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On Stickiness, Cash in Advance, and Persistence

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Abstract

This paper shows that a model which combines sticky prices and sticky wages with investment in the cash-in-advance constraint generates business cycle dynamics consistent with empirical evidence. The model reproduces the responses of the key macroeconomic variables to technology and money supply shocks; in particular, it generates enough output and inflation persistence with standard stickiness parameters. This setup is also able to generate the liquidity effect after a money injection, overcoming a weakness in standard new Keynesian models. When taken to the data, the model explains qualitatively well the US postwar period, and does quantitatively better for the *great inflation* of the 70s.

Keywords: sticky prices, sticky wages, monetary facts, labor market facts, cash-in-advance.

JEL Class.: E32, E41, E52

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1 Introduction

It is well known that standard new Keynesian models fail to generate enough output and inflation persistence. Additionally, there is no unique and simple model which can reproduce both the liquidity effect (see for instance Galí, 2003) and labor market dynamics (see for instance Liu and Phaneuf, 2006). The main challenge facing dynamic stochastic general equilibrium models (henceforth DSGE models) is how much the mechanism with nominal rigidities can deliver in transmitting business cycle shocks. Standard DSGE models have so far achieved mixed success along this dimension.

Christiano, Eichenbaum and Evans (2005) have shown that it is possible to reproduce the main stylized facts in a fully specified model. The authors find that the key factors driving the results are those rigidities preventing marginal costs from overreacting after the shock, in particular, wage stickiness and variable capital utilization. Also important factors are the introduction of working capital and the use of price indexation for those firms not adjusting prices. This last fact implies a lagged inflation term in the new Phillips curve, inducing more persistence in the response of inflation. However, this assumption is not completely supported by the data.[1]

This paper shows that a sticky-price, sticky-wage model with investment in the CIA constraint can generate enough output and inflation persistence without the need for price indexation. In this sense, this framework is suitable for analyzing episodes of high and persistent inflation, like the *great inflation* of the 70s. In addition, this framework permits the reproduction of monetary and labor market facts.

The model is based on two main pillars. First, investment is partially financed with cash, and second, wages are sticky. These elements are not new. Wang and Wen (2006) analyze output persistence in a sticky price model with investment in the CIA constraint. They find that investment being a cash good is crucial for generating output persistence in a standard sticky price model. Our setup is similar to theirs in that we also consider sticky prices *à-la*-Calvo and investment as a cash good. However, we go further and investigate alternative channels that may generate persistence. First,

[1] See for example, Dhyne et al. (2005) for some evidence on Euro area data.

we consider sticky wages à-la-Calvo as in Erceg, Henderson and Levin (2000), and show that this is a more important mechanism in generating persistence than sticky prices.[2] Second, our focus also differs from Wang and Wen's paper. While their main objective is output persistence, we also focus on inflation persistence and study the dynamic properties of this framework with regard to some key monetary and labor market stylized facts.

In contrast to previous new Keynesian models, where the role of monetary holdings is usually modeled as real balances in the utility function, we introduce money through a CIA constraint. In spite of the different setup, the timing is equivalent to that of a model with money in the utility function, but at the same time it allows for extensions of interest such as making investment a cash good. Previous research stressed the role of inflation on investment demand, and introduced investment decisions constrained that way (Stockman, 1981; Abel, 1985). Empirically, although it is still topic of debate, there seems to be some evidence regarding the effects of firms' internal cash flows on investment demand in the context of capital market imperfections (Fazzari, Hubbard and Peterson, 1988). In this sense, cash flows are often used as a proxy for net worth in determining investment. Recently, some studies for the US and countries in the Euro area reveal a significant effect of cash flows on investment demand, although the strength of the effect varies across countries (Chirinko, Fazzari and Meyer, 1999; Angeloni, Kashyap and Mojon, 2003). The relevance of cash flows for investment demand, and therefore, the ability of firms to react to shocks can be addressed in our model by including investment in the CIA constraint.

The results show that a model which combines sticky wages, sticky prices and investment as a cash good reproduces the stylized facts after a technology shock and also after a money injection. Our model generates enough inflation and output persistence compared to that observed in the data, with reasonable degrees of stickiness. The key factor driving these results is the inclusion of investment in the CIA constraint, which

[2] Adding wage stickiness to a sticky price model has been shown to be quite successful in recent literature, in particular, in generating output persistence. See for instance Christiano, Eichenbaum and Evans, 2005.

delays the response of demand to shocks. Not only do we study whether the model is able to generate qualitative dynamics but also quantitatively. The model proves to be a good toolbox for analyzing episodes of high and persistent inflation such as the *great inflation* of the 70s in the US.[3] However, the model fails to reproduce the impact response of inflation to a money injection. Finally, our setup is able to generate the liquidity effect. This result stresses the relevance of sticky wages versus sticky prices in modeling the monetary transmission mechanism. Also, we need investment completely financed with cash to obtain the liquidity effect. The mechanism behind these results is the delayed response of aggregate demand to shocks, due to the CIA constraint, together with marginal costs being affected by the interest rate.

The paper is structured as follows. We present the model in Section 2. In Sections 3 and 4, we calibrate the model and solve for equilibrium. We proceed to analyze the dynamics of the model after a positive technology shock and a monetary injection in Section 5. Section 6 focuses on the persistence generated by the model. Section 7 covers the estimation and Section 8 closes the paper.

2 The Model

The economy is populated by a large number of identical, infinitely-lived households and consists of two sectors: one producing intermediate goods and the other final goods. The intermediate good is produced with capital and labor, and the final good with intermediate goods. The final good is homogeneous and can be used for consumption and investment purposes.

[3]Other papers analyzing the *great inflation* with different mechanisms include Collard and Dellas (2006) and Dupor, Kitamura and Tsuruga (2006), among others.

2.1 Final goods sector

The final good is produced by combining intermediate goods. This process is described by the following CES function:

$$Y_t = \left(\int_0^1 Y_t(j)^{\frac{1}{\lambda_f}} dj \right)^{\lambda_f}, \tag{1}$$

where $\lambda_f \in [1, \infty)$ determines the elasticity of substitution between the various inputs. Producers in this sector are assumed to behave competitively, and to determine their demand for each good, $Y_t(j)$, $j \in (0,1)$ by maximizing the static profit equation

$$\max_{\{Y_t(j)\}_{j\in(0,1)}} P_t Y_t - \int_0^1 P_t(j) Y_t(j) dj,$$

subject to (1), where $P_t(j)$ denotes the price of the intermediate good j. This yields input demand functions of the form

$$Y_t(j) = \left(\frac{P_t}{P_t(j)} \right)^{\frac{\lambda_f}{\lambda_f - 1}} Y_t,$$

and the following aggregate price index:

$$P_t = \left(\int_0^1 P_t(j)^{\frac{1}{1-\lambda_f}} dj \right)^{1-\lambda_f}.$$

2.2 Intermediate goods producers

Each firm $j \in (0,1)$ produces an intermediate good by means of capital and labor according to the following constant returns-to-scale production function:

$$Y_t(j) = a_t K_t(j)^{\alpha} L_t(j)^{1-\alpha} \quad \text{with} \quad \alpha \in (0,1), \tag{2}$$

where $K_t(j)$ and $L_t(j)$, respectively, denote the physical capital and the labor input used by firm j in the production process; a_t is an exogenous stationary stochastic technology shock, whose properties will be defined later. Assuming that each firm j operates under perfect competition in the input markets, the firm determines its production plan to minimize its total cost

$$\min_{\{K_t(j), L_t(j)\}} P_t w_t L_t(j) + P_t r_t^k K_t(j),$$

subject to (2). This yields to the following expression for total costs:

$$P_t\phi_t Y_t(j),$$

where the real marginal cost, ϕ_t, is given by $\dfrac{w_t^{1-\alpha}(r_t^k)^\alpha}{\chi a_t}$, with $\chi = \alpha^\alpha(1-\alpha)^{1-\alpha}$.

Intermediate goods producers are monopolistically competitive, and therefore set prices for the good they produce. We follow Calvo (1983) in assuming that firms set their prices for a stochastic number of periods. In each and every period, a firm either gets the chance to adjust its price (an event occurring with probability $1-\xi_p$) or it does not. When the firm does not reset its price, it just applies steady state inflation, π^*, to the price it charged in the last period such that $P_t(j) = \pi^* P_{t-1}(j)$. When it gets a chance to do it, firm j resets its price, $\tilde{P}_t(j)$, in period t in order to maximize the expected discounted profit flow which this new price will generate. In period t, the profit is given by $\Pi(\tilde{P}_t(j))$. In period $t+1$, either the firm resets its price, such that it will get $\Pi(\tilde{P}_{t+1}(j))$ with probability $1-\xi_p$, or it does not and its $t+1$ profit will be $\Pi(\pi^*\tilde{P}_t(j))$ with probability ξ_p. Likewise in $t+2$. The expected profit flow generated by setting $\tilde{P}_t(j)$ in period t is obtained from

$$\max_{\tilde{P}_t} E_t \sum_{\tau=0}^{\infty} \Phi_{t+\tau} \left(\xi_p\right)^{\tau-1} \Pi(\pi^{*\tau}\tilde{P}_t(j)),$$

subject to the total demand it faces

$$Y_t(j) = \left(\frac{P_t}{P_t(j)}\right)^{\frac{\lambda_f}{\lambda_f-1}} Y_t,$$

where $\Pi(\pi^{*\tau}\tilde{P}_{t+\tau}(j)) = \left(\pi^{*\tau}\tilde{P}_t(j) - P_{t+\tau}\phi_{t+\tau}\right) Y_{t+\tau}(j)$ and $\Phi_{t+\tau}$ is an appropriate discount factor related to the way a household values future, as opposed to current consumption, such that

$$\Phi_{t+\tau} \propto \beta^\tau \frac{\Lambda_{t+\tau}}{\Lambda_t}.$$

This leads to the price setting equation

$$\frac{1}{\lambda_f}\tilde{P}_t(j) E_t \sum_{\tau=0}^{\infty} (\beta\pi^*\xi_p)^\tau \Lambda_{t+\tau} \left(\frac{\pi^{*\tau}\tilde{P}_t(j)}{P_{t+\tau}}\right) Y_{t+\tau} = E_t \sum_{\tau=0}^{\infty} (\beta\xi_p)^\tau \Lambda_{t+\tau} \left(\frac{\pi^{*\tau}\tilde{P}_t(j)}{P_{t+\tau}}\right)^{\frac{\lambda_f}{1-\lambda_f}} P_{t+\tau}\phi_{t+\tau} Y_{t+\tau}, \quad (3)$$

from which it is clear that all firms which reset their price in period t set it at the same level ($\tilde{P}_t(j) = \tilde{P}_t$, for all $j \in (0, 1)$).

