) + F]$, with $V_\tau$ denoting the marginal cost of production at time $\tau$.

Solving the profit-maximization problem yields the following optimal pricing de-
cision rule

$$P_t(j) = \left( \frac{\theta}{\theta - 1} \right) \left[ \frac{E_t \sum_{\tau = t}^{\infty} (\xi_p)^{\tau-t} D_{t,\tau} X^d_{\tau}(j)V_\tau}{E_t \sum_{\tau = t}^{\infty} (\xi_p)^{\tau-t} D_{t,\tau} X^d_{\tau}(j)} \right].$$

(4)

This rule says the optimal price is a constant markup over a weighted average of the
marginal costs for the periods the price will remain effective.

Solving the firm’s cost minimization problem yields the following marginal cost
function:

$$V_\tau = \overline{\phi} P^\phi_\tau [(R^k_\tau)^\alpha (W_\tau)^{1-\alpha}]^{1-\phi},$$

(5)

where $\overline{\phi}$ is a constant term determined by $\phi$ and $\alpha$, and $R^k_\tau$ is the nominal rental
rate on capital services. With roundabout production, the marginal cost function
records three components ($P_\tau$, $R^k_\tau$ and $W_\tau$). The impact on marginal cost of assuming
input-output linkages among firms increases with the share of materials input $\phi$. 

6
Without roundabout production ($\phi = 0$), the marginal cost function records only two components ($R^k_\tau$ and $W_\tau$).

The conditional demand functions for the intermediate input and for the primary factor inputs used in the production of $X^d_{t+\tau}(j)$ and derived from cost-minimization are

$$\Gamma_\tau(j) = \phi \frac{V_\tau[X^d_\tau(j) + F]}{P_\tau},$$

$$\tilde{K}_\tau(j) = \alpha(1 - \phi) \frac{V_\tau[X^d_\tau(j) + F]}{R^k_\tau},$$

and

$$L_\tau(j) = (1 - \alpha)(1 - \phi) \frac{V_\tau[X^d_\tau(j) + F]}{W_\tau}.$$  

A firm which is not allowed to reoptimize its price in a given period nonetheless chooses the inputs of the intermediate good, capital services and the composite labor that minimize production cost.

### 2.2 Monopolistically Competitive Households and Staggered Wage Decisions

Each household $i$ has a subjective discount factor $\beta \in (0, 1)$ and a utility function

$$E \sum_{t=0}^{\infty} \beta^t \left\{ \log(C_t(i) - bC_{t-1}) - \eta \frac{L^d_t(i)^{1+\chi}}{1+\chi} \right\},$$

where $C_t(i)$ is individual consumption, $C_{t-1}$ is past-period aggregate consumption, $b > 0$ measures the relative importance of habit formation, and $L^d_t(i)$ is the demand schedule for the household’s labor skills given by (1).

The budget constraint that household $i$ faces at time $t$ is

$$P_t[C_t(i) + I_t(i) + a(Z_t(i))K_t(i)] + E_tD_{t,t+1}B_{t+1}(i) \leq W_t(i)L^d_t(i) + R^k_t\tilde{K}_t(i) + \Pi_t(i) + B_t(i) + T_t(i),$$

where $B_{t+1}(i)$ is household $i$’s holdings of a nominal bond representing a claim to one dollar in $t + 1$ and costs $D_{t,t+1}$ dollars at time $t$, $W_t(i)$ is the nominal wage rate for labor skill of type $i$, $L^d_t(i)$ is a demand schedule for type $i$ labor specified in (1), $R^k_t$ is a nominal rental rate on capital services, $P_t a(Z_t(i))K_t(i)$ is the cost of changing capital utilization, $\Pi_t(i)$ is household $i$’s profit share, and $T_t(i)$ is a lump-sum transfer the household $i$ receives from the government.
The physical capital accumulation equation is
\[ K_t(i) = (1 - \delta)K_{t-1}(i) + \left[ 1 - S \left( \frac{I_t(i)}{I_{t-1}(i)} \right) \right] I_t(i), \tag{11} \]
where \( \delta \) is the physical rate of depreciation, \( I_t(i) \) denotes time \( t \) purchases of investment goods, and \( S \) is function restricted to satisfy \( S(1) = S'(1) = 0 \), and \( \kappa \equiv S''(1) > 0 \).

The amount of effective capital the households can rent to the firms is
\[ \widehat{K}_t(i) = Z_t(i)K_t(i), \tag{12} \]
where \( Z_t(i) \) denotes the utilization rate of capital. We impose two restrictions on the capital utilization function \( a(Z_t(i)) \): the rate of capital utilization in the steady state equals one and \( a(1) = 0 \).

Each household acts as a price-taker in the goods market and a monopolistic competitor in the labor market. It chooses consumption \( C_t(i) \), hours worked \( L_t(i) \), bonds \( B_t(i) \), investment \( I_t(i) \) and capital utilization \( Z_t(i) \) that maximizes (9) subject to (10) and a borrowing constraint \( B_{t+1}(i) \geq -B \), for some large positive number \( B \). The initial conditions on bond and capital are given.

It can also set a nominal wage for its differentiated labor skill, taking the demand schedule (1) as given. The probability that a household sets a new wage is \( 1 - \xi_w \). At date \( t \), if household \( i \) sets a new wage, its optimal choice of nominal wage will be given by
\[ W_t(i) = \left( \frac{\sigma}{\sigma - 1} \right) \left[ \frac{E_t \sum_{\tau=t}^{\infty} (\xi_u)^{\tau-t}D_{t,\tau}MRS_{\tau}(i)L^d_{\tau}(i)}{E_t \sum_{\tau=t}^{\infty} (\xi_u)^{\tau-t}D_{t,\tau}L^d_{\tau}(i)} \right], \tag{13} \]
where \( MRS \) denotes the marginal rate of substitution between leisure and income. Equation (13) says the optimal wage is a constant markup over a weighted average of the \( MRS \)'s for the periods the wage rate will remain effective.\(^2\)

### 2.3 Endogenous Monetary Policy

Monetary policy is described by the following Taylor rule:
\[ \tilde{R}_t = \rho_r \tilde{R}_{t-1} + (1 - \rho_r)(\rho_n \tilde{n}_t + \rho_y \tilde{y}_t) + \epsilon_{r,t}, \tag{14} \]
\(^2\)We have used the standard first-order condition for bond holdings in deriving (13).
where \( \pi_t = \log(P_t/P_{t-1}) \) and \( g_Y = \log(Y_t/Y_{t-1}) \); \( \tilde{R}_t \), \( \tilde{\pi}_t \), and \( \tilde{g}_Y \) denote the deviations of the nominal interest rate, the rate of inflation and the growth rate of real GDP (to be defined below) from their steady-state values, and \( \varepsilon_{r,t} \) is an i.i.d. normal process, with a zero mean and a finite variance. The policy rule (14) states that the monetary authority smooths short-term movements in the nominal interest while systematically reacting to deviations of inflation and output growth from targets (see also Erceg and Levine, 2003; Galí and Rabanal, 2004; Liu and Phaneuf, 2007).

### 2.4 Equilibrium and Market-Clearing Conditions

An equilibrium for this economy consists of allocations \( C_t(i), \hat{K}_t(i), B_{t+1}(i), Z_t(i) \) and wage \( W_t(i) \) for household \( i \), for all \( i \in [0,1] \), allocations \( \Gamma_t(j), \hat{K}_t(j), L_t(j) \) and price \( P_t(j) \) for firm \( j \), for all \( j \in [0,1] \), together with prices \( D_{t,t+1}, P_t, R^k_t \), and \( W_t \), satisfying the following conditions: (i) taking the wages and all prices but its own as given, each firm’s allocations and price solve its maximization problem; (ii) taking prices and all wages but its own as given, each household’s allocations and wage solve its utility maximization problem; (iii) markets for bonds, capital, the composite labor and the composite good clear; (iv) monetary policy is as specified.

