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New Perspectives on Capital and Sticky Prices

by

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New Perspectives on Capital and Sticky Prices*

Tommy Sveen† Lutz Weinke‡

February 23, 2004

Abstract

We model capital accumulation in a dynamic New-Keynesian model with staggered price setting à la Calvo. It is assumed that firms do not have access to a rental market for capital. We compare our model with an alternative specification where households accumulate capital and rent it to firms. The difference in implied equilibrium dynamics is large, as we justify by proposing a simple metric. This result invites us to interpret some of the puzzling empirical findings that have been obtained using models with staggered price setting *and* a rental market for capital as an artefact of this particular set of assumptions.

Keywords: Sticky Prices, Investments, Rental Market.

JEL Classification: E22, E31

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1 Introduction

In the field of New-Keynesian macroeconomics there has been recent interest in models with staggered price setting that allow for capital accumulation.[1] The main reason is that many research questions can only be addressed if capital accumulation is taken into account.[2] Moreover, it has been argued that modeling investment demand might help explain some empirical regularities once additional features are introduced into the model, which would be hard to entertain if consumption was the only component of aggregate demand.[3] However, it is unclear *a priori* how capital accumulation should be introduced into such a model. As has been argued by Woodford (2003, Ch. 5), combining the assumptions of staggered price setting and a rental market for capital is convenient but potentially unappealing: it affects the determination of the marginal cost at the firm level in a non-trivial way. Our understanding of New-Keynesian models with staggered price setting and capital accumulation is therefore obscured as long as the quantitative consequences of the widely used rental market assumption remain opaque.

The present paper fills that gap in the existing literature: the rental market case is compared with a baseline model where we assume that firms make investment decisions, and importantly, that they do not have access to a rental market for capital.[4] In both models we assume staggered price setting à la Calvo and the following (standard) restrictions on capital formation: the additional capital resulting from an investment decision becomes productive with a one period delay, and there is a convex adjustment cost in the process of capital accumulation. The two models are compared in a simulation exercise where we analyze the respective impulse responses

[1] For an early New-Keynesian model, which allows for capital accumulation see, e.g., Yun (1996).

[2] See, e.g., Galí et al. (2003). The authors consider rule-of-thumb consumers in addition to optimizing consumers. They argue that the distinction between the two groups is only meaningful if capital accumulation is introduced explicitly into the model.

[3] Christiano et al. (2001) and Smets and Wouters (2003) use the assumption of investment adjustment costs and show that it generates a hump shaped output response after a monetary policy shock. Edge (2000) introduces time-to-build capital combined with investment adjustment costs into a Calvo style sticky price model. She shows that these assumptions help generating a liquidity effect.

[4] The baseline model has been analyzed by Sveen and Weinke (2004). There we show that the price setting problem in the presence of an investment decision at the firm level has not been solved in a correct way by Woodford (2003, Ch. 5).

to a shock in the exogenous growth rate of money balances.

Our main finding is the following: for any given restriction on price adjustment there is a substantial amount of additional price stickiness in the baseline model compared with the rental market specification. We justify this claim by proposing a metric, which gives a precise quantitative meaning to it. The intuition behind our result is plain from a comparison of the price setters in the two models: with a restriction on capital adjustment at the firm level, as in the baseline model, an increase in a firm's price is associated with a decrease in its marginal cost.[5] We refer to this feature of the baseline model as short run decreasing returns to scale. This effect is absent if a rental market for capital is assumed. The latter implies that each firm in the economy faces the same marginal cost, which is independent of the quantity supplied by any individual firm. This mechanism has been discussed by Sbordone (2001) and Galí et al. (2001) for models with decreasing returns to scale resulting from a *fixed* capital stock at the firm level.[6] Our work shows that *short run* decreasing returns to scale in the baseline model suffice to imply equilibrium dynamics that are quantitatively different from the ones associated with the rental market specification. The different price setting incentives in the two models are indeed the driving force behind our result: the only difference between the two models lies in the characterization of the respective inflation dynamics.[7] As we will see, this theoretical result invites us to interpret some of the puzzling empirical findings that have been obtained using models with staggered price setting *and* a rental market for capital as an artefact of this particular set of assumptions.

