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**Francesco Giuli e Massimiliano Tancioni**

# Firm-Specific Capital, Productivity Shocks and Investment Dynamics

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# Firm-Specific Capital, Productivity Shocks and Investment Dynamics

Francesco Giuli and Massimiliano Tancioni*
Sapienza University of Rome

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**Abstract**

The theoretical literature on business cycles predicts a positive investment response to productivity improvements. In this work we question this prediction from theoretical and empirical standpoints. We first show that a negative short-term response of investment to a positive technology shock is consistent with a plausibly parameterized new Keynesian DSGE model in which capital is firm-specific and monetary policy is not fully accommodative. Employing Bayesian techniques, we then provide evidence that permanent productivity improvements have short-term contractionary effects on investment. Even if this result emerges in both the firm-specific and rental capital specifications, only with the former the estimated average price duration is in line with microeconometric evidence. In the firm-specific capital model, strategic complementarity in price setting leads to a degree of price inertia which is higher than that implied by the frequency at which firms change their prices.

JEL CLASSIFICATION: E32, E22, C11.

KEYWORDS: firm-specific capital, NK-DSGE model, technology shocks, investment dynamics, Bayesian inference.

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## 1 Introduction

The strong and positive covariation between GDP and investment is one of the most uncontroversial stylized facts of macroeconomic dynamics. This empirical regularity is consistent with the RBC view on economic fluctuations, and with the predictions of a broader class of business cycle models pointing at technology shocks as one of the main determinants of the procyclical investment dynamics. In this paper we show, from a theoretical and empirical point of view, that even if the sample correlation between productivity and investment is positive, their conditional correlation is negative.

A recent and vast literature interprets the contractionary effects of productivity improvements as evidence of the fact that technology shocks play only a minor role in business cycle determination. However, existing contributions have mainly focused on the negative short-term response of hours to positive technology shocks (Galì, 1999, 2004; Galì and Rabanal, 2004; Francis and Ramey, 2002, 2005), often referred to as "productivity-employment puzzle". By contrast, the inverted short-term investment response to supply shocks has not been throughly addressed in the literature on business cycles. Despite this evidence being often detectable in the results of influential empirical analyses, it has been mostly overlooked or attributed to a drawback in the empirical methodology[1].

To the best of our knowledge, one major exception is the empirical analysis provided by Basu, Fernald and Kimball (BFK, 2006) who show that, once a "purified" measure of TFP is considered, technology improvements turn out to be contractionary on impact[2]. In particular, they find that the impulse response of labor and investment to a "pure" positive technology shock is negative, statistically significant on impact and quite persistent. According to their analysis, variable inputs utilization and non-constant returns explain most of the procyclicality of the standard Solow residual, while the correlation between their direct measure of technology and inputs is negative. The theoretical explanation suggested by BFK focuses on the role of nominal frictions. Their intuition is that simple sticky price models, differently from frictionless RBC models, are consistent with the finding of contractionary supply shocks. However, they do not provide an analytical model to support their theoretical arguments.

Our paper improves on this literature in two respects: first, by showing that the short-term response of investment to a positive supply shock is negative, we provide further evidence that other sources of fluctuation have to be considered to explain the positive unconditional correlation in the data; second, we provide a theoretical explanation of this evidence employing a formal model, and detail the limitations of BFK's preferred theoretical conclusion.

In the first part of the analysis we develop a monetary DSGE model in which capital is firm-specific (Altig *et al.*, 2005; Woodford, 2005; Sveen and Weinke, 2005, 2007), and confront its predictions with those of a more standard rental capital specification. By simulating these

[1] In King *et al.* (1991) the response of investment to a positive supply shock is negative in the short-term when employing a six variables structural vector error correction model (top right panel in figure 4 on page 834). Francis and Ramey (2002) find a similar result with a five variables SVAR (bottom left panels in figures 2b and 2c on pages 43-44). Uhlig (2006) obtains a negative capital response to technology shocks in its discussion of Francis and Ramey (2005)'s results, but considers this evidence as theoretically unreasonable and potentially due to mis-identification of the technology shocks. Giuli and Tancioni (2009) explicitly address this evidence employing structural vector error correction models.

[2] BFK obtain their direct measure of TFP by controlling for non-technological effects (variable capacity and effort) in the computation of the aggregate Solow residual.

alternative model specifications we show that, under rental capital market, the emergence of the negative investment response to productivity improvements requires either very low degree of monetary policy accommodation[3] and/or a degree of nominal stickiness that is inconsistent with micro-econometric evidence. By contrast, once firm-specific capital is considered, the reverse investment response to technology shocks emerges even with plausible degrees of nominal rigidity and of monetary policy accommodation.

The economic rationale for these results is mostly related to the fact that the new Keynesian Phillips curve (NKPC) characterizing the firm-specific capital specification is flatter than that emerging under rental capital, resulting in a reduced operation of the price adjustment mechanism (Altig *et al.*, 2005; Eichenbaum and Fisher, 2007). Following a positive productivity shock, marginal costs tend to fall, but the presence of strategic complementarity in price setting implies that the reduction in inflation is smaller than in the baseline rental capital model. This leads to a weaker demand expansion and to a reduced use of inputs in production.

In the presence of relevant demand contraints, monetary policy design plays a key role. We assume that monetary authorities adjust the interest rate according to a contemporaneous Taylor rule targeting trend output instead of the theory-consistent potential output. Even if unappealing from a normative point of view, this hypothesis is empirically relevant, as shown by the abundant literature providing evidence that the conduct of monetary policy is not fully accommodative[4].

In the second part of the analysis we provide the empirical evaluation of the firm-specific and rental capital model specifications on US data. To do this, we estimate our NK-DSGE models employing a Bayesian Monte Carlo Markov Chain (MCMC) procedure in the spirit of Fernandez-Villaverde and Rubio-Ramirez (2004), Juillard *et al.* (2008) and Smets and Wouters (2003, 2007). We use unfiltered data in order to preserve the low frequency information and to enhance the comparability of results with those obtained employing structural vector autoregregressions (SVAR) identified with long-run restrictions. Moreover, we assume that the evolution of productivity is approximated by a nonstationary second-order autoregressive process[5]. The choice for such a flexible specification of the technology process is motivated by the need of separating the model-specific dynamics from that potentially originating in a fairly general specification of the stochastic components. In fact, for a particular specification of the stochastic process of productivity, even RBC models can be made consistent with the negative investment response to positive technology shocks, since the dynamic properties of DSGE models depend on both model design (economics) and the chosen autocorrelation structure of shocks[6].

[3] BFK justify their conclusion in favor of a sticky-price explanation on the basis of the results of simulation experiments in which the monetary authority does not accommodate the shock on impact. In fact, their conclusions refer to Kimball (1998), who assumes a fixed money growth commitment, and to Basu (1998), who considers a backward-looking Taylor rule.

[4] Galì *et al.* (2003) show that this has been the case in the pre-Volker period. BFK provide evidence that FED's policy has been not fully accommodative even in the post-Volker period. Moreover, since a reliable measure of potential output is hardly in the information set of policy makers, a rule targeting trend output may result welfare-improving with respect to a rule targeting an incorrect measure of potential output (Orphanides, 2003a, 2003b, 2007).

[5] The hypothesis that productivity evolves following a nonstationary second order process is less restrictive than the random walk hypothesis, since it allows both slow adjustment to long-run equilibrium and short-term overshooting. Altig *et al.*, (2005), Del Negro *et al.* (2005) and Juillard *et al.* (2008), adopt an AR(2) process for TFP.

[6] Lindè (2004) shows that if the positive short-run effect of a technology shock on productivity is lower than its long-run effect,

Even adopting a prior parameterization for which our extended model does not generate the negative conditional correlation between productivity and investment, we obtain posterior estimates that are consistent with this outcome. Posterior impulse responses show that the supply shock leads to a fall in investment and hours under both firm-specific and rental capital specifications. Our results also show that, while with the former the estimated average price duration is of nearly three quarters, with the latter the estimated average price duration is of 10 quarters, an implausibly high value when compared to the available evidence at the firm-level (Bils and Klenow, 2004). Moreover, from Bayesian model comparison we obtain strong evidence in favor of the firm-specific capital specification.

According to our estimates, the negative investment response emerges as a result of model-specific attributes affecting the slope of the NKPC (i.e. the capital share, the degree of price stickiness and demand elasticity) and of the degree of policy accommodation of the shock, while the degree of autocorrelation in productivity growth plays no role.

A major advantage of our structural methodological perspective is that it allows us to support BFK's results through the identification of the theoretical mechanisms that are responsible for the emergence of the contractionary effects of supply shocks. Moreover, our empirical results are potentially more challenging with respect to those provided by the literature on the negative short-term response of hours, since *i*) we focus on the dynamics of the most pro-cyclical macro-variable; *ii*) the critical arguments advanced by the opponents to the "productivity-employment puzzle", basically addressing SVAR identification problems and stochastic specification issues[7], do not apply to our analysis.

The paper proceeds as follows. Section 2 introduces the sticky price/wage model with firm-specific capital. Section 3 compares the dynamic properties of the firm-specific capital model with those obtainable under the rental capital market specification. Section 4 provides the details of the Bayesian MCMC estimate of the model and a discussion of results. Section 5 concludes.

## 2 The model economy

In this section we provide the basic features of a cash-in-advance sticky price/wage NK-DSGE model in which capital is firm-specific and a financial cost channel influences the monetary transmission mechanisms. The model economy is populated by maximizing households, firms and financial intermediaries and is subject to nonstationary productivity shocks giving rise to a common stochastic trend in real variables. Since the model displays balanced growth, long-run stationary ratios among real variables (and between each real variable and productivity) emerge.

The peculiar theoretical features of the model, with respect to the baseline NK-DSGE model, are basically three: *i*) capital accumulation is decided by firms; *ii*) intermediate sector

then a negative short-term effect on hours and investment can be observed. Rotemberg (2003) suggests an explanation based on technological diffusion delays.

[7] Cooley and Dwyer (1998) and Chari *et al.* (2005) show that SVAR-based results may be seriously affected by the use of long-run restrictions in small samples. Cristiano *et al.* (2004) criticizes the results obtained by Galì (1999) and by the following literature on the employment puzzle sustaining that it emerges because of the wrong consideration of nonstationary hours. This critical argument does not apply to the stochastic properties of the investment time series, whose nonstationary behavior is consistent with the balanced growth hypothesis.

firms borrow money to pay their wage bill; *iii*) since productivity shocks are permanent, the model economy evolves around a stochastic growth path.