We assume that (implicit) state-contingent financial contracts insure each household against the idiosyncratic income risk that may arise from the staggering of wage adjustments. As in Rotemberg and Woodford (1997), Huang, Liu and Phaneuf (2004) and Christiano, Eichenbaum and Evans (2005), such financial arrangements ensure that equilibrium consumption and investment are identical across households, although nominal wages and hours worked may differ. Under this assumption, we have \( Y_t(i) = \int_0^1 Y_t(i) \, di = Y_t \) for all \( i \). Given this relation, along with (6), the market-clearing condition \( \int_0^1 Y_t(i) \, di + \int_0^1 \Gamma_t(j) \, dj = X_t \) for the composite good implies that equilibrium real GDP is related to gross output by

\[
Y_t = X_t - \phi \frac{V_t}{P_t} \left[ G_t X_t + F \right],
\]

where \( G_t \equiv \int_0^1 [P_t(j)/P_t]^{-\theta} \, dj \) captures the price-dispersion effect of staggered price contracts.

The market-clearing conditions are \( \int_0^1 \hat{K}_t^d(j) \, dj = \int_0^1 \hat{K}_t(i) \, di = \hat{K}_t \) for capital services and \( \int_0^1 L_t(j) \, dj = L_t \) for the composite skill. These market-clearing conditions along with (7) – (8) imply that equilibrium aggregate capital services and composite
skill are related to gross output by

\[ \hat{K}_t = \alpha (1 - \phi) \frac{V_t}{W_t} [G_t X_t + F], \quad (16) \]

\[ L_t = (1 - \alpha)(1 - \phi) \frac{V_t}{W_t} [G_t X_t + F]. \quad (17) \]

Equations (15), (16) and (17), together with the price-setting equation (4) and the wage-setting equation (13), characterize an equilibrium.

The overall resource constraint of the economy is

\[ C_t + I_t + a(Z_t)K_t \leq Y_t. \quad (18) \]

### 3 Parameter Calibration

The parameters we need to calibrate include the subjective discount factor \( \beta \), the preference parameters \( b \) and \( \chi \), the technology parameters \( \phi \) and \( \alpha \), the elasticity of substitution between differentiated goods \( \theta \) and between differentiated labor skills \( \sigma \), the capital depreciation rate \( \delta \), the investment adjustment cost parameter \( \kappa \), the capital utilization elasticity \( \sigma_a \), the probability of price non-reoptimization \( \xi_p \), the probability of wage non-reoptimization \( \xi_w \), and the monetary policy parameters \( \rho_r \), \( \rho_\pi \), \( \rho_Y \) and \( \sigma_\varepsilon \). The values assigned to these parameters are summarized in Table 1.

Following the standard business cycle literature, we set \( \beta = 0.99 \), \( \chi = 2 \), and \( \delta = 0.025 \) implying an annualized real interest rate of 4 percent in the steady state, an intertemporal elasticity of labor hours of 0.5, and an annual capital depreciation rate of 10 percent. We set the coefficient of habit formation \( b \) to 0.8 (Fuhrer, 2000; Boldrin, Christiano and Fisher, 2001). The investment adjustment cost parameter \( \kappa \) is fixed at 3 (Christiano, Eichenbaum and Evans, 2005), and the capital utilization elasticity \( \sigma_a \) at 1.5 (Basu and Kimball, 1997; Dotsey and King, 2006). With zero steady-state profits, the parameter \( \alpha \) corresponds to the share of payments to capital in total value-added in the National Income and Product Account (NIPA), implying \( \alpha = 0.4 \) (see also Cooley and Prescott, 1995).

The elasticity of substitution between differentiated goods \( \theta \) determines the steady-state markup of prices over marginal cost, with a markup of \( \theta/(\theta - 1) \). Rotemberg and Woodford (1997) assume a value-added markup of 1.2, implying \( \theta = 6 \). Christiano,
Eichenbaum and Evans (2005) estimate the value-added markup at 1.2 in a model controlling for variable capital utilization. Nakamura and Steinsson (2010) assume $\theta = 4$ and a value-added markup of 1.33 in a menu-cost model featuring roundabout production. We set $\theta = 6$, so the value-added markup is 1.2. Similarly, we set the elasticity of substitution between differentiated labor skills $\sigma = 6$ (Huang and Liu, 2002; Huang, Liu and Phaneuf, 2004).

The parameter $\phi$ measures the share of payments to intermediate input in total production cost or cost share. With markup pricing, it equals the product of the steady-state markup and the share of intermediate input in gross output or revenue share. We rely on two different sources of data to calibrate $\phi$ for the postwar U.S. economy. The first source is a study by Jorgenson, Gollop and Fraumeni (1987) suggesting that the revenue share of intermediate input in total manufacturing output is about 50 percent. With a steady-state markup of 1.2, this implies $\phi = 0.6$. The second source relies on the 1997 Benchmark Input-Output Tables of the Bureau of Economic Analysis (BEA, 1997). In the Input-Output Table, the ratio of "total intermediate" to "total industry output" in the manufacturing sector or revenue share is 0.68. With a steady-state markup of 1.2, this implies $\phi = 0.816$. Admissible values of $\phi$ hence range between 0.6 and 0.816. Huang, Liu and Phaneuf (2004) and Nakamura and Steinsson (2010) choose $\phi = 0.7$. Here, we take a conservative stand and set the baseline value of $\phi$ at 0.6. Later, we assess the sensitivity of our findings to higher values of $\phi$.

The parameter $\xi_p$ measures the probability of price non reoptimization. In a survey of U.S. postwar evidence, Taylor (1999) documents that prices have changed about once a year on average. However, evidence on price behavior from microeconomic data suggests otherwise. Using summary statistics from the Consumer Price Index micro data compiled by the U.S. Bureau of Labor Statistics for 350 categories of consumer goods and services, Bils and Klenow (2004) document that the median waiting time between price adjustments is 4.3 months when taking into account price changes during temporary sales, and 5.5 months when they are excluded from their sample. Cogley and Sbordone (2008, footnote 19) argue that approximating the waiting time to the next price change by $\xi_p^t$, the median waiting time between price adjustments is given by $-\ln(2)/\ln(\xi_p)$. By setting $\xi_p = 2/3$, the median waiting time between price changes is 5.1 months.

We believe our choice of $\xi_p = 2/3$ is a conservative one for the following reasons. The most detailed evidence reported in Bils and Klenow (2004) covers only the years

\footnote{Basu (1995) and Bergin and Feenstra (2000) suggest a higher range for $\phi$ between 0.8 and 0.9.}
1995-1997. Using less disaggregated price data, they report evidence indicating that $\xi_p$ has been higher over the period 1959-2000 (see Bils and Klenow, 2004, Table 4 and Figures 2 and 3). Also, Nakamura and Steinsson (2008) show that if price changes occurring during temporary sales and those associated with product substitutions are excluded, prices remain effective for $8-11$ months, while if price changes for product substitutions are included, prices remain effective for $7-9$ months. Therefore, $\xi_p$ could have been higher.

The probability of wage non reoptimization, $\xi_w$, is chosen as follows. A study by Barattieri, Basu and Gottschalk (2010), exploiting a panel of micro data from the Survey of Income and Program Participation for the years 1996-1999, suggests nominal wages have changed less frequently than prices. Based on their estimates, they argue the average duration of wage contracts relevant for the calibration of macroeconomic models should be about 16.6 months. On the other hand, macroeconomic studies report estimates of $\xi_w$ implying an average duration of wage contracts between 3 and 4 quarters (Christiano, Eichenbaum and Evans, 2005; Smets and Wouters, 2007). That is, whether we consider evidence from micro or macro studies, nominal wages seem to adjust less frequently than prices. Hence, once accounting for both sticky wages and sticky prices, we adopt a conservative stand and set $\xi_w = 3/4$. Later, we examine the consequences of widening the gap between $\xi_p$ and $\xi_w$ as micro evidence seems to suggest.

