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Investment, Matching and Persistence in a modified Cash-in-Advance Economy*

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Abstract

We simulate and estimate a new Keynesian search and matching model with sticky wages in which capital has to be financed with cash, at least partially. Our objective is to assess the ability of this framework to account for the persistence of output and inflation observed in the data. We find that 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 any other nominal or real rigidity. The 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, we investigate the conditions under which our model specification generates the liquidity effect, a fact which is absent in most sticky price models.

Keywords: persistence, sticky prices, staggered bargaining wages, monetary facts, labor market facts, cash-in-advance.
JEL Classification: 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]

We contribute to this literature by setting up a unified framework to jointly analyze technology and money supply shocks, which is able to explain at the same time the dynamics of both output and inflation, as well as labor market variables. To this end we analyze a new Keyensian model with capital and frictions in the labor market. We find that having to finance capital with cash, and the existence of sluggish labor markets are essential frictions to generate enough persistence as in the data.

Our model builds on Wang and Wen (2006) in that we consider investment in the CIA constraint in a sticky price model, but we go further in modeling the labor market. We consider an economy with search and matching in the labor market with sticky nominal wages in the line of Trigari (2006), Thomas (2008) and Christoffel et al. (2009) among many others. We analyze the response of the economy to technology and money supply shocks under different degrees of nominal rigidities. Finally, we use Bayesian methods to estimate the parameters of the model, in particular to assess the relevance of the cash

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

constraint on capital in U.S. data. Therefore, our model extends Wang and Wen (2006) to an economy with labor market frictions, and generalizes Christoffel et al. (2009) to an economy with investment.

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. In Auray and de Blas (2011), we use 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] However, in that case, the model fails to reproduce the impact response of inflation to a money injection and fully sticky wages were required to obtain the liquidity effect pointing to a better modeling of the labor market to reproduce the data.

Recently, a growing branch of the literature is considering imperfect labor markets in otherwise standard new Keynesian economic models to enhance persistence of macroeconomic variables. However, some degree of wage rigidity is also needed in these models, and the search and matching structure is the ideal scenario for this analysis. However, there is no clear consensus on the persistence generated by real wage rigidities. Krause and Lubik (2007) find that real wage rigidity, although it helps improve labor market dynamics, is irrelevant for persistence after a monetary shock, whereas it is an important channel in Christoffel and Linzert (2005), Thomas (2008), Christoffel et al. (2009), Faccini and Ortigueira (2010) among others. Lechthaler, Wolfgang and Snower (2010) show that a search and matching model with labor turnover costs generates enough output persistence to temporary monetary shocks. Their model has no capital and monetary policy follows a Taylor rule, but is able to reproduce the Beveridge curve. Most of these papers abstract from physical capital, and focus mainly on monetary policy shocks. Merkl and Snower (2009) find that wage and price staggering are complementary in generating monetary persistence, and analyze their relative importance in a model with homogeneous and firm-specific capital. They find that under homogeneous capital, wage staggering generates

[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.

more persistence than price staggering. The opposite is true when firm-specific capital is considered. The authors also consider the complementarity of both degrees of staggering in output persistence to monetary shocks.

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; Boileau and Moyen, 2010; Acharya, Almeida and Campello, 2011). 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. Notice that introducing investment as a cash good operates in a way similar to adjustment costs in investment, reducing the speed of adjustment in aggregate demand, while being or providing a more clear economic interpretation. We estimate the relevance of this assumption for this model.

Our model permits the reproduction of monetary and labor market facts thanks to the interaction of the labor and goods markets frictions *i.e.* the search friction, the sticky wages assumption and investment in the cash–in–advance friction. It 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 delays the response of demand to shocks. Finally, we investigate the conditions under which our setup is able to generate the liquidity effect. We find that this result stresses the relative relevance of sticky wages and labor market frictions versus sticky prices in modeling the monetary transmission mechanism. Also, we need investment partially or completely financed with cash to obtain the liquidity effect, an assumption that is supported by the data. 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 Section 3, we calibrate the model. We proceed to analyze the quantitative performance of the model in Section 4. The dynamics of the model after a positive technology shock and a monetary injection are studied in Section 5. Section 6 focuses on the estimation of the model, and Section 7 closes the paper.

2 The Model

The economy is populated by a large number of identical, infinitely-lived households who consume, invest in bonds and physical capital, and work. Within each household, individuals can be either employed or unemployed. The productive side of the economy consists of three sectors: one producing intermediate labor goods (*intermediate labor goods* sector), another one producing wholesale differentiated goods (*wholesale* sector), which are sold to the third one in charge of producing the final homogeneous good (*retail* sector). The intermediate labor good is produced competitively with capital and labor. The labor market is subject to turnover costs and staggered bargaining wages. Wholesale producers transform the homogeneous intermediate labor good into differentiated output in a monopolistic competitive market and change prices à-la-Calvo. The final good is homogeneous and can be used for consumption and investment purposes.

2.1 The household

There is a continuum of households in the interval $[0, 1]$. We follow Merz (1995) and assume that the household is big, in the sense of providing with some insurance for the risk in labor income. Household preferences are characterized by the lifetime utility function:

$$H_t(n_{lt}) = E_t \sum_{l=0}^{\infty} \beta^{l-t} \left(\frac{c_t^{1-\sigma}}{1-\sigma} - \Psi \int_0^1 n_{lt} \frac{h_{lt}^{1+\psi}}{1+\psi} dl \right), \tag{1}$$

where $0 < \beta < 1$ is a constant discount factor, σ denotes the inverse of the intertemporal elasticity of consumption, ψ is the inverse of the elasticity of labor supply with respect to real wages, and Ψ is a scale parameter. The variable c denotes consumption, n_{lt} is labor supply at firm l, and h_{lt} is the number of hours that each individual of the household works at the firm.

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 output persistence.

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

$$\frac{\frac{B_{t+1}}{R_t} + M_{t+1}}{P_t} + c_t + \varphi x_t + (1-\varphi) x_t + T_t \leq \tag{2}$$
$$\frac{B_t + M_t}{P_t} + Profits_t + \int_0^1 w_{lt} n_{lt} h_{lt} dl + (1 - n_t) b + r_t^k k_t,$$

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; r_t^k is the real rental rate of capital; k_t is the aggregate stock of capital; w_{lt} is the real wage paid by firm l; n_{lt} is the number of employees working h_{lt} hours at firm l; b denotes the unemployment benefit received if not working; and $n_t = \int_0^1 n_{lt} dl$. In this economy, bonds are in zero net supply, that is, $B_t = 0$ in equilibrium. The household also makes an additional investment of x_t, and consumes c_t, and has to pay taxes T_t. Moreover, it receives the profits, $\mathit{Profits}_t$, earned by the firms which he owns: retail, wholesale and intermediate labor good 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

$$u'(c_t) - \lambda_t - \gamma_t = 0, \tag{3}$$

$$-\varphi\gamma_t - \lambda_t + \beta E_t \left[\lambda_{t+1}\left(r_{t+1}^k + 1 - \delta\right) + \varphi(1-\delta)\gamma_{t+1}\right] = 0, \tag{4}$$

$$-\frac{\lambda_t}{P_t} + \frac{\gamma_t}{P_t} + \beta E_t \frac{\lambda_{t+1}}{P_{t+1}} = 0, \tag{5}$$

$$-\frac{\lambda_t}{R_t P_t} + \beta E_t \frac{\lambda_{t+1}}{P_{t+1}} = 0, \tag{6}$$

$$M_t - P_t c_t - \varphi P_t \left[k_{t+1} - (1-\delta)k_t\right] = 0, \tag{7}$$

$$\begin{aligned} B_t + M_t - P_t c_t - \varphi P_t x_t + \mathit{Profits}_t + \int_0^1 w_{lt} n_{lt} h_{lt} dl + (1-n_t)b + P_t r_t^k k_t \\ -\left(\frac{B_{t+1}}{R_t} + M_{t+1}\right) - (1-\varphi)P_t\left[k_{t+1} - (1-\delta)k_t\right] - P_t T_t = 0, \end{aligned} \tag{8}$$

where λ_t denotes the Lagrange multiplier associated with the budget constraint, and γ_t is the Lagrange multiplier associated with the CIA constraint, both measured in consumption units.

2.2 Retail sector

The final good is produced by combining a continuum of differentiated wholesale goods indexed by j. This process is described by the following CES function:

$$Y_t = \left(\int_0^1 Y_t(j)^{\frac{1}{\lambda_f}} dj\right)^{\lambda_f}, \tag{9}$$

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 (9), 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:

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

2.3 Wholesale sector

In our model each wholesale firm $j \in (0,1)$ produces a differentiated wholesale good, $Y_t(j)$, for the final good sector through a constant returns to scale production function, by use of a homogeneous intermediate labor good purchased at nominal price $P_t \phi_t$.