The remainder of the paper is organized as follows: Section 2 outlines the baseline model and the rental market specification. In Section 3 we conduct the abovementioned simulation exercise. Section 4 concludes.

[5] In the baseline model we assume that the capital stock at the firm level is predetermined *and* that there exists a capital adjustment cost. One of the two assumptions would suffice to imply that a firm's price setting decision affects its marginal cost. The role of a predetermined capital stock at the firm level *per se*, i.e. abstracting from capital adjustment costs, has been analyzed by Sveen and Weinke (2003).

[6] See Woodford (1996) for an early model with differences in marginal costs among producers.

[7] The latter holds up to the first order approximation to the equilibrium dynamics, which we are going to consider later on.

2 The Model Economy

There are three types of agents: households, a perfectly competitive final good producer, and monopolistically competitive intermediate goods producers. The only source of aggregate uncertainty in the model economy comes from the growth rate of money balances, which we assume to follow an AR(1) process:

$$\Delta m_t = \rho_m \Delta m_{t-1} + \varepsilon_t, \tag{1}$$

where $m_t \equiv \log M_t$, with M_t denoting time t nominal money balances. The parameter ρ_m is assumed to be strictly positive and less than one, and ε_t is *iid* with zero mean and variance σ_ε^2.

2.1 Households

A representative household maximizes expected discounted utility:

$$E_t \sum_{k=0}^{\infty} \beta^k U\left(C_{t+k}, N_{t+k}\right), \tag{2}$$

where β is the household's discount factor, C_t is consumption of the final good, and N_t are hours worked. We assume the following period utility function:

$$U\left(C_t, N_t\right) = \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\phi}}{1+\phi}, \tag{3}$$

where parameters σ and ϕ are positive. The former is the household's relative risk aversion, or equivalently, the inverse of the household's intertemporal elasticity of substitution. The latter can be interpreted as the inverse of the Frisch aggregate labor supply elasticity. Moreover, we assume that households have access to a complete set of contingent claims and that the labor market is perfectly competitive.

The household's problem is subject to the following sequence of budget constraints:

$$P_t C_t + E_t \left\{Q_{t,t+1} D_{t+1}\right\} \leq D_t + W_t N_t + T_t, \tag{4}$$

where P_t is the time t price of the final good, and W_t is the nominal wage as of that period. Moreover, D_{t+1} is the nominal payoff of the portfolio held at the end of period t, $Q_{t,t+1}$ is the stochastic discount factor for random nominal payments, and T_t denotes profits resulting from ownership of firms. This structure implies the following first order conditions for the household's optimal choices:

$$C_t^{\sigma} N_t^{\phi} = \frac{W_t}{P_t}, \tag{5}$$

$$\beta \left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \left(\frac{P_t}{P_{t+1}} \right) = Q_{t,t+1}. \tag{6}$$

The first equation is the optimality condition for labor supply, and the second is a standard intertemporal optimality condition. The time t price of a risk-less one-period bond is given by $R_t^{-1} = E_t Q_{t,t+1}$, with R_t denoting the gross nominal interest rate as of that period. Later on, we will follow Galí (2000) and assume a standard demand for real balances in addition to the household's structural equations.

2.2 Firms

There is a continuum of monopolistically competitive firms[8] indexed on the unit interval. These firms produce differentiated intermediate goods. The latter are used as inputs by a perfectly competitive firm producing a single final good.