Recall now that the price index is given by

$$P_t = \left(\int_0^1 P_t(j)^{\frac{1}{1-\lambda_f}} dj \right)^{1-\lambda_f}.$$

In fact, the price index comprises surviving contracts and newly set prices. Given that in each and every period a price contract has probability $1 - \xi_p$ of ending, the probability that a contract signed in period $t - s$ survives until period t, and ends at the end of period t is given by $(1 - \xi_p)\xi_p^s$. Therefore, the aggregate price level may be expressed as the average of all surviving contracts, namely

$$P_t = \left(\sum_{s=0}^{\infty} (1 - \xi_p)\xi_p^s \left(\pi^{*j} \tilde{P}_{t-s} \right)^{\frac{1}{1-\lambda_f}} \right)^{1-\lambda_f},$$

which can be expressed recursively as

$$P_t = \left((1 - \xi_p)\tilde{P}_t^{\frac{1}{1-\lambda_f}} + \xi_p \left(\pi^* P_{t-1} \right)^{\frac{1}{1-\lambda_f}} \right)^{1-\lambda_f}. \tag{4}$$

A log-linear approximation of (3) around a zero inflation steady state yields the new Keynesian Phillips curve in this model

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \frac{(1 - \xi_p)(1 - \beta\xi_p)}{\xi_p} \hat{\phi}_t,$$

where current inflation depends on expected future inflation and marginal costs.

2.3 The household

There is a continuum of households in the interval $[0, 1]$. Household preferences are characterized by the lifetime utility function:

$$E_t \sum_{l=0}^{\infty} \beta^{l-t} \left(\frac{c_t^{1-\sigma}}{1 - \sigma} - \Psi \frac{h_{it}^{1+\psi}}{1 + \psi} \right), \tag{5}$$

where $0 < \beta < 1$ is a constant discount factor, c denotes consumption and h is labor supply.

Consumption and investment purchases have to be made in cash. Therefore, the household is subject to the following CIA constraint:

$$c_t + \varphi x_t \leq \frac{M_t}{P_t},$$

with capital accumulating according to the law of motion

$$x_t = k_{t+1} - (1 - \delta)k_t,$$

where $\delta \in [0, 1]$ denotes the rate of depreciation. Notice that investment enters with a coefficient φ in the CIA constraint. In the simulations below, we will set $\varphi \in [0, 1]$, allowing for investment into or out of the CIA constraint. As shown in Wang and Wen (2006), this extension of the model ends up having important implications in terms of persistence.

In each and every period, the representative household faces a budget constraint of the form

$$\frac{\frac{B_t}{R_t} + M_t}{P_t} + c_t + x_t \leq \frac{B_{t-1} + M_{t-1}}{P_t} + \Pi_t + w_{it}h_{it} + r_t^k k_t, \tag{6}$$

where B_t and M_t are nominal bonds and money holdings acquired during period t, P_t is the nominal price of the final good, R_t is the gross nominal interest rate, w_{it} and r_t^k are the real wage rate and real rental rate of capital, respectively. In this economy, bonds are in zero net supply, that is, $B_t = 0$ in equilibrium. The household owns k_t units of physical capital which is rented to the firm at a price r_t^k. The household also makes an additional investment of x_t, consumes c_t and supplies h_{it} units of labor. Moreover, it receives the profits, Π_t, earned by the firms.

The representative household maximizes utility subject to the CIA and the budget constraint by choosing the paths of c_t, k_{t+1}, M_t and B_t. The first order conditions are

$$u'(c_t) - \lambda_t - \gamma_t = 0, \tag{7}$$

$$-\varphi\gamma_t - \lambda_t + \beta E_t \left[\lambda_{t+1}\left(r_{t+1}^k + 1 - \delta\right) + \varphi(1-\delta)\gamma_{t+1}\right] = 0, \tag{8}$$

$$-\frac{\lambda_t}{P_t} + \frac{\gamma_t}{P_t} + \beta E_t \frac{\lambda_{t+1}}{P_{t+1}} = 0, \tag{9}$$

$$-\frac{\lambda_t}{R_t} + \beta E_t \lambda_{t+1} = 0, \tag{10}$$

$$M_t - P_t C_t - \varphi P_t \left[K_{t+1} - (1-\delta)K_t\right] = 0, \tag{11}$$

$$B_{t-1} + M_{t-1} + P_t \Pi_t + P_t w_{it} h_{it} + P_t r_t^k k_t - \left(\frac{B_t}{R_t} + M_t\right) - P_t c_t - P_t\left[k_{t+1} - (1-\delta)k_t\right] = 0, \tag{12}$$

where λ_t denotes the Lagrange multiplier associated with the budget constraint, and γ_t is the Lagrange multiplier associated with the CIA constraint.

2.3.1 Sticky wages

In addition, we follow Erceg, Henderson, and Levin (2000), and assume that each household $i \in (0,1)$ is a monopolistic supplier of a differentiated labor service, h_{it}. Each household sells this service to a representative, competitive firm which transforms it into an aggregate labor input, L_t, using the following technology:

$$h_t = \left[\int_0^1 h_{it}^{\frac{1}{\lambda_w}} di\right]^{\lambda_w},$$

with $\lambda_w > 1$ being the Dixit elasticity of substitution among differentiated labor services.

Following the same procedure as for final firms, it can be shown that the demand curve for h_{it} is given by

$$h_{it} = \left(\frac{W_t}{W_{it}}\right)^{\frac{\lambda_w}{\lambda_w - 1}} h_t. \tag{13}$$

The aggregate nominal wage index is given by

$$W_t = \left[\int_0^1 W_{it}^{\frac{1}{1-\lambda_w}} di\right]^{1-\lambda_w},$$

where W_{it} denotes individual household nominal wage.

To introduce sticky wages, Erceg, Henderson and Levin (2000) assume that households reset nominal wages with a probability $1-\xi_w$ and choose a new wage $\tilde{W}_{it}$; and with probability ξ_w, nominal wages are set according to

$$W_{i,t+l} = \pi^* W_{i,t}.$$

We also assume that households have access to a complete set of state contingent contracts. This ensures the same marginal utility of consumption for all workers in equilibrium (Erceg, Henderson and Levin, 2000; Sbordone, 2001).

The representative household chooses the optimal nominal wage $\tilde{W}_{i,t}$ to maximize utility (5) subject to the budget constraint (6) and the labor demand (13) under the scenario of being unable to reset wages, taking h_t, P_t and W_t as given.

The first order condition is

$$E_t \sum_{l=0}^{\infty} \beta^l \xi_w^l \left[-z'(h_{i,t+l}) \frac{\partial h_{i,t+l}}{\partial W_{i,t+l}} + \lambda_{t+l} \left(h_{i,t+l} + W_{i,t+l} \frac{\partial h_{i,t+l}}{\partial W_{i,t+l}} \right) \right] = 0, \tag{14}$$

that is, the present discounted value of the disutility of working $h_{i,t}$ hours at the new wage must equal the benefit of working, measured in terms of the marginal utility of consumption.

Plugging (13) into (14) and taking into account that

$$\frac{\partial h_{i,t+l}}{\partial W_{i,t+l}} = \left(\frac{W_{t+l}}{W_{i,t+l}} \right)^{\frac{\lambda_w}{\lambda_w - 1}} h_{t+l} \frac{1}{W_{i,t+l}} \left(\frac{-\lambda_w}{\lambda_w - 1} \right),$$

and the utility function of labor, the FOC becomes

$$E_t \sum_{l=0}^{\infty} \beta^l \xi_w^l \left\{ \begin{array}{c} -\Psi h_{i,t+l}^{\psi} \left(\frac{W_{i,t+l}}{W_{t+l}} \right)^{\frac{\lambda_w}{1-\lambda_w} - 1} h_{t+l} \frac{1}{W_{t+l}} \left(\frac{\lambda_w}{1-\lambda_w} \right) + \\ \lambda_{t+l} \left[h_{i,t+l} + W_{i,t+l} \left(\frac{W_{i,t+l}}{W_{t+l}} \right)^{\frac{\lambda_w}{1-\lambda_w} - 1} h_{t+l} \frac{1}{W_{t+l}} \left(\frac{\lambda_w}{1-\lambda_w} \right) \right] \end{array} \right\} = 0,$$

using the fact that for those who can adjust, the optimal price will be W_t^*

$$W_{i,t+l} = W_t^*,$$

and that

$$h_{it} = \left(\frac{W_{i,t}}{W_t} \right)^{\frac{\lambda_w}{1-\lambda_w}} h_t = \left(\frac{W_t^*}{W_t} \right)^{\frac{\lambda_w}{1-\lambda_w}} h_t,$$

we obtain

$$E_t \sum_{l=0}^{\infty} \beta^l \xi_w^l \left\{ \Psi \lambda_w h_{t+l}^{1+\psi} \frac{1}{W_{t+l}} (W_t^*)^{\frac{\psi\lambda_w}{1-\lambda_w}-1} \right\} (W_t^*)^{1-\frac{\psi\lambda_w}{1-\lambda_w}} \left(\frac{W_t^*}{W_{t+l}} \right)^{\frac{(1+\psi)\lambda_w}{1-\lambda_w}-1} =$$

$$E_t \sum_{l=0}^{\infty} \beta^l \xi_w^l \left\{ \lambda_{t+l} h_{t+l} \left(\frac{W_t^*}{W_{t+l}} \right)^{1-\frac{\psi\lambda_w}{1-\lambda_w}} \right\} \left(\frac{W_t^*}{W_{t+l}} \right)^{\frac{(1+\psi)\lambda_w}{1-\lambda_w}-1}. \qquad (15)$$

After some algebra we obtain the wage-inflation equation

$$\widehat{\pi}_t^w = \frac{(1-\beta\xi_w)(1-\xi_w)}{\xi_w \left(1+\frac{\psi\lambda_w}{\lambda_w-1}\right)} \left\{ \psi \widehat{h}_t - \widehat{\lambda}_t - \widehat{w}_t \right\} + \beta E_t \widehat{\pi}_{t+1}^w.$$

Finally, recall that $\widehat{mrs}_t = \psi \widehat{h}_t - \widehat{\lambda}_t$, then

$$\widehat{\pi}_t^w = \frac{(1-\beta\xi_w)(1-\xi_w)}{\xi_w \left(1+\frac{\psi\lambda_w}{\lambda_w-1}\right)} \left\{ \widehat{mrs}_t - \widehat{w}_t \right\} + \beta E_t \widehat{\pi}_{t+1}^w,$$

where current wage-inflation depends on future wage-inflation and on the marginal rate of substitution between consumption and labor derived in this model. Notice that sticky wages introduce a wedge between the marginal product of labor and the marginal cost of firms in hiring workers: marginal costs now depend on the aggregate wage index, which is affected by wage stickiness, and the marginal rate of substitution between labor and consumption.