Wholesale 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 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

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

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

$$\Phi_{t+\tau} \propto \beta^{\tau} \left(\frac{\lambda_{t+\tau} + \gamma_{t+\tau}}{\lambda_t + \gamma_t}\right).$$

This leads to the price setting equation

$$\frac{1}{\lambda_f} \tilde{P}_t(j) E_t \sum_{\tau=0}^{\infty} (\beta \pi^* \xi_p)^{\tau} \Lambda_{t+\tau} \left(\frac{\pi^{*\tau} \tilde{P}_t(j)}{P_{t+\tau}}\right) Y_{t+\tau} = E_t \sum_{\tau=0}^{\infty} (\beta \xi_p)^{\tau} \Lambda_{t+\tau} \left(\frac{\pi^{*\tau} \tilde{P}_t(j)}{P_{t+\tau}}\right)^{\frac{\lambda_f}{1-\lambda_f}} P_{t+\tau}\phi_{t+\tau} Y_{t+\tau}, \tag{10}$$

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

$$P_t = \left((1-\xi_p)\tilde{P}_t^{\frac{1}{1-\lambda_f}} + \xi_p \left(\pi^* P_{t-1}\right)^{\frac{1}{1-\lambda_f}} \right)^{1-\lambda_f}. \tag{11}$$

A log-linear approximation of (10) 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 real marginal costs, $\hat{\phi}_t$.

2.4 Intermediate labor goods producers

In our model, there is a continuum of intermediate labor goods producers, y_{lt}, who sell their output in a competitive market to the wholesale producers. These firms use capital and labor as input factors according to the following constant returns-to-scale production function:

$$y_{lt} = a_t k_{lt}^{\alpha} \left(n_{lt} h_{lt}\right)^{1-\alpha} \quad \text{with} \quad \alpha \in (0,1), \tag{12}$$

where k_{lt} is the physical capital input used by firm l in the production process; n_{lt} denotes the number of members of the household who work h_{lt} hours at firm l; a_t is an exogenous stationary stochastic technology shock common to all firms, whose properties will be defined later.

We assume that each firm l operates under perfect competition in the input market for capital, and bargains with workers to determine the wage and hours worked.[3] As in Thomas (2008), we assume firms post vacancies in the labor market at time t to hire workers in the same period. This implies a utility cost of vacancy posting $\mathcal{C}\left(v_{lt}\right) = \frac{\chi}{1+\varepsilon_c}\left(\frac{v_{lt}}{n_{lt-1}}\right)^{1+\varepsilon_c} n_{l,t-1}$, where $\chi > 0$ is a scaling factor, and $\varepsilon_c > 0$ is the elasticity of hiring costs with respect to vacancies. Notice, however, that our timing is different to that in Thomas (2008). Here we assume that new hires become effective at time t, as in Blanchard and Galí (2010).

[3] Following Mortensen and Pissarides (1999) we assume these firms can hire at most one worker, otherwise their production would be zero.

The problem of the firm is to choose $\upsilon_{lt}, n_{lt},$ and k_{lt} to maximize the present discounted value of current and future profits, $\mathcal{J}_t$, subject to bargaining power over wages and hours,

$$\mathcal{J}_{l,t}(n_{l,t-1}) = \phi_t y_{l,t} - \frac{W_{l,t}}{P_t} n_{l,t} h_{l,t} - \frac{\chi}{1+\varepsilon_c}\left(\frac{\upsilon_{lt}}{n_{lt-1}}\right)^{1+\varepsilon_c} \frac{n_{l,t-1}}{\lambda_t+\gamma_t} - r_t^k k_{l,t} + E_t \Phi_{t,t+1} \mathcal{J}_{l,t+1}(n_{l,t}) \tag{13}$$

subject to the production function given by equation (12), and

$$n_{l,t} = (1-\rho) n_{l,t-1} + ma_{l,t}, \tag{14}$$

where $\Phi_{t+\tau} = \beta^{\tau} \frac{c_{t+\tau}^{-\sigma}}{c_t^{-\sigma}}$ is the discount factor for firms, which depends on households' marginal utility, given that firms are owned by the households; and ma_{lt} is the number of matches at firm l.

The first order conditions are given by

$$r_t^k = \phi_t \alpha a_t k_{lt}^{\alpha-1} \left(n_{lt} h_{lt}\right)^{1-\alpha}, \tag{15}$$

$$\frac{\chi z_{lt}^{\varepsilon_c}}{\lambda_t+\gamma_t} = \zeta_{l,t} q(\theta_t), \tag{16}$$

$$\zeta_{l,t} = \phi_t mpl_{l,t} h_{l,t} - w_{l,t} h_{l,t} + E_t \Phi_{t+1}\left[\chi \frac{\varepsilon_c}{1+\varepsilon_c} \frac{z_{l,t+1}^{1+\varepsilon_c}}{\lambda_{t+1}+\gamma_{t+1}} + (1-\rho)\zeta_{l,t+1}\right], \tag{17}$$

where $\zeta_{l,t}$ is the marginal value of one more employee at t; and $mpl_{l,t} = (1-\alpha) k_{l,t}^{\alpha} \left(n_{l,t} h_{l,t}\right)^{-\alpha}$ is the marginal product of labor. Notice that from (15), and given constant returns to scale in production, all firms have the same capital-labor ratio $k_{lt}/n_{lt}h_{lt} = k_t/n_t h_t$ for all l, what implies that the marginal product of labor is also the same for all firms, i.e. $mpl_{l,t} = mpl_t, \forall l$. After substituting in the job creation condition (16), we get the Euler equation for vacancies

$$\frac{\chi z_{lt}^{\varepsilon_c}}{q(\theta_t)(\lambda_t+\gamma_t)} = \phi_t mpl_t h_{l,t} - w_{l,t} h_{l,t} + E_t \Phi_{t+1}\left[\frac{\varepsilon_c}{1+\varepsilon_c} \frac{\chi z_{l,t+1}^{1+\varepsilon_c}}{(\lambda_{t+1}+\gamma_{t+1})} + (1-\rho) \frac{\chi z_{l,t+1}^{\varepsilon_c}}{q(\theta_{t+1})(\lambda_{t+1}+\gamma_{t+1})}\right], \tag{18}$$

which states that the cost of posting a vacancy to hire an additional worker equals the marginal benefit that the additional worker brings into the firm, i.e. the marginal revenue product net of wage payments, plus the continuation value of the job and the savings for the firm for not having to post another vacancy at $t+1$.

2.5 Labor market

As mentioned above, we assume that intermediate labor goods firms bargain with workers in the labor market to determine the nominal wage, $W_{l,t}$, and hours worked, $h_{l,t}$.

Job formation is assumed to involve a matching process where the matching function is given by

$$ma_t = \sigma_m \left(u_t^s\right)^{\vartheta} v_t^{1-\vartheta}, \tag{19}$$

where v_t is the number of vacancies in the job market; u_t^s is the number of effective work seekers in period t; $\sigma_m > 0$ is the scale parameter of the matching function; and, $\vartheta \in (0,1)$ is the elasticity of the unemployed searchers in the matching function. Let us denote $\theta_t = v_t/u_t^s$ the degree of tightness in the labor market. As usual in this setup, the probability that an unemployed worker finds a job is given by

$$s_t = \frac{ma_t}{u_t^s} = \sigma_m \theta_t^{1-\vartheta} \equiv s(\theta_t), \tag{20}$$

and the probability of a vacancy being filled by

$$q_t = \frac{ma_t}{v_t} = \sigma_m \theta_t^{-\vartheta} \equiv q(\theta_t). \tag{21}$$

Notice that using this notation, we have that $s(\theta_t) = \theta_t q(\theta_t)$. Also, we assume that an exogenous fraction of the firm-worker matches, ρ, is broken each period. This implies the following employment dynamics:

$$n_t = (1-\rho) n_{t-1} + ma_t. \tag{22}$$

In using this notation, we follow the line of the literature (e.g. Blanchard and Galí, 2010) that allows for some workers and vacancies to find matches immediately, that is, without spending a full period unemployed. This implies that shocks can be adjusted both by unemployment and by hours per worker.[4]

Staggered nominal wages

It has been shown by recent literature that wage stickiness is an important determinant of inflation dynamics (e.g. Christiano et al. 2005). We follow recent work (Trigari, 2006; Krause and Lubik, 2007; Thomas, 2008; Christoffel et al. 2009; and Faccini, Millard and Zanetti, 2011) and introduce sticky nominal wages in a setup of search and matching in the labor market. We assume that every period all workers in a given firm, including new hires, are paid the previous period wage with a probability ξ_w, and with probability $1-\xi_w$ the firm is free to negotiate their nominal wage with their workers. Those firms adjusting to the new nominal wage will in equilibrium set the same wage, W_t^*, given that we have no idiosyncratic productivity shocks.