2.2.1 Final Good Firm

The constant returns to scale technology of the representative final good producer is given by:

$$Y_t = \left(\int_0^1 Y_t^d (i)^{\frac{\varepsilon-1}{\varepsilon}} di \right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{7}$$

where Y_t is time t production of the final good, $Y_t^d (i)$ is the quantity of intermediate good i used as an input, and ε is a parameter strictly greater than one. The latter can be interpreted as the elasticity of substitution between intermediate goods. Profit maximization by the final good producer implies the following demand for each

[8] Monopolistic competition rationalizes the assumption that a firm is willing to satisfy unexpected increases in demand even when a constraint not to change its price is binding. See, e.g., Erceg et al. (2000).

intermediate good:

$$Y_t^d(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon} Y_t, \tag{8}$$

where $P_t(i)$ denotes the time t price of intermediate good i. Imposing the zero profit condition, we obtain:

$$P_t = \left(\int_0^1 P_t(i)^{1-\varepsilon} di\right)^{\frac{1}{1-\varepsilon}}. \tag{9}$$

2.2.2 Intermediate Goods Firms

Intermediate goods firms set prices and make investment decisions with the objective of maximizing the values of their dividend streams.[9] Each firm $i \in [0,1]$ is assumed to produce a differentiated good using the following Cobb-Douglas production function:

$$Y_t(i) = N_t(i)^{1-\alpha} K_t(i)^{\alpha}, \tag{10}$$

where $\alpha \in [0,1)$ is a constant, $K_t(i)$ denotes firm i's capital stock in period t, and $N_t(i)$ is the amount of labor used by that firm in its time t production of output denoted $Y_t(i)$.

The feature of price staggering is introduced into the model by invoking the Calvo (1983) assumption, i.e. each firm is allowed to change its price in any given period with a constant and exogenous probability, which is common to all firms. This way we capture the fact that firms change prices only infrequently. Moreover, each firm makes an investment decision at any point in time. There is a convex capital adjustment cost and the additional capital resulting from an investment decision becomes productive with a one period delay. Next we consider price setting and investment decison making in more detail.

Price Setting A price setter i takes into account that the choice of its time t nominal price, $P_t^*(i)$, might affect not only current but also future profits. The associated first order condition is:

$$\sum_{k=0}^{\infty} \theta^k E_t \left\{Q_{t,t+k} Y_{t+k}(i) \left[P_t^*(i) - \mu MC_{t+k}(i)\right]\right\} = 0, \tag{11}$$

[9] See the Appendix for a formal statement of the intermediate goods firms' price setting and investment problems.

where θ denotes the probability that an intermediate goods firm is not allowed to change its price, $\mu \equiv \frac{\varepsilon}{\varepsilon-1}$ is the frictionless mark-up, and $MC_t(i)$ is firm i's nominal marginal cost at time t. The latter is given by:

$$MC_t(i) = \frac{W_t}{MPL_t(i)}, \tag{12}$$

where $MPL_t(i)$ denotes firm i's marginal product of labor at time t.

Equation (11) takes the form of the standard first order condition for price setting in the Calvo model: the price is chosen in such a way that a weighted average of current and future expected marginal profits is equalized to zero. However, since a firm's capital stock is among the determinants of its marginal product of labor, we cannot solve the price setting problem without considering the firm's investment behavior. We turn to this next.

Investment Behavior Given firm i's time t capital stock $K_t(i)$ the quantity of the final good $I_t(i)$ that needs to be purchased by that firm in order to have a capital stock $K_{t+1}(i)$ in place in the next period is given by:

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

where $I(\cdot)$ is an increasing and convex function. The latter is consistent with the existence of a convex capital adjustment cost. Moreover, we follow Woodford (2003, Ch. 5) in assuming $I(1) = \delta$, $I'(1) = 1$, and $I''(1) = \epsilon_\psi$, where δ is the depreciation rate and the parameter $\epsilon_\psi > 0$ measures the capital adjustment cost in a log-linear approximation to the equilibrium dynamics.