Finally, the parameters of the Taylor rule are set as follows: $\rho_r = 0.8$, $\rho_\pi = 1.5$ and $\rho_Y = 0.125$. These values are broadly consistent with recent estimates reported in Smets and Wouters (2007) and Justiniano and Primiceri (2008), and with the calibration in Christiano, Eichenbaum and Evans (2005). The standard deviation of the monetary policy shock $\sigma_r$ is set at 0.004 (Ireland, 2007).

4 Staggered Price-Setting and the MPS

Basu (1995) presents evidence suggesting that the interplay between intermediate goods used in an input-output structure and sticky prices can give rise to a multiplier for price stickiness (MPS). In this section, we assess Basu’s conjecture using a version of the model described in the previous section that combines input-output linkages between firms, staggered price contracts, flexible wage decisions and endogenous monetary policy. We are interested in the effects of the MPS on inflation inertia and on the persistence in aggregate quantities following a monetary policy shock. Figure 1 displays the impulse-response functions of the following variables to a 1-percent
negative shock to the nominal interest rate:

• the price level, the inflation rate and the real interest rate;

• output, consumption and investment;

• the marginal cost, the real wage rate and the rental rate;

• hours worked, materials input and capital utilization.

4.1 Short-Run Inflation Dynamics

Several impulse responses differ widely when the model includes an input-output production structure and when it does not. Without roundabout production, the marginal cost function (5) records two components, the rental rate on capital services and the wage index. Both are flexible, so inflation is weakly persistent. With input-output linkages, the marginal cost function records a third component in the form of the rigid intermediate input price. This reduces the sensitivity of marginal cost to the policy shock. Specifically, with materials input, the increase of marginal cost is more than 2 times smaller on impact of a positive monetary policy shock. Prices rise more gradually towards their new higher steady state level, and inflation is more persistent.

Another way to assess the importance of the MPS is by generating the autocorrelation functions of inflation implied by sticky-price models with and without intermediate goods. Fuhrer and Moore (1995) report evidence showing that macroeconomic models embedding rational expectations and overlapping wage contracts (Phelps, 1978; Taylor, 1980) generate weakly autocorrelated movements of inflation. To better fit the data, they propose a framework in which agents care about relative real wages while contracts remain effective (Buiter and Jewitt 1981). This contractual arrangement results into higher-order backward-looking elements in the wage contract equation. This in turn results in higher serial correlation of inflation. However, the contracts in Fuhrer and Moore are not cast within explicit individual optimization problems for households and firms.

Nelson (1998) performs a similar exercise, but for a wider range of sticky-price models, including new keynesian pricing models with microfoundations. Nelson examines whether these models can replicate the high and slowly decaying positive autocorrelations of the quarterly first difference of the log U.S. GDP deflator. Among the models studied by Nelson, only those of Fuhrer and Moore (1995) and King and
Watson (1996) imply a high serial correlation of inflation. Fuhrer and Moore rely on *ad hoc* backward-looking elements, whereas King and Watson (1996) assume that prices adjust only once every 2.5 years on average, which is implausible in light of evidence from microeconomic studies.

Table 2a reports the autocorrelations of the quarterly first difference of the log nonfarm business sector implicit deflator (NBD) and of the log GDP implicit price deflator (GDPD) for the years 1959:I-2007:III. Also reported in this table are the autocorrelations of the quarterly first difference of the log compensation of the nonfarm business sector (NBC) and of the log average hourly earnings of private industries (AHEP). First-order autocorrelations of price inflation are above 0.8 and higher-order autocorrelations are high and positive. Autocorrelations of wage inflation are also high, but they are somewhat higher with the AHEP.

Tables 2b and 2c compare the autocorrelations of price inflation and wage inflation in the sticky-price models with and without roundabout production. The autocorrelations of price inflation are denoted by $\rho_\pi(k)$ for $k = 1, ..., 6$, $\rho_\pi(k)$ representing the $k^{th}$ order of autocorrelation of price inflation. Those corresponding to wage inflation are $\rho_\omega(k)$ for $k = 1, ..., 6$. For the sake of comparison with our models, we also include the autocorrelations of price inflation of the Fuhrer and Moore (1995) and King and Watson (1996) models generated by Nelson (1998).

Without input-output linkages, the model predicts a first-order autocorrelation of price inflation of 0.65, and rapidly decaying autocorrelations at a higher order. With intermediate goods, the autocorrelations of price inflation are significantly higher. Specifically, $\rho_\pi(1) = 0.814$ and the higher-order autocorrelations decay less rapidly. Now, recall that these findings correspond to a share of intermediate goods of 0.6, while the admissible values of $\phi$ range between 0.6 to 0.816. Hence, we also report the autocorrelations with $\phi = 0.7$ and 0.8.

Increasing $\phi$ enhances the autocorrelations of price inflation. The first-order theoretical autocorrelations are 0.83 for $\phi = 0.7$ and 0.85 for $\phi = 0.8$. Note also that the autocorrelations are now significantly higher for $k = 5, 6$ than in the Fuhrer and Moore model, but that they remain somewhat smaller than in the King and Watson model. The autocorrelations of price inflation the MPS helps generate are high considering that wage inflation is weakly autocorrelated due to flexible wage decisions.

Other approaches have been followed in reaction to the inability of the standard New Keynesian Phillips Curve (NKPC) model to account for inflation persistence. In the standard NKPC model, firms allowed to reoptimize their prices in a given

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5Our sample period ends before the so-called Great Recession of 2007:4-2009:4.
period are purely forward-looking. The optimal pricing decisions depend on a discounted stream of expected future marginal costs, or equivalently on a discounted stream of expected future output gaps. Because the standard NKPC is inherently forward-looking, the NKPC model has to rely on a very high probability of price non-reoptimization to account for inflation persistence, such as in the model of King and Watson.

To better track actual inflation, Gali and Gertler (1999) incorporate lagged inflation into the NKPC model. As in Calvo’s model, each firm is able to adjust its price in any given period with a fixed probability. Firms allowed to reset their prices upon receiving the appropriate Calvo signal are divided in two groups. One group sets new prices optimally as in the standard model, while the other group follows a simple rule of thumb. Rule-of-thumbers set new prices equal to average prices in the most recent round of price adjustment, plus a correction for previous period inflation. They are therefore backward-looking. While improving the empirical fit of the model, rule-of-thumb behavior lacks a convincing microeconomic justification.

Christiano, Eichenbaum and Evans (2005) introduce full backward indexation of wages and prices in a DSGE framework with Calvo wage and price contracts. Firms may or may not reoptimize their prices in a given period depending on the stochastic signal they receive. Firms entitled to price reoptimization do so in a forward-looking manner, while the other firms index their prices to lagged inflation. Households are similarly divided in two groups. A first group sets new wages optimally upon receiving the appropriate stochastic signal, while the other group not entitled to wage reoptimization index wages to lagged inflation. Smets and Wouters (2007) use a similar indexing mechanism.

Backward-looking assumptions have been criticized by Woodford (2007), Sbordone (2007), Cogley and Sbordone (2008) and Chari, Kehoe and McGrattan (2009). One criticism is that these assumptions cannot be linked to the optimizing behavior of households and firms. Another criticism, specific to wage and price indexation is that, when combined with Calvo contracts, indexation implies that all wages and prices in the economy change every 3 months. While micro level studies indicate that the prices of some consumer goods and services change very frequently, for other goods and services prices adjust infrequently (Bils and Klenow, 2004; Nakamura and Steinsson, 2008). Assuming that all wages in the economy change every 3 months is simply as implausible in light of micro evidence on the behavior of nominal wages (Barattieri, Basu and Gottschalk, 2010).