### 2.1 Households

We consider a continuum of households indexed by $j \in [0,1]$ that have access to a complete set of contingent claims[8]. Each household maximizes the expected present discounted value of a nonseparable CRRA utility over consumption $C_t$ and leisure $(1-H_t)$[9]:

$$E_t \sum_{t=0}^{\infty} \chi_t \beta^t \frac{\{C_t [(1-\xi_t H_t(j))]^{\varphi}\}^{1-\sigma}}{1-\sigma}$$

where $E_t$ is the time $t$ expectation operator, $\beta$ is the discount factor, $\sigma$ defines the inverse intertemporal elasticity of substitution and $\varphi$ is the inverse labor supply Frish elasticity. The terms $\chi_t$ and $\xi_t$ are preference shocks and are assumed to follow the stationary first order autoregressive (AR(1)) processes $\chi_t = \chi_{t-1}^{\rho_\chi} e^{\varepsilon_t^\chi}$ and $\xi_t = \xi_{t-1}^{\rho_\xi} e^{\varepsilon_t^\xi}$, respectively. The first shock can be interpreted as affecting the inter-temporal consumption-savings choice, while the latter affects labor supply. Aggregate consumption $C_t$ is obtained employing the CES aggregator $C_t = \left[\int_0^1 C_t(i)^{\frac{\epsilon-1}{\epsilon}} di\right]^{\frac{\epsilon}{\epsilon-1}}$, where $\epsilon$ denotes the elasticity of substitution among differentiated goods $i$.

From households' cost minimization, the following demand function for each good is obtained:

$$C_t^d(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon} C_t \tag{1}$$

where $P_t = \left[\int_0^1 P_t(i)^{1-\epsilon} di\right]^{\frac{1}{1-\epsilon}}$ is the price index.

#### 2.1.1 Consumption and saving decisions

Each household purchases consumption goods by means of cash holdings net of deposits and labor income. Let $M_t(j)$ be the nominal balance held at the beginning of period $t$ by household $j$, $W_t(j) H_t(j)$ the nominal labor income and $D_t(j)$ the deposit made at the beginning of period $t$. Consumption expenditures are restricted by the cash-in-advance (CIA) constraint $P_t C_t(j) \leq M_t(j) + W_t(j) H_t(j) - D_t(j) + P_t T_t(j)$, where $P_t T_t(j)$ is a government lump-sum net transfer. Household $j$'s budget constraint is thus given by:

$$M_{t+1}(j) + B_{t+1}(j) + D_t(j) = M_t(j) + W_t(j) H_t(j) + \Pi_t + R_t^D D_t(j) + R_t B_t(j) + P_t T_t(j) - P_t C_t \tag{2}$$

[8]Erceg, *et al.* (2000) show that this hypothesis is needed to ensure that in equilibrium households are homogeneous with respect to consumption and asset holdings.

[9]We assume nonseparable utility to obtain offsetting income and substitution effects of wage changes on labor supply (King and Rebelo, 2000). This ensures that the model displays balanced growth.

where $\Pi_t$ denotes aggregate lump-sum profits from the ownership of firms and of financial intermediaries, $B_t(j)$ denotes government bond holdings and $R_t^D$ $(R_t)$ is the gross nominal interest rate on deposits (bonds). Since at the equilibrium the CIA constraint must hold with equality, household's budget constraint resolves to $M_{t+1}(j) = \Pi_t + R_t^D D_t(j) + R_t B_t(j) - B_{t+1}(j)$. By eliminating money holdings from (2) we obtain an alternative expression for the budget constraint:

$$P_t C_t = W_t(j) H_t(j) + \Pi_{t-1} + R_{t-1}^D D_{t-1}(j) - D_t(j) + R_{t-1} B_{t-1}(j) - B_t(j) \tag{3}$$

Note that, since deposits and government bonds are risk-free, the deposit rate $R_t^D$ equals the nominal interest rate set by the monetary authority $R_t$, i.e.: $R_t^D = R_t = (1 + r_t)$. From the first order condition for the representative household optimization problem we obtain the Euler equation:

$$\beta E_t \left\{ \frac{\chi_{t+1}}{\chi_t} \left( \frac{C_{t+1}}{C_t} \right)^{-\sigma} \left[ \frac{(1 - \xi_{t+1} H_{t+1})}{(1 - \xi_t H_t)} \right]^{\varphi(1-\sigma)} \frac{P_t}{P_{t+1}} \right\} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} = R_t^{-1} \tag{4}$$

where $\lambda_t$ in (4) is the time $t$ Lagrange multiplier, and the optimal labor supply equation $mrs_t = \varphi (1 - \xi_t H_t)^{-1} \xi_t C_t = W_t^r$, which relates the real wage to the real marginal rate of substitution between consumption and leisure $mrs_t$. The presence of hours in the Euler equation is due to the hypothesis of nonseparable consumption and labor supply choices.

#### 2.1.2 Labor supply and wage determination

We assume that labor unions differentiate homogeneous labor services supplied by households and offer these services indexed by $l \in [0, 1]$ to intermediate labor packers. Intermediate sector firms employ a composite labor input $H_t$ aggregated by packers (Smets and Wouters, 2007) according to the CES aggregator $H_t = \left[ \int_0^1 H_t(l)^{1-\epsilon_H} dl \right]^{\frac{1}{1-\epsilon_H}}$, where $\epsilon_H$ denotes the elasticity of substitution in the composite labor input. Labor unions are thus monopolistically competitive suppliers of differentiated labor services $H_t(l)$, while packers operate in a perfectly competitive environment. The hypothesis that labor services are homogeneous at the household level guarantees that the labour supply decision is the same for all households. This ensures homogeneity of consumption across households even under non-separable preferences. Packers' first order condition for profit maximization leads to:

$$H_t^d(l) = \left( \frac{W_t(l)}{W_t} \right)^{-\epsilon_H} H_t^d \tag{5}$$

where $W_t = \left[ \int_0^1 W_t(l)^{1-\epsilon_H} dl \right]^{\frac{1}{1-\epsilon_H}}$ is the wage index and $W_t(l)$ is the nominal wage for type-$l$ labor.

The monopolistically competitive labor suppliers set the wage in staggered contracts. Each period only a randomly drawn fraction $(1 - \theta_w)$ can reset the wage, while the fraction $\theta_w$ adjusts the wage mechanically according to long-run productivity growth and to a weighted average (with weights $\iota_w$ and $1 - \iota_w$) of last period's inflation and of steady state inflation:

$$W_t(l) = \gamma_{p,t-1}^{\iota_w} \gamma_p^{(1-\iota_w)} \gamma_z W_{t-1}(l) \tag{6}$$

where $\gamma_z$ denotes the deterministic component in the technology growth process $Z_t$, $\gamma_p$ is steady state inflation and $\gamma_{p,t-1} = P_{t-1}/P_{t-2}$ is last period's inflation. Under wage indexation, the relevant labor demand constraint (5) resolves to:

$$H_{t+k}^d(l) = \left( \frac{W_t(l)\,\Phi_{t,k}}{W_{t+k}} \right)^{-\epsilon_H} H_{t+k}^d \tag{7}$$

where $\Phi_{t,k}^w = 1$ for $k = 0$ and $\Phi_{t,k}^w = \prod_{f=1}^k \gamma_{p,t+f-1}^{\iota_w} \gamma_p^{(1-\iota_w)} \gamma_z$ for $k > 0$.

The wage mark-up stemming from monopoly power is distributed to households. Their utility is maximized when unions maximize the difference between the newly set wage $W_t(l)$ and the marginal rate of substitution, subject to the type-$l$ labor demand schedule (7). The maximization problem thus takes the form:

$$\max_{W_t^*(l)} \sum_{k=0}^{\infty} (\theta_w \beta)^k E_t \left\{ \frac{\lambda_{t+k}}{\lambda_t} \frac{P_{t+k}}{P_t} H_{t+k}^d(l) \left[ \frac{\Phi_{t,k}^w W_t(l)}{P_{t+k}} - mrs_{t+k} \right] \right\} \tag{8}$$

resulting in the following first order condition:

$$\sum_{k=0}^{\infty} (\theta_w \beta)^k E_t \left\{ \frac{\lambda_{t+k}}{\lambda_t} \frac{P_{t+k}}{P_t} H_{t+k}^d(l) \left[ \frac{\Phi_{t,k}^w W_t^*(l)}{P_{t+k}} - \frac{\epsilon_H}{\epsilon_H - 1} mrs_{t+k} \right] \right\} = 0 \tag{9}$$

Finally, considering the Calvo-scheme and the wage indexation rule, the aggregate wage equation is obtained:

$$W_t = \left\{ (1-\theta_w) W_t^{*(\epsilon_H - 1)} + \theta_w \left[ \gamma_{p,t-1}^{\iota_w} \gamma_p^{(1-\iota_w)} \gamma_z W_{t-1} \right]^{(\epsilon_H - 1)} \right\}^{\frac{1}{\epsilon_H - 1}} \tag{10}$$

## 2.2 Firms

### 2.2.1 The competitive final goods sector

Each period $t$ a homogeneous final consumption good is produced by firms operating in a perfectly competitive environment. Production requires only intermediate (differentiated) commodities $Y_t(i)$ indexed by $i \in [0,1]$, that are combined employing the CES technology $Y_t = \left[ \int (Y_t(i))^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}$.

Each final sector firm takes input prices as given and maximizes its profits $\Pi_t = P_t Y_t - \int P_t(i) Y_t(i)\, di$ considering the final goods production technology. The first order condition and the free-entry assumption lead to the following demand schedule for intermediate goods:

$$Y_t^d(i) = \left( \frac{P_t(i)}{P_t} \right)^{-\epsilon} Y_t^d \tag{11}$$

where $Y_t^d$ is aggregate demand.

#### 2.2.2 The intermediate goods sector

Each period $t$ a continuum of monopolistically competitive firms indexed on the unit interval maximizes the present value of their future dividend stream by combining the owned capital stock $K_{t-1}(i)$ with hired labor services $H_t(i)$ in a Cobb-Douglas production function:

$$Y_t(i) = K_{t-1}(i)^{\alpha} \left(Z_t H_t(i)\right)^{1-\alpha} \tag{12}$$

where $Z_t$ is a stochastic process defining the evolution of the labor-augmenting technology level. We assume a fairly general specification for $Z_t$, i.e. a trending nonstationary AR(2) process $Z_t = Z_{t-1}\gamma_{z,t}$, where $\gamma_{z,t} = \gamma_z^{(1-\rho_z)} \gamma_{z,t-1}^{\rho_z} e^{\varepsilon_t^z}$, $\gamma_z$ defines the deterministic trend component (the constant growth rate) and $\varepsilon_t^z$ is the i.i.d. technology shock[10].

Each firm $i$ rents labor services from the households and makes an investment decision at any point in time. We assume that the firm borrows funds $W_t(i) H_t(i)$ at the nominal interest rate $R_t^L = 1 + r_t^L$ from the financial intermediary to pay its wage bill and pays back $R_t^L W_t(i) H_t(i)$ at the end of the period. The firm changes its price according to a random duration Calvo scheme.

Firm-owned capital becomes productive with one period lag, is subject to convex capital adjustment costs and evolves according to the following law of motion:

$$I_t(i) = \zeta_t I\left(\frac{K_t(i)}{K_{t-1}(i)}\right) K_{t-1}(i) \tag{13}$$

The investment function $I(.)$ is increasing and convex, with steady state value $I(1) = \delta + \gamma_z - 1$ and derivatives $I'(1) = 1$ and $I''(1) = \epsilon_\psi$. The parameter $\delta$ is the rate of capital depreciation, $\epsilon_\psi > 0$ denotes the degree of capital adjustment costs and $\zeta_t$ is a shock to the capital adjustment cost function, which is assumed to follow the stationary AR(1) process $\zeta_t = \zeta_{t-1}^{\rho_\zeta} e^{\varepsilon_t^\zeta}$.