The first order condition associated with firm i's time t investment decision is given by the following equation:

$$\frac{dI_t(i)}{dK_{t+1}(i)}P_t = E_t\left\{Q_{t,t+1}\left[MS_{t+1}(i) - \frac{dI_{t+1}(i)}{dK_{t+1}(i)}P_{t+1}\right]\right\}, \tag{14}$$

where $MS_{t+1}(i)$ denotes the nominal marginal savings in firm i's labor cost at time $t+1$ associated with having one additional unit of capital in place. The latter is given by:

$$MS_{t+1}(i) = W_{t+1}\frac{MPK_{t+1}(i)}{MPL_{t+1}(i)}, \tag{15}$$

where $MPK_{t+1}(i)$ denotes firm i's marginal product of capital at time $t+1$.

Equation (14) takes a standard form.[10] It is noteworthy, however, that a firm's marginal return to capital is measured by the marginal savings in its labor cost, as opposed to its marginal revenue product of capital. As has been emphasized by Woodford (2003, Ch. 5), firms are demand constrained. This implies that the return from having an additional unit of capital in place derives from the fact that this allows to produce the quantity that happens to be demanded using less labor.

When forming the time t expectation of $MS_{t+1}(i)$, an optimizing firm i takes rationally into account that its time $t+1$ price, $P_{t+1}(i)$, might be optimally chosen in period $t+1$. The reason is that $MS_{t+1}(i)$ depends on firm i's demand at time $t+1$, which is a function of its relative price as of that period. Sveen and Weinke (2004) show that this aspect of a firm's investment behavior has important consequences for its price setting decision: it implies that the latter depends, to some extent, on expected future *optimally* chosen prices. This has been overlooked by Woodford (2003, Ch. 5).[11] We come back to this point later on when characterizing the inflation dynamics associated with the baseline model.

2.3 Market Clearing

Clearing of the labor market, the intermediate goods markets, and the final good market requires that the following conditions are satisfied for all t:

$$\begin{aligned} N_t &= \int_0^1 N_t(i)\, di, & (16)\\ Y_t(i) &= Y_t^d(i), & (17)\\ Y_t &= C_t + I_t, & (18) \end{aligned}$$

where $I_t \equiv \int_0^1 I_t(i)\, di$. Moreover, it is useful to define aggregate capital for all t:

[10] For a short discussion, see Sveen and Weinke (2004).

[11] The same critique applies to Casares (2002).

$$K_t \equiv \int_0^1 K_t(i)\, di. \tag{19}$$

Finally, we define the following auxiliary variable:

$$\widetilde{Y}_t \equiv K_t^{\alpha} N_t^{1-\alpha}. \tag{20}$$

It is easy to see that the difference between Y_t in (7) and $\widetilde{Y}_t$ in (20) is of the second order. Hence, we can safely ignore it for the purpose of a log-linear approximation to the equilibrium dynamics. We turn to this next.

2.4 Some Linearized Equilibrium Conditions

We consider a log-linear approximation to the equilibrium dynamics around a symmetric steady state with zero inflation. Throughout, a hat on a variable denotes the percent deviation of the original variable with respect to its steady state value. We start by collecting some standard equilibrium conditions, while leaving the characterization of the inflation dynamics for the next paragraph.

2.4.1 Households

Taking conditional expectations on both sides of (6) and log-linearizing yields the household's Euler equation:

$$\widehat{C}_t = E_t \widehat{C}_{t+1} - \frac{1}{\sigma}\left(i_t - E_t \pi_{t+1} - \rho\right), \tag{21}$$

where $i_t \equiv \log R_t$ denotes the nominal interest rate at time t and $\pi_t \equiv \log\left(\frac{P_t}{P_{t-1}}\right)$ is the rate of inflation as of that period. Moreover, $\rho \equiv -\log\beta$ is the time discount rate. Equation (21) reflects the household's incentive to smooth consumption.