Following the same reasoning as with sticky prices, the aggregate wage index can be expressed recursively as a weighted average of reset and old wages

$$\overline{W}_t = \left[(1-\xi_w)(\widetilde{W}_t)^{\frac{\lambda_w}{1-\lambda_w}} + \xi_w(\pi^* \overline{W}_{t-1})^{\frac{\lambda_w}{1-\lambda_w}} \right]^{\frac{1-\lambda_w}{\lambda_w}}. \qquad (16)$$

2.4 The monetary authority

Money is exogenously supplied by the central bank according to the following money growth rule:

$$M_t = \mu_t M_{t-1},$$

where $\mu_t \geqslant 1$ is the exogenous gross rate of money growth, such that

$$N_t = M_t - M_{t-1} = (\mu_t - 1) M_t.$$

The growth rate of money is assumed to be an exogenous stochastic process, which follows an AR(1) process, with autoregressive coefficient ρ_μ.

3 Equilibrium

Given the description of the model, we proceed to define an equilibrium.

Definition 1 *A competitive general equilibrium in this model is given by a set of allocations* $\left\{Y_t, Y_{jt}, K_{t+1}, K_{jt+1}, H_t, H_{it}, C_t, M_t, B_t, W_t, W_{it}, P_t, P_{jt}, r_t^k, R_t\right\}$ *such that:*

i) taking prices and shocks as given, the household's problem is optimally solved, and the F.O.C. (7)-(12) are satisfied, and the CIA constraint holds with equality

$$C_t + \varphi X_t = \frac{M_t}{P_t};$$

ii) taking prices, wages and shocks, the final good firm's problem is optimally solved;

iii) taking wages and shocks, the intermediate firm's problem is optimally solved;

iv) markets clear, that is,

$$\begin{aligned}
Y_t &= C_t + X_t, \\
X_t &= K_{t+1} - (1-\delta) K_t, \\
M_t &= M_{t-1} + N_t, \\
h_t &= \left[\int_0^1 h_{it}^{\frac{1}{\lambda_w}} di\right]^{\lambda_w} = L_t, \\
Y_t &= \left(\int_0^1 Y_t(j)^{\frac{1}{\lambda_f}} dj\right)^{\lambda_f};
\end{aligned}$$

v) prices satisfy equations (3) and (4);

vi) and wages satisfy equations (15) and (16).

The model is log-linearized around a nonstochastic steady state and then simulated to analyze the responses under technology and money supply shocks.

4 Calibration

When possible we follow parameter values which are standard in the literature. The baseline parameter values are given in Table 1. The model is parameterized using US quarterly data for the post-WWII period.

Preferences

The subjective discount factor, β, is equal to 0.988 implying a 5% annual rate of discount for households. The intertemporal elasticity of substitution for consumption is $\sigma = 2$. The inverse of the labor supply elasticity with respect to wages is $\psi = 1$.

Technology

The capital share of output, α, is standard and equals 0.36. Capital depreciates at an annual rate of 10%, that is, $\delta = 0.025$. Monopolistically competitive firms charge a 10% markup on prices, and households charge a 20% on wages, implying λ_p, and λ_w equal to 0.85 and 0.80 respectively, consistent with estimates provided by Christiano, Eichenbaum and Evans (2005). Regarding price and wage setting, we assume that there is a probability $\xi_p = \frac{1}{4}$ of resetting prices, and a probability $\xi_w = \frac{1}{5}$ of resetting wages in each period, (implying an average contract duration of 4 and 5 quarters, respectively); these are close to those employed by Erceg, Henderson and Levin (2000).[4]

Shock processes

The productivity shock is assumed to follow an AR(1) process with autocorrelation $\rho_a = 0.99$ and standard deviation $\sigma_a = 0.008$. We assume that gross money growth follows an autoregressive process with autocorrelation $\rho_\mu = 0.6$, and standard deviation $\sigma_\mu = 0.006$. These are the same as that those employed by Wang and Wen (2006).

[4]Recently, there is a growing debate on the true value of the Calvo parameter (Nakamura and Steinsson, 2007). However, for the sake of comparison with previous studies we stick to the values reported above.

5 Dynamics of the model

Next, we evaluate the qualitative performance of the model. To this end, we study the dynamics of the model in response to technology shocks and to monetary shocks.

5.1 Labor market and technology shocks

We now analyze the dynamics of the model under three specifications of stickiness (price, wage or both) to a one percent technology shock at time $t = 1$.

Figure 1 displays the response of the model with sticky prices and wages in each of the three scenarios. The solid line depicts the case when investment is a credit good $(\varphi = 0)$; the dashed line refers to investment as a partially cash good ($\varphi = 0.6$); and the dotted line denotes investment fully financed with cash $(\varphi = 1)$. This figure indicates that to reproduce labor market dynamics after a technology shock, both rigidities and investment, either completely or partially financed with cash, are needed. In particular, hours fall after a technology shock (as in Galí, 1999), and real wages are also consistent with the data: nominal wages hardly react on impact to a combination of sticky wages and prices, driving real wages up. This is in line with Liu and Phaneuf (2006), who use a model which combines sticky prices and sticky wages with habit formation to reproduce labor market dynamics after a technology shock. Their findings after a rise in productivity are replicated in Figure 1: a weak response in nominal wage inflation, a mild decline in price inflation and modest rise in real wages.

Notice that we need both nominal rigidities and φ positive to reproduce the dynamics of both hours and real wages. However, for all the rigidities considered we obtain a fall in hours after a positive technology shock, as long as investment is a cash good, with the exception of the sticky price model with $\varphi = 1$. Figure 2 shows the responses for the pure sticky price and pure sticky wage models with $\varphi = \{0, 1\}$.

In spite of the similar setup, our model outperforms that of Liu and Phaneuf (2006). In contrast to their paper, we find that, in a purely sticky wage model, hours fall after a technology shock as long as investment is financed with cash (either completely or partially), which is consistent with Galí (1999) and the literature thereafter. The intuition behind this result is that the response of consumption and investment is subject to agents holding real balances in advance. In this case, the rise in output is smoothed with respect to the rise in productivity, and hours fall. Our model also differs from Liu and Phaneuf (2006) in that the sticky price model generates a rise in the real wage (with nominal wages falling) as long as $\varphi = 1$. In general, sticky price models cannot account for nominal wage dynamics after a technology shock. In our pure sticky price model we obtain the same: either nominal wages go up (when $\varphi = 1$), or they fall considerably for just one period, which is not consistent with the data. As a result, we find that real wages go up, but due to the positive reaction of nominal wages and a great fall in prices. This result is reversed when sticky wages are considered whenever investment appears in the CIA constraint.

5.2 Money supply shocks and the liquidity effect

In this section we show that a sticky-price-sticky-wage model with investment in the CIA constraint generates a fall in nominal interest rates after a money injection, that is, the liquidity effect, which has been a failure common to most standard new Keynesian models (Galí, 2003).

Figure 3 plots the responses of the sticky price-sticky wage model to a one percent rise in money supply at time $t = 1$. As in the previous section, we consider alternative specifications for investment in the CIA constraint $(\varphi = \{0, 0.6, 1\})$.

The model with both frictions and investment as a cash good generates a rise in output and inflation, with a fall in the nominal interest rate after a money injection, which is consistent with the empirical evidence documented in Christiano, Eichenbaum and Evans (1997), among others. In a recent paper, Christiano, Eichenbaum and Evans (2005) argue that having working capital (mainly, firms borrowing to pay the wage bill) together with variable capital utilization is key to get the liquidity effect after a money injection, since changes in the nominal interest rate will have a direct effect on marginal costs. Notice that in our setup making investment a cash good introduces the nominal interest rate into marginal costs of the firm, in a similar way as in Christiano, Eichenbaum and Evans (2005). Sticky prices and wages combined with both consumption and investment being cash goods reduce the response of aggregate demand to the money injection, resulting in a falling nominal interest rate.

The advantage of the setup presented here is that no extra frictions are needed (e.g. habit formation, variable capital utilization, ...) in contrast to Christiano, Eichenbaum and Evans (2005). There are no specific assumptions on consumers' preferences, as suggested in Andrés, López-Salido and Vallés (1999), to generate the liquidity effect. Just modeling money demand with a CIA constraint that affects all aggregate demand (that is, when both consumption and investment are fully financed with cash) and sticky wages in an otherwise standard sticky price model is enough to generate the fall in interest rates, as shown in Figure 3. This result overcomes the failure reported by Huang and Liu (2002) for a staggered wage setting model, and by Wang and Wen (2006) for a pure sticky price setup. Both failures are captured in Figure 4. In particular, the well-known failure of sticky price models to generate the liquidity effect, independently on the proportion of investment financed with cash.

6 Output and inflation persistence

As mentioned in the introduction, the inability of new Keynesian models to generate persistence is one of the workhorses of recent business cycle literature (Mankiw, 2001; Huang and Liu, 2002). Empirical studies show the long-lasting effects of monetary policy shocks on aggregate variables, as well as for technology shocks (e.g., Christiano, Eichenbaum and Evans, 2005).

In addition to generating real and nominal dynamics close, the stylized facts after technology and money supply shocks, our model also generates persistence in output and inflation. This is in line with Wang and Wen (2006), who also consider the role of investment as a cash good in generating output persistence and maintain that such a framework is key to generate output persistence. The reason is the delayed response of aggregate demand to any impulse of the economy due to the CIA constraint.

In Figure 5, we show that combining sticky prices and sticky wages can generate enough output and inflation persistence and hump-shape reaction in output as long as investment is included in the CIA constraint. We also find the well known result that inflation dynamics fail in a pure sticky price model, whereas output dynamics can be replicated as long as investment is a cash good (Wang and Wen, 2006). However, in response to a technology shock, the pure sticky wage model cannot generate a hump-shaped response in output in any of the cases considered.