Given the capital stock inherited from the previous period $K_{t-1}(i)$, each firm $i$ chooses a time contingent plan for $\{H_{t+k}(i),\ K_{t+k}(i)\}_{k=0}^{\infty}$ and reoptimizes its price $P_{t+k}(i)$ with a constant probability $(1-\theta_p)$, while with probability $\theta_p$ it adjusts its price mechanically according to a weighted average (with weights $\iota_p$ and $1-\iota_p$) of last period and steady state inflation:

$$P_t(j) = \gamma_{p,t-1}^{\iota_p} \gamma_p^{(1-\iota_p)} P_{t-1}(j) \tag{14}$$

Taking into account the dynamic indexation equation (14) and the Calvo-scheme, the profit maximization problem can be written as follows:

$$\underset{H_{t+k}(i),\ K_{t+k}(i),\ P_{t+k}^*(i)}{\text{Max}} \Pi_{t,h} = \sum_{k=0}^{\infty} \beta^k E_t \left\{ \frac{\lambda_{t+k}}{\lambda_t} \left[ Y_{t+k}(i)^d P_{t+k}(i) - R_{t+k}^L W_{t+k}(i) H_{t+k}(i) - P_{t+k} I_{t+k}(i) \right] \right\}$$

$$\text{s.t. } P_{t+k+1}(i) = \left\{ \begin{array}{ll} P_{t+k+1}^*(i) & \text{with probability } (1-\theta_p) \\ P_{t+k+1}(i) = \gamma_{p,t+k}^{\iota_p} \gamma_p^{(1-\iota_p)} P_{t+k}(i) & \text{with probability } \theta_p \end{array} \right\},$$

and (11), (12), (13).

[10] This specification implies the pure random walk and the random walk with drift processes as special cases, for $[\gamma_z = 1,\ \rho_z = 0]$ and $\rho_z = 0$, respectively.

By solving the problem with respect to $P_{t+k}^{*}(i)$, the usual price setting equation is obtained:

$$\sum_{k=0}^{\infty}(\beta\theta_p)^k E_t\left\{\frac{\lambda_{t+k}}{\lambda_t}Y_{t+k}(i)\left[P_t^{*}(i)\,\Phi_{t,k}^{P}-\frac{\epsilon}{\epsilon-1}MC_{t+k}(i)\right]\right\}=0 \tag{15}$$

where $\Phi_{t,k}^{P}=1$ for $k=0$ and $\Phi_{t,k}^{P}=\prod_{f=1}^{k}\gamma_{p,t+f-1}^{\iota_p}\gamma_p^{(1-\iota_p)}$ for $k>0$. The term $MC_t(i)$ denotes the marginal cost $MC_t(i)=\frac{R_t^L W_t(i)}{(1-\alpha)\left(\frac{K_{t-1}(i)}{Z_t H_t(i)}\right)^{\alpha}}$.

This equation establishes that firms set their prices according to a mark-up over their expected marginal cost, taking into account the forward probabilities of not being allowed to change price again. The Calvo-scheme implies the following aggregate price equation:

$$P_t=\left\{(1-\theta_p)\,P_t^{*(\epsilon-1)}+\theta_p\left[\gamma_{p,t-1}^{\iota_p}\gamma_p^{(1-\iota_p)}P_{t-1}\right]^{(\epsilon-1)}\right\}^{\frac{1}{\epsilon-1}} \tag{16}$$

By solving the maximization problem with respect to $K_{t+k}(i)$, the following first order condition for capital accumulation is obtained:

$$\zeta_t\frac{dI_t(i)}{dK_t(i)}P_t=\beta E_t\left\{\frac{\lambda_{t+1}}{\lambda_t}\left[MS_{t+1}(i)-\zeta_{t+1}\frac{dI_{t+1}(i)}{dK_t(i)}P_{t+1}\right]\right\}=0 \tag{17}$$

where $MS_t(i)=R_t^L W_t\frac{\alpha}{(1-\alpha)}\frac{Z_t H_t(i)}{K_{t-1}(i)}$ is the marginal return of the firm-specific capital expressed in terms of marginal savings in labor costs.

Firm-specificity is evident in the fact that the marginal saving and the marginal cost are firm-specific. An important implication of the firm-specific capital hypothesis is that reoptimizing firms choose different prices, since their marginal costs are affected by past decisions on accumulation and price setting (Woodford, 2005).

The optimal investment equation under rental capital market can be obtained by replacing the firm-specific marginal saving $MS_t(i)$ in (17) with the expression for marginal returns to capital, that are common to all firms (Sveen and Weinke, 2005). We shall return on the different implications of the firm-specific and rental capital assumptions when analyzing the dynamic properties of the models in Section 3.

### 2.3 Financial intermediaries and interest rate spread

Each period $t$ a continuum of perfectly competitive financial intermediaries indexed on the unit interval receives deposits $D_t$ from the households and supply loans $L_t$ to firms at the nominal interest rate $R_t^L$ for anticipated wage payments $W_t H_t$. At the end of each period the credit sector pays back the interest-augmented initial deposit $R_t^D D_t$ and ownership profits to households. Each financial intermediary maximize its profit function $\hat{\Pi}_t^{FI}=R_t^L\hat{L}_t-R_t^D\hat{D}_t$, subject to the credit demand constraint $L_t=F_t D_t$, where $F_t=F_0\left(\frac{R_t^L}{\left(R_{t-1}^L\right)^{\rho_{rL}}}\right)^{\nu}$, $\nu\geq 0$, is an intermediation cost function, which depends on changes in the lending rate. The demand constraint defines the amount of loans that the financial intermediary can create from a given amount of deposits $D_t$. By log-linearizing the first order condition for profit maximization a relation between the interest rate on loans and the risk-free (deposit) interest rate is obtained[11]:

$$r_t^L = \frac{1}{1+\nu} r_t^D + \rho_{r^L} \frac{\nu}{1+\nu} r_{t-1}^L + \log \Upsilon_t \tag{18}$$

where the size of the autocorrelation coefficient $\rho_{r^L}$ defines the degree of smoothness in lending rate adjustments and $\log \Upsilon$ is the log-linear representation of a stochastic disturbance term, which is assumed to be white noise around a non zero constant term, i.e. $\Upsilon_t = \gamma_{r^L} e^{\varepsilon_t^{\Upsilon}}$. The deterministic component $\gamma_{r^L}$ captures the non zero mean interest rate spread found in the data. When $\nu = 0$ the interest rate on loans equals the risk-free (deposit) rate. In such a case, the economic interpretation of the financial sector is straightforward and fully equivalent to that provided in the analyses of Ravenna and Walsh (2006).

The emergence of a financial cost channel in the monetary policy transmission mechanism implies that, since monetary authorities (partly) accommodate the supply shock by reducing the interest rate, labor hire may become cheaper than capital self-financing. This, other things being equal, can stimulate less capital-intensive production technologies.

## 2.4 Public sector and market equilibrium conditions

Monetary authorities are assumed to set the nominal interest rate $R_t \equiv 1 + r_t$ according to a contemporaneous rule satisfying the Taylor principle for stability. The empirical rule considers the inflation deviation from a non zero-mean policy target $\gamma_p$ and the output growth deviation from the deterministic rate of growth $\gamma_z$. The policy instrument is adjusted gradually, giving rise to interest rate smoothing:

$$R_t = R_{t-1}^{\rho_r} \left[ \overline{R^r} \gamma_p \left( \frac{\gamma_{p,t}}{\gamma_p} \right)^{\phi_\pi} \right]^{1-\rho_r} \left( \frac{Y_t / Y_{t-1}}{\gamma_z} \right)^{\phi_{\Delta y}} \mu_t \tag{19}$$

where $\overline{R^r} = 1/\beta \gamma_z^{-\sigma}$ and $\rho_r$ defines the degree of interest rate smoothing. Note that the constant policy target $\gamma_p$ determines steady state inflation. The stochastic term $\mu_t$ denotes the monetary policy shock, which is assumed follow the AR(1) process $\mu_t = \mu_t^{\rho_\mu} e^{\varepsilon_t^\mu}$.

Like money-growth rules, the implementation of such a policy rule does not require the knowledge of the natural rate of interest or of the level of potential output (both unobserved). The hypothesis that the central bank targets trend output instead of the output that would have prevailed in the absence of nominal rigidities has been adopted in the empirical DSGE literature (e.g. Adolfson *et al.*, 2007) and turns out consistent with the main objective of our analysis, which is basically empirical[12]. We will further discuss the justifications and implications of the chosen policy rule when discussing model dynamics in Section 3.

[11] A recent literature suggests several ways of modelling the credit sector (see e.g, Bernanke and Gertler, 1995; Christiano *et al.* 2005; Goodfriend and McCallum, 2007). However, the derivation of a specific microfoundation of banks' behavior is out of the scope of our analysis, which only requires the representation of a financial cost channel with interest rate smoothing. For this reason we follow the simple approach provided by Kaufmann and Scharler (2009).

[12] Note that there is no consensus about the appropriate output gap measure under firm-specific capital. When capital is endogenous, at least two alternative concepts of potential output emerge: the first is defined with respect to the level of output that would prevail if current and future prices were flexible (Woodford, 2005); the second is defined by taking into account the potential output that would have been obtained if prices had also been flexible in the past (Neiss and Nelson, 2003).

The fiscal authority levies lump-sum taxes and provides lump-sum transfers to households ensuring public sector solvency, i.e., ensuring that $\lim_{k\to\infty} = (B_{t+k} + M_{t+k}) \prod_{h=1}^{k} (1 + r_{t+h})^{-1} = 0$. The additional assumption of zero net government bond supply holds. Under these assumptions, non Ricardian fiscal policy effects are ruled out. The budget constraint for the public sector is thus given by $M_{t+1} - M_t + B_{t+1} - R_t B_t + G_t = P_t T_t$, where $G_t$ denotes public expenditure. Labor and goods market equilibrium is satisfied when demand equals supply for each variety of labor $j$ and of commodities $i$. By plugging net government transfers and households' ownership profits in the households budget constraint and integrating across household, equilibrium in all markets implies:

$$Y_t = C_t + I_t + G_t \tag{20}$$

where $I_t = \int I_t(i)\,di$ is aggregate investment. The term $I_t(i)$ denotes firm $i$'s demand of the composite investment good, which is aggregated in the same proportion of the consumption index. Moreover, by defining aggregate capital for all $t$ as $K_t = \displaystyle\int K_t(i)\,di$ and the auxiliary variable $\breve{Y}_t = (Z_t H_t)^{1-\alpha} K_t^{\alpha}$, it is easy to verify that the difference between $Y_t$ and $\breve{Y}_t$ is of second order and thus it can be ignored in the log-linear approximation.

### 2.5 The (stationary) linearized model and the NK Phillips Curve

Since the nonstationary technology process induces a stochastic trend in real variables, before log-linearizing the model we have to express it in terms of detrended variables, i.e. we have to derive the stationary representation of the model. Stationarity is obtained by imposing the following transformations:

$$Y_t = \hat{Y}_t Z_t, \quad C_t = \hat{C}_t Z_t, \quad I_t = \hat{I}_t Z_t, \quad K_t = \hat{K}_t Z_t, \quad \frac{W_t}{P_t} = \hat{W}_t^r Z_t$$

where the "hat" superscript indicates that level variables are expressed in terms of stationary ratios[13].