As in Thomas (2008), we assume that hours, $h_{l,t}$, are bargained to match the total surplus of both workers and firms. Let us define the worker's surplus in consumption units, $\mathcal{S}_{l,t}^w \equiv \frac{\partial H_t/\partial n_{lt}}{\lambda_t+\gamma_t}$, as follows:

$$\mathcal{S}_{l,t}^w = w_{l,t}h_{l,t} - b - \frac{\Psi}{\lambda_t+\gamma_t}\frac{h_{l,t}^{1+\psi}}{1+\psi} - \beta(1-\rho)E_t s(\theta_{t+1})\Phi_{t,t+1}\int_0^1 \frac{\upsilon_{L,t+1}}{\mathcal{V}_{t+1}}\mathcal{S}_{L,t+1}^w dL + (1-\rho)E_t\Phi_{t,t+1}\mathcal{S}_{l,t+1}^w, \tag{23}$$

where $s(\theta_t)\frac{\upsilon_{L,t+1}}{\mathcal{V}_{t+1}}$ denotes the probability of being matched with firm L at time $t+1$. Equation (23) states that the worker's surplus equals wage payments at the firm plus continuation value, minus disutility of working, and in case of being unemployed, the benefits and expected surplus of being matched with any firm at $t+1$. Similarly, the firm's surplus, $\mathcal{S}_{l,t}^f \equiv \zeta_{l,t}$, is given by

$$\mathcal{S}_{l,t}^f = \phi_t mpl_l h_{l,t} - w_{l,t}h_{l,t} + E_t\Phi_{t,t+1}\left[(1-\rho)\mathcal{S}_{l,t+1}^f + \frac{\varepsilon_c}{1+\varepsilon_c}q\left(\theta_t\right)\mathcal{S}_{l,t+1}^f\right]. \tag{24}$$

Given this, hours are chosen as follows:

$$\max_{h_{l,t}}\left(\mathcal{S}_{l,t}^w + \mathcal{S}_{l,t}^f\right). \tag{25}$$

[4] Furthermore, this notation is useful from the empirical point of view, in particular if the calibration is quarterly, as is the case here.

The first order condition with respect to $h_{l,t}$ yields

$$\phi_t mpl_t = \frac{\Psi}{\lambda_t + \gamma_t} h_{l,t}^{\psi}, \tag{26}$$

implying that $h_{l,t} = h_t$ for all l.

For those firms adjusting wages, we follow Thomas (2008), and assume that the wage set by the renegotiating firm l satisfies the following sharing rule:

$$\eta \mathcal{S}_{l,t}^{f*} = (1-\eta)\mathcal{S}_{l,t}^{w*}, \tag{27}$$

where η is the bargaining power of the workers, and the superscript $*$ denotes renegotiating workers and firms. This sharing rule implies that renegotiating workers obtain a fraction of the total surplus equal to their bargaining power. Notice that this is different from Nash bargaining. With Nash bargaining wages maximize a weighted average of the joint surplus. Nash bargaining delivers the sharing rule only if wages are continuously renegotiated. As shown by Gertler and Trigari (2009), in an economy with staggered wage negotiations, Nash bargaining implies that the share parameter η fluctuates over the cycle. This follows from the fact that workers and firms face different time horizons when they consider the effects of different wages. However, Gertler and Trigari (2009) suggest that this "horizon effect" has quantitatively negligible implications. We therefore choose to follow Thomas (2008) and adopt this sharing rule as it simplifies the analysis considerably.

Notice that we can rewrite equation (23) as follows:

$$\mathcal{S}_{l,t}^{w} = w_{l,t}h_t - \underline{w}_t + (1-\rho)E_t\Phi_{t,t+1}\mathcal{S}_{l,t+1}^{w}, \tag{28}$$

where $\underline{w}_t = b + \frac{\Psi}{\lambda_t+\gamma_t}\frac{h_t^{1+\psi}}{1+\psi} + \beta(1-\rho)E_t s(\theta_{t+1})\Phi_{t,t+1}\int_0^1 \frac{\upsilon_{L,t+1}}{\mathcal{V}_{t+1}}\mathcal{S}_{L,t+1}^{w}dL$ does not vary across firms because from (26) h_t is the same for all l.

Respectively, for equation (24) we have

$$\mathcal{S}_{l,t}^{f} = \overline{w}_{l,t} - w_{l,t}h_t + (1-\rho)E_t\Phi_{t,t+1}\mathcal{S}_{l,t+1}^{f}, \tag{29}$$

where $\overline{w}_{l,t} = \phi_t mpl_l h_{l,t} + E_t \Phi_{t,t+1} \left[\chi \frac{\varepsilon_c}{1+\varepsilon_c} \frac{z_{l,t+1}^{1+\varepsilon_c}}{\lambda_{t+1}+\gamma_{t+1}} \right]$.

Given wage stickiness, we can write the surplus of a firm renegotiating at time t as

$$\mathcal{S}_{l,t}^{f*} = \overline{w}_{l,t} - \frac{W_{l,t}^*}{P_t} h_t + (1-\rho) E_t \Phi_{t,t+1} \left[\xi_w \mathcal{S}_{l,t+1|t}^{f} + (1-\xi_w) \mathcal{S}_{l,t+1}^{f*} \right], \tag{30}$$

where $\mathcal{S}_{l,t+1|t}^{f}$ denotes the surplus of a firm who renegotiated wages at time t but not at $t+1$; and $\mathcal{S}_{l,t+1}^{f*}$ denotes the surplus of a renegotiating firm. Alternatively, in nonrecursive form we can write

$$\mathcal{S}_{l,t}^{f*} = E_t \sum_{\tau=0}^{\infty} \Phi_{t,t+\tau} (1-\rho)^\tau \xi_w^\tau \left[\overline{w}_{l,t+\tau|t} - \frac{W_{l,t}^*}{P_{t+\tau}} h_{t+\tau} \right] + (1-\rho)(1-\xi_w) E_t \sum_{\tau=0}^{\infty} \Phi_{t,t+\tau} (1-\rho)^\tau \xi_w^\tau \mathcal{S}_{l,t+\tau+1}^{f*}. \tag{31}$$

If we proceed the same way for those renegotiating workers, we have

$$\mathcal{S}_{l,t}^{w*} = \frac{W_{l,t}^*}{P_t} h_t - \underline{w}_t + (1-\rho) E_t \Phi_{t,t+1} \left(\xi_w \mathcal{S}_{l,t+1|t}^{w} + (1-\xi_w) \mathcal{S}_{l,t+1}^{w*} \right), \tag{32}$$

that is,

$$\mathcal{S}_{l,t}^{w*} = E_t \sum_{\tau=0}^{\infty} \Phi_{t,t+\tau} (1-\rho)^\tau \xi_w^\tau \left(\frac{W_{l,t}^*}{P_{t+\tau}} h_{t+\tau} - \underline{w}_{t+\tau} \right) + (1-\rho)(1-\xi_w) E_t \sum_{\tau=0}^{\infty} \Phi_{t,t+\tau} (1-\rho)^\tau \xi_w^\tau \mathcal{S}_{l,t+\tau+1}^{w*}. \tag{33}$$

Using the sharing rule (27), the following condition holds:

$$E_t \sum_{\tau=0}^{\infty} \Phi_{t,t+\tau} (1-\rho)^\tau \xi_w^\tau \left(\frac{W_{l,t}^*}{P_{t+\tau}} h_{t+\tau} - w_{l,t+\tau|t}^{tar} \right) = 0, \tag{34}$$

where $w_{l,t}^{tar} = (1-\eta)\overline{w}_{l,t} + \eta \underline{w}_t$ denotes the real wage to which both parties would agree if wages were totally flexible.[5]

Finally, the law of motion of the average nominal wage is given by:

$$W_t = \int_0^1 W_{l,t} dl = \xi_w W_{t-1} + (1-\xi_w) W_t^*. \tag{35}$$

[5] We refer the reader to Thomas (2008) for a description of the flexible wage solution.

2.6 The monetary authority

Money is exogenously supplied by the central bank according to the following 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.

2.7 Equilibrium

Recall that we obtained from equation (16) that $k_{lt}/(n_{lt}h_{lt}) = k_t/(n_t h_t), \forall l$, which implies that $mpl_{lt} = mpl_t, \forall l$. These two results in equation (26) mean that $h_{lt} = h_t, \forall l$, and given that

$$\int_0^1 n_{lt}h_{lt}dl = n_t h_t,$$

we obtain

$$\int_0^1 n_{lt}dl = n_t.$$

Given constant returns to scale in the production of intermediate labor goods and using the aggregation results from above, we can write aggregate labor good output in equation (12) as follows:

$$\int_0^1 a_t k_{lt}^{\alpha} \left(n_{lt}h_{lt}\right)^{1-\alpha} dl = a_t \int_0^1 n_{lt}h_{lt} \left(\frac{k_{lt}}{n_{lt}h_{lt}}\right)^{\alpha} dl = a_t \overline{k}_t^{\alpha} \int_0^1 n_{lt}h_{lt}dl = a_t \overline{k}_t^{\alpha} n_t h_t.$$

In equilibrium, total output of intermediate labor goods must equal total demand by wholesale producers, whose supply will be equal to total demand by retailers. In sum,

$$a_t \overline{k}_t^{\alpha} n_t h_t = \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{\frac{\lambda_f - 1}{\lambda_f}} Y_t(j)dj = Y_t. \tag{36}$$

We close the model with the aggregate resource constraint

$$Y_t = C_t + X_t, \tag{37}$$

where C_t is aggregate consumption, and X_t is aggregate investment defined as $X_t = K_{t+1} - (1-\delta)K_t$. And finally, we have that transfers adjust to pay for unemployment benefits $T_t = (1 - n_t)b$.

Given the description of the model, we proceed to define an equilibrium. The whole set of equilibrium equations is reported in the Appendix.