To quantify how close these results are to the persistence found in the data, we compare the impulse response functions generated by our qualitatively best model (sticky-price-sticky-wage model with investment in the CIA) with those obtained from an estimated structural vector autoregression model[5] (henceforth SVAR), and with those by Wang and Wen (2006). Figure 6 reports the results for a positive technology shock. We find that impulse responses generated by our model mostly fall within the confidence intervals of SVAR estimation. It is worth noticing that the model generates inflation dynamics which are close to those in the data, both on impact and in terms of persistence: after a rise in productivity, inflation falls and returns to steady state after five quarters, approximately. The dynamics implied for output, though still consistent with the estimation, denote more persistence than the data. Notice, however, that the model by Wang and Wen (2006) still generates further persistence.

That sticky wages and investment in the CIA constraint add persistence in the case of money supply shocks is shown in Figure 7. Considering only sticky wages or sticky prices and sticky wages with investment in the CIA constraint outperforms the sticky price model regarding both output and inflation dynamics. In this case, when compared to the SVAR estimation and to Wang and Wen (2006) (Figure 8), we can see that the specification that generates the best qualitative results (sticky price, sticky wages and investment fully financed with cash), provides a stronger response of output and more persistence than those in the data. Regarding inflation dynamics, although the best model generates more inflation persistence than the standard sticky price setup, it reports an initial rise in inflation (which is much higher for Wang and Wen,

[5]The impulse responses for the SVAR are estimations for US data during the period 1963:1-2003:4. The estimation method is described below.

2006), contrary to SVAR evidence. This means that there is still room for improvement regarding inflation dynamics.

7 Output and inflation persistence in the data

Given the results above, we test the model to see if it can account for the persistence in inflation observed in U.S. data. To this end, we take data for the main macroeconomic variables in the U.S. and estimate the most relevant parameters of the model regarding persistence. We consider two periods, from 1963:1-1983:4 also known as the *great inflation,* and 1984:1-2003:1 which includes the period known as the *great moderation.* Our aim is to replicate the response of such variables to their empirical counterparts after both technology and money supply shocks.

7.1 Econometric methodology

We follow the original work by Rotemberg and Woodford (1997) and estimate the model parameters ψ by minimizing a measure of the distance between the empirical responses of key aggregate variables obtained from two different SVARs (one for technology shocks and another for monetary shocks) and their model counterparts.

More precisely, we focus our attention on the responses of the vector of actual variables Z_t. We let θ_k be the vector of responses to a given shock at horizon $k \geq 0$, as implied by the above SVAR estimated on actual data, *i.e.*

$$\theta_j = \frac{\partial Z_{t+j}}{\partial \epsilon_t}, \quad j \geq 0,$$

where ϵ_t is the monetary policy shock previously identified.

Given a selected horizon k, we seek to match $\theta = \text{vec}([\theta_0, \theta_1, \ldots, \theta_k])'$ where we exclude from θ_0 the responses corresponding to the elements in Z_t that belong to Ω_t. Then let $h(\cdot)$ denote the mapping from the structural parameters $\psi_1 = (\varphi, \xi_p, \xi_w, \rho_a, \sigma_a)'$ for the technology shock and $\psi_2 = (\varphi, \xi_p, \xi_w, \rho_\mu, \sigma_\mu)'$ for the monetary shock to model counterparts of θ. Our estimates of ψ_i is solution to the following problem

$$\hat{\psi}_T = \arg\min_{\psi\in\Psi}(h(\psi_i) - \hat{\theta}_T)V_T(h(\psi_i) - \hat{\theta}_T)',$$

where $i = 1, 2$, $\hat{\theta}_T$ is an estimate of θ, T is the sample size, Ψ is the set of admissible values of ψ, and V_T is a weighting matrix which we assume to be the inverse of the diagonal matrix containing the variances of each element of θ. These variances are obtained from the SVAR parameters.

For further references, let us define the objective function at convergence

$$\mathcal{J} = (h(\widehat{\psi}_T) - \hat{\theta}_T)V_T(h(\widehat{\psi}_T) - \hat{\theta}_T)'.$$

Under the null hypothesis, as shown in Hansen (1982), $\mathcal{J} \sim \chi^2(\dim(\theta) - \dim(\psi))$. Given our choice of weighting matrix, we can further decompose $\mathcal{J}$ into components pertaining to each element of Z_t, according to

$$\mathcal{J} = \sum_{i=1}^{\dim(Z)} \mathcal{J}_i.$$

The latter decomposition provides a simple diagnostic tool allowing us to locate those dimensions on which the model succeeds or fails to replicate the impulse response functions implied by the SVAR.

7.2 Estimation results

We use data for the US postwar period from 1963:1 to 2003:4, and we also consider two subsamples splitted at 1983:4. The data, obtained from FRED at St. Louis Fed, are quarterly and have been logged and detrended.[6] Given the distinct nature of the shocks considered, we estimate them separately following different identification schemes.

First, we estimate the impulse response functions of the model to a technology shock. We follow the same ordering as in Galí and Rabanal (2004) for the identification. That is, we estimate a five order SVAR with four lags in the variables output, inflation, wage inflation, hours, real wage, consumption and investment. Figures 9 and 10 show

[6] A more detailed explanation of the data is in the appendix.

that the model does a very good job at matching the hump-shape in output, investment and inflation. The model is also able to reproduce the fall in hours but it is much more pronounced than the one in the data. For the period 1963:1-1983:4, the so-called *great inflation*, the model is able to reproduce the high persistence of inflation after an increase in technology. The estimates in Table 2 show that the model needs a high proportion of investment partially financed with cash ($\varphi > 0$ and significant), which confirms the relevance of cash flows on investment demand in periods of high inflation. The model also needs both sticky prices and wages in order to reproduce the dynamics for any of the two subsamples. Over all the samples considered, the required degree of wage stickiness is higher than for price stickiness, stressing the key role of this rigidity in explaining the dynamics in the data.

As for money supply shocks, we take the standard SVAR approach of Christiano et al. (2005). We estimate a one time increase in money supply in a seven variable SVAR in inflation, output, consumption, investment, money growth, the nominal interest rate and wage inflation. The results in Figures 11 and 12 show that the model is able to reproduce the persistence of output and investment. This means an improvement upon previous models which required additional rigidities such as adjustment costs in investment or habits in consumption to generate such persistence. However, in the data inflation hardly reacts on impact, whereas in the model it immediately jumps up and slowly goes back to its initial level. In spite of this flaw, the model does well regarding persistence of inflation. For the model to perform this way, we need price stickiness, investment in the CIA constraint and completely sticky wages ($\xi_w = 1$), as shown in Table 2. Note that the estimated values are slightly smaller after 1984, except for ξ_w which still equals 1. This confirms the results pointed out by Christiano et al. (2005), that sticky wages is a much more relevant source of persistence than sticky prices, as shown in Section 5. Looking just at postwar US data (63-03) may lead to the conclusion that sticky prices are more relevant to reproduce the effects of money supply shocks, while sticky wages are so for technology perturbations. However, a closer look at the different subsamples indicates that in fact it is sticky wages what is needed in any period and for any of the two shocks. In particular, for the *great inflation*, wage-stickiness seems to have been a key determinant to explain high and persistent inflation. This result disappears when a period of low and stable inflation is considered.

To summarize, we need a model with investment in the CIA constraint as an extra mechanism to induce persistence. This friction may seem similar to introducing habits in consumption, but it is not exactly the same. Under habits in consumption, an increase in money supply means a transfer from consumption today to consumption tomorrow because of the anticipated inflation effect. This generates persistence but not the liquidity effect. Introducing investment in the CIA constraint, breaks some of the inflation effect after a money injection by delaying the purchases of investment. This adds persistence to the model. At the same time, the nominal interest rate falls to clear the money market, generating the liquidity effect.

8 Conclusions

In this paper, we present a model with sticky prices, sticky wages and investment in the CIA constraint which generates business cycle dynamics consistent with empirical evidence. First, our setup generates enough output and inflation persistence with standard stickiness parameters. The key factor driving these results is the inclusion of investment in the CIA constraint, rather than introducing any other nominal or real rigidity. Second, the model reproduces the responses of the key macroeconomic variables to technology and money supply shocks. As for technology shocks, our model reproduces labor market dynamics after a positive increase in productivity: hours fall, nominal wages hardly react, and real wages go up. Regarding money supply shocks, our model specification generates the liquidity effect, a fact which is absent in most sticky price models. Therefore, including investment in the CIA constraint seems to be a simple modeling device to significantly improve the qualitative and quantitative properties of new Keynesian models.

A Data

For the estimation of the impulse response functions, the series employed are the following:

- Real gross domestic product.
- Gross domestic product deflator.
- Nonfarm business sector: hours of all persons.
- Nonfarm business sector: compensation per hour.
- Consumption includes Personal consumption expenditures of nondurables, services, and government consumption expenditures.
- Investment includes Personal consumption expenditures of durable goods, and fixed private investment.
- Money supply is measured by M2.
- The nominal interest rate is the federal funds rate.