The scaled model is then log-linearized around the steady state, taking into account that the presence of a deterministic term in the productivity growth process (the steady state balanced growth term $\gamma_z$) affects the coefficients of the dynamic equations.

The economic system is composed of four equations obtained by log-linearizing the first order conditions (4), (17), (15) taking into account (16), and (9) taking into account (**??**), and of five equations obtained by log-linearizing (12), (13), (19) and (20) and by considering the interest rate pass-through equation (18). Finally, other 9 equations are obtained by log-linearizing the stochastic processes that drive model dynamics. Leaving out the stochastic processes, the complete system of log-linear equations in stationary form is the following:

[13] A detailed analytical derivation of the stationary model is provided in the technical appendix, available upon request from the authors.

$$\hat{c}_t = E_t\left(\hat{c}_{t+1} + \log\gamma_{z,t+1} - \log\gamma_z\right) + \varphi\frac{H}{1-H}\frac{1-\sigma}{\sigma}\left(h_{t+1} - h_t\right) - \frac{1}{\sigma}\left(r_t - E_t\pi_{t+1} - \rho\right) + \\ + \varphi\frac{H}{1-H}\frac{1-\sigma}{\sigma}E_t\left(\Delta\log\xi_{t+1}\right) - \frac{1}{\sigma}E_t\left(\Delta\log\chi_{t+1}\right) \tag{22.1}$$

$$\hat{k}_t = \frac{1}{\left(1+\beta\gamma_z^{1-\sigma}\right)}\hat{k}_{t-1} + \frac{\beta\gamma_z^{1-\sigma}}{\left(1+\beta\gamma_z^{1-\sigma}\right)}E_t\hat{k}_{t+1} + \\ + \frac{1-\beta\gamma_z^{-\sigma}\left(1-\delta\right)}{\epsilon_\psi\gamma_z\left(1+\beta\gamma_z^{1-\sigma}\right)}\left[E_t\left(r_{t+1}^L + \hat{w}_{t+1}^r + h_{t+1} + \log\gamma_{z,t+1} - \log\gamma_z\right) - \hat{k}_t\right] + \\ - \frac{1}{\epsilon_\psi\gamma_z\left(1+\beta\gamma_z^{1-\sigma}\right)}\left(r_t - E_t\pi_{t+1} - \rho\right) - \frac{1}{\left(1+\beta\gamma_z^{1-\sigma}\right)}\left(\log\gamma_{z,t} - \log\gamma_z\right) + \\ + \frac{\beta\gamma_z^{1-\sigma}}{\left(1+\beta\gamma_z^{1-\sigma}\right)}\left(\log\gamma_{z,t+1} - \log\gamma_z\right) + \frac{1}{\epsilon_\psi\gamma_z\left(1+\beta\gamma_z^{1-\sigma}\right)}\left[\beta\gamma_z^{-\sigma}\left(1-\delta\right)E_t\log\zeta_{t+1} - \log\zeta_t\right] \tag{22.2}$$

$$\pi_t = \iota_p\pi_{t-1} + \beta\gamma_z^{1-\sigma}E_t\left(\pi_{t+1} - \iota_p\pi_t\right) + \kappa\left(r_t^L + \hat{w}_t^r - \hat{y}_t + h_t\right) + \log u_t^\pi \tag{22.3}$$

$$\hat{\pi}_{w,t} = \beta\gamma_z^{1-\sigma}E_t\left[\hat{\pi}_{w,t+1} + \left(\pi_{t+1} - \iota_w\pi_t\right) + \log\gamma_{z,t+1} - \log\gamma_z\right] - \left(\log\gamma_{z,t} - \log\gamma_z\right) - \left(\pi_t - \iota_w\pi_{t-1}\right) + \\ + \frac{\left(1-\beta\gamma_z^{1-\sigma}\theta_w\right)\left(1-\theta_w\right)}{\theta_w}\left(\frac{H}{1-H}h_t + \widehat{c}_t - \hat{w}_t^r + \frac{1}{1-H}\xi_t\right) + \log u_t^{\pi_w} \tag{22.4}$$

$$\hat{y}_t = \alpha\hat{k}_{t-1} + \left(1-\alpha\right)h_t + \alpha\left(\log\gamma_{z,t} - \log\gamma_z\right) \tag{22.5}$$

$$\gamma_z\hat{k}_t = \left(\delta + \gamma_z - 1\right)\hat{\imath}_t + (1-\delta)\hat{k}_{t-1} + \left(\delta - 1\right)\left(\log\gamma_{z,t} - \log\gamma_z\right) \tag{22.6}$$

$$r_t = \rho_r r_{t-1} + \left(1-\rho_r\right)\left[-\log\left(\beta\right) + \sigma\log\gamma_z + \log\gamma_p + \phi_\pi\left(\pi_t - \log\gamma_p\right)\right] + \\ + \phi_{\Delta y}\left(\Delta y_t - \log\gamma_z\right) + \log\mu_t \tag{22.7}$$

$$\hat{y}_t = \left(1 - \lambda_I - \lambda_G\right)\hat{c}_t + \lambda_I\hat{\imath}_t + \lambda_G\log u_t^{me} \tag{22.8}$$

$$r_t^L = \frac{1}{1+\nu}r_t + \rho_{r^L}\frac{\nu}{1+\nu}r_{t-1}^L + \log\Upsilon_t \tag{22.9}$$

where lower-case letters denote log-deviations from the steady-state. For a comparison with the nonlinear specification of the model, consider that $\rho = \log\overline{R^r}$, $\pi_t = \log\gamma_{p,t}$, $\hat{\pi}_{w,t} = \hat{w}_t^r - \hat{w}_{t-1}^r$ and $\Delta y_t = \Delta\hat{y}_t + \log\gamma_{z,t}$. The coefficient $\lambda_I = \frac{\alpha(\delta+\gamma_z-1)}{\frac{\epsilon}{\epsilon-1}\gamma_z(\rho+\delta)}$ is the steady state investment to output ratio, while $\lambda_G$ is the steady state government expenditure to output ratio. The term $\log u_t^{me}$ is an AR(1) measurement error capturing the evolution of public expenditure and other exogenous components affecting the aggregate resource constraint. To account for the relevant changes in US net exports, we follow Smets and Wouters (2007) and assume that exogenous expenditure is also affected by the technology shock, i.e. $\log u_t^{me} = \rho_{me}\log u_{t-1}^{me} + \varepsilon_t^{me} + \rho_{z,me}\varepsilon_t^z$. The terms $\log u_t^\pi$ and $\log u_t^{\pi_w}$ are AR(1) measurement error processes ($\log u_t^\pi = \rho_\pi\log u_{t-1}^\pi + \varepsilon_t^\pi$, $\log u_t^w = \rho_w\log u_{t-1}^w + \varepsilon_t^w$), which are imposed to overcome the stochastic singularity of the model at the estimation stage[14]. The choice of allowing for serially correlated errors has two potential advantages: first, it should enhance the ability of the model of tracking the autocorrelated structure of the data; second, it should allow us to disentangle the role of the

[14] The empirical literature often suggests an interpretation in terms of cost-push shocks or in terms of disturbances affecting the mark-up in labor and goods markets.

economic model from that of the stochastic components in addressing the persistence in the data (Ireland, 2004).

The coefficient $\kappa$ determines the slope of the NKPC. Its computation is not straightforward and can only be obtained with the method of undetermined coefficients[15]. However, since the convolution of structural parameters $\kappa = \frac{(1-\beta\theta_p)(1-\theta_p)}{\theta_p}\frac{1-\alpha}{1-\alpha+\alpha\epsilon}$ provides a satisfying approximation of the NKPC slope coefficient under firm-specific capital (Sveen and Weinke, 2004; 2005), we will adopt this formulation at the estimation stage. This choice allows the estimation of the NKPC slope coefficient in its structural form expression, enhancing parameters identification and the economic interpretability of results.

### 2.6 Firm-specific v. rental capital market: main implications

The sole difference between the log-linear representation of the firm-specific and rental capital models concerns the slope of the NKPC. Under rental capital hypothesis, the NKPC slope coefficient has a standard expression in terms of the Calvo-parameter $\theta_p$ and of the discount factor $\beta\gamma_z^{1-\sigma}$, i.e. $\kappa = \frac{\left(1-\beta\gamma_z^{1-\sigma}\theta_p\right)(1-\theta_p)}{\theta_p}$. Considering Sveen and Weinke's (2004, 2005) approximation, the only difference characterizing the firm-specific capital model NKPC from that implied by the rental capital model is the presence of the multiplicative term $\frac{1-\alpha}{1-\alpha+\alpha\epsilon}$. Note that this term reduces the slope of the curve for any plausible parameterization of the model. This apparently minor difference provides a key distinction in terms of model properties, as it implies a flatter NKPC resulting in a reduced price sensitivity to changes in the marginal cost. This implies that, other things being equal, the firm-specific capital model is characterized by a slower operation of the price adjustment mechanism. Table 1 below, for $\beta = 0.998$, $\gamma_z = 1.005$ and $\sigma = 2$, provides an appreciation of such a reduction, as captured by the size of the reduced-form NKPC slope coefficient resulting from different degrees of nominal stickiness (defined by the Calvo parameter $\theta_p$) and of demand elasticity $\epsilon$. The last row of Table 1 provides the NKPC slope coefficient implied by different values of $\theta_p$ in the rental capital ($RK$) model.

Table 1 - The NKPC slope coefficient

| | $\theta_p$ | | | | | |
|---|---|---|---|---|---|---|
| $\epsilon$ | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
| 6 | 0.207 | 0.115 | 0.062 | 0.030 | 0.012 | 0.003 |
| 11 | 0.126 | 0.070 | 0.037 | 0.018 | 0.007 | 0.002 |
| 21 | 0.071 | 0.039 | 0.021 | 0.010 | 0.004 | 0.001 |
| 41 | 0.038 | 0.021 | 0.011 | 0.005 | 0.002 | 0.000 |
| $RK$ | 0.904 | 0.503 | 0.269 | 0.131 | 0.051 | 0.012 |

Note: $\theta_p$: degree of nominal rigidity; $\epsilon$: demand elasticity parameter

The inflation response is decreasing in the elasticity parameter $\epsilon$ because firm's marginal costs depend on the level of output (since capital is predetermined), which in turn depends on the demand elasticity to price changes. This implies that, when making their pricing

[15] A description of the procedure to derive $\kappa$ with the method of undetermined coefficients can be found in Altig *et al.* (2004) and Christiano (2004) in a simpler model.

decisions, firms face a trade-off between the expected effects on demand and the expected effects on marginal costs, with the latter moving in the opposite direction of the price change. The higher the elasticity of demand (i.e. the lower the degree of monopolistic competition in the economy), the lower the incentive to change prices.

# 3 Supply shocks and investment dynamics

In this section we provide an evaluation of the investment dynamics implied by the theoretical model, based on the short-term impulse response of investment to a positive technology shock. The analysis focuses on the relevance of the size of the NKPC slope coefficient and of the degree of monetary policy accommodation (defined by the Taylor rule parameters $\phi_\pi$ and $\phi_{\Delta y}$) for the conditional investment dynamics, in both the firm-specific and rental capital specifications.