Definition 1 *A competitive general equilibrium in this model is given by a set of functions* $\{\mathcal{S}^f_{l,t}, \mathcal{S}^w_{l,t}, \mathcal{S}^{f*}_{l,t}, \mathcal{S}^{w*}_{l,t}\}$; *a set of prices* $\{\tilde{P}_t, P_t, W^*_{lt}, W_t, R_t, r^k_t\}$, *and a set of allocations* $\{Y_t, Y_{jt}, c_t, k_{t+1}, k_{l,t+1}, n_t, n_{lt}, h_t, h_{lt}, M_{t+1}, B_{t+1}\}$ *such that:*

i) taking prices, wages and shocks, the retailer firm's problem is optimally solved,

ii) for the wholesale producer, $\tilde{P}_t$ *satisfies (10), and* P_t *is given by the Calvo process for prices (11);*

iii) intermediate labor good producers choose v_{lt}, n_{lt}, k_{lt} *to satisfy (15)-(18); wage bargaining yields* h_{lt}, W_{lt}, v_{lt} *that satisfy (26),(27); and* W_t *is given by the Calvo process for wages (35);*

iv) on the household's problem, c_t, k_{t+1}, M_{t+1} *satisfy (3)-(9); bonds are in zero net supply, i.e.,* $B_{t+1} = B_t = 0$;, *and the CIA constraint holds with equality*

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

v) and markets clear, that is,

$$Y_t = C_t + X_t,$$

$$
\begin{aligned}
X_t &= K_{t+1} - (1-\delta) K_t, \\
M_t &= M_{t-1} + N_t, \\
n_t &= (1-\rho) n_{t-1} + m a_t \\
a_t \overline{k}_t^{\alpha} n_t h_t &= \int_0^1 \left(\frac{P_t(j)}{P_t} \right)^{\frac{\lambda_f - 1}{\lambda_f}} Y_t(j) dj = Y_t.
\end{aligned}
$$

The model is log-linearized around a zero–inflation non–stochastic steady state and then simulated to analyze the responses under technology and money supply shocks.

3 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 second World War period.

Preferences

The subjective discount factor, β, is equal to 0.99 annually, implying a 4% 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 13% markup on prices, implying λ_p equal to 1.13, consistent with estimates provided by Christiano, Eichenbaum and Evans (2005). Regarding price and wage setting, we assume that there is a probability $(1 - \xi_p) = \frac{1}{4}$ of resetting prices, and a probability $(1 - \xi_w) = \frac{1}{6}$ 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).[6]

Shock processes

The productivity shock is assumed to follow an AR(1) process with autocorrelation $\rho_a = 0.983$ and standard deviation $\sigma_a = 0.008$. We assume that gross money growth follows

[6] Recently, there is a growing debate on the true value of the Calvo parameter (Nakamura and Steinsson, 2008). However, for the sake of comparison with previous studies we stick to the values reported above.

an autoregressive process with autocorrelation $\rho_\mu = 0.5$, and standard deviation $\sigma_\mu = 0.006$. These are the same as that those employed by Wang and Wen (2006).

Job market

We follow Thomas (2008) in most of the parametrization of the job market. The monthly rate of separation, ρ, is set equal to 0.035. The elasticity of unemployed searchers in the matching function, ϑ is assumed to be 0.6; and the bargaining power of workers, η, is 0.5. We set the scale parameter in the matching function, $\sigma_m = 1$. Regarding the cost of posting a vacancy, the elasticity ϵ_c is assumed to be 1. Finally, we set the probability that an unemployed worker finds a job equal to 0.3 at a monthly frequency.

4 Summary statistics

Given the benchmark parameterization described above, Table 2 reports summary statistics of the main variables in the model and in the U.S. data: standard deviations, autocorrelations and contemporaneous correlations with output. The data run from 1951:1 – 2004:4, and correspond to real Gross Domestic Product, real Consumption of non-durable and services, real Gross Domestic Investment, GDP deflator, the Federal Funds Rate, total hours, unemployment rate, employment rate, labor productivity per person, total real wage, vacancies, and the ratio of vacancies over unemployed. Notice that for the Federal funds rate, data start in 1955. Data for real output, real consumption, real investment (in billions of chained 2005 dollars), Federal funds rate, and the GDP deflator are quarterly and are obtained from FRED, the database at the Federal Reserve Bank of St. Louis. We use data provided by Shimer[7] for the separation rate, the separation probabilities, vacancies (v) and the ratio (v/u), while all the others data concerning the labor market are obtained from the Bureau of Labor Statistics. All data are first logged and then detrended using the Hodrick-Prescott filter with smoothing parameter 1600.

Table 2 shows that as usual in business cycle models, consumption and investment are persistent and procyclical, with consumption being less volatile than output and investment more so. Employment and hours are less volatile than output and very persistent, as found

[7] These data are available in his website at http://sites.google.com/site/robertshimer/research/flows

in Cole and Rogerson (1999). Hours are negatively correlated with output, in contrast with the data, whereas employment is mildly procyclical. Labor productivity is slightly more volatile than output, but highly persistent and procyclical. Notice how the stylized facts regarding the high volatility of unemployment, vacancies, and tightness widely documented in the literature (Costain and Reiter, 2008; Andrés, Doménech and Ferri, 2008; Faccini and Ortigueira, 2010) are present in this model. However, their relative volatilities are lower than in the data. The real wage is highly persistent and procyclical, but contrary to what Costain and Reiter (2008) find, the real wage is, like labor productivity, slightly more volatile than output, as found in Faccini and Ortigueira (2010). Regarding inflation variables, both are less volatile than output, while wage inflation is more persistent than in the data and shows moderately stronger procyclicality than price inflation. Finally, although not shown here, the model displays a strong negative correlation between unemployment and vacancies, the Beveridge curve, equal to -0.9594. All in all, the model generates lower relative volatility than in de data, while persistence is significantly improved upon previous work.

Regarding persistence, Table 3 reports the autocorrelations of the main variables in the model under the benchmark calibration for $\varphi = 0.6$, and two limit cases when investment is a credit good $\varphi = 0$ and when it is considered purely a cash good $\varphi = 1$. In all the variables considered, having to finance a larger proportion of investment with cash improves the persistence generated by the model. This is especially remarkable for investment and price inflation.

5 Dynamics

Next, we evaluate the performance of the model in response to technology shocks and to monetary shocks under our benchmark calibration, that is when $\varphi = 0.6$.

5.1 Labor market and technology shocks

Figure 1 shows the response of the model to a one percent increase in technology at time $t = 1$. The model displays the traditional response of the main variables in a new Keynesian model after a rise in productivity (Galí, 1999). Hours fall after a technology shock, labor productivity increases, and employment falls on impact to increase afterwards. We observe that vacancies fall and therefore the cost of posting a vacancy decreases (i.e. the cost of hiring) since firms simply take advantage of the increase in productivity and adjust the extensive margin later, reducing their hiring. That is, right after the shock it is the extensive margin that adjusts. This leads to an increase in output that spreads to consumption and investment. Labor productivity rises, as mentioned above, and stays high for a while due in part to the increase in investment, this is what allows output to increase on impact despite the fall in hours and the number of workers. Overtime, investment stays high and so does labor productivity, what increases the cost of hiring. All in all, the first effect dominates, so there is an increase in the number of hires, tightness and a fall in unemployment. Notice that the model reproduces the Beveridge curve, i.e. the negative correlation between vacancies and unemployment. The response of real wages is also consistent with the data: nominal wages hardly react on impact given the combination of sticky wages and prices, driving real wages up. This is in line with Liu and Phaneuf (2007), 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.

Regarding the role of investment in the cash-in-advance constraint, $\varphi > 0$, we find it is crucial to generate persistence in the response of output. The left two panels in Figure 3 report the response of output and inflation to a positive technology shock when $\varphi = \{0, 0.6(benchmark), 1\}$. With sticky wages and frictions in the labor market, marginal costs adjust slowly to a change in technology. Introducing capital will reduce stickiness of prices due to the response of the rental rate (see Huang, Liu and Phaneuf, 2004). However, if $\varphi > 0$, capital cannot be adjusted so freely, and part of the reaction of the rental rate is slowered, making prices more sluggish and reducing the response of aggregate demand. Otherwise, with $\varphi = 0$, firms would switch resources from investment to labor, and output would fall on impact, because of the strong adjustment of investment, which is at odds with the data (see Heer and Maussner (2010) who obtain a fall in output in response to an increase in productivity). In sum, we need both sticky wages, sticky prices and labor market frictions plus some delay in demand. Faccini and Ortigueira (2010) use costs of adjustment in capital and labor for the same purpose.[8]

5.2 Money supply shocks and the liquidity effect

Figure 2 plots the responses of the model to an increase in money supply at time $t = 1$ under the benchmark calibration. The money injection delivers a hump-shaped response of output, investment and consumption. Price inflation reacts strongly on impact, as does wage inflation, but the price increase is stronger so that real wages go down. Notice that both price and wage inflation rates decay slowly overtime. The reason is the sluggish response of marginal costs. Christoffel et al. (2004) find that labor market rigidities are not enough to match the dynamics of inflation to a money supply shock, but add that probably another real rigidity would also be needed. In our case, sticky wages and investment as a cash good seem to be working in that direction. Recall that wholesale prices are sticky, but the intermediate good price is not, so the rise of wholesale inflation makes intermediate goods more profitable, triggering an increase in hours and hires. Notice we find the same for vacancies and the probability of finding a job. This lasts longer than a quarter as demand takes time to adjust, in the spirit of Heer and Maussner (2010). However, in contrast to these authors who use habits in consumption, our model's persistence is enhanced due to $\varphi > 0$. Indeed, the mechanism behind this result is driven by the fact that investment is a cash good: an increase in money supply allows for more investment but the adjustment is gradual. Despite the relatively low autocorrelation of the money supply shock, the model generates responses of unemployment and price inflation which are quite persistent. In this sense, investment partially financed by cash would help increase the degree of stickiness in the economy, favoring the delayed response of the economy. Our results are consistent with previous literature such as Christoffel and Linzert (2005). These authors find that higher degrees of sticky wages increase the response of price inflation, whereas unemployment persistence also depends on other labor market fundamentals. Given wage rigidities, the authors find that extra frictions, in particular how wages are bargained, also affect the

[8] Not shown here, but the higher φ, the stronger the delay in the response of the number of workers.

persistence in the economy. In our case, this extra friction would be the need to finance investment with cash.