From equation (5) we obtain the household's log-linearized labor supply as follows:

$$\widehat{\left(\frac{W_t}{P_t}\right)} = \phi \widehat{N}_t + \sigma \widehat{C}_t. \tag{22}$$

In order to create a demand for real balances we follow Galí (2000) in assuming a standard relationship:

$$\widehat{\left(\frac{M_t}{P_t}\right)} = \widehat{Y}_t - \eta\left(i_t - \rho\right), \tag{23}$$

where η denotes the semi-elasticity of the demand for real balances with respect to the nominal interest rate.

2.4.2 Firms

We obtain the law of motion of capital from averaging investment decisions. Our starting point is the log-linearized real marginal savings in the labor cost of an intermediate goods firm i:

$$\widehat{ms}_t(i) = \widehat{ms}_t - \frac{\varepsilon}{1-\alpha}\widehat{p}_t\left(i\right) - \frac{1}{1-\alpha}\widehat{k}_t\left(i\right), \tag{24}$$

where $p_t\left(i\right) \equiv \frac{P_t(i)}{P_t}$ is firm i's relative price, and $k_t\left(i\right) \equiv \frac{K_t(i)}{K_t}$ denotes firm i's relative to average capital stock at time t. Finally, ms_t denotes the average real marginal savings in labor costs as of that period. The latter is given by:

$$ms_t = \frac{W_t}{P_t}\frac{MPK_t}{MPL_t}, \tag{25}$$

where MPL_t and MPK_t denote, respectively, the average time t marginal product of labor and capital. They are obtained from equation (20).

Log-linearizing the first order condition for investment (14), averaging over all intermediate goods firms[12], and invoking (21) and (24), we obtain the following law of motion of aggregate capital:

$$\begin{aligned}\widehat{K}_{t+1} &= \frac{1}{1+\beta}\widehat{K}_t + \frac{\beta}{(1+\beta)}E_t\widehat{K}_{t+2} \\ &+ \frac{1-\beta(1-\delta)}{\epsilon_\psi\left(1+\beta\right)}E_t\widehat{ms}_{t+1} - \frac{1}{\epsilon_\psi\left(1+\beta\right)}\left(i_t - E_t\pi_{t+1} - \rho\right).\end{aligned} \tag{26}$$

Assuming a capital adjustment cost implies that capital is a forward-looking variable.

[12] Note that the first order condition associated with the investment decision takes the same functional form irrespective of whether a firm is allowed or restricted to change its price.

2.4.3 Market Clearing

Log-linearizing the final good market clearing condition (18) yields:

$$\widehat{Y}_t = \frac{\rho + \delta(1-\alpha)}{\rho+\delta}\widehat{C}_t + \frac{\alpha}{\rho+\delta}\left[\widehat{K}_{t+1} - (1-\delta)\widehat{K}_t\right]. \tag{27}$$

Moreover, log-linearizing equation (20) and recalling that the difference between Y_t in (7) and $\widetilde{Y}_t$ in (20) is of the second order results in:

$$\widehat{Y}_t = \alpha\widehat{K}_t + (1-\alpha)\widehat{N}_t. \tag{28}$$

The last equation is the log-linearized aggregate production function.

2.5 Linearized Price Setting

In order to characterize the inflation dynamics associated with the baseline model, we average and aggregate price setting decisions in the way discussed below. A natural starting point is the real marginal cost at the firm level, denoted $mc_t(i) \equiv \frac{MC_t(i)}{P_t}$. Log-linearizing the latter yields:

$$\widehat{mc}_t(i) = \widehat{mc}_t - \frac{\varepsilon\alpha}{1-\alpha}\widehat{p}_t(i) - \frac{\alpha}{1-\alpha}\widehat{k}_t(i), \tag{29}$$

where mc_t is the average time t real marginal cost. The following relationship holds true:

$$mc_t = \frac{W_t/P_t}{MPL_t}. \tag{30}$$

We refer to $\widehat{k}_t(i)$ as firm i's capital gap at time t. The intuition behind equation (29) is the following: the relative price term is exactly as in Sbordone (2001) and Galí et al. (2001) for models with decreasing returns to scale and labor as the only variable productive input. As they discuss, *ceteris paribus*, an increase in a firm's relative price is associated with a decrease in its marginal cost. The reason is an increase in the firm's marginal product of labor resulting from a decrease in its supply for a fixed capital stock. The role of the capital gap term has been discussed by Sveen and Weinke (2004): *ceteris paribus*, an increase in a firm's capital stock is associated with a decrease in its marginal cost. The reason is that for a fixed supply a firm's marginal product of labor increases with the capital stock it uses in production.