B Set of linearized equations

After deflating and log-linearizing the equilibrium equations around the nonstochastic steady state, the model reduces to the following set of equations.
The new Keynesian Phillips curve

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \frac{(1-\xi_p)(1-\beta\xi_p)}{\xi_p}\hat{\phi}_t. \tag{A1}$$

F.O.C. on consumption

$$(2-\beta)\,\hat{\lambda}_t + \beta\hat{r}_t + \sigma\,(2-\beta)\,\hat{c}_t = 0. \tag{A2}$$

F.O.C. on capital

$$\left[r^k + (1-\delta)(1-\varphi\beta)\right] E_t\hat{\lambda}_{t+1} + \varphi\beta(1-\delta)E_t\hat{r}_{t+1} + r^k E_t\hat{r}^k_{t+1} = \varphi\beta\hat{r}_t + (1-\varphi\beta)\hat{\lambda}_t. \tag{A3}$$

This last equation will change depending on the specification considered:

- if $\varphi = 0$, investment is fully financed with credit, and does not appear in the cash-in-advance constraint. Therefore, the equation becomes

$$\left[r^k + (1-\delta)\right] E_t\hat{\lambda}_{t+1} + r^k E_t\hat{r}^k_{t+1} = \hat{\lambda}_t, \tag{A4}$$

- if $\varphi = 1$, investment is fully financed with cash, and is, therefore, affected by the nominal interest rate. Then, the equation becomes

$$\left[r^k + (1-\delta)(1-\beta)\right] E_t\hat{\lambda}_{t+1} + \beta(1-\delta)E_t\hat{r}_{t+1} + r^k E_t\hat{r}^k_{t+1} = \beta\hat{r}_t + (1-\beta)\hat{\lambda}_t. \quad \text{(A5)}$$

Goods market clearing

$$\frac{y}{k}\hat{y}_t - \frac{c}{k}\hat{c}_t - \hat{k}_{t+1} = -(1-\delta)\hat{k}_t. \quad \text{(A6)}$$

Rental price of capital

$$\hat{r}^k_t - \hat{\phi}_t - \hat{y}_t = -\hat{k}_t. \quad \text{(A7)}$$

Real wage

$$\hat{w}_t - \hat{\phi}_t - \hat{y}_t + \hat{h}_t = 0. \quad \text{(A8)}$$

Law of motion of capital (definition of investment)

$$\hat{k}_{t+1} - \delta\hat{x}_t = (1-\delta)\hat{k}_t. \quad \text{(A9)}$$

Law of motion of money

$$\hat{m}_t - \hat{\mu}_t + \hat{\pi}_t = \hat{m}_{t-1}. \quad \text{(A10)}$$

Cash-in-advance constraint

$$\frac{c}{k}\hat{c}_t + \varphi\hat{k}_{t+1} + \frac{m}{k}\hat{m}_t = \varphi(1-\delta)\hat{k}_t. \quad \text{(A11)}$$

Real marginal costs

$$\hat{\phi}_t - \alpha\hat{r}^k_t - (1-\alpha)\hat{w}_t + \hat{a}_t = 0. \quad \text{(A12)}$$

Law of motion of real wage

$$\hat{w}_t = \hat{w}_{t-1} + \hat{\pi}^w_t - \hat{\pi}_t. \quad \text{(A13)}$$

Output

$$\hat{y}^f_t - \alpha\hat{k}_t - (1-\alpha)\hat{h}_t - \hat{a}_t = 0. \quad \text{(A14)}$$

Definition of output gap

$$u_t = \hat{y}_t - \hat{y}^f_t. \quad \text{(A15)}$$

Wage-inflation Phillips curve

$$\widehat{\pi}^w_t = \frac{(1-\beta\xi_w)(1-\xi_w)}{\xi_w\left(1 + \frac{\psi\lambda_w}{\lambda_w - 1}\right)}\left\{\widehat{mrs}_t - \widehat{w}_t\right\} + \beta E_t\widehat{\pi}^w_{t+1}. \quad \text{(A16)}$$

Marginal rate of substitution

$$\widehat{mrs}_t = \psi\widehat{h}_t - \hat{\lambda}_t. \quad \text{(A17)}$$

Plus shock processes.

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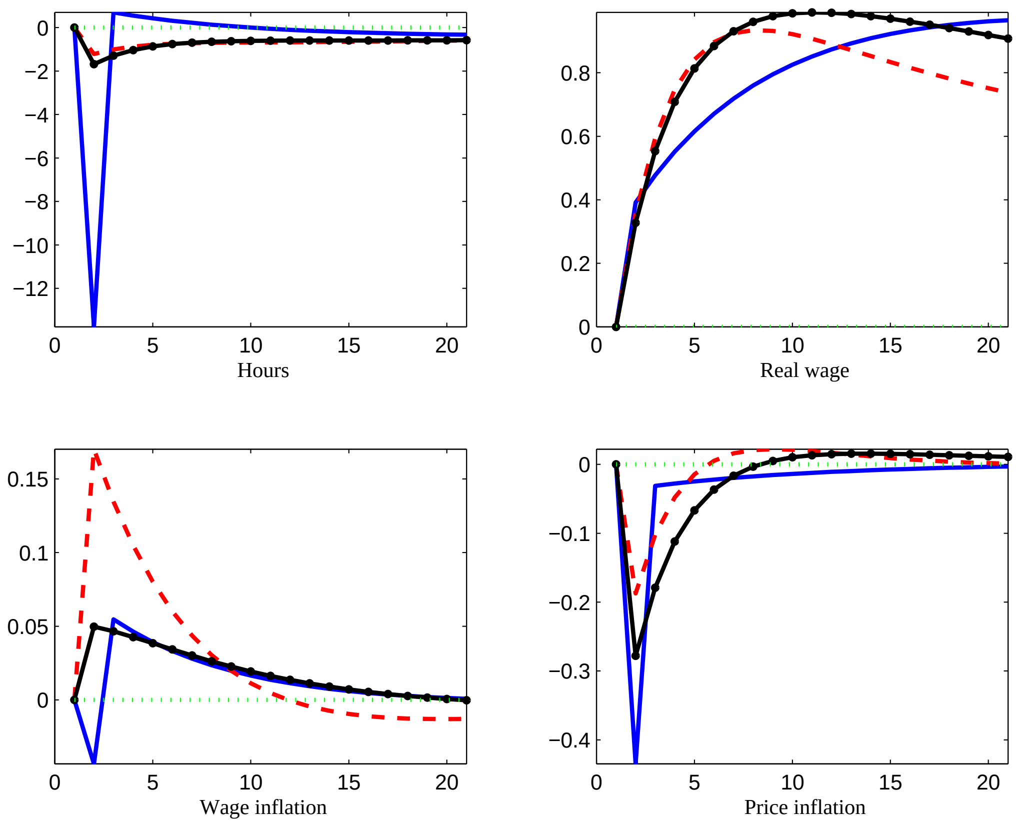
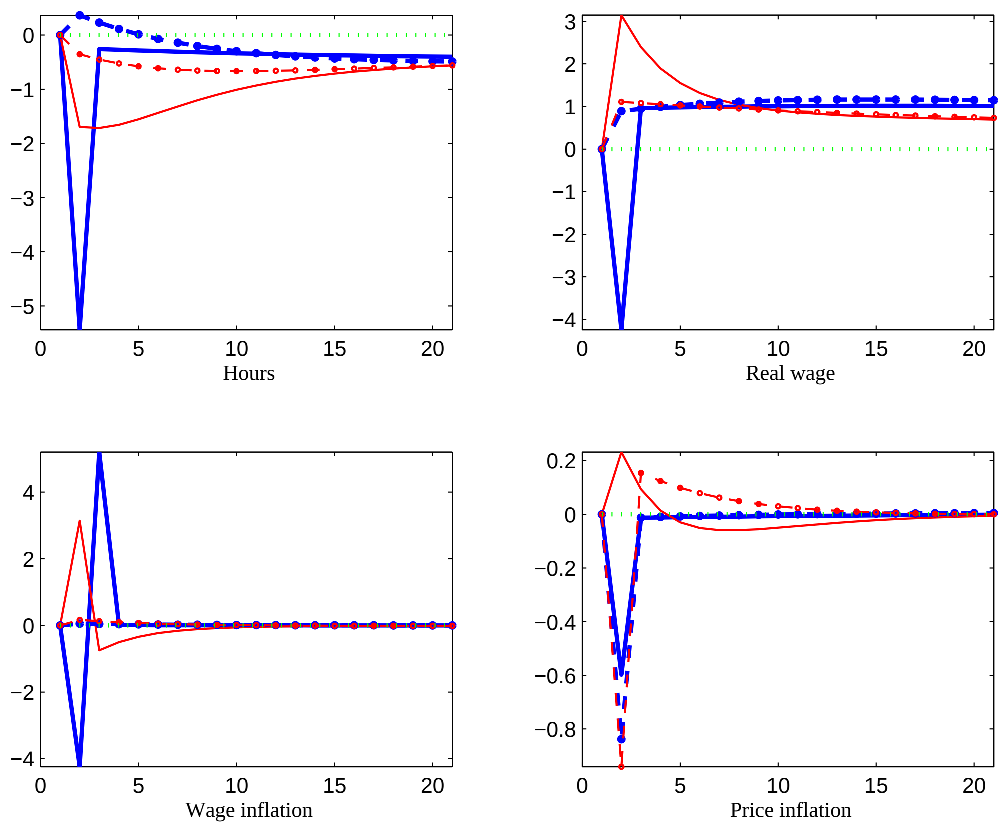
Figures

Figure 1: Impulse response functions of the model with sticky prices and sticky wages to technology shock.



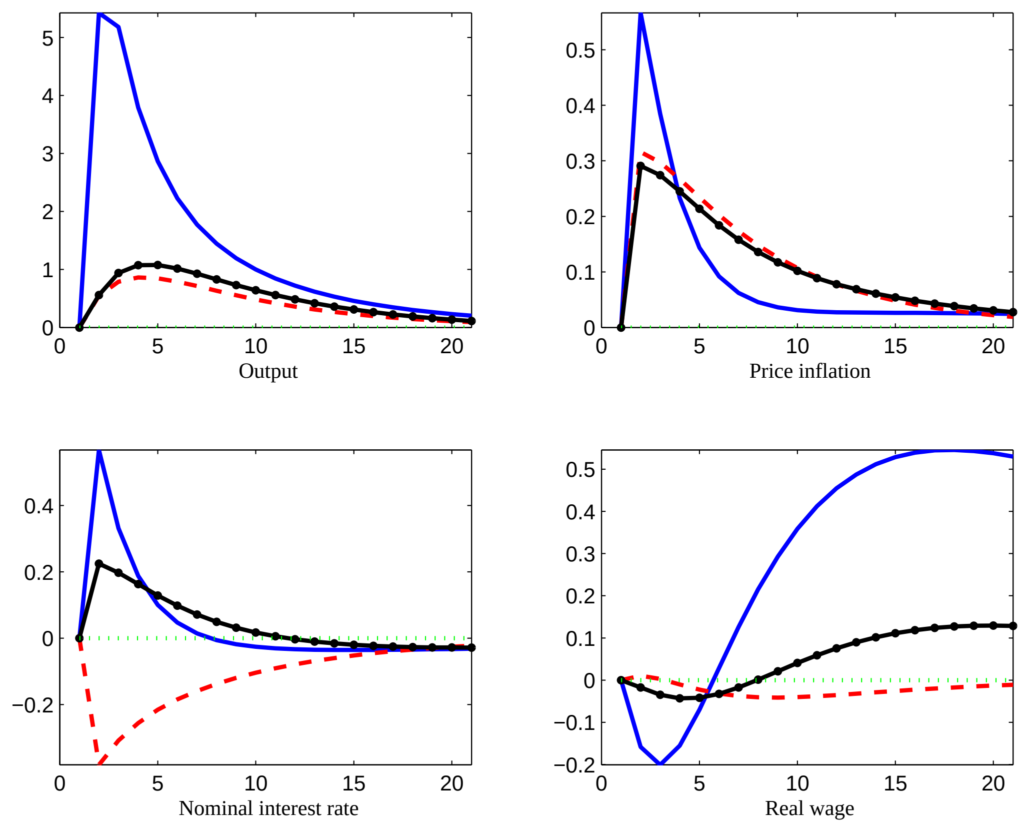
Note: Plots depict the model without capital in the CIA (solid line), with capital in the CIA (dashed line), and with capital partially financed with cash (dotted line).