We assume complete dynamic indexation (i.e. $\iota_p = \iota_w = 1$), a degree of nominal wage stickiness $\theta_w = 0.5$ and fix to zero the financial intermediation cost parameter $\nu$, i.e. we assume that there are no financial market imperfections, such that the interest rate on loans equals the risk-free deposit rate. In order to isolate the model-specific dynamics from that potentially arising from the AR(2) specification of the process characterizing the evolution of the technology level $Z_t$, we assume no autocorrelation in growth rates, that is $\rho_z = 0$. For the remaining parameters we employ a standard calibration, which mirrors the priors adopted for the Bayesian estimation of the model, whose details and results will be discussed in section 4 (see Table 2).

## 3.1 Nominal rigidities, strategic complementarity and the inverted investment response

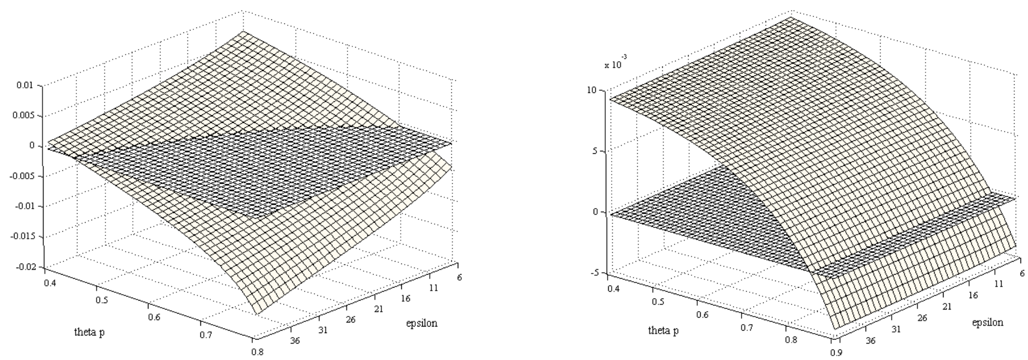
Figure 1 reports the four-quarters average investment response (vertical scale) to a one percent standard deviation supply shock, for different degrees of price stickiness (left horizontal scale) and of demand elasticity (right horizontal scale). The simulation considers a standard parameterization for the monetary policy reaction rule, i.e. $\phi_\pi = 1.5$ and $\phi_{\Delta y} = 0.2$.

The negative short-term investment response may emerge under both model specifications. However, under rental capital market it is only observed for a very high degree of price rigidity (i.e. for values above 0.85). In this case the role played by the demand elasticity parameter $\epsilon$ is negligible, since it does not affect the NKPC slope coefficient. This result provides a first indication that BFK's conclusion that standard NK monetary models can account for the contractionary effects of supply shocks is not fully legitimate, since the required degree of nominal rigidity is inconsistent with the available econometric evidence on average price duration[16]. By contrast, under firm-specific capital the reverse investment response to supply shocks emerges for degrees of price rigidity that are consistent with firm-level evidence of price reoptimization, and for reasonable values of the demand elasticity parameter. The degree of price rigidity which is needed to observe the inverted investment response is decreasing in

[16] The average price duration implied by Calvo parameter values higher than 0.85 is above 6.6 quarters. Even if a number of macroeconometric studies on U.S. data report an high average duration of price fixity (Galì and Gertler, 1999 and Eichenbaum and Fisher, 2004 obtain average durations of nearly six quarters), results from microeconometric studies indicate lower degrees of price rigidity. Bils and Klenow (2004) analyze firm-level data and report an average price duration of roughly two quarters.

the demand elasticity parameter: when $\epsilon = 11$, a value consistent with a 10% mark-up, the threshold $\theta_p$ is approximately 0.6. When $\epsilon = 21$ (consistent with a 5% mark-up), the reverse investment response emerges even with a Calvo parameter value of 0.52, which implies a price duration of roughly two quarters.

Figure 1 - Average four quarters investment response to a technology shock: for different degrees of nominal rigidity and demand elasticity




*a*: Firm-specific capital model | *b*: Rental capital model

Note: the parameter $\theta_p$ defines the degree of nominal rigidity; the parameter $\epsilon$ denotes demand elasticity

The key point is thus the flatter NKPC emerging under firm-specific capital hypothesis. With this assumption at work, firms' marginal costs are increasing with their own output, which in turn depends on demand elasticity. This implies that reoptimizing firms facing a positive supply shock are induced to cut their prices by a smaller amount than in the rental capital model, since they anticipate that price reductions eventually lead to higher marginal costs due to increased demand and output. This leads to a weaker demand response that constrains the use of inputs in production. The incentive for a price reduction implied by a productivity improvement is decreasing in the degree of elasticity of demand. The elasticity parameter $\epsilon$ thus defines the degree of strategic complementarity affecting firms' pricing behavior.

It is worth mentioning that, according to our calibrations, the supply shock is still expansionary for consumption and output, even when it induces a negative short-term response of hours and investment. This is due to the wealth effect of the permanent improvement in productivity. Moreover, by specifying the technology process such that the impact effect of a positive technology shock on productivity is lower than its long-run effect - i.e. by fixing the coefficient $\rho_z$ above zero - we obtain even stronger short-term reductions in the use of inputs, since they are expected to become more productive in the future, when the technology level reaches its long-run potential[17].

### 3.2 The role of the degree of monetary policy accommodation

Figure 2 shows the four-quarters average investment response (vertical scale) to a one percent standard deviation shock, for different degrees of monetary policy accommodation, as defined

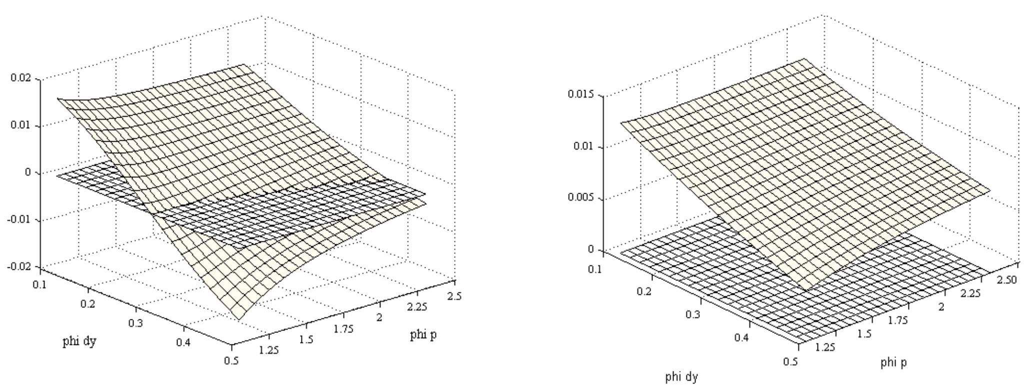
[17] This is basically the reason behind the result that news about *future* TFP may result contractionary even assuming a frictionless model economy (Danthine *et al.*, 1998; Beaudry and Portier, 2007).

by the Taylor rule coefficients $\phi_\pi$ and $\phi_{\Delta y}$. We consider an average price duration of two quarters ($\theta_p = 0.5$), an average price mark-up of 5% (i.e. $\epsilon = 21$) and a degree of interest rate smoothness $\rho_r = 0.6$.

The main result is that the negative investment response is not observed under rental capital while under firm-specific capital it emerges even considering reasonable degrees of policy activism. With $\phi_\pi = 1.5$, the inverted short-term investment response emerges when the policy response to output growth (i.e. $\phi_{\Delta y}$) is above 0.25. The threshold value for $\phi_{\Delta y}$ increases with the degree of policy activism with respect to inflation and is decreasing in the degree of interest rate smoothness.

Since we have ruled out the effects of expected increases in the productivity level (i.e. $\rho_z = 0$), the fundamental factor explaining the investment dynamics is the weak demand response. Central bank's behavior thus plays a key role: when a technology shock hits the economy, the degree to which real activity follows its natural level depends on nominal interest and price adjustments, jointly determining the real interest rate. We have seen that under firm-specific capital the incentive to cut prices perceived by the firm is countervailed by the expectation for higher marginal costs, which are increasing in demand and output. Other things being equal, the emergence of this trade-off implies that a given Taylor rule is less accommodative in the firm-specific capital model than in the rental capital model.

Figure 2 - Investment response to a technology shock:
for different values of the policy rule coefficients




*a*: Firm-specific capital model *b*: Rental capital model

Note:$\phi_\pi$: MP response to inflation deviations from the policy target; $\phi_{dy}$ MP response to output deviations from trend growth

We are aware of the fact that a policy rule targeting potential output would make the negative investment response less likely, while a policy rule targeting the long-term growth rate implies that authorities might underestimate the actual growth rate of natural output, resulting in a not fully accommodative interest rate response. However, there are at least three reasons justifying our choice for an empirical rule: first, since our interest is mainly empirical, the chosen policy rule should be consistent with both the standard and the inverted investment response for a reasonable parameterization of the model. Second, a rule targeting the theory-based output gap requires perfect knowledge of the natural level of output, which is - by definition - unobservable. In other terms, we have to consider how policy makers - in real life operations - form their opinions about the natural level of output, which is hardly in monetary authorities' information set. For this reason, an output gap targeting can result inferior to one responding to output deviations from trend (Orphanides, 2003a, 2003b, 2007; Del Negro *et al.*, 2005)[18]. Third, since in our model the "divine coincidence" result does not hold[19], the interest rate response to the technology shock implies a relevant trade-off between inflation and output stabilization. This implies that the definition of the policy rule is not straightforward even on purely theoretical grounds.

## 4 Bayesian estimation, model comparison and simulation

This section provides some details of the strategy adopted to estimate the structural parameters of the monetary DSGE model presented in the previous sections. For the purpose of model comparison, we estimate both the firm-specific and the rental capital versions of the model.

The estimation of DSGE models is a cumbersome task, since in general there are relevant nonlinearities in model parameters that may affect the performances of the Full Information Maximum Likelihood (FIML) estimator. Even if a viable solution would be to restrict the parameters space by fixing the values of certain parameters, or by forcing them within a "reasonable" range (i.e. to employ a constrained FIML estimator), in our analysis we employ a Bayesian Monte Carlo Markov Chain (MCMC) estimator. In both approaches, the final estimates depend on prior assumptions on the range of admissible values, with the difference that distributional priors are specified with the Bayesian approach[20].

### 4.1 The posterior distribution

The scope of the Bayesian estimator is to get the posterior distribution for the structural parameters conditioning on prior beliefs on models $M_j$ $(j = 1, 2, ...)$, structural parameters $\boldsymbol{\theta}_j$, and sample information. The methodology thus nests the formalized prior distribution $P(\boldsymbol{\theta}_j, M_j)$ for $j$-th model's parameters vector $\boldsymbol{\theta}_j$ and the conditional distribution (pseudo-likelihood) $P(\mathbf{Y}_T \mid \boldsymbol{\theta}_j, M_j)$ to get the posterior density $P(\boldsymbol{\theta}_j \mid \mathbf{Y}_T, M_j)$, where $\mathbf{Y}_T = \{\mathbf{y}_t\}_{t=1}^{T}$ contains sample information. This is obtained by employing the Bayes rule:

$$P(\boldsymbol{\theta}_j \mid \mathbf{Y}_T, M_j) = \frac{P(\mathbf{Y}_T \mid \boldsymbol{\theta}_j, M_j)\, P(\boldsymbol{\theta}_j, M_j)}{P(\mathbf{Y}_T, M_j)} \tag{22}$$

where $P(\mathbf{Y}_T, M_j)$ is the marginal data density, that can be normalized since it does not depend on $\boldsymbol{\theta}_j$.