Invoking equations (11) and (29) firm i's optimal relative price at time t, $p_t^*(i) \equiv \frac{P_t^*(i)}{P_t}$, can be log-linearized as:

$$\widehat{p}_t^*(i) = \sum_{k=1}^{\infty} (\beta\theta)^k E_t \pi_{t+k} + \xi \sum_{k=0}^{\infty} (\beta\theta)^k E_t \widehat{mc}_{t+k} - \psi \sum_{k=0}^{\infty} (\beta\theta)^k E_t \widehat{k}_{t+k}(i), \qquad (31)$$

where $\xi \equiv \frac{(1-\beta\theta)(1-\alpha)}{1-\alpha+\varepsilon\alpha}$, and $\psi \equiv \frac{(1-\beta\theta)\alpha}{1-\alpha+\varepsilon\alpha}$.[13] The last equation shows that, in addition to the standard inflation and average marginal cost terms, a firm's optimal price setting decision does also depend on its current and future expected capital gaps over the expected lifetime of the chosen price.

As we show in Sveen and Weinke (2004), the relevant capital gap terms in equation (31) are affected by firm i's time t expectation of its future *optimally* chosen prices.[14] This aspect of a firm's price setting decision has been overlooked by Woodford (2003, Ch. 5).

The problem of characterizing the resulting inflation dynamics is intricate. However, in Sveen and Weinke (2004) we show that a tractable approximation can be obtained without any sizeable loss of accuracy. The basic idea is to use the following property of the model: in steady state, all firms choose to hold the same capital stock. Therefore, a price setter takes rationally into account that it will eventually close its capital gap. Our strategy is to go through the following steps: in the first step we assume that price setters expect a zero capital gap already one period after the price setting decision is made. In the next step price setters expect that it takes two periods until their capital gaps are closed. We keep going. At each step an inflation equation is obtained from averaging and aggregating the price setting decisions. Finally, we assess numerically the quantitative consequences of using the different inflation equations associated with the steps. Surprisingly, it turns out that

[13] The price setting problem is stated in terms of variables that are constant in the steady state.

[14] This is the crucial conceptual difference with respect to the specification where a rental market for capital is assumed. In the latter case *all* of a firm's future expected relative prices that are relevant for a price setting decision can be obtained from combining the *current* optimally chosen price of that firm with the expectation of future changes in the *aggregate* price level.

the equilibrium dynamics are almost identical at *each* step.[15] This justifies the use of the following simple inflation equation, which can easily be obtained from the first step:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa \widehat{mc}_t, \tag{32}$$

where $\kappa = \frac{\xi(1-\theta)}{\theta}$. Our intuition for why future expected capital gaps affect price setting decisions so little is based on the forward-looking nature of investment decision making in the presence of a capital adjustment cost: if the relevant planning horizon for the investment decision is long enough then price setters and non-price setters do not make (on average) very different investment decisions since they face the same probabilities of being allowed or restricted to adjust prices in the future.

This completes our characterization of the relevant equilibrium conditions for the baseline model.

2.6 The Model with a Rental Market for Capital

We assume that a representative household accumulates the capital stock and rents it to intermediate goods firms. The household maximizes the objective function given in (2) subject to the following sequences of constraints:

$$P_t (C_t + I_t) + E_t \{Q_{t,t+1} D_{t+1}\} \leq D_t + W_t N_t + R_t^k K_t + T_t, \tag{33}$$

$$I_t = I\left(\frac{K_{t+1}}{K_t}\right) K_t, \tag{34}$$

where R_t^k denotes the time t rental rate of capital. Hence, $R_t^k K_t$ is the income that accrues to the household in period t for renting the capital stock K_t. $P_t I_t$ denotes nominal expenditure on investment.