Cogley and Sbordone (2008) adopt a different strategy. Referring to a number of...
studies in which U.S. trend inflation is modeled as a driftless random walk (Cogley and Sargent, 2005; Stock and Watson, 2007), they incorporate variations in trend inflation into an otherwise NKPC model. In general equilibrium, trend inflation ought to be determined by the long-run target in the central bank’s policy rule (Ireland, 2007). Accounting for time-varying trend inflation, their estimate of the parameter determining backward price indexing becomes statistically insignificant. Furthermore, the frequency of price adjustment is broadly consistent with microeconomic evidence. Yet, their model provides a reasonable account of inflation dynamics.

4.2 Real Persistence

We now turn our attention to the impulse responses of aggregate quantities to a monetary policy shock. In a provocative study, Chari, Kehoe and McGrattan (2000) argue that when staggered price contracts are incorporated in a business cycle model with microfoundations, they fail to generate persistent output fluctuations in response to a monetary policy shock. This anomaly, known as the persistence problem, has elicited a rapidly growing literature aimed at identifying new sources of output persistence in DSGE models. To generate their findings, Chari, Kehoe and McGrattan first estimate the impulse response of output to the shock in a univariate autoregression model. Then, they measure output persistence by the time it takes following the shock for the deviation of output from trend to shrink to half of its impact value. The impact of staggered price contracts to output persistence is then approximated by the contract multiplier, expressed as the ratio of the half-life of output deviations after a monetary shock with staggered price-setting to the corresponding half-life with flexible price decisions. The contract multiplier hence conveys information about the longevity of the response of output following a monetary shock.

However, evidence from the broader empirical literature on monetary policy also emphasizes the timing in the response of output following a monetary policy shock. At the onset of an expansionary monetary policy shock, output will gradually rise during 4-6 quarters, and then will slowly return to its preshock level at the end of 3-4 years (Barro, 1978; Mishkin, 1982; Galí, 1992; Bernanke and Mihov, 1998; Christiano, Eichenbaum and Evans, 1999; Romer and Romer, 2004; Normandin and Phaneuf, 2004). While persistent, the response of output is also hump-shaped.

Some models developed in reaction to Chari, Kehoe and McGrattan’s findings have been able to generate a higher output persistence. These models, however, have generally implied monotonically declining rather than hump-shaped impulse
responses, failing to capture the timing in the response of output and other aggregate quantities following a monetary policy shock (Bergin and Feenstra, 2000; Huang and Liu, 2002; Edge, 2002; Neiss and Pappa, 2005).

Figure 1 presents the impulse responses of aggregate quantities to a 1-percent negative shock to the nominal interest rate. Without intermediate goods, the impulse responses of output, consumption, investment and hours are relatively small and weakly persistent. Also, there is no hump-shaped response of output. Christiano, Eichenbaum and Evans (2005) report that a model with sticky prices and real frictions delivers a response of output following a monetary policy shock which is small and short-lived. With input-output linkages embedded in the model, the responses of output, consumption, investment and hours become larger, more persistent and hump shaped in the aftermath of a policy shock.

We provide further evidence of the strength of internal propagation induced by the MPS. In the spirit of Cogley and Nason (1995), we generate the autocorrelation functions of the growth rates of aggregate quantities in the sticky-price models with and without intermediate goods. They are reported in Table 3. Table 3a presents the unconditional autocorrelations for the growth rates of output, consumption, investment and hours observed in the U.S. data. Consumption is measured by the sum of consumption expenditures on nondurable goods and services. Investment is the sum of consumption expenditures on durable goods, gross nonresidential investment (structures and equipment) and residential investment. Output is the sum of consumption and investment. Total hours are those of the non-farm business sector.

Theoretical autocorrelations are reported in Table 3b. Without intermediate goods, the sticky-price model predicts that only first-order autocorrelations of the growth rates of aggregate quantities are positive. With both intermediate goods and sticky prices, the first and second-order autocorrelations are positive for all variables, while the third-order autocorrelations are also positive for output, investment and hours growth. Note that these autocorrelations increase with $\phi$.

How does endogenous monetary policy affect the MPS? The Taylor rule (14) assumes the Federal Reserve systematically adjusts the nominal interest rate in response to deviations of inflation and output growth from targets. The Fed also smooths short-run variations in the nominal interest rate. The fear of disruption in financial markets (Goodfriend, 1991) and the uncertainty about the effects of interest rate

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6These autocorrelations are driven only by the monetary policy shock, and we do not pretend they should match the unconditional autocorrelations in the data. However, they provide an indication of the strength of endogenous propagation induced by the MPS.
changes (Sack, 1998) are among possible reasons why the Fed practices interest-rate smoothing. Clarida, Gali and Gertler (2000) estimate monetary policy rules for different subperiods and report estimates of $\rho_r$ ranging between 0.65 and 0.91. Smets and Wouters (2007) estimate $\rho_r$ at 0.82, while Justiniano and Primiceri (2008) obtain an estimate of 0.85. Hence, the consensus is that the degree of policy inertia is high.

How does policy inertia impact on the MPS? In the experiment that follows, $\rho_r$ is set at 0.5, 0.7, and 0.9. Other parameters keep their benchmark values. Figure 2 displays the impulse responses corresponding to different values of $\rho_r$. With $\rho_r = 0.5$, the impulse responses of aggregate quantities to a monetary policy shock are relatively small, weakly persistent and they do not display a typical hump-shaped pattern. Furthermore, the autocorrelations of output growth with $\rho_r = 0.5$ are 0.09, −0.02 and −0.06, for $k = 1, 2, 3$, while those of price inflation are 0.6, 0.4, 0.28, 0.21, 0.17 and 0.14, for $k = 1,...,6$. But $\rho_r = 0.5$ is clearly outside the range of admissible values. With $\rho_r = 0.7$, the model generates persistent and hump-shaped responses of output, consumption, investment and hours. Note however that changes in the value of $\rho_r$ between 0.7 and 0.9 have a much stronger impact on the responses of aggregate quantities than changes between 0.5 and 0.7. Clearly, the higher is the degree of policy inertia, the stronger is the MPS.

While our model emphasizes interactions between input-output linkages, sticky prices and policy inertia, Bouakez, Cardia and Ruge-Murcia (2005) suggest that joining sticky prices, habit formation and capital adjustment costs can give rise to a persistent and hump-shaped response of output at the onset of a monetary policy shock. Using maximum likelihood techniques, they estimate a sticky-price model that abstracts from intermediate goods and where monetary policy is an exogenous money growth rule. Their estimate of the habit parameter is 0.982 and that of the Calvo-probability of price non-reoptimization is 0.847, implying a frequency of price adjustment of once every 19.6 months on average.

Figure 3 reports the results of the following experiment. We exclude materials input from our model and set $b = 0.98$; monetary policy is endogenous rather than exogenous as assumed by Bouakez, Cardia and Ruge-Murcia, and the Calvo probability of price non-reoptimization $\xi_p$ is more realistically set at $2/3$. Because of strong habit formation, there is almost no response of consumption to a monetary policy shock. The responses of output, investment and hours are relatively small and weakly persistent, and there is no pronounced hump-shaped response of output following a monetary policy shock. We conclude that if monetary policy is endogenous and the frequency of price adjustment is consistent with microeconomic evidence, the
combination of habit formation and investment adjustment costs does not generate by itself persistent and hump-shaped responses of aggregate quantities to a policy shock in the absence of input-output linkages.

Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007) report persistent and hump-shaped responses of output, consumption and investment to a monetary policy shock obtained from DSGE models that do not embed input-output linkages. These models include sticky wages, sticky prices, backward indexation of wages and prices, and a selection of real frictions. Christiano, Eichenbaum and Evans (2005) further impose that output, consumption, investment, the aggregate price level, the real wage and labor productivity respond only with a one-period lag to a monetary policy shock in order to match the short-run restrictions used in a structural vector autoregression to identify a monetary policy shock and estimate its effects on macroeconomic variables.\footnote{Normandin and Phaneuf (2004) show that the short-run restrictions generally imposed in SVARs to identify monetary policy shocks are strongly rejected and statistically invalid.} Here, we obtain similar findings in a sticky-price model that excludes backward-looking components and adjustment lags but includes round-about production and endogenous monetary policy.

### 4.3 Shortcomings

While delivering several interesting results, the sticky-price model with roundabout production is subject to a few significant shortcomings. One has to do with the relative variations in employment and real wages implied by the model. Variations in real wages ought to be much smaller than movements in employment during the business cycle (Lucas and Rapping, 1969). Christiano, Eichenbaum and Evans (1997, 2005) provide evidence of a weak increase in the real wage following an expansionary monetary policy shock.

By contrast, Figure 1 tells that the sticky-price model with materials input delivers a sharp increase in the real wage following an expansionary policy shock. This can be explained as follows. Consider first how the real wage adjusts in a sticky-price model with no materials input. The expansionary policy shock generates increases in consumption and output. The higher demand for goods puts an upward pressure on the demand for labor input. With a flexible nominal wage rate, the optimal wage-setting equation (13) implies that the real wage is a constant markup over the marginal rate of substitution (MRS) between consumption and leisure. The marginal disutility of working rises with a higher labor demand, and the marginal utility of
consumption falls with a higher consumption. The MRS therefore increases along with the real wage. Adding intermediate inputs to the model does not dampen the response of real wage. With roundabout production, prices become stickier and the responses of consumption and hours are stronger. Both the MRS and the real wage remain strongly procyclical.

The second shortcoming reflects the observation that materials input, which represents a large fraction of gross output in many industries, should vary proportionately to value-added and hours worked over the business cycle (e.g., see Dotsey and King, 2006). The sticky-price model with roundabout production predicts that short-run fluctuations in materials input significantly exceed fluctuations in hours and output in the aftermath of a policy shock.

The evidence presented in this section suggests that the interactions between intermediate inputs, sticky prices and endogenous monetary policy deliver a strong multiplier for price stickiness. The MPS represents a significant source of endogenous persistence in inflation and aggregate quantities. Furthermore, it helps generate pronounced hump-shaped responses of output, consumption, investment and hours following a monetary policy shock. However, the sticky-price model generates fluctuations in the real wage which are too large relative to fluctuations in hours, and movements in materials input that exceeds movements in hours and value-added.

5 Adding Sticky Wages

To overcome the shortcomings identified in the previous section, we add sticky nominal wages to the model featuring roundabout production, sticky prices and endogenous monetary policy. To understand why sticky wages should dampen the response of real wage following a monetary policy shock, consider first what would happen if sticky wages were combined to flexible price decisions in a model without materials input. Then, prices would be a constant markup over marginal cost. The marginal cost function (5) has two components: the wage index which is rigid due to sticky wages and the flexible rental rate on capital services. Since marginal cost and prices are more responsive to the monetary policy shock than the wage index, the real wage is strongly countercyclical. With flexible price decisions, adding materials input to the model would have little effect on this. Without staggered price contracts, firms set the same price in a symmetric equilibrium. The optimal pricing decision is therefore the same with or without materials input, and the real wage remains strongly countercyclical.
Once combining materials input, sticky wages and sticky prices, the marginal cost function has three components: two—the intermediate input price and the wage index—are rigid, while the rental rate on capital services is flexible. Wages and prices being rigid, the real wage can either be procyclical or countercyclical in response to a monetary policy shock depending on the importance of the share of materials input $\phi$. If this share is large enough, the real wage is procyclical but less procyclical than in a model with materials input and sticky prices only. Otherwise, the real wage is countercyclical.\footnote{Huang, Liu and Phaneuf (2004) provide evidence showing that the interactions between a rising share of materials input and nominal rigidities explains why the U.S. real wage has switched from mildly countercyclical during the interwar period to mildly procyclical during the postwar period.}

Figure 4 displays the impulse responses obtained with our more complete model with materials input, sticky wages and sticky prices. The Calvo-probability of price non reoptimization is $2/3$ and that of wage non reoptimization is $3/4$. We also include the impulse responses from the sticky-price model with materials input for comparison. From strongly procyclical with flexible wage decisions, the real wage now becomes weakly procyclical following an expansionary monetary policy shock. Interestingly, the real wage response is also more persistent and hump-shaped. Sticky wages also magnify the effects of a monetary policy shock on hours and output, so that fluctuations in hours and output now become roughly proportionate to movements in materials input. The response of materials input is also more persistent and hump-shaped in the aftermath of a monetary policy shock, and so is the response of capital utilization.\footnote{Christiano, Eichenbaum and Evans (2005) offer evidence of a persistent and hump-shaped response of capital utilization in the wake of a monetary policy shock.}

While helping to resolve both shortcomings, sticky wages also strengthen our main findings about inflation inertia and output persistence. Prices increase less, while adjusting more gradually towards their higher steady state level. Inflation is more persistent. The responses of aggregate quantities are stronger, more persistent and hump shaped. The autocorrelations of price and wage inflation are higher (see Tables 2b and 2c). The theoretical autocorrelations of price inflation are now close to actual autocorrelations observed in the data and exceed by far those in Fuhrer and Moore’s (1995) model. The autocorrelations of price inflation implied by the model match those found in the King and Watson (1996) model in which prices are assumed to change only once every 2.5 years on average. The autocorrelations of wage inflation are high and positive, as in the data.
5.1 Robustness Analysis

We analyze the robustness of our findings along a number of dimensions. We examine four scenarios: (a) a Taylor rule which is purely backward-looking or forward-looking with respect to deviations of inflation and output growth from targets rather than contemporaneous, (b) a higher frequency of price reoptimization implying a median waiting time between price adjustments of only 4.1 months (Bils and Klenow, 2004), (c) a lower frequency of wage reoptimization implying that nominal wages are reset only once every 16.6 months on average (Barattieri, Basu and Gottschalk, 2010) and (d) the inclusion of backward indexation and its effect on the impulse response of inflation. For each scenario, other structural parameters keep their benchmark values. The impulse responses corresponding to each scenario are displayed in Figures 5-8, together with the impulse responses from our more complete model.

5.1.1 Alternative Policy Rule Specifications

The Taylor rule (14) implies a contemporaneous feedback of nominal interest rate to deviations of inflation and output growth from targets, whereas Taylor’s (1993) rule is purely backward-looking. On the other hand, Clarida, Galí and Gertler (2000) estimate forward-looking policy rules. Therefore, we consider replacing (14) by the following policy rules:

\[ \tilde{R}_t = r_t \tilde{R}_{t-1} + \left(1 - \rho_r\right)(\rho_{\pi} \tilde{\pi}_{t-1} + \rho_y \tilde{g}_{t-1}) + \varepsilon_{r,t}, \]  

and,

\[ \tilde{R}_t = r_t \tilde{R}_{t+1} + \left(1 - \rho_r\right)(\rho_{\pi} \tilde{\pi}_{t+1} + \rho_y \tilde{g}_{t+1}) + \varepsilon_{r,t}. \]

We report only the impulse responses for price inflation and output. They are displayed in Figure 5. The contemporaneous and backward-looking policy rules produce almost identical results. The forward-looking policy rule is somewhat more accommodative, but the results are broadly similar to those with the contemporaneous rule.\(^{10}\) Our results are quite insensitive to changing the timing of the Taylor rule.