The posterior distribution is the result of a weighted average of prior and conditional distributions, where weights are inversely related to the variance of the prior distributions and of sample information, respectively[21].

[18] Real-time data on potential output are subject to relevant imperfections, as testified by the their frequent and substantial revisions. Moreover, under model uncertainty and when technology evolves according to a random walk with drift process, the estimated long-term deterministic growth component $\gamma_z$ might represent the best prediction for output growth.

[19] The divine coincidence addresses the equivalence in stabilizing inflation and the welfare-relevant output gap (see Blanchard and Galì, 2007).

[20] The Bayesian technique can in fact be considered equivalent to constrained Maximum Likelihood from a Bayesian perspective, i.e. one in which restrictions (priors) are defined in terms of probability distributions.

[21] Formalizing a tight prior will result in a highly constrained estimation, while a diffuse prior will result in a weakly constrained

The posterior density of interest is a complex nonlinear function of the deep parameters $\boldsymbol{\theta}_j$, thus its analytical calculation is not generally feasible. For this reason, the Bayesian MCMC posterior estimates are obtained employing a two-steps procedure: the Kalman smoother provides the approximation of the conditional distribution and the Metropolis-Hastings (M-H) algorithm performs Monte Carlo integration[22].

The empirical performances of the firm-specific and rental capital models (FSK and RK, respectively) are then compared employing the Bayes factor ($BF_{FSK,RK}$), i.e. the ratio between marginal likelihoods $\frac{P(\mathbf{Y}_T|M_{FSK})}{P(\mathbf{Y}_T|M_{RK})}$ - times the model priors ratio $\frac{P(M_{FSK})}{P(M_{RK})}$[23]. To calculate the marginal likelihoods we employ the Laplace approximation. We will adopt Jeffrey's (1961) scale of evidence to derive our conclusions on the preferred specification.

## 4.2 Data and prior distributions

### 4.2.1 Data

For the Bayesian estimation of our model and its comparison with the rental capital version we employ unprocessed quarterly time series for the sample period 1954:3 - 2007:3. Eight variables are considered: (log differences of) real GDP ($\Delta y_t$), real consumption ($\Delta c_t$), real investment ($\Delta i_t$), real wage ($\Delta w_t$), (log levels of) hours ($h_t$), GDP price inflation ($\pi_t$) the federal funds rate ($r_t$) and the prime loan rate $\left(r_t^L\right)$. Data for real variables and the GDP price deflator are obtained from the BEA database, while data employed to construct the labor supply measure are obtained from the BLS database[24]. The nominal interest rates are obtained from the FRED database. The vector of observables $\mathbf{x}_t' = \begin{bmatrix} \Delta y_t & \Delta c_t & \Delta i_t & \Delta w_t & h_t & \pi_t & r_t & r_t^L \end{bmatrix}$ is thus employed.

### 4.2.2 Prior distributions

Both the firm-specific and the rental capital specifications are characterized by a 39-dimensional parameters vector $\left(\boldsymbol{\theta}'_{FSK,RK}\right)$. Note that 19 of these parameters pertain to the stochastic structure of the model, since 18 define the standard errors and the persistence of shocks and one the cross-correlation between the aggregate resources constraint disturbance and the technology shock.

estimation. Asymptotically, the conditional distribution dominates the prior distribution and the posterior distribution of the parameters collapses to their pseudo-true values. This property guarantees that the relevance of priors in posterior estimates vanishes as the sample size increases. A further feature of the Bayesian estimator that is particularly important in standard applications is that its small sample performances outperform those of the FIML estimator (Fernandez-Villaverde and Rubio-Ramirez, 2004).

[22] The posterior mode is estimated employing the Sims' optimizer, while numerical integration is performed employing five parallel chains of 250000 M-H replications each. The fraction of drops of the initial parameters vector estimates is set at 30%. The scale parameter for the variance of the jumping distribution is calibrated such that we obtain an acceptance rate of nearly 25% in the five blocks. This value guarantees that the M-H algorithm explores the entire support of the posterior distributions. For the application of the Bayesian method we employ the open-source software Dynare 4.02 for Matlab.

[23] Since we don't have prior model preferences, we assume that the firm-specific and the rental capital models have the same probability, i.e. $P\left(M_{FSK}\right) = P\left(M_{RK}\right)$, thus the Bayes factor is equivalent to the posterior odds ratio.

[24] Labor supply is calculated as the log ratio between non farm total hours worked and the population aged over 16. The use of the hours to population ratio as the labor supply measure is standard in the literature (Galì and Rabanal, 2004; Chari *et al.,* 2005; Del Negro *et al.,* 2005). A more detailed description of data and data manipulations is provided in the technical appendix, available upon request from the authors.

We impose one dogmatic prior only by fixing the discount factor $\beta$ to 0.998. The high value of $\beta$ is chosen to enhance a data-consistent estimate of the long-run growth parameter $\gamma_z$ and of the steady-state inflation parameter $\gamma_p$, given a reasonable prior parameterization for consumption curvature $\sigma$[25]. All the remaining parameters are estimated.

The shape of the prior distributions is chosen according to the following standard practice: the reference distribution for the structural shocks is the inverted gamma, which is defined over the $\mathbb{R}^+$ range; for parameters theoretically defined in a $[0-1]$ interval a beta distribution is assumed, while the normal distribution is adopted for priors on parameters theoretically defined over the $\mathbb{R}$ range. Concerning prior variability, a tight prior is chosen when information on parameter values can be derived by sample data, as in the case of steady state values and long run ratios. This strategy has the potential advantage of enhancing the identification of other structural parameters, when these are not variation-free with respect to the former set.

For the parameters defining the steady state value of productivity growth $(\gamma_z)$, inflation $(\gamma_p)$ and of the interest rate spread $(\gamma_{r^L})$ we adopt an informative prior defined by a normal distribution centered on the respective sample means (1.0045, 1.0088 and 1.005), with standard deviations equal to 0.001. Concerning the the steady state labor supply and exogenous expenditure (government) shares $H$ and $\lambda_G$, we adopt a beta-distributed prior with means 1/3 and 1/5 and standard deviations 0.05 and 0.025. An informative beta-distributed prior is also adopted for $\alpha$ and $\delta$, whose prior means (standard deviations) are set to 0.36 and 0.025 (0.015 and 0.002), respectively. The chosen mean values of this first set of parameters are consistent with average figures from sample data.

The prior distributions for the consumption curvature and the inverse labor supply Frish elasticity parameters are assumed to be normal and centered around $\sigma = 2$ and $\varphi = 0.5$, with standard deviations equal to 0.2 and 0.1, respectively. The prior for the parameter defining the convex capital adjustment cost $\epsilon_\psi$ follows a normal distribution with prior mean 3 (Woodford, 2005) and standard deviation 0.2.

Concerning the Calvo parameters $\theta_p$ and $\theta_w$, we adopt a beta-distributed prior with mean 0.5 and a prior standard deviation 0.1. These values are in line with the microeconometric evidence produced by Bils and Klenow (2004), suggesting an average price duration of two quarters, even if they are smaller than those generally obtained at the macro level, that indicate an average price duration above six quarters (Galì and Gertler, 1999; Eichenbaum and Fisher, 2007; Del Negro *et al.*, 2005).

A further key parameter affecting the slope of the NKPC under firm-specific capital hypothesis is the elasticity of substitution among differentiated goods $\epsilon$. The standard practice has been that of employing values implied by a dogmatic prior on the price mark-up $\epsilon\,(\epsilon-1)^{-1}-1$. Unfortunately, a wide range of values is found in the literature, since the hypothesized mark-up ranges from 20% (Smets and Wouters, 2003) to 1% (Altig *et al.*, 2005). For this reason, and given its importance for model dynamics, we adopt a very diffuse prior for $\epsilon$, assuming a normal distribution with prior mean 21 (consistent with a 5% mark-up) and prior standard deviation 10.

Concerning the indexation parameters $\iota_p$ and $\iota_w$, we adopt a beta-distributed prior with

[25] Our sample data indicate that quarterly output growth has been, on average, nearly 0.45%, while quarterly inflation and nominal interest rates have been 0.88% and 1.42%, respectively.

mean 0.75 and standard deviation 0.1. The chosen prior mean is higher than the values obtained by Smets and Wouters (2007), who initialize the estimation over a lower prior support centered on a mean equal to 0.5. This choice allows us to minimize the degree of autocorrelation in inflation explained by the stochastic components

The coefficients of the monetary policy reaction rule are assumed to follow a normal distribution centered on prior mean values $\phi_\pi = 1.5$ and $\phi_{\Delta y} = 0.2$, with standard deviations equal to 0.1 and 0.05, respectively. The autoregressive coefficient $\rho_r$ defining the degree of interest rate smoothness is beta-distributed with prior mean 0.6 and prior standard deviation 0.1. Concerning the parameters affecting the interest rate pass-through $\nu$ and $\rho_{r^L}$, we assume a normal distribution with prior mean (standard deviation) 0.1 (0.05) and a beta distribution with prior mean (standard deviation) 0.5 (0.1), respectively.

It is worth emphasizing that, given the prior parameterization, the estimates are initialized over a parameter space for which the model does not replicate the negative conditional correlation between productivity and investment.

Concerning the stochastic components, we adopt a normal distribution with zero prior mean $\rho_z = 0$ and a standard deviation of 0.2 for the coefficient defining the autocorrelation in log-differences of $Z_t$, i.e. we adopt a random walk with drift prior For the autoregressive coefficients of the shocks affecting the capital adjustment cost and the aggregate resources constraint ($\rho_\zeta$, $\rho_{me}$, respectively) we assume a beta distribution with prior mean 0.75 and standard deviation 0.1, while a prior mean value 0.5 is assumed for the cross-correlation parameter $\rho_{z,me}$. A beta-distributed prior with mean 0.5 and standard deviation 0.1 is adopted for the autoregressive coefficients of the shocks to the discount factor and labor supply $\left(\rho_\chi, \rho_\xi, \text{respectively}\right)$. The degree of autocorrelation of the monetary policy shock $\rho_{\mu_t}$ is assumed to follow a beta distribution with prior mean of 0.25 and standard deviation 0.1. Finally, for the autoregressive coefficients, $\rho_\pi$, and $\rho_{\pi_w}$, we assume a beta-distributed prior with mean 0.15 and standard deviation 0.05. The choice for such a low degree of autocorrelation for the price and wage-push measurement errors should enhance the identification of the *economic* sources of persistence, since it forces the autocorrelation in the data to be captured by the size of the structural parameters. The estimated Calvo parameters are in fact particularly sensitive to the prior degree of persistence of the stochastic components[26].