The liquidity effect

It is well known that the standard new Keynesian model finds it difficult to generate the fall in nominal interest rates after a money injection. Additional rigidities such as habits in consumption, adjustment costs in investment or variable capital utilization are required for that fact to obtain (Christiano, Eichenbaum and Evans, 2005). The benchmark calibration of the model analyzed above does not deliver the liquidity effect. However any model that attempts to serve as a workhorse for the analysis of economic policy should account for it. Therefore, we investigate further the model specification that would lead us to generate the liquidity effect.

The liquidity effect obtains when after a money injection we observe in the data a fall in the nominal interest rate. The intuition behind is that the opportunity cost of holding money needs to fall for the money market to clear. In models like ours, households hold money to consume and invest. The faster they adjust their money demand to changes in the money supply, the less likely is the nominal interest rate to fall. Then, frictions are introduced to reduce the response of money demand and force the nominal interest rate to fall, for example limited participation in financial markets. However, as we show below, other types of frictions which delay the response of the demand side of the economy also help reproduce the liquidity effect of a money injection.

We find that the dynamics of the nominal interest rate to an increase in money supply are very sensible to three parameters: φ the proportion of investment to be financed with cash; ξ_w the degree of wage stickiness; and η the workers' bargaining power. The first two parameters should not come as a surprise since both of them delay the response of aggregate demand to a money injection, making it necessary for the interest rate to fall in order to clear the money market. The last parameter, however, deserves some more discussion. The value of η measures the bargaining power of workers with respect to firms. The fact that $\eta = \vartheta$, i.e. that the bargaining power of workers equals the elasticity of new matches to unemployed searchers, is called the Hosios condition (2001). Under this condition the equilibrium wage obtained from negotiation delivers efficient levels of employment and unemployment. In our benchmark calibration, $\eta < \vartheta$ following previous literature for U.S. data. However, under such calibration, the model does not generate the liquidity effect after a money injection. Christoffel and Linzert (2005) find this parameter is key in the response of unemployment to monetary shocks. Relatively higher bargaining power for workers ($\eta > \theta$) implies that wages would adjust more in response to shocks relative to hours and the number of workers, also reducing the adjustment in the demand for capital. Notice that this supply-side mechanism ends up affecting the aggregate demand side of the economy, delaying the response of money demand in favor of the liquidity effect.

In our model, setting $\eta > \vartheta$ generates the same mechanism on the demand side and goes in favor of the liquidity effect as shown in Figure 4. This figure shows the response of the nominal interest rate to a money injection under different degrees of investment in the cash in advance, bargaining power of workers and wage stickiness. To isolate effects, all impulse response functions are done for the flexible price case. We can observe that it is not price but wage stickiness what is essential to generate the liquidity effect, as shown in Auray and de Blas (2011), and Christiano, Eichenbaum and Evans (2005). Furthermore, we need high bargaining power of workers relative to the elasticity of matches with respect to unemployed searchers, and a high level of wage stickiness to obtain the liquidity effect. Notice that given these parameters, the higher the proportion of investment to be financed with cash, the more likely is to obtain the liquidity effect.

6 Bayesian estimation

We find in the simulations above, that having investment in the cash in advance is crucial to improve the performance of the model. Our results are in line with other papers which include other frictions in an attempt to reproduce appropriate output and inflation dynamics. However, one may argue to what extent our friction is more or less relevant compared to the others. We estimate the importance of including investment in the CIA constraint as compared with sticky prices, sticky wages, and labor market frictions.

We estimate the model using Bayesian methods. Bayesian estimation of general equilibrium models has some advantages with respect to other estimation methods. On one hand, it makes use of the complete solved model, instead of considering only a given set of equilibrium conditions; it allows for the consideration of prior information about the parameters which improves their identification; and it overcomes the potential misspecification problem by adding observational shocks, leading to a way of comparing across models based on the fit of the model to the data.

The procedure we follow for the Bayesian estimation is as follows. For a given model m we have some parameter set, Θ_m, with its corresponding priors, $p(\Theta_m|m)$. We also have access to observed data, $y^T = \{y_t\}_{t=1}^T$, so that we can compute the likelihood function of that sample given the parameters and the model, $L(\Theta_m|y^T, m) \equiv p(y^T|\Theta_m, m)$. We are interested in obtaining as much information from the likelihood in the data to update our priors on the parameters, i.e., we want to estimate the parameters that best fit the data which will lead us to our posterior $p(\Theta_m|y^T, m)$. In general, the Bayes theorem allows us to compute

$$p(\Theta|y^T) = \frac{p(\Theta, y^T)}{p(y^T)}, \text{ and } p(y^T|\Theta) = \frac{p(\Theta, y^T)}{p(\Theta)},$$

so that $p(\Theta, y^T) = p(y^T|\Theta)p(\Theta)$, and $p(\Theta|y^T)$ can be written as $\frac{p(y^T|\Theta)p(\Theta)}{p(y^T)}$. In particular, for a given model m this last expression becomes $p(\Theta_m|y^T, m) = \frac{p(y^T|\Theta_m, m)p(\Theta_m|m)}{p(y^T|m)}$, where $p(y^T|m)$ denotes the marginal density of the data in a given model, which notice is constant or invariant to the parameter set. Then, we use the Kalman filter to estimate the likelihood function $p(y^T|\Theta_m, m)$ and update our priors $p(\Theta_m|m)$ using a random sampling method, in our case the Metropolis-Hastings method,[9] to obtain the posterior kernel of our parameter set, $p(\Theta_m|y^T, m)$, as follows:

$$p(\Theta_m|y^T, m) \propto p(y^T|\Theta_m, m)p(\Theta_m|m)$$

6.1 Data

Following recent literature (Rabanal and Rubio-Ramírez, 2005; Gertler, Sala and Trigari, 2008; Mandelman and Zanetti, 2008; among many others) we fix some of the structural

[9]Results below are based on 200,000 draws of the Metropolis-Hastings algorithm.

parameters and estimate a subset given by $\{\varphi, \xi_p, \xi_w, \chi, \sigma_m, \rho_a, \sigma_a, \rho_\mu, \sigma_\mu\}$. We explain the joint behavior of output and inflation. The sample runs from 1951:1 – 2004:4. A detailed explanation of the data and sources employed is provided in Section 4.

6.2 Priors

Table 4 reports the prior distributions of the parameters.[10] Most of the priors are in line with previous literature (Gertler, Sala, and Trigari, 2008; Mandelman and Zanetti, 2008; Faccini, Millard and Zanetti, 2010). We use the beta distribution for those parameters that take values between 0 and 1 ($\varphi, \xi_p, \xi_w, \rho_a, \rho_\mu$); the gamma distribution for parameters which are strictly positive (χ, σ_m); and the inverse gamma distribution for the shock variances (σ_a, σ_μ).

6.3 Posteriors and model comparison

Table 4 also reports the results from the estimation, while Figure 5 shows the prior and posterior densities. We find that the data support that more than 60% of investment be financed with cash, supporting our assumption. The degree of price stickiness required by the data is relatively high, around 0.9, what means 10 quarters probability of not adjusting prices. The data do not seem to be very informative about wage stickiness, although the parameter is significantly larger than zero. It is important to note that the estimation results validate the need for both price and wage stickiness, however only sticky wages are required to generate the liquidity effect, as shown in the previous section. As for labor market frictions, the data support them, meaning that the cost of hiring is positive and relevant. The same is true for the scale parameter in the matching function. Regarding the parameters of the shock processes, notice that autocorrelations are lower than those used in the calibration above, in particular that for technology shocks, whereas its volatility is higher and much higher than the volatility of the money supply process.

Table 5 shows the second order moments of the model when the posterior estimated parameters are employed. Compared to the results in Table 2, the estimated parameters

[10] Although not reported here, estimation results on parameters, mainly φ, are robust to alternative values for the prior mean and standard deviation.

improve the relative volatility of the model, while reducing somewhat the persistence of the labor market variables and their cyclical behavior.