Figure 2: Impulse response functions to a technology shock.



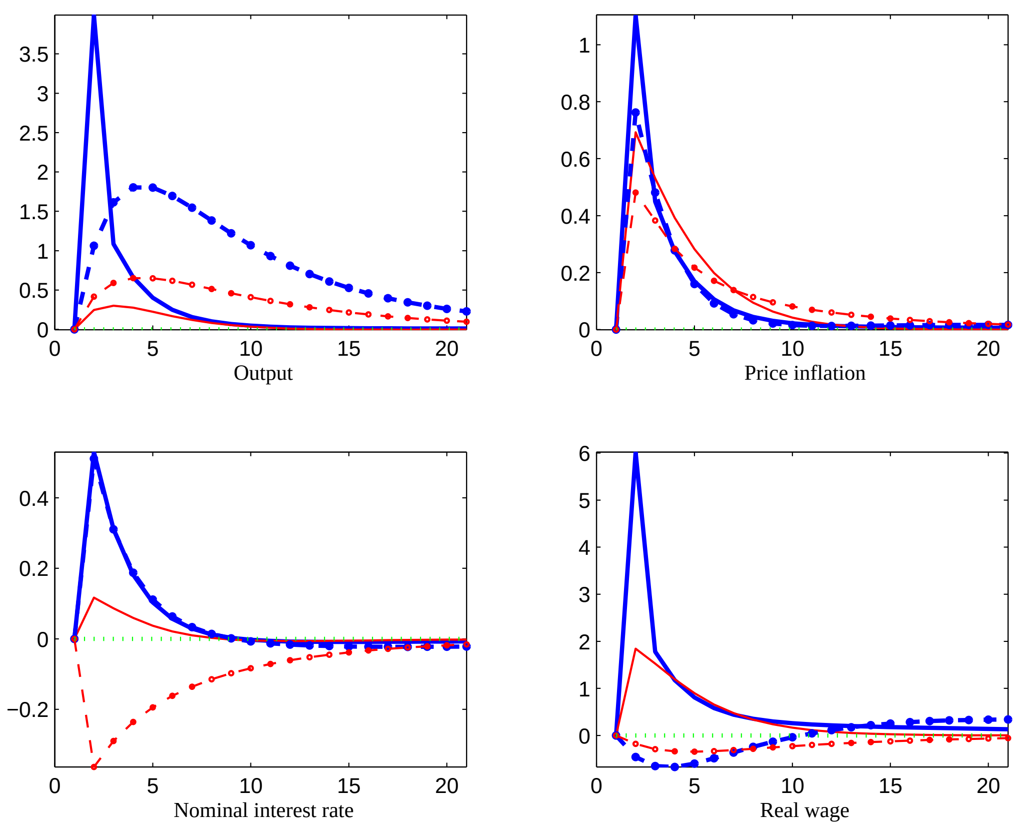
Note: Pure sticky price model without capital in the CIA (strong solid line), and with capital in the CIA (strong dotted line). Pure sticky wage model without capital in the CIA (solid line), with capital in the CIA (dotted line).

Figure 3: Impulse response functions of the model with sticky prices and sticky wages to a money supply shock.



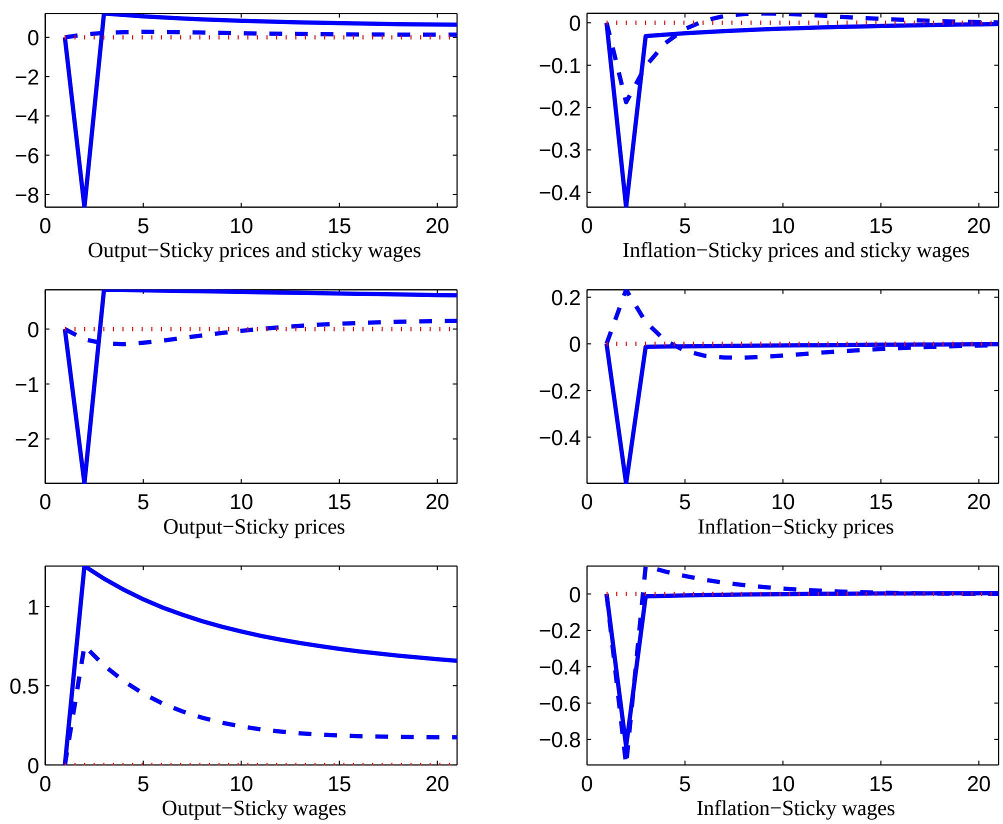
Note: Plots depict the model with capital as a credit good (solid line), with capital fully finance with cash (dashed line), and with capital partially financed with cash (dotted line).

Figure 4: Impulse response functions to a money supply shock.



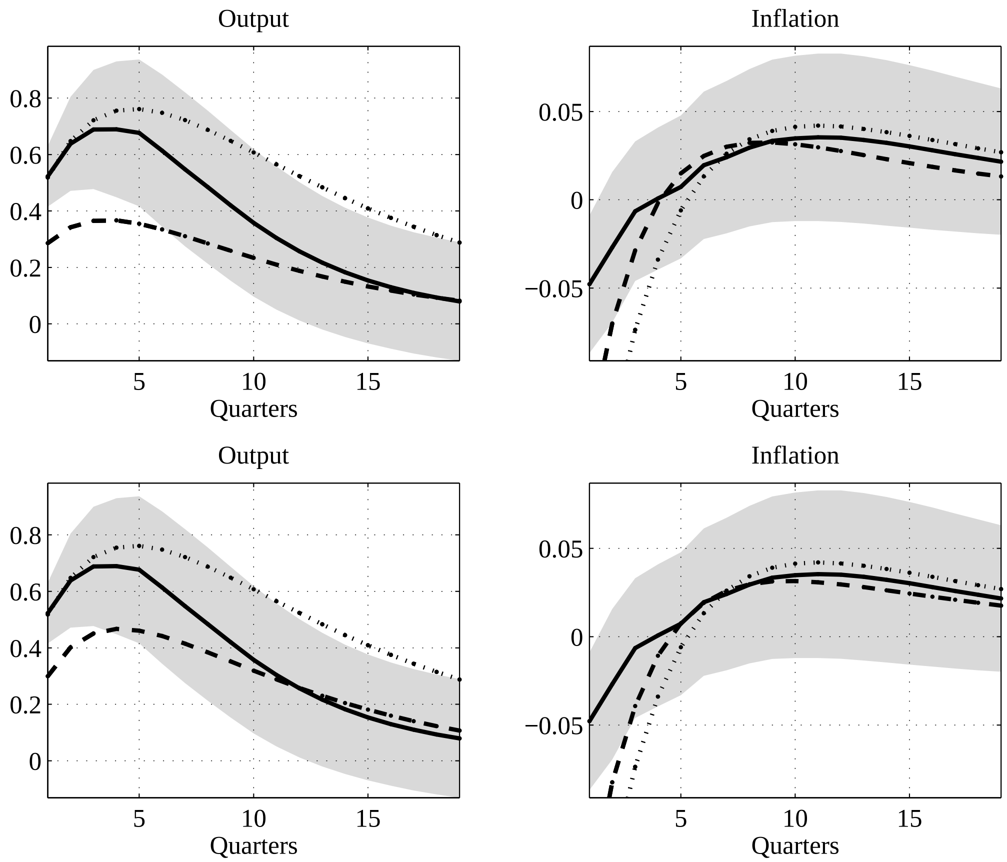
Note: Pure sticky price model without capital in the CIA (strong solid line), and with capital in the CIA (strong dotted line). Pure sticky wage model without capital in the CIA (solid line), with capital in the CIA (dotted line).

Figure 5: Impulse response functions to a positive technology shock: output and inflation dynamics.