For the standard errors of innovations we assume a prior mean of 0.01 with two degrees of freedom when entering stationary stochastic processes. We instead assume an infinite standard deviation for the shock driving the nonstationary AR(2) process. These diffuse priors on perturbations reflect a very imprecise opinion about the dimensionality of shocks. All these prior opinions on structural parameters are summarized in the first three columns of Table 2.

### 4.3 Estimation results

Table 2 reports the posterior mode and mean parameter estimates for the firm-specific and the rental capital specifications ($\boldsymbol{\theta}_{FSK}$ and $\boldsymbol{\theta}_{RK}$, respectively). Panel *a* contains the results

[26] Smets and Wouters (2007), by assuming a higher prior value for the autoregressive coefficients (0.5), estimate a very high degree of *stochastic* persistence for price and wage dynamics (nearly 0.9). This reduces the size of the estimated Calvo parameters, i.e. the degree of persistence explained by economic relations.

for the estimated parameters defining the model structure, while panel $b$ the estimates of the parameters defining the persistence and size of the stochastic components[27].

Table 2a - Priors and posterior distribution of structural parameters

| | Prior distribution | | Posterior distribution | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\theta_{FSK}$ and $\theta_{RK}$ | | $\theta_{FSK}$ | | | | $\theta_{RK}$ | | | |
| | Distr | Mean (St.Dev) | Mode (St.Dev) | Mean | 10% | 90% | Mode (St.Dev) | Mean | 10% | 90% |
| $\gamma_z$ | $\mathcal{N}$ | 1.005 (0.001) | 1.005 (0.001) | 1.005 | 1.004 | 1.006 | 1.005 (0.001) | 1.005 | 1.004 | 1.007 |
| $\gamma_p$ | $\mathcal{N}$ | 1.009 (0.001) | 1.009 (0.001) | 1.009 | 1.007 | 1.010 | 1.009 (0.001) | 1.009 | 1.007 | 1.011 |
| $\gamma_{r^L}$ | $\mathcal{N}$ | 1.005 (0.001) | 1.005 (0.001) | 1.005 | 1.003 | 1.007 | 1.005 (0.001) | 1.005 | 1.003 | 1.007 |
| $H$ | $\mathcal{B}$ | 0.330 (0.050) | 0.279 (0.044) | 0.271 | 0.200 | 0.341 | 0.266 (0.042) | 0.268 | 0.199 | 0.337 |
| $\lambda_G$ | $\mathcal{B}$ | 0.200 (0.025) | 0.245 (0.024) | 0.241 | 0.203 | 0.280 | 0.244 (0.024) | 0.242 | 0.203 | 0.281 |
| $\alpha$ | $\mathcal{B}$ | 0.360 (0.015) | 0.299 (0.011) | 0.301 | 0.282 | 0.320 | 0.299 (0.011) | 0.302 | 0.283 | 0.320 |
| $\delta$ | $\mathcal{B}$ | 0.025 (0.002) | 0.030 (0.002) | 0.030 | 0.027 | 0.034 | 0.030 (0.002) | 0.030 | 0.027 | 0.034 |
| $\sigma$ | $\mathcal{N}$ | 2.000 (0.200) | 2.286 (0.152) | 2.281 | 2.026 | 2.536 | 2.211 (0.148) | 2.199 | 1.952 | 2.447 |
| $\varphi$ | $\mathcal{N}$ | 0.500 (0.100) | 0.286 (0.104) | 0.318 | 0.153 | 0.482 | 0.342 (0.103) | 0.332 | 0.151 | 0.496 |
| $\epsilon$ | $\mathcal{N}$ | 21.00 (10.00) | 39.66 (7.647) | 41.97 | 29.12 | 54.82 | 21.00 (10.02) | 22.30 | 7.787 | 35.57 |
| $\epsilon_\psi$ | $\mathcal{N}$ | 3.000 (0.200) | 3.609 (0.183) | 3.594 | 3.292 | 3.896 | 3.614 (0.183) | 3.606 | 3.303 | 3.916 |
| $\theta_p$ | $\mathcal{B}$ | 0.500 (0.100) | 0.654 (0.036) | 0.644 | 0.584 | 0.704 | 0.922 (0.013) | 0.917 | 0.894 | 0.940 |
| $\theta_w$ | $\mathcal{B}$ | 0.500 (0.100) | 0.719 (0.069) | 0.726 | 0.618 | 0.834 | 0.751 (0.066) | 0.748 | 0.648 | 0.854 |
| $\iota_w$ | $\mathcal{B}$ | 0.750 (0.100) | 0.461 (0.102) | 0.449 | 0.295 | 0.604 | 0.436 (0.098) | 0.449 | 0.290 | 0.607 |
| $\iota_p$ | $\mathcal{B}$ | 0.750 (0.100) | 0.780 (0.074) | 0.763 | 0.644 | 0.882 | 0.757 (0.070) | 0.748 | 0.638 | 0.870 |
| $\nu$ | $\mathcal{N}$ | 0.100 (0.050) | 0.414 (0.063) | 0.401 | 0.297 | 0.505 | 0.415 (0.063) | 0.408 | 0.309 | 0.512 |
| $\rho_{r^L}$ | $\mathcal{B}$ | 0.500 (0.100) | 0.825 (0.042) | 0.809 | 0.737 | 0.880 | 0.825 (0.042) | 0.814 | 0.742 | 0.885 |
| $\rho_r$ | $\mathcal{B}$ | 0.600 (0.100) | 0.468 (0.048) | 0.479 | 0.410 | 0.547 | 0.484 (0.049) | 0.496 | 0.420 | 0.567 |
| $\phi_\pi$ | $\mathcal{N}$ | 1.500 (0.100) | 1.665 (0.072) | 1.675 | 1.566 | 1.783 | 1.654 (0.071) | 1.665 | 1.550 | 1.783 |
| $\phi_{\Delta y}$ | $\mathcal{N}$ | 0.200 (0.050) | 0.674 (0.042) | 0.654 | 0.610 | 0.697 | 0.681 (0.042) | 0.658 | 0.621 | 0.695 |

[27] Detalied diagnostic results are provided in the technical appendix, available upon request from the authors.

Table 2b - Priors and posterior distribution of shock processes

| | Prior distribution $\theta_{FSK}$ and $\theta_{RK}$ | | Posterior distribution $\theta_{FSK}$ | | | | Posterior distribution $\theta_{RK}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Distr | Mean (St.Dev) | Mode (St.Dev) | Mean | 10% | 90% | Mode (St.Dev) | Mean | 10% | 90% |
| $\rho_z$ | $\mathcal{N}$ | 0.000 (0.200) | 0.152 (0.041) | 0.151 | 0.082 | 0.221 | 0.201 (0.039) | 0.200 | 0.135 | 0.264 |
| $\rho_\xi$ | $\mathcal{B}$ | 0.500 (0.100) | 0.944 (0.014) | 0.936 | 0.917 | 0.955 | 0.944 (0.015) | 0.934 | 0.915 | 0.953 |
| $\rho_\chi$ | $\mathcal{B}$ | 0.500 (0.100) | 0.888 (0.020) | 0.890 | 0.858 | 0.921 | 0.885 (0.020) | 0.886 | 0.855 | 0.918 |
| $\rho_\zeta$ | $\mathcal{B}$ | 0.750 (0.100) | 0.935 (0.010) | 0.933 | 0.917 | 0.950 | 0.935 (0.010) | 0.933 | 0.915 | 0.950 |
| $\rho_{me}$ | $\mathcal{B}$ | 0.750 (0.100) | 0.977 (0.008) | 0.976 | 0.964 | 0.988 | 0.978 (0.007) | 0.977 | 0.965 | 0.989 |
| $\rho_\pi$ | $\mathcal{B}$ | 0.150 (0.050) | 0.088 (0.035) | 0.105 | 0.044 | 0.166 | 0.079 (0.032) | 0.096 | 0.037 | 0.152 |
| $\rho_{\pi_w}$ | $\mathcal{B}$ | 0.150 (0.050) | 0.120 (0.042) | 0.128 | 0.061 | 0.195 | 0.115 (0.041) | 0.125 | 0.059 | 0.190 |
| $\rho_\mu$ | $\mathcal{B}$ | 0.250 (0.100) | 0.024 (0.012) | 0.028 | 0.009 | 0.047 | 0.025 (0.012) | 0.030 | 0.009 | 0.050 |
| $\rho_{z,me}$ | $\mathcal{B}$ | 0.500 (0.100) | 0.416 (0.089) | 0.434 | 0.291 | 0.576 | 0.415 (0.089) | 0.421 | 0.281 | 0.568 |
| $\sigma_z$ | $\mathcal{IG}$ | 0.010 (inf) | 0.010 (0.001) | 0.010 | 0.010 | 0.011 | 0.011 (0.001) | 0.011 | 0.010 | 0.012 |
| $\sigma_\xi$ | $\mathcal{IG}$ | 0.010 (2) | 0.011 (0.002) | 0.012 | 0.009 | 0.016 | 0.011 (0.002) | 0.013 | 0.009 | 0.017 |
| $\sigma_\chi$ | $\mathcal{IG}$ | 0.010 (2) | 0.017 (0.002) | 0.017 | 0.015 | 0.020 | 0.016 (0.002) | 0.017 | 0.014 | 0.019 |
| $\sigma_\zeta$ | $\mathcal{IG}$ | 0.010 (2) | 0.012 (0.001) | 0.012 | 0.011 | 0.014 | 0.012 (0.001) | 0.012 | 0.011 | 0.014 |
| $\sigma_{me}$ | $\mathcal{IG}$ | 0.010 (2) | 0.019 (0.003) | 0.020 | 0.016 | 0.024 | 0.019 (0.003) | 0.020 | 0.016 | 0.024 |
| $\sigma_\pi$ | $\mathcal{IG}$ | 0.010 (2) | 0.004 (0.000) | 0.004 | 0.003 | 0.004 | 0.004 (0.000) | 0.004 | 0.003 | 0.004 |
| $\sigma_{\pi_w}$ | $\mathcal{IG}$ | 0.010 (2) | 0.006 (0.000) | 0.005 | 0.005 | 0.006 | 0.006 (0.000) | 0.005 | 0.005 | 0.006 |
| $\sigma_\mu$ | $\mathcal{IG}$ | 0.010 (2) | 0.006 (0.000) | 0.006 | 0.005 | 0.006 | 0.006 (0.000) | 0.006 | 0.005 | 0.007 |
| $\sigma_\Upsilon$ | $\mathcal{IG}$ | 0.010 (2) | 0.002 (0.000) | 0.002 | 0.002 | 0.002 | 0.002 (0.000) | 0.002 | 0.002 | 0.002 |

#### 4.3.1 Posterior estimates

According to the estimated posterior mode and standard deviations, all the structural parameter estimates are significant at standard pseudo-$t$ values, with the exception of the coefficient $\rho_{\pi_w}$. The finding of a small size of $\rho_z$, shows that $Z_t$ can be approximated by a random walk with drift process. This implies that the impact and the long-run responses of productivity to a technology shock are nearly the same, providing evidence in favor of a NK explanation of the contractionary effects of supply shocks. The absence of relevant technological diffusion delays rules out the possibility short-run drops in the use of inputs due to intertemporal substitution effects stimulated by expected improvements in productivity (Lindé, 2004).