In order to assess the relevance of the key rigidities included in the paper, we proceed to run a model comparison. Table 6 reports the log-likelihood functions of the benchmark model and five alternative specifications. These alternative specifications include the limit cases of investment fully financed with credit (ICredit model) ($\varphi = 0$), and fully financed with cash (ICash model) ($\varphi = 1$), as well as the fully flexible price ($\xi_p = 0$) and wages ($\xi_w = 0$) setups, and the model without labor market frictions ($\chi = 0$). Following Rabanal and Rubio-Ramírez (2005) we can compute the relative relevance of each model specification by comparing their likelihood. In particular, the difference between the ICredit model and the benchmark is 1355.98-1231.24=124.74 what would mean a distance of $exp(124.74)$ which according to Rabanal and Rubio-Ramírez (2005) is too far and goes in favor of our benchmark model with $\varphi > 0$. However, notice that the data cannot distinguish between the benchmark model and the ICash model, what means having investment in the cash in advance is a relevant enough assumption. Using Bayesian estimation also allows us to rank the models, and in this case sticky prices seem to be a more relevant assumption than sticky wages, followed by the need to have investment at least partially financed with cash; whereas the data cannot distinguish among sticky wages, labor market frictions and our benchmark model.

7 Conclusions

In this paper, we evaluate the ability of a model with sticky prices, sticky wages, labor market frictions and investment in the CIA constraint to generate business cycle dynamics consistent with empirical evidence, in particular output and inflation persistence. 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. We also test the performance of the model in response 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, we find that the model needs sticky wages plus two real rigidities (high bargaining power of workers and investment in the cash-in-advance constraint) to generate the liquidity effect. All in all, 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 Equations defining the general equilibrium

$$c_t^{-\sigma} = \lambda_t \left(2 - \frac{1}{R_t}\right), \quad \text{(A.1)}$$

$$\varphi\lambda_t \left(1 - \frac{1}{R_t}\right) + \lambda_t = \beta E_t \lambda_{t+1} \left[r_{t+1}^k + 1 - \delta + \varphi(1-\delta)\left(1 - \frac{1}{R_{t+1}}\right)\right], \quad \text{(A.2)}$$

$$\lambda_t = R_t \beta E_t \frac{\lambda_{t+1}}{\pi_{t+1}}, \quad \text{(A.3)}$$

$$m_t = c_t + \varphi\left[k_{t+1} - (1-\delta)k_t\right], \quad \text{(A.4)}$$

$$m_{t+1} = \mu_t \frac{m_t}{\pi_t}, \quad \text{(A.5)}$$

$$E_t \sum_{\tau=0}^{\infty} (\beta\pi^* \xi_p)^\tau \Phi_{t+\tau} Y_{t+\tau} \left[\frac{\tilde{P}_t(j)}{\lambda_f}\left(\frac{\pi^{*\tau}\tilde{P}_t(j)}{P_{t+\tau}}\right) - \frac{P_{t+\tau}\phi_{t+\tau}}{\pi^{*\tau}}\left(\frac{\pi^{*\tau}\tilde{P}_t(j)}{P_{t+\tau}}\right)^{\frac{\lambda_f}{1-\lambda_f}}\right] = 0, \quad \text{(A.6)}$$

$$r_t^k = \phi_t \alpha a_t k_t^{\alpha-1} \left(n_t h_t\right)^{1-\alpha}, \quad \text{(A.7)}$$

$$\frac{\chi z_{l,t}^{\varepsilon_c}}{q(\theta_t)} = c_t^{-\sigma}\left(\phi_t mpl_t - w_{l,t}\right) h_t + \chi\beta E_t \left[\frac{\varepsilon_c}{1+\varepsilon_c} z_{l,t+1}^{1+\varepsilon_c} + (1-\rho)\frac{z_{l,t+1}^{\varepsilon_c}}{q(\theta_{t+1})}\right], \quad \text{(A.8)}$$

$$n_t = (1-\rho)n_{t-1} + \sigma_m \frac{\upsilon_t}{\theta_t^{\vartheta}}, \quad \text{(A.9)}$$

$$u_t^s = 1 - (1-\rho)n_{t-1}, \quad \text{(A.10)}$$

$$E_t \sum_{\tau=0}^{\infty} \Phi_{t+\tau}(1-\rho)^\tau \xi_w^\tau \left(\frac{W_{l,t}^*}{P_{t+\tau}} h_{t+\tau} - w_{l,t+\tau|t}^{tar}\right) = 0, \quad \text{(A.11)}$$

$$\phi_t mpl_t = \frac{\Psi}{c_t^{-\sigma}} h_t^{\psi}, \quad \text{(A.12)}$$

$$mpl_t = (1-\alpha) a_t k_t^{\alpha} \left(n_t h_t\right)^{-\alpha}, \quad \text{(A.13)}$$

$$y_t = c_t + k_{t+1} - (1-\delta)k_t, \quad \text{(A.14)}$$

$$y_{l,t} = a_t k_{l,t}^{\alpha} \left(n_{l,t} h_{l,t}\right)^{1-\alpha}, \quad \text{(A.15)}$$

$$\upsilon_t = \theta_t u_t^s, \quad \text{(A.16)}$$

$$\Phi_{t+1} = \beta \frac{c_{t+1}^{-\sigma}}{c_t^{-\sigma}}, \quad \text{(A.17)}$$

$$z_{l,t} = \frac{\upsilon_{l,t}}{n_{l,t-1}}, \quad \text{(A.18)}$$

$$w_t^{tar} = (1-\eta)\left(\phi_t mpl_t h_t + E_t \Phi_{t,t+1} \frac{\chi\varepsilon_c}{1+\varepsilon_c} \frac{z_{l,t+1}^{1+\varepsilon_c}}{c_{t+1}^{-\sigma}}\right) + \quad \text{(A.19)}$$

$$\eta\left(b + \frac{\Psi}{c_t^{-\sigma}} \frac{h^{1+\psi}}{1+\psi} + (1-\rho)E_t \Phi_{t,t+1} s(\theta_{t+1}) \int_0^1 \frac{\upsilon_{L,t+1}}{\mathcal{V}_{t+1}} \mathcal{S}_{L,t+1}^w dL\right).$$

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Tables

Table 1. Baseline calibration

Preferences		
Discount factor	β	0.99
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	1.15
Probability of not resetting prices	ξ_p	0.75
Probability of not resetting wages	ξ_w	0.83
Job market		
Monthly rate of separation	ρ	0.035
Elasticity of unemployed searchers	ϑ	0.6
Bargaining power of workers	η	0.5
Scale parameter in matching function	σ_m	1
Elasticity of posting a vacancy	ε_c	1
Monthly probability that an unemployed finds a job	$s(\theta)$	0.3
Shock processes		
Persistence of productivity shock	ρ_a	0.983
Standard deviation of productivity shock	σ_a	0.008
Persistence of monetary shock	ρ_μ	0.500
Standard deviation of monetary shock	σ_μ	0.006
Other parameters		
Percentage of investment financed with cash	φ	0.6

Table 2. Summary statistics

		U.S. Data (1951:1-2004:4)				Model (benchmark calibration)			
Variable	z	σ_z	$\frac{\sigma_z}{\sigma_y}$	$\rho(z_t, z_{t-1})$	$\rho(z_t, y_t)$	σ_z	$\frac{\sigma_z}{\sigma_y}$	$\rho(z_t, z_{t-1})$	$\rho(z_t, y_t)$
output	y	1.58	1.00	0.8374	1.0000	5.70	1.00	0.9937	1.0000
consumption	c	1.28	0.81	0.8545	0.8704	4.14	0.73	0.9957	0.9540
investment	x	6.93	4.38	0.7668	0.8741	9.49	1.66	0.9818	0.9657
nominal interest rate	R	1.41	0.89	0.7030	0.4018	0.36	0.06	0.7031	0.1984
employment	n	0.99	0.62	0.8883	0.7917	1.95	0.34	0.9654	0.3935
hours	h	1.76	1.11	0.8952	0.8748	2.07	0.36	0.8712	-0.7150
unemployment	u	12.52	7.91	0.8727	-0.8348	34.27	6.01	0.9654	-0.3935
labor productivity	mpl	1.32	0.83	0.7617	0.6962	6.91	1.21	0.9853	0.9282
vacancies	v	13.93	8.79	0.9046	0.8933	22.32	3.91	0.8863	0.3855
tightness	θ	25.76	16.27	0.8956	0.8830	31.73	5.57	0.9433	0.3942
real wage	w	1.71	1.08	0.8623	0.7165	6.53	1.14	0.9980	0.9037
wage inflation	π^w	0.89	0.57	0.4204	0.4914	0.28	0.05	0.9250	0.3082
price inflation	π	0.79	0.50	0.7252	0.2280	0.53	0.09	0.7080	0.1492

Table 3. Autocorrelations under $\varphi = \{0, 0.6, 1\}$

Variable		$\varphi = 0$	$\varphi = 0.6$ (*benchmark*)	$\varphi = 1$
output	y	0.8336	0.9937	0.9954
consumption	c	0.9968	0.9957	0.9962
investment	x	0.6352	0.9818	0.9895
nominal interest rate	R	0.5115	0.7031	0.7318
employment	n	0.9144	0.9654	0.9692
hours	h	0.2418	0.8712	0.9041
unemployment	u	0.9144	0.9654	0.9692
labor productivity	mpl	0.9257	0.9853	0.9865
vacancies	v	0.6701	0.8863	0.8981
tightness	θ	0.8357	0.9433	0.9495
real wage	w	0.9963	0.9980	0.9981
wage inflation	π^w	0.7780	0.9250	0.9332
price inflation	π	0.2987	0.7080	0.7303