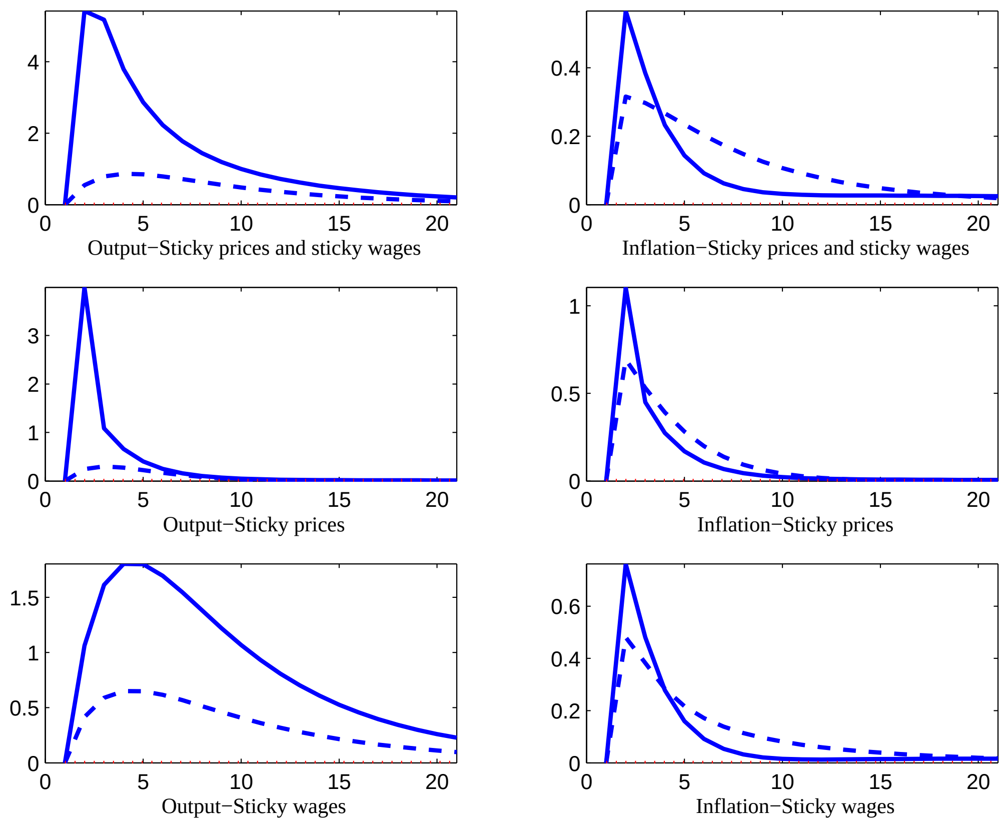
Note: Left column is for output, right column for inflation. All three setups considered. Solid line denotes no capital in the CIA, dashed line stands for capital in the CIA constraint.

Figure 6: Impulse response functions to a positive technology shock, sample 1963:1-2003:4.



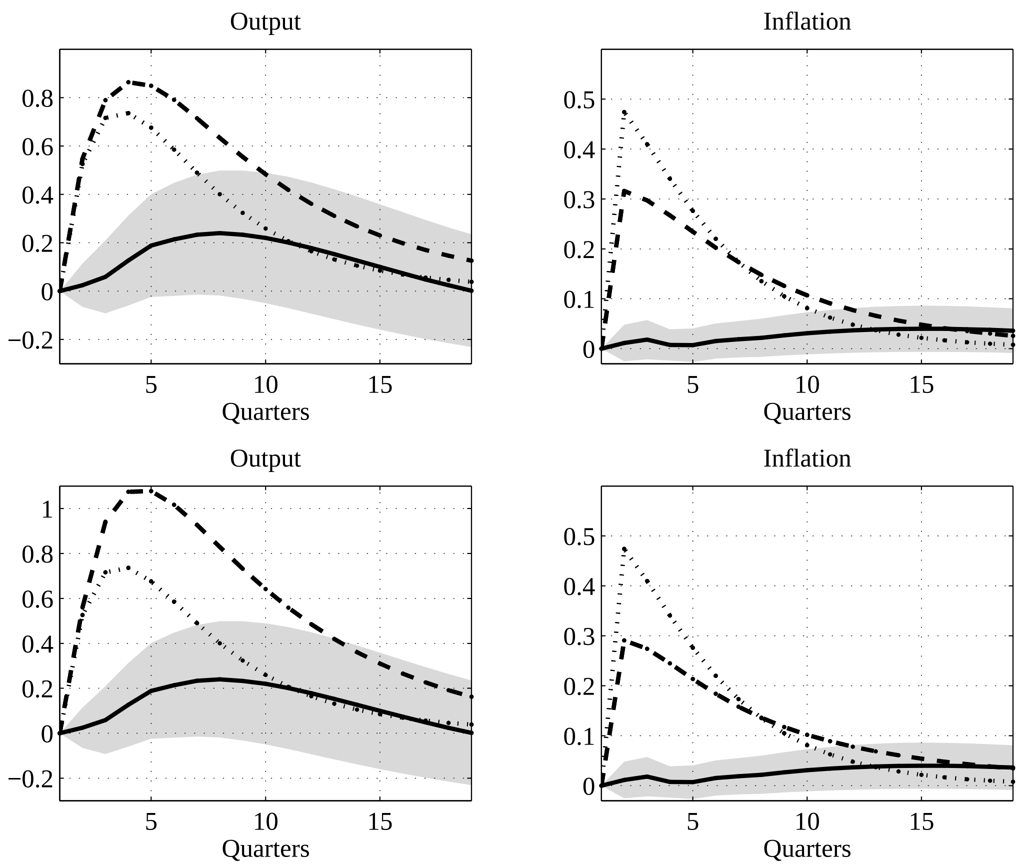
Note: Solid line stands for our own SVAR estimation, pointed line stands for Wang and Wen (2006), and dashed line stands for the sticky price-sticky wage model. Top panels: model with investment partially financed with cash ($\varphi = 0.6$), bottom panels: model with investment fully financed with cash ($\varphi = 1$).

Figure 7: Impulse response functions to a positive money supply shock: output and inflation dynamics.



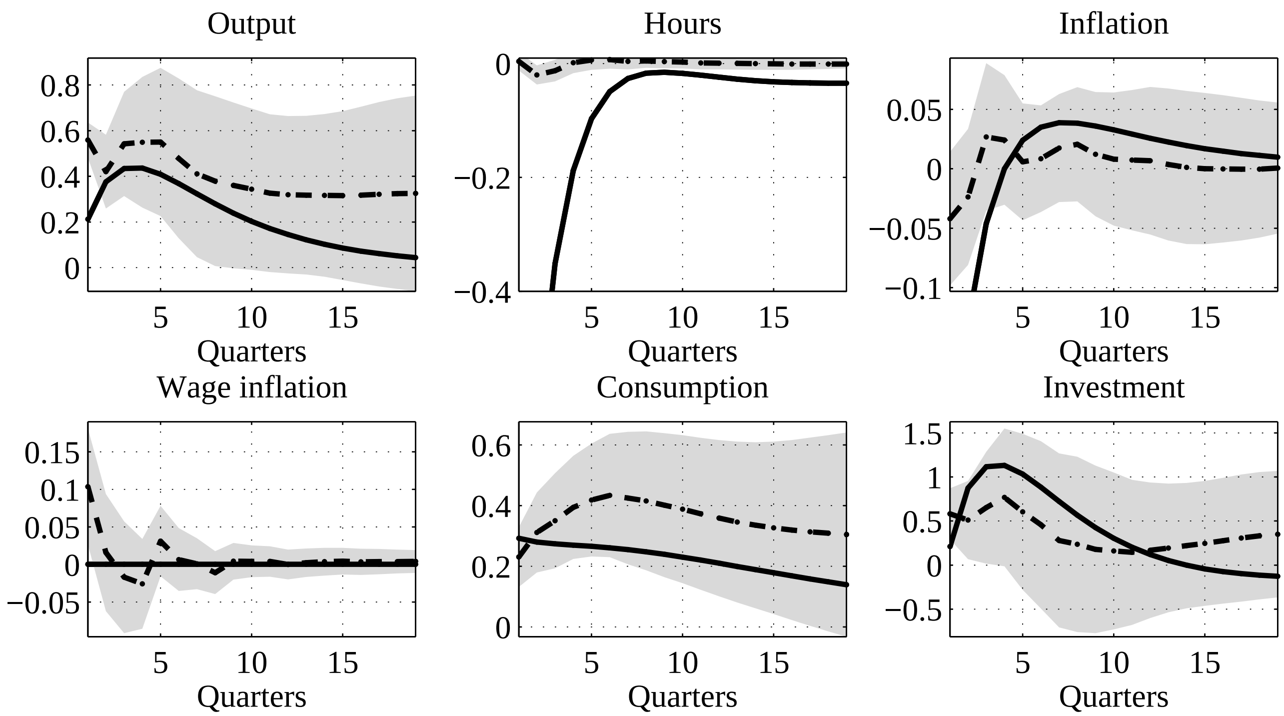
Note: Left column is for output, right column for inflation. All three setups considered. Solid line denotes no capital in the CIA, dashed line stands for capital in the CIA constraint.

Figure 8: Impulse response functions to a positive money supply shock, sample 1963:1-2003:4.