5.1.2 Higher Frequency of Price Reoptimization

Our benchmark value for the Calvo-probability of price non-reoptimization \(\xi_p\) is 2/3, implying a median waiting time between price adjustments of 5.1 months. Bils and

\(^{10}\)We have also replaced the output gap measured in growth rate by its counterpart in level. With the output gap in level, the Taylor rule is somewhat less accommodative, but the response of output remains persistent and hump shaped and inflation responds less to a policy shock (not reported).
Klenow (2004) report a median waiting time of 4.3 months when price changes of temporary sales are included in the sample of data. Lowering $\xi_p$ from $2/3$ to 0.6 is equivalent to decreasing the median waiting between price changes time from 5.1 to 4.1 months. We also present results with $\xi_p = 0.55$. These results are presented in Figure 6.

With $\xi_p = 0.6$, the model still delivers sluggish inflation, and persistent and hump-shaped responses in aggregate quantities. The real wage remains weakly procyclical, but the increase in the real wage is somewhat smaller since the countercyclical effect of sticky wages is stronger due to increased price flexibility. Also, with higher price flexibility, the increase in prices is somewhat stronger and so is the short-run increase in inflation.

5.1.3 Lower Frequency of Wage Reoptimization

A recent micro level study by Barattieri, Basu and Gottschalk (2010) suggests that the average waiting time between wage adjustments relevant for medium-scale macro models would be about 16.6 months for the years 1996-1999. This implies a probability of wage non-reoptimization of 0.82 instead of 3/4. As Figure 7 suggests, increasing $\xi_w$ results in a higher persistence in wage and price inflation and a stronger response of aggregate quantities to a policy shock. However, this also increases the countercyclical pressure on the real wage. Still, we find that the real wage is weakly procyclical in the aftermath of an expansionary monetary policy shock.

5.1.4 Hump-Shaped Response of Inflation

While Fuhrer and Moore (1995) and Nelson (1998) focus on the autocorrelations of inflation to measure persistence, Walsh (2005) asks whether a particular model can deliver a persistent and hump-shaped response of inflation following a monetary policy shock. His model includes sticky prices, labor market search, habit persistence and full indexation of prices to last period inflation.

Our assessment of the empirical literature on the response of inflation to a monetary policy shock is that it is hard to tell with any high degree of confidence what the evidence is. For example, while Fuhrer and Moore (1995) report high autocorrelations of inflation, their model with relative real wage contracts does not deliver a hump-shaped impulse response of inflation, but instead an inflation response which is quite similar to those implied by our models featuring roundabout production and nominal

In any case, like Walsh (2005), we momentarily add backward indexation to our model featuring input-output linkages and nominal rigidities. Since our model includes both sticky wages and sticky prices, we consider the backward indexation of wages and prices. Figure 8 shows that with backward indexation our model will also generate a hump-shaped response of inflation to a monetary policy shock. However, the hump-shaped impulse response of inflation reflects the \textit{ad hoc} backward indexation assumption. This is likely to be the case in other DSGE models with backward indexation like those of Christiano, Eichenbaum and Evans (2005), Walsh (2005) and Smets and Wouters (2007).

6 Neutral and Investment-Specific Technology Shocks

While according to Woodford (2009), examining the effects of a monetary policy shock is certainly a useful test confronting alternative models, this section examines the effects of neutral and investment-specific technology shocks through the lens of our DSGE model. A wide range of studies suggest that monetary policy shocks explain a modest percentage of the variance of output fluctuations. According to many observers, real disturbances also are an important source of business cycle fluctuations.

Building on Greenwood, Hercowitz and Krusell (1997) and Galí (1999), Fisher (2006) proposes a structural vector autoregression approach in which long-run restrictions are used to identify investment-specific and neutral technology shocks and estimate their effects. Chari, Kehoe and McGrattan (2009) argue that among the many disturbances currently driving new keynesian models, only shocks to monetary policy, total factor productivity and investment-specific technology are truly structural and hence have a clear economic interpretation.

Here, we assume that the neutral technology shock is permanent. This implies

\footnote{See Fuhrer and Moore (1995, Figure III).}

\footnote{See Christiano, Eichenbaum and Evans (2005, equations 8 and 16) for the details of indexation.}
(2) is replaced by the following production function for a good of type $j$:

$$X_t(j) = \begin{cases} 
A_t \Gamma_t(j)^\phi \hat{K}_t(j)^\alpha L_t(j)^{(1-\alpha)1-\phi} - A_t F, & \text{if } A_t \Gamma_t(j)^\phi \hat{K}_t(j)^\alpha L_t(j)^{(1-\alpha)1-\phi} \geq A_t F \\
0, & \text{otherwise,}
\end{cases}$$

(21)

where the productivity shock $A_t$ is assumed to follow the random-walk process:

$$\ln(A_t) = \ln(a) + \ln(A_{t-1}) + \eta^a_t, \quad \eta^a_t \sim N(0, \sigma^2_a).$$

(22)

The physical capital accumulation equation (11) is also replaced by,

$$K_t(i) = (1-\delta)K_{t-1}(i) + \varepsilon^i_t \left[ 1 - S \left( \frac{I_t(i)}{I_{t-1}(i)} \right) \right] I_t(i),$$

(23)

where $\varepsilon^i_t$ stands for an investment-specific shock that follows the exogenous process:

$$\ln \varepsilon^i_t = \rho_i \ln \varepsilon^i_{t-1} + \eta^i_t, \quad \eta^i_t \sim N(0, \sigma^2_i).$$

(24)

Real variables are divided by the level of neutral technology to ensure stationarity.

Figure 9 displays impulse responses to a positive one-percent innovation to neutral technology. Following the neutral technology shock, output modestly increases on impact, and then gradually rises afterwards until reaching its new long-run level. Inflation declines. The real wage increases modestly on impact, and then gradually rises towards its new long-run level. These impulse responses are broadly consistent with empirical evidence offered by Galí (1999), Francis and Ramey (2005), Basu, Fernald and Kimball (2006) and Liu and Phaneuf (2007).

Total hours worked decrease within the year in the wake of a positive technology shock, and increase afterwards with a lag of up to 4-5 quarters. Galí (1999) using a five-variable SVAR model, and Basu, Fernald and Kimball (2006) using a purified Solow residual controlling for non technological factors that affect measured total factor productivity, find similar responses of hours. The short-run decline of hours implied by our model is however inconsistent with evidence presented in Christiano, Eichenbaum and Vigfusson (2004). Working from a SVAR with hours in log-levels instead of log-differences, they obtain a rise in hours following a positive neutral technology shock. Fernald (2007) argues that a different treatment of hours is unimportant if statistically significant and economically plausible productivity slowdown

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\[13\] In Fisher (2006), the investment-specific shock is permanent, an assumption which is not required in the our context since we do not confront the impulse responses from our model to those of a structural vector autoregression with long-run identifying restrictions.
and speedup are taken into account in the estimation. Technology improvements are unambiguously followed by short-run declines of hours worked.

Figure 10 summarizes the effects of a positive shock to investment-specific technology. The impulse responses of output, investment, hours, materials input and capacity utilization are persistent and hump shaped. In contrast, using a version of the competitive equilibrium growth model inspired by Greenwood, Hercowitz and Krusell (1997), Fisher (2006) finds that output, investment and hours surge in response to an investment-specific shock. As in Fisher’s model, consumption weakly declines. The real wage is weakly procyclical. Marginal cost and inflation are not too sensitive to the investment-specific shock, and movements in value-added, hours and materials input are roughly proportionate.

A strong positive comovement between hours and output has characterized the postwar business cycle. Seen through the lens of our model, monetary policy and investment-specific technology shocks appear to be plausible driving forces behind this comovement, not neutral technology shocks.

7 Conclusion

A recent trend in new keynesian DSGE modeling has seen the number of frictions, adjustment lags and shocks increase considerably to better track short-run inflation dynamics and the persistence in aggregate fluctuations. This modeling strategy has been severely criticized. Some structural features, like backward-looking components in the NKPC model, can be seen as questionable since they lack a convincing microeconomic justification or are at odds with microeconomic evidence on the frequency of wage and price adjustments. Furthermore, of the numerous shocks now driving these models, some are dubiously structural and are thus difficult to interpret.