The first order conditions associated with the household's choices over leisure and the time path of consumption are identical to the ones given in equations (5) and (6), respectively. The first order condition associated with the household's investment decision is:

$$\frac{dI_t}{dK_{t+1}} P_t = E_t \left\{ Q_{t,t+1} \left[R_{t+1}^k - \frac{dI_{t+1}}{dK_{t+1}} P_{t+1} \right] \right\}. \tag{35}$$

[15] This result is remarkably robust with respect to the chosen calibration. For a discussion of the accuracy of the approximation, see Sveen and Weinke (2004).

Cost minimization implies that each firm produces at the same capital labor ratio. The marginal cost is therefore common to all firms, and this allows us to write the rental rate of capital as follows:

$$R_t^k = W_t \frac{MPK_t}{MPL_t}. \tag{36}$$

Log-linearizing equation (35) and invoking (21) we recover the same log-linearized law of motion of capital as the one given in equation (26). This means that, up to a log-linear approximation to the equilibrium dynamics, the set of equilibrium conditions is identical to the one associated with the baseline model, except for the inflation equation: with a rental market for capital a firm's marginal cost is independent of its price setting decision. The resulting inflation equation takes the following standard form:

$$\pi_t = \beta E_t \pi_{t+1} + \lambda \widehat{mc}_t, \tag{37}$$

where $\lambda \equiv \frac{(1-\beta\theta)(1-\theta)}{\theta}$, and the average marginal cost is defined in the same way as in the baseline model.[16]

3 Simulation Results

As we have already noted, the inflation equation is the only structural equation that takes a different form depending on whether or not a rental market for capital is assumed. This means that, given the specification of monetary policy in (1), the equilibrium processes for the nominal interest rate, consumption, real wage, real balances, capital, output, hours, and inflation are determined by equations (21), (22), (23), (26), (27), (28), and an inflation equation. The latter is given by equation (32) for the baseline model and by equation (37) for the rental market specification. For both models the average marginal cost is given by equation (30). The average marginal savings in labor costs and the rental rate of capital are obtained from equations (25) and (36), respectively.[17]

[16] See Galí (2003) et al. for a detailed development of a Calvo type model with a rental market for capital.

[17] To solve the dynamic stochastic system of equations we use Dynare (http://www.cepremap.cnrs.fr/dynare/).

3.1 Baseline Calibration

The period length is one quarter. Assuming $\sigma = 2$ is consistent with empirical estimates of the intertemporal elasticity of substitution.[18] We set $\phi = 1$, implying a unit labor supply elasticity. Our choice $\eta = 1$ implies an empirically plausible value of about 0.05 for the interest rate elasicity. We assign a standard value of 0.36 to the capital share in the production function, α. Setting $\beta = 0.99$ implies an average annual real return of about 4 percent. Assuming $\theta = 0.75$ means that the average lifetime of a price is equal to one year. We choose $\rho_m = 0.5$ and $\sigma_\varepsilon^2 = 0.1$, which is in line with the empirical evidence on the autoregressive process for M1 in the United States.[19] Consistent with a frictionless markup of 10 percent, we choose $\varepsilon = 11$.[20] Finally, we set $\epsilon_\psi = 3$.[21]

3.2 Results

We analyze impulse responses associated with a positive one standard deviation shock to the growth rate of money balances. We compare the baseline model with an alternative specification where firms have access to a rental market for capital.