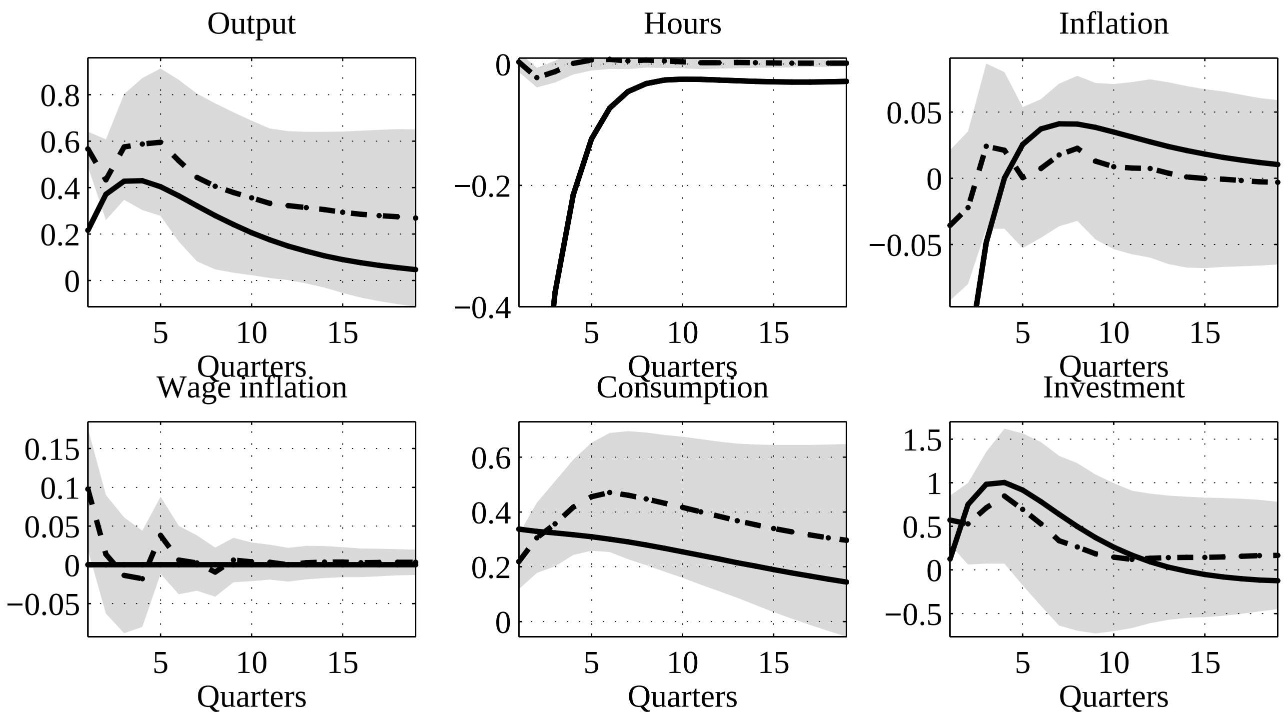
Note: Solid line stands for our own SVAR estimation, pointed line stands for Wang and Wen (2006), and dashed line stands for the sticky price-sticky wage model. Top panels: model with investment partially financed with cash ($\varphi = 0.6$), bottom panels: model with investment fully financed with cash ($\varphi = 1$).

Figure 9: Impulse response functions to a positive productivity shock: subsample 1963:1-1983:4



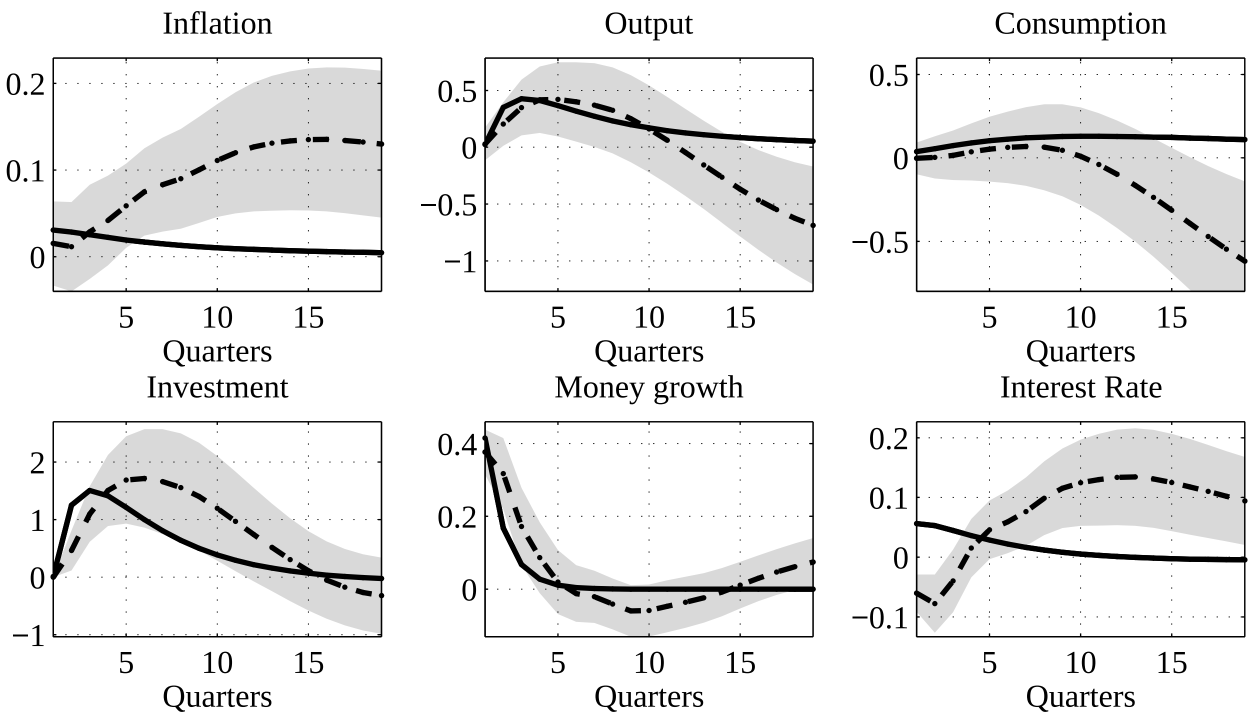
Note: Dashed line stands for SVAR estimation and the solid line stands for the sticky price-sticky wage model.

Figure 10: Impulse response functions to a positive productivity shock: subsample 1984:1-2003:4



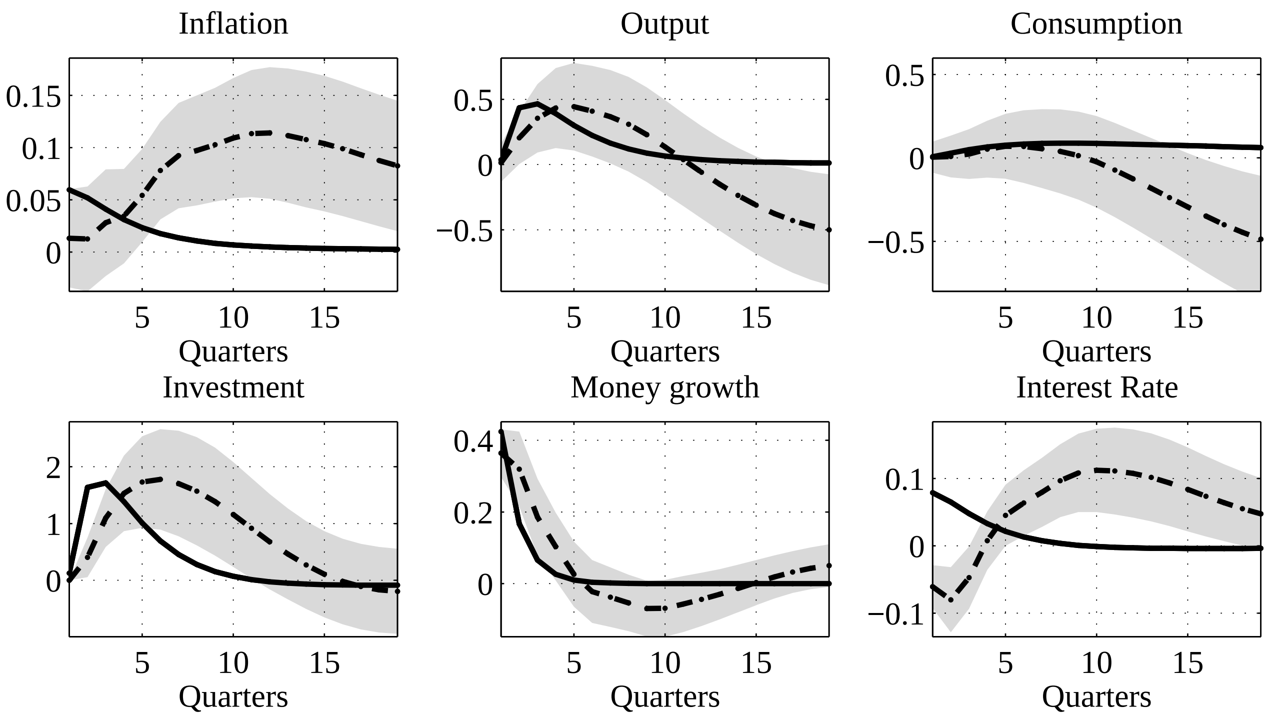
Note: Dashed line stands for SVAR estimation and the solid line stands for the sticky price-sticky wage model.

Figure 11: Impulse response functions to a positive money supply shock: subsample 1963:1-1983:4



Note: Dashed line stands for SVAR estimation and the solid line stands for the sticky price-sticky wage model.

Figure 12: Impulse response functions to a positive money supply shock: subsample 1984:1-2003:4



Note: Dashed line stands for SVAR estimation and the solid line stands for the sticky price-sticky wage model.

Tables

Table 1: Baseline calibration

Preferences		
Discount factor	β	0.988
Intertemporal elasticity of substitution	σ	2.000
Inverse labor supply elasticity	ψ	1.000
Technology		
Capital share	α	0.360
Depreciation rate	δ	0.025
Elasticity of substitution across goods	λ_p	10/9
Elasticity of substitution across labor inputs	λ_w	6/5
Probability of not resetting prices	ξ_p	0.750
Probability of not resetting wages	ξ_w	0.750
Shock processes		
Persistence of productivity shock	ρ_a	0.990
Standard deviation of productivity shock	σ_a	0.008
Persistence of monetary shock	ρ_μ	0.600
Standard deviation of monetary shock	σ_μ	0.006

Table 2: Estimated parameter values

		φ	ξ_p	ξ_w	ρ_a	σ_a	ρ_μ	σ_μ
Benchmark parameters		0,0.6,1	0.75	0.75	0.99	0.008	0.6	0.006
Technology shocks only	63:1-03:4	0.3441 (0.1913)	0.6991 (0.0792)	0.8513 (0.5221)	0.8021 (0.0609)	0.0113 (0.0000)	n.a.	n.a.
	63:1-83:4	0.5636 (0.3290)	0.6937 (0.0808)	0.9813 (0.5660)	0.8201 (0.0509)	0.0063 (0.0000)	n.a.	n.a.
	84:1-03:4	0.5404 (0.3302)	0.6834 (0.0869)	0.9840 (0.5768)	0.8223 (0.0492)	0.0007 (0.0000)	n.a.	n.a.
Money supply shocks only	63:1-03:4	0.9421 (0.1405)	0.9124 (0.0466)	0.8168 (0.0843)	n.a.	n.a.	−0.0184 (0.1230)	0.0153 (0.0000)
	63:1-83:4	0.2372 (0.0859)	0.9195 (0.0336)	1.0000 (0.0000)	n.a.	n.a.	0.4042 (0.0853)	0.0108 (0.0000)
	84:1-03:4	0.1425 (0.0672)	0.8526 (0.0455)	1.0000 (0.0000)	n.a.	n.a.	0.3931 (0.0752)	0.0128 (0.0000)