The shocks affecting preferences ($\xi_t$ and $\chi_t$), the aggregate resources constraint ($\varepsilon_t^{me}$) and capital adjustment costs ($\zeta_t$) are highly persistent, while the remaining stationary disturbances denote a moderate degree of autocorrelation. In particular, the degree of autocorrelation of the measurement error process for inflation is very low, signalling that the economic model accounts a major fraction of the inflation persistence in the data. The exogenous innovations are all significant according to their standard errors and there are signals that the most important shocks are those affecting the exogenous components in $u_t^{me}$, preferences and the capital adjustment cost.

The steady state values for productivity growth $(\gamma_z)$, inflation $(\gamma_p)$ and the interest rate spread $(\gamma_{r^L})$ are estimated to be 0.48%, 0.88% and 0.5% on a quarterly basis. These values are strictly in line with priors and sample information. The estimated mean values of the capital share and capital depreciation coefficients ($\alpha = 0.30$ and $\delta = 0.03$, respectively) are instead relatively distant from the corresponding priors.

The posterior mean estimates of the "deep" parameters are close to the corresponding modal values and do not depart excessively from prior opinions. There are however some key exceptions that we deem as particularly important for the scopes of our analysis. First, the estimated price/wage Calvo parameters are higher than their prior mean values ($\theta_p = 0.64$, $\theta_w = 0.73$). Second, even if the estimation of the demand elasticity parameter $\epsilon$ is initialized with a relatively high value ($\epsilon = 21$), we obtain an even higher posterior mean estimate for this parameter, consistent with a 2.5% mark-up ($\epsilon = 41$). Third, despite the relatively low prior mean value for the parameter indicating the response of the monetary authority to output deviations from long-run growth (0.2), the posterior estimate is $\phi_{\Delta y} = 0.65$. Fourth, contrary to the findings of previous analyses (e.g. Smets and Wouters, 2007), we obtain a relatively high degree of indexation in price setting ($\iota_p = 0.71$), while confirming the moderate indexation of wages.

These results drive the model over a parameter space for which the contractionary effects of positive supply shocks on investment are relevant and persistent. The reduced-form NKPC slope coefficient $\kappa$ implied by our estimates is 0.01, which denotes a particularly flat curve[28], and monetary policy does not fully accommodate the shock, as implied by the size of the policy response to output deviations from trend growth.

Our estimates signal that the high degree of inflation inertia is mostly explained by the presence of relevant strategic complementarity in price setting, i.e. by the high demand elasticity estimate, while the frequency of price reoptimization implicit to the estimated Calvo parameter (nearly three quarters) is basically in line with microeconometric evidence.

#### 4.3.2 Model comparison

We now consider how the outcomes obtained with the firm-specific capital specification compare with those obtained with the more standard rental capital model. Major differences are found with respect to the estimated price stickiness and demand elasticity parameters ($\theta_p = 0.91$ and $\epsilon = 22$ respectively). The higher estimate for $\theta_p$ in the rental capital specification balances the (missing) effect of $\epsilon$ on the slope of the NKPC. In fact, according to the estimated parameterization, the reduced-form NKPC slope coefficient is again 0.01, even if at

[28]By imposing the (standard) dogmatic prior $\epsilon = 11$, we obtain $\hat{\theta}_p = 0.8$, which confirms the particularly flat NKPC (the reduced-form slope coefficient $\kappa$ is in this case 0.009). By increasing the dogmatic prior to $\epsilon = 21$ we obtain $\hat{\theta}_p = 0.73$, which again implies $\hat{k} = 0.011$.

the cost of forcing the Calvo parameter to a value that is distant from available evidence on the frequency of price reoptimization at the firm-level (Bils and Klenow, 2004).

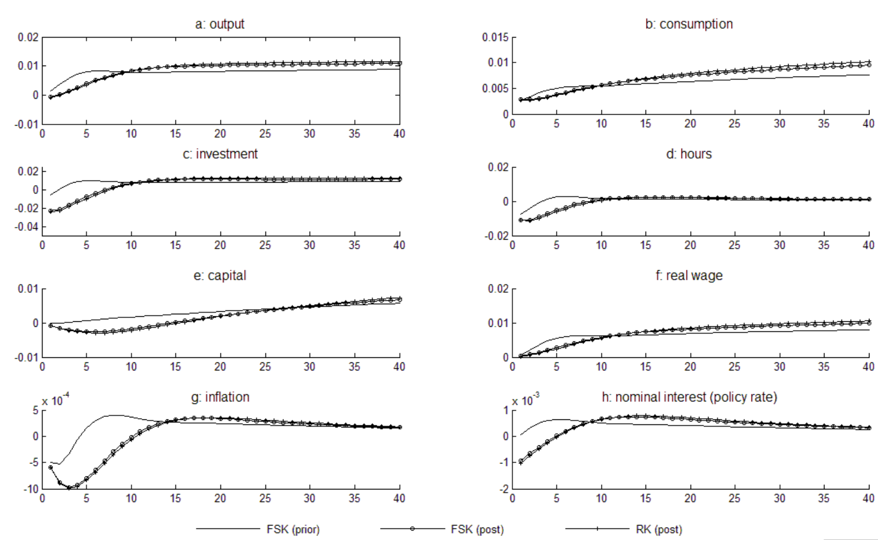
Concerning the remaining parameters, the estimated $\boldsymbol{\theta}_{RK}$ vector is basically equal to $\boldsymbol{\theta}_{FSK}$, suggesting that the estimated firm-specific and rental capital specifications are similar. Should we conclude that the models are empirically equivalent? The Laplace approximation of the log likelihood is, for the firm-specific and the rental capital models, 6156.5 and 6139.1, thus the Bayes factor is $BF_{FSK,RK} = e^{[\log P(\mathbf{Y}_T|M_{FSK}) - \log P(\mathbf{Y}_T|M_{RK})]} > 10^2$. According to Jeffrey's (1961) scale of evidence, this result signals that there is decisive evidence in support of the firm-specific capital model.

#### 4.3.3 Posterior impulse responses

Figure 3 shows the posterior impulse responses to a positive supply shock under firm-specific/rental capital specifications, and compares them with the impulse responses obtained under the prior parametrization of the firm-specific capital model. Note that, under the prior, the technology shock is expansionary even in the short run.

There are at least five indications from posterior IRFs that merit to be highlighted. First, the firm-specific and the rental capital specifications display a similar dynamics, signalling that results do not depend excessively on model and prior specifications. Second, the investment response is negative in the short-term, and becomes positive after nearly seven periods (when the demand constraint becomes less binding as more firms cut their prices). Third, the response of hours is negative for nearly nine periods, indicating that both specifications are consistent with the well-known productivity-employment puzzle. Fourth, consumption, output and real wage responses are standard: consumption increases because of the expected permanent increase in productivity and output, driving the expansionary aggregate demand response (output), while the real wage increases following the increase in productivity. Fifth, the interest rate reduction signals that the degree of accommodation implied by the estimated monetary policy rule is not enough to prevent a decrease in inflation.

Figure3-Prior and posterior impulse responses to a productivity improvement



Our model is thus able to reproduce the apparently puzzling evidence on the short-term contractionary effects of technology shocks on hours and investment addressed by BFK, and to provide some indications on the underlying theoretical mechanisms that explain them.

#### 4.3.4 A brief comparison with previous analyses

Our results decisively contrast those obtained by the recent literature on business cycles developed within the DSGE approach. Here we briefly highlight the differences with respect to the outcomes of two key literature contributions. Smets and Wouters (2006) estimate a NK-DSGE model with nominal and real frictions characterized by a particularly flexible dynamics, obtaining good adaptability to sample data and out of sample performances. However, even if they obtain a drop in hours following a positive technology shock, the impulse response of investment implied by their estimates is positive even on impact. The basic reason for this result is that Smets and Wouters (2006) assume that the monetary authority targets flexible price output, resulting in a particularly accommodative rule which prevents the short-term contraction of investment after the productivity improvement. In other terms, the presence of real and nominal frictions is not sufficient to counterbalance the expansionary effects on investment of the interest rate adjustment.

Altig *et al.* (2005) develop a firm-specific capital monetary model that can account for the negative short-run response of investment to supply shocks even under a plausible parameterization. However, from the empirical evaluation of their model, based on an impulse response matching strategy, they are forced to rule out such a result, since their benchmark SVAR signals a positive short-term response of inputs[29]. In our opinion, the evidence produced with a matching estimator applied to a model with a particularly flexible dynamics cannot be considered conclusive, since it does not provide additional evidence to that implied by the SVAR impulse responses. This strategy simply forces the model calibration to a parameters space for which the implied model dynamics is consistent with the SVAR-based impulse responses.

We deem our results as more reliable with respect to those obtainable from weakly identified SVARs, that generally do not provide a satisfying representation of the nonstationary and co-trending properties of the data, and are subject to relevant biases due to approximation problems and small samples (Cooley and Dwyer, 1998; Chari *et al.*, 2005; Erceg *et al.*, 2005).

## 5 Conclusions

Our results both complement and depart from those obtained by the vast literature on the contractionary effects of technology shocks. On the one hand, by addressing the investment response to permanent technology improvements, we obtain a confirmation of BFK's results, providing additional support to the idea that standard flexible price models cannot explain the observed pro-cyclicality of productivity, investment and hours as driven by positive supply shocks. On the other hand, we show that the interpretation based on nominal rigidities only

[29] From the calibration of their model, Altig *et al.* (2005) also obtain a counterfactual increase in inflation after a neutral technology shock, due to the particularly accommodative monetary policy response. The strong response of money growth is needed in order to account for the general rise in economic activity obtained with the benchmark SVAR.

is not supported by the data, since it would imply a degree of nominal stickiness contrasting with the available evidence on the frequency of price optimization at the firm level.

The calibration experiments and the simulations based on posterior estimates show that the negative investment response to supply shocks basically depends on the presence of relevant demand constraints. These emerge not only because of a not fully accommodative monetary policy, but also because of the nearly flat NKPC characterizing the firm-specific capital model. Our results also show that a firm-specific capital model specification is needed to obtain a plausible estimate of the degree of nominal stickiness, signalling that the limited operation of the price mechanism (i.e. the weak relation between the marginal cost and inflation) does not depend only on the frequency at which firms are allowed to change their prices. The strategic complementarity in price setting emerging in the firm-specific capital model introduces an additional source of price inertia in the model. It implies that, following a positive productivity shock, reoptimizing firms are reluctant to cut their price since they anticipate that price reductions eventually affect marginal costs, due to increased demand and output at the firm level. Our structural approach allows a direct estimate of the demand elasticity parameter, and thus an empirical evaluation of the relevance of the role played by strategic complementarity.

Clearly, aside from firm-specificity of capital, there are other theoretical hypotheses that can induce strategic complementarity in price setting. Among these hypotheses, the firm-specific labor and endogenous demand elasticity assumptions have been employed in the literature (Eichenbaum and Fisher, 2007; Smets and Wouters, 2007). Our results should not be considered as evidence in favor of one of these options, but as evidence of a limited operation of price and monetary policy transmission mechanisms. A theoretical and empirical evaluation of the implications and of the relative importance of these alternative sources of real rigidity is left for future research.

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