We find that the inflation response to the shock is relatively smaller on impact in the baseline model. However, it becomes eventually larger than the corresponding level in the rental market specification. Moreover, the output reaction is larger in the baseline model both on impact and during the transition. This is shown in Figure 1. The intuition is as follows: to the extent that prices are sticky a positive monetary policy shock affects real interest rates and stimulates aggregate demand. This implies an increase in current and future expected marginal costs. Without a rental market for capital a price setter is more reluctant to change its price in response to the shock. The reason is that the firm takes into account that its marginal cost is affected, to some extent, by the chosen price: due to the restrictions on a firm's capital adjustment a price increase is associated with a decrease in its marginal cost. This effect is absent if a rental market for capital is assumed. In

[18] See, e.g., Basu and Kimball (2003) and the references herein.
[19] Our calibration of ϕ, α, β, θ, ρ_m, and σ_ε^2 is justified in Galí (2000) and the references herein.
[20] This is consistent with the empirical estimate in Galí et al. (2001).
[21] This value is justified in Woodford (2003, Ch. 5) and the references herein.

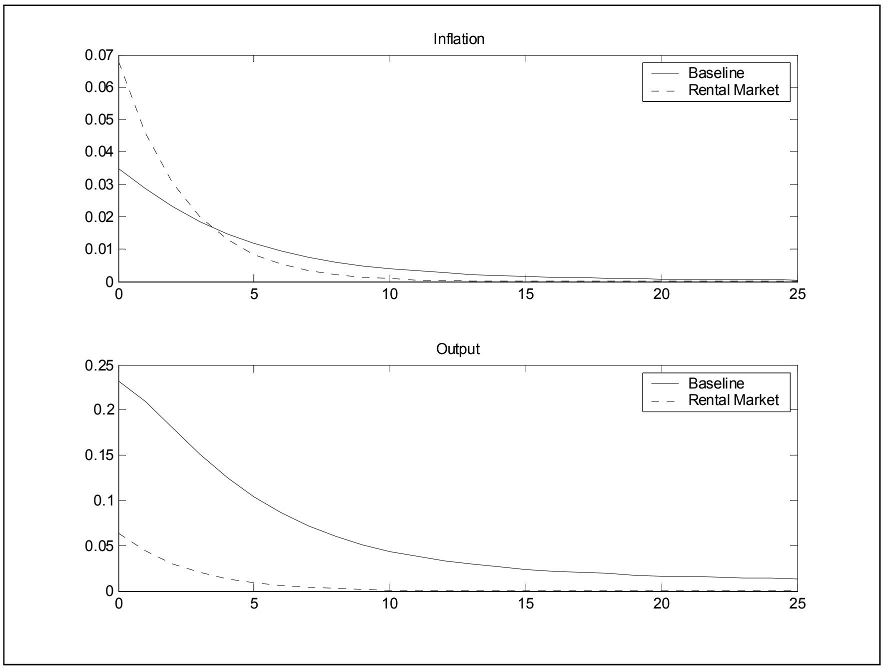

Figure 1: Inflation and output response to a monetary policy shock in the baseline model compared with the rental market specification.

that case each firm produces at the same marginal cost, which is independent of the quantity an individual firm supplies. This means that for any given restriction on price adjustment there is additional price stickiness in the baseline model with respect to the rental market specification.

In order to assess if the differences between the two models are quantitatively important we construct a simple metric, which is based on the following observation: it is possible to reproduce the impulse responses associated with the baseline model if we increase the degree of price stickiness in the model with a rental market for capital.[22] We find that the differences in the impulse responses shown in Figure 1 are as important as a change in the average expected lifetime of a price from 4 to about 10 quarters in the rental market model. Recently, it has been argued (on intuitive grounds) that the assumption of a rental market for capital in a Calvo style sticky price model might be problematic because the researcher who uses such

[22] For the abovementioned reasons we restrict attention to the simple inflation equation (32) in the baseline model. This implies that the price stickiness parameter in the rental market specification can be adjusted in such a way that we recover *exactly* the same equilibrium dynamics as in the baseline case. The value is $\theta = 0.9007$, if the other parameters are held at their baseline values.