Our paper has offered a macroeconomic framework which is fully consistent with the optimizing behavior of households and firms and does not have to rely on ad hoc backward components to account for inflation inertia and persistence in aggregate quantities. In our model, the interactions between input-output linkages, nominal rigidities and monetary policy give rise to a strong multiplier for price stickiness (MPS).

A natural step forward would be to explore how the MPS interacts with other interesting mechanisms such as time-varying trend inflation. Based on preliminary work we have done so far along these lines, such a framework would have the potential to explain large swings in macroeconomic volatility and significant changes
in the structure of some comovements which have characterized the so-called Great Moderation.
References


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Table 1: Calibrated Parameter Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjective discount factor</td>
<td>$\beta = 0.9$</td>
</tr>
<tr>
<td>Preferences</td>
<td>$b = 0.8, \quad \chi = 2$</td>
</tr>
<tr>
<td>Technology parameters</td>
<td>$\phi = 0.6, \quad \alpha = 0.4$</td>
</tr>
<tr>
<td>Elasticity of substitution between differentiated goods</td>
<td>$\theta = 6$</td>
</tr>
<tr>
<td>Elasticity of substitution between differentiated labor skills</td>
<td>$\sigma = 6$</td>
</tr>
<tr>
<td>Capital depreciation rate</td>
<td>$\delta = 0.025$</td>
</tr>
<tr>
<td>Investment adjustment cost parameter</td>
<td>$\kappa = 3$</td>
</tr>
<tr>
<td>Capital utilization elasticity</td>
<td>$\sigma_a = 1.5$</td>
</tr>
<tr>
<td>Probability of price non-reoptimization</td>
<td>$\xi_p = 2/3$</td>
</tr>
<tr>
<td>Probability of wage non-reoptimization</td>
<td>$\xi_w = 3/4$</td>
</tr>
<tr>
<td>Monetary policy parameters</td>
<td>$\rho_r = 0.8, \quad \rho_\pi = 1.5$</td>
</tr>
<tr>
<td></td>
<td>$\rho_Y = 0.125, \quad \sigma_{\epsilon_r} = 0.004$</td>
</tr>
</tbody>
</table>
Table. 2a U.S. Autocorrelations of Wage and Price Inflation (1959:I to 2007:III)

<table>
<thead>
<tr>
<th>Order of autocorrelation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price inflation measured by the NBD</td>
<td>0.826</td>
<td>0.799</td>
<td>0.756</td>
<td>0.661</td>
<td>0.580</td>
<td>0.536</td>
</tr>
<tr>
<td>Price inflation measured by the GDPD</td>
<td>0.870</td>
<td>0.820</td>
<td>0.801</td>
<td>0.787</td>
<td>0.716</td>
<td>0.676</td>
</tr>
<tr>
<td>Wage inflation measured by the NBC</td>
<td>0.527</td>
<td>0.483</td>
<td>0.445</td>
<td>0.518</td>
<td>0.442</td>
<td>0.443</td>
</tr>
<tr>
<td>Wage inflation measured by the AHEP</td>
<td>0.794</td>
<td>0.775</td>
<td>0.755</td>
<td>0.726</td>
<td>0.701</td>
<td>0.697</td>
</tr>
</tbody>
</table>

Notes: NBD refers to nonfarm business sector implicit deflator, GDPD to GDP implicit price deflator, NBC to nonfarm business sector compensation, and AHEP to average hourly earning of private industries

Table. 2b Autocorrelations of Price Inflation in Alternative Models

<table>
<thead>
<tr>
<th>Order of autocorrelation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. SP</td>
<td>0.65</td>
<td>0.38</td>
<td>0.20</td>
<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>2. SP-RP (φ = 0.6)</td>
<td>0.81</td>
<td>0.63</td>
<td>0.48</td>
<td>0.37</td>
<td>0.27</td>
<td>0.20</td>
</tr>
<tr>
<td>3. SP-RP (φ = 0.7)</td>
<td>0.83</td>
<td>0.67</td>
<td>0.54</td>
<td>0.43</td>
<td>0.34</td>
<td>0.26</td>
</tr>
<tr>
<td>4. SP-RP (φ = 0.8)</td>
<td>0.85</td>
<td>0.71</td>
<td>0.59</td>
<td>0.48</td>
<td>0.39</td>
<td>0.31</td>
</tr>
<tr>
<td>5. SP-SW-RP (φ = 0.6)</td>
<td>0.89</td>
<td>0.78</td>
<td>0.68</td>
<td>0.58</td>
<td>0.49</td>
<td>0.41</td>
</tr>
<tr>
<td>5. SP-SW-RP (φ = 0.7)</td>
<td>0.90</td>
<td>0.80</td>
<td>0.70</td>
<td>0.60</td>
<td>0.52</td>
<td>0.43</td>
</tr>
<tr>
<td>5. SP-SW-RP (φ = 0.8)</td>
<td>0.91</td>
<td>0.81</td>
<td>0.72</td>
<td>0.62</td>
<td>0.54</td>
<td>0.46</td>
</tr>
<tr>
<td>6. FM</td>
<td>0.92</td>
<td>0.75</td>
<td>0.58</td>
<td>0.42</td>
<td>0.26</td>
<td>0.13</td>
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<tr>
<td>7. KW</td>
<td>0.88</td>
<td>0.77</td>
<td>0.67</td>
<td>0.59</td>
<td>0.53</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Notes: SP stands for sticky-price model without roundabout production, SP-RP for sticky-price model with roundabout production, SP-SW-RP for model with sticky prices, sticky wages and roundabout production, FM for Fuhrer and Moore’s (1995) model, and KW for King and Watson’s (1996) model
Table. 2c Autocorrelations of Wage Inflation in Alternative Models

<table>
<thead>
<tr>
<th>Order of autocorrelation</th>
<th>1</th>
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<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. SP</td>
<td>-0.10</td>
<td>-0.10</td>
<td>-0.10</td>
<td>-0.08</td>
<td>-0.05</td>
<td>-0.02</td>
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<tr>
<td>2. SP-RP ($\phi = 0.6$)</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.02</td>
</tr>
<tr>
<td>3. SP-RP ($\phi = 0.7$)</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>4. SP-RP ($\phi = 0.8$)</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.02</td>
</tr>
<tr>
<td>5. SP-SW-RP ($\phi = 0.6$)</td>
<td>0.83</td>
<td>0.69</td>
<td>0.56</td>
<td>0.46</td>
<td>0.37</td>
<td>0.30</td>
</tr>
<tr>
<td>6. SP-SW-RP ($\phi = 0.7$)</td>
<td>0.83</td>
<td>0.68</td>
<td>0.56</td>
<td>0.45</td>
<td>0.36</td>
<td>0.29</td>
</tr>
<tr>
<td>7. SP-SW-RP ($\phi = 0.8$)</td>
<td>0.83</td>
<td>0.68</td>
<td>0.55</td>
<td>0.44</td>
<td>0.35</td>
<td>0.28</td>
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<table>
<thead>
<tr>
<th>$k$</th>
<th>1</th>
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<tbody>
<tr>
<td>$\rho_Y(k)$</td>
<td>0.38</td>
<td>0.30</td>
<td>0.20</td>
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<tr>
<td>$\rho_C(k)$</td>
<td>0.23</td>
<td>0.19</td>
<td>0.12</td>
</tr>
<tr>
<td>$\rho_I(k)$</td>
<td>0.31</td>
<td>0.27</td>
<td>0.17</td>
</tr>
<tr>
<td>$\rho_N(k)$</td>
<td>0.58</td>
<td>0.36</td>
<td>0.17</td>
</tr>
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</table>
Table 3b: Autocorrelations of the Growth Rates of Aggregate Quantities in Alternative Models