Table 4. Priors and posteriors

Parameter	Prior mean	Prior std.dev.	Distribution	Range	Posterior	Confidence interval	
φ	0.50	0.20	Beta	[0,1]	0.6344	0.4399	0.8328
ξ_p	0.80	0.20	Beta	[0,1]	0.9174	0.8958	0.9399
ξ_w	0.50	0.20	Beta	[0,1]	0.5049	0.1900	0.8155
χ	3.50	1.00	Gamma	$\mathbb{R}$	3.4704	1.8164	5.0159
σ_m	1.00	0.10	Gamma	$\mathbb{R}$	1.0125	0.8498	1.1837
ρ_a	0.50	0.25	Beta	[0,1]	0.4548	0.3504	0.5577
ρ_μ	0.50	0.10	Beta	[0,1]	0.2454	0.1580	0.3258
σ_a	0.15	0.15	Inv.Gamma	$\mathbb{R}^+$	0.0807	0.0435	0.1194
σ_μ	0.01	0.10	Inv.Gamma	$\mathbb{R}^+$	0.0058	0.0042	0.0075
Log-likelihood	1355.985019						

Table 5. Summary statistics in the model under the posterior estimates

Variable	z	σ_z	$\frac{\sigma_z}{\sigma_y}$	$\rho(z_t, z_{t-1})$	$\rho(z_t, y_t)$
output	y	2.32	1.00	0.9397	1
consumption	c	0.88	0.39	0.9260	0.5076
investment	x	6.22	2.68	0.9195	0.9705
nominal interest rate	R	0.36	0.15	0.5731	0.5280
employment	n	1.39	0.60	0.6045	0.2495
hours	h	12.33	5.31	0.4055	-0.0765
unemployment	u	24.46	10.54	0.6045	-0.2495
labor productivity	mpl	13.90	5.99	0.4401	0.2098
vacancies	v	25.51	10.99	0.1697	0.3855
tightness	θ	27.16	11.71	0.3873	0.2406
real wage	w	3.62	1.56	0.8382	0.1540
wage inflation	π^w	2.34	1.01	0.1541	0.1845
price inflation	π	0.34	0.15	0.5048	0.3838

Table 6. Log-likelihood functions of alternative parameterizations

	Benchmark model	Investment as credit good ($\varphi = 0$)	Investment as cash good ($\varphi = 1$)	Flexible prices ($\xi_p = 0$)	Flexible wages ($\xi_w = 0$)	No labor market frictions ($\chi = 0$)
Log-likelihood	1355.98	1231.24	1357.88	1153.76	1355.73	1354.69

Figure 1: IRFs after a technology shock ($\varphi = 0.6$).

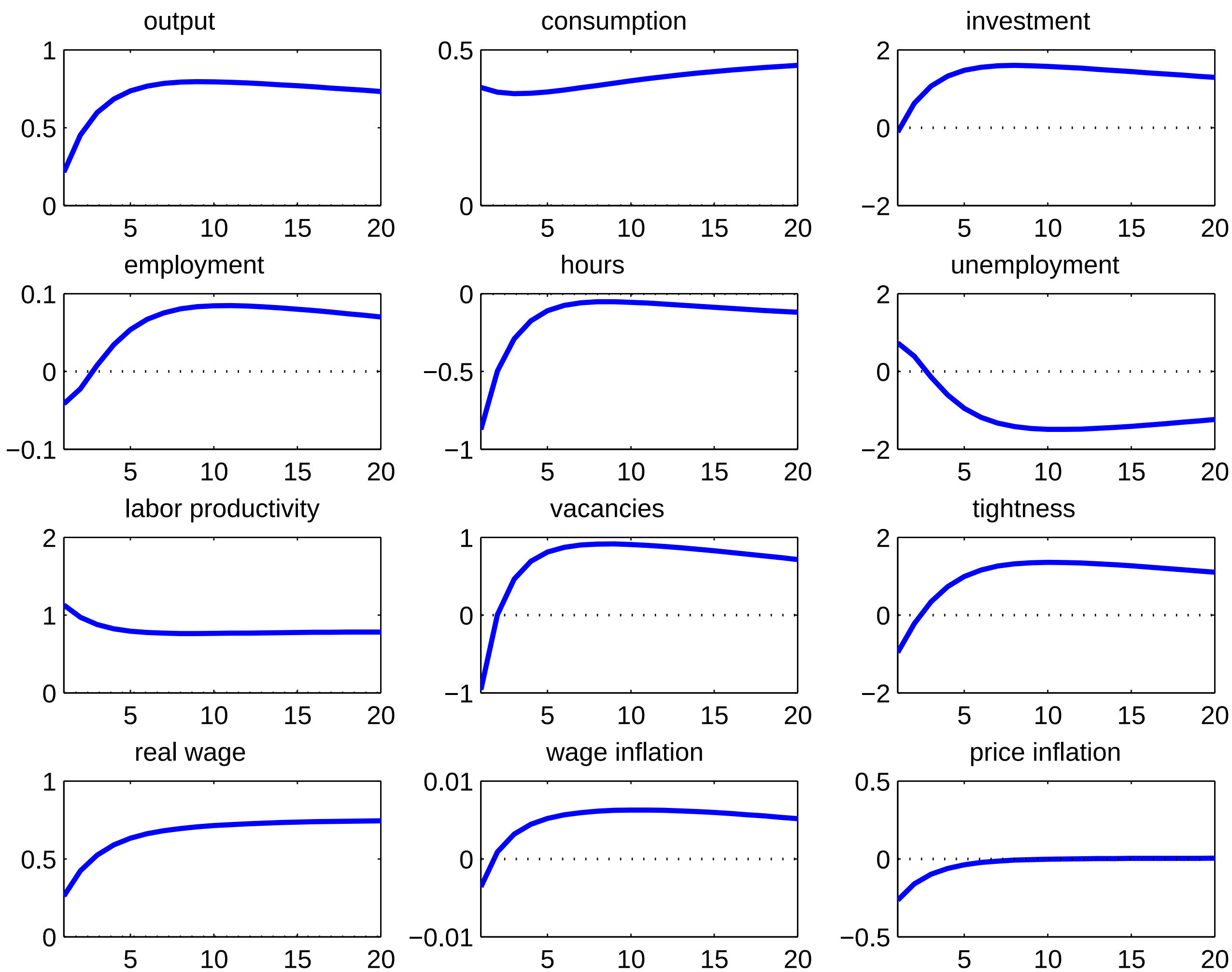

Figure 2: IRFs after a money supply shock ($\varphi = 0.6$).

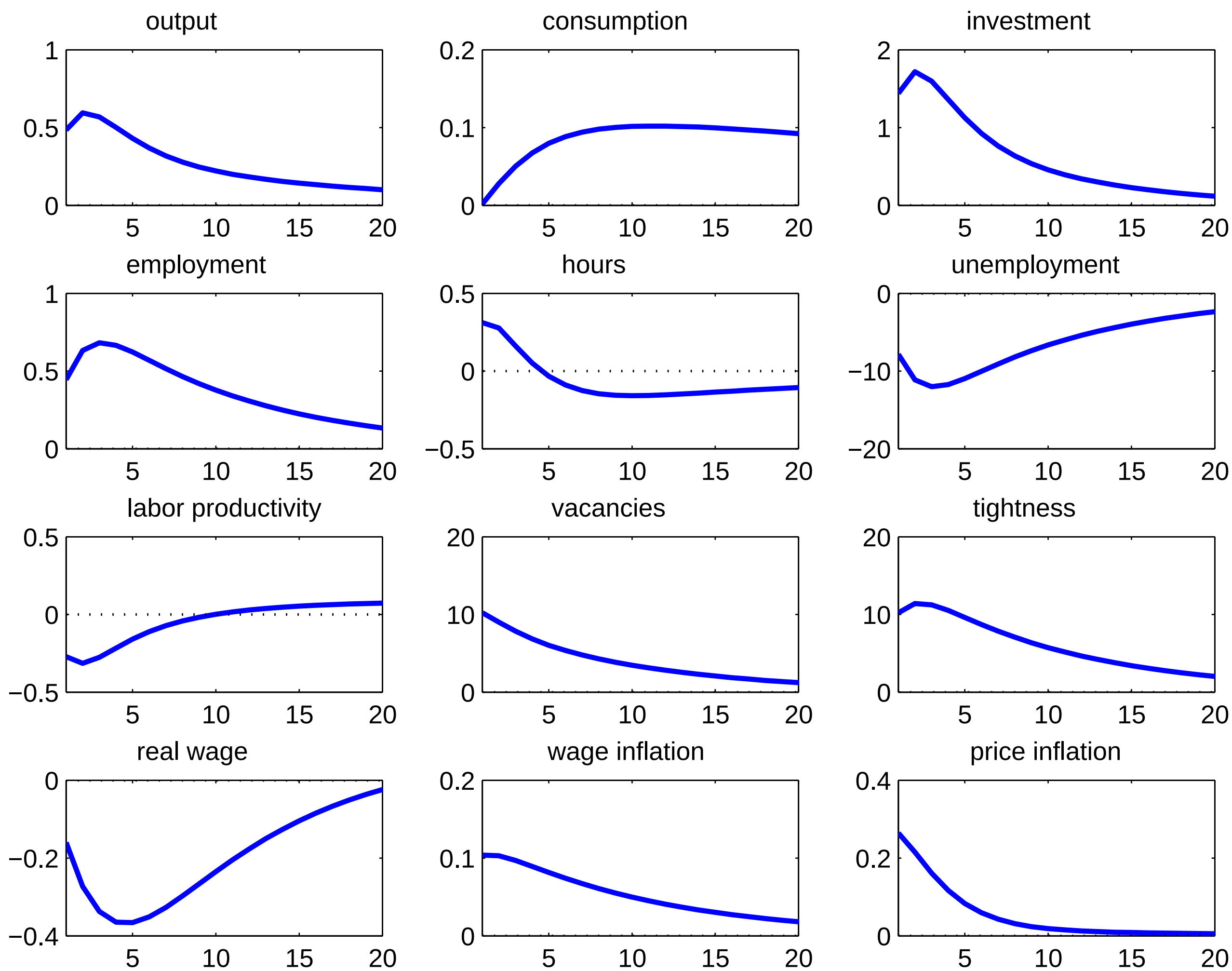

Figure 3: IRFs after a technology and money supply shocks ($\varphi = \{0, 0.6, 1\}$).

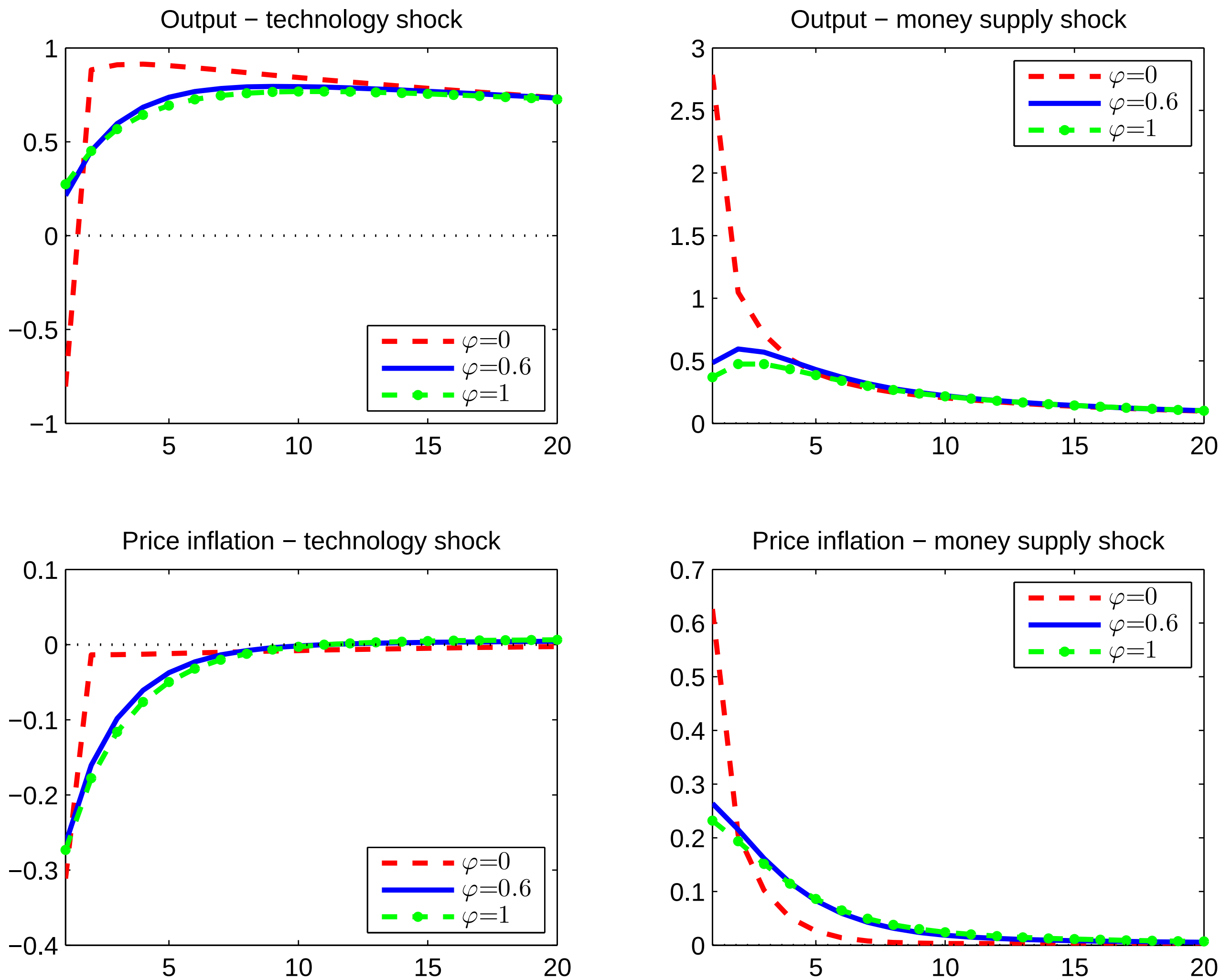

Figure 4: Nominal interest rate responses to a positive money supply shock under alternative setups.

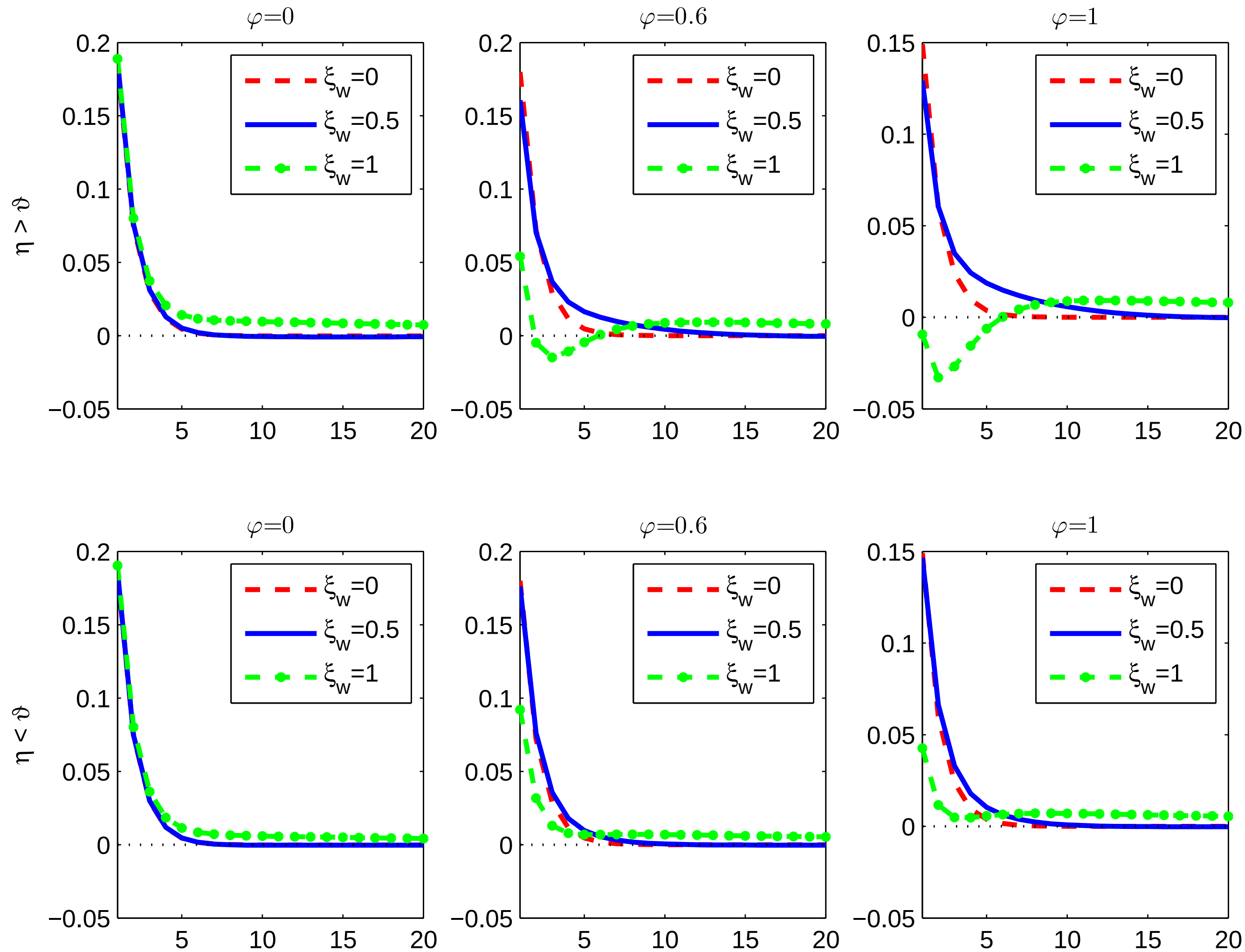

Figure 5: Prior (dash) and posterior (solid) densities of the estimated parameters.