<table>
<thead>
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<th>Order of autocorrelation</th>
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<th>3</th>
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</thead>
<tbody>
<tr>
<td>Output Growth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. SP</td>
<td>0.15</td>
<td>-0.05</td>
<td>-0.13</td>
</tr>
<tr>
<td>2. SP-RP ($\phi = 0.6$)</td>
<td>0.45</td>
<td>0.17</td>
<td>0.02</td>
</tr>
<tr>
<td>3. SP-RP ($\phi = 0.7$)</td>
<td>0.53</td>
<td>0.24</td>
<td>0.08</td>
</tr>
<tr>
<td>4. SP-RP ($\phi = 0.8$)</td>
<td>0.58</td>
<td>0.31</td>
<td>0.13</td>
</tr>
<tr>
<td>5. SP-SW-RP ($\phi = 0.6$)</td>
<td>0.61</td>
<td>0.34</td>
<td>0.15</td>
</tr>
<tr>
<td>6. SP-SW-RP ($\phi = 0.7$)</td>
<td>0.62</td>
<td>0.35</td>
<td>0.16</td>
</tr>
<tr>
<td>7. SP-SW-RP ($\phi = 0.8$)</td>
<td>0.64</td>
<td>0.37</td>
<td>0.19</td>
</tr>
<tr>
<td>Consumption Growth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. SP</td>
<td>0.26</td>
<td>-0.07</td>
<td>-0.19</td>
</tr>
<tr>
<td>2. SP-RP ($\phi = 0.6$)</td>
<td>0.43</td>
<td>0.10</td>
<td>-0.06</td>
</tr>
<tr>
<td>3. SP-RP ($\phi = 0.7$)</td>
<td>0.48</td>
<td>0.16</td>
<td>-0.01</td>
</tr>
<tr>
<td>4. SP-RP ($\phi = 0.8$)</td>
<td>0.52</td>
<td>0.21</td>
<td>0.03</td>
</tr>
<tr>
<td>5. SP-SW-RP ($\phi = 0.6$)</td>
<td>0.53</td>
<td>0.23</td>
<td>0.04</td>
</tr>
<tr>
<td>6. SP-SW-RP ($\phi = 0.7$)</td>
<td>0.54</td>
<td>0.24</td>
<td>0.05</td>
</tr>
<tr>
<td>7. SP-SW-RP ($\phi = 0.8$)</td>
<td>0.55</td>
<td>0.26</td>
<td>0.07</td>
</tr>
<tr>
<td>Investment Growth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. SP</td>
<td>0.34</td>
<td>0.01</td>
<td>-0.14</td>
</tr>
<tr>
<td>2. SP-RP ($\phi = 0.6$)</td>
<td>0.57</td>
<td>0.27</td>
<td>0.09</td>
</tr>
<tr>
<td>3. SP-RP ($\phi = 0.7$)</td>
<td>0.60</td>
<td>0.32</td>
<td>0.13</td>
</tr>
<tr>
<td>4. SP-RP with ($\phi = 0.8$)</td>
<td>0.62</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>5. SP-SW-RP ($\phi = 0.6$)</td>
<td>0.64</td>
<td>0.38</td>
<td>0.19</td>
</tr>
<tr>
<td>6. SP-SW-RP ($\phi = 0.7$)</td>
<td>0.65</td>
<td>0.40</td>
<td>0.21</td>
</tr>
<tr>
<td>7. SP-SW-RP ($\phi = 0.8$)</td>
<td>0.67</td>
<td>0.42</td>
<td>0.24</td>
</tr>
<tr>
<td>Hours Growth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. SP</td>
<td>0.60</td>
<td>0.04</td>
<td>-0.19</td>
</tr>
<tr>
<td>2. SP-RP ($\phi = 0.6$)</td>
<td>0.74</td>
<td>0.34</td>
<td>0.08</td>
</tr>
<tr>
<td>3. SP-RP ($\phi = 0.7$)</td>
<td>0.76</td>
<td>0.35</td>
<td>0.10</td>
</tr>
<tr>
<td>4. SP-RP ($\phi = 0.8$)</td>
<td>0.78</td>
<td>0.37</td>
<td>0.13</td>
</tr>
<tr>
<td>5. SP-SW-RP ($\phi = 0.6$)</td>
<td>0.61</td>
<td>0.33</td>
<td>0.14</td>
</tr>
<tr>
<td>6. SP-SW-RP ($\phi = 0.7$)</td>
<td>0.62</td>
<td>0.35</td>
<td>0.16</td>
</tr>
<tr>
<td>7. SP-SW-RP ($\phi = 0.8$)</td>
<td>0.63</td>
<td>0.36</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Figure 1: Roundabout Production, Sticky Prices and the MPS
Figure 2: Policy Inertia and the MPS

- Price level
- Output
- Real marginal cost
- Hours worked
- Inflation rate
- Consumption
- Real wage
- Materials input
- Real interest rate
- Investment
- Rental rate
- Capital utilization rate

SP–RP ($\phi=0.6$); $\rho_r=0.5$

SP–RP ($\phi=0.6$); $\rho_r=0.7$

SP–RP ($\phi=0.6$); $\rho_r=0.9$
Figure 3: Sticky Prices and Habit Formation

- **Price level**
- **Output**
- **Real marginal cost**
- **Hours worked**
- **Inflation rate**
- **Consumption**
- **Real wage**
- **Materials input**
- **Real interest rate**
- **Investment**
- **Rental rate**
- **Capital utilization rate**

- **SP−RP (φ=0.6); b=0.8**
- **SP; b=0.98**
Figure 4: Roundabout Production, Sticky Prices and Sticky Wages
Figure 5: Backward vs Forward-Looking Policy Rules

Inflation rate

Output

- SP–SW–RP ($\phi=0.6$); Contemporaneous Rule
- SP–SW–RP ($\phi=0.6$); Forward–Looking Rule
- SP–SW–RP ($\phi=0.6$); Backward–Looking Rule
Figure 6: High Frequency of Price Reoptimization

\[
\begin{align*}
\text{Price level} & \quad \text{Output} & \quad \text{Real marginal cost} & \quad \text{Hours worked} \\
\text{Inflation rate} & \quad \text{Consumption} & \quad \text{Real wage} & \quad \text{Materials input} \\
\text{Real interest rate} & \quad \text{Investment} & \quad \text{Rental rate} & \quad \text{Capital utilization rate}
\end{align*}
\]

- \( \text{SP-SW-RP (}\phi=0.6; \xi_p=2/3) \)
- \( \text{SP-SW-RP (}\phi=0.6; \xi_p=0.6) \)
- \( \text{SP-SW-RP (}\phi=0.6; \xi_p=0.55) \)
Figure 7: Low Frequency of Wage Reoptimization

Price level

Output

Real marginal cost

Hours worked

Inflation rate

Consumption

Real wage

Materials input

Real interest rate

Investment

Rental rate

Capital utilization rate

SP–SW–RP ($\phi=0.6$; $\xi_w=3/4$

SP–SW–RP ($\phi=0.6$; $\xi_w=0.82$
Figure 8: Hump-Shaped Response of Inflation
Figure 9: The Effects of Neutral Technology Shocks

- Price level
- Inflation rate
- Real interest rate
- Output
- Consumption
- Investment
- Real marginal cost
- Real wage
- Rental rate
- Materials input
- Hours worked
- Capital utilization rate

SP-SW-RP (φ=0.6)
Figure 10: The Effects of Investment-Specific Shocks

- Price level
- Output
- Real marginal cost
- Hours worked
- Inflation rate
- Consumption
- Real wage
- Materials input
- Real interest rate
- Investment
- Rental rate
- Capital utilization rate

SP=SW−RP (\(\alpha=0.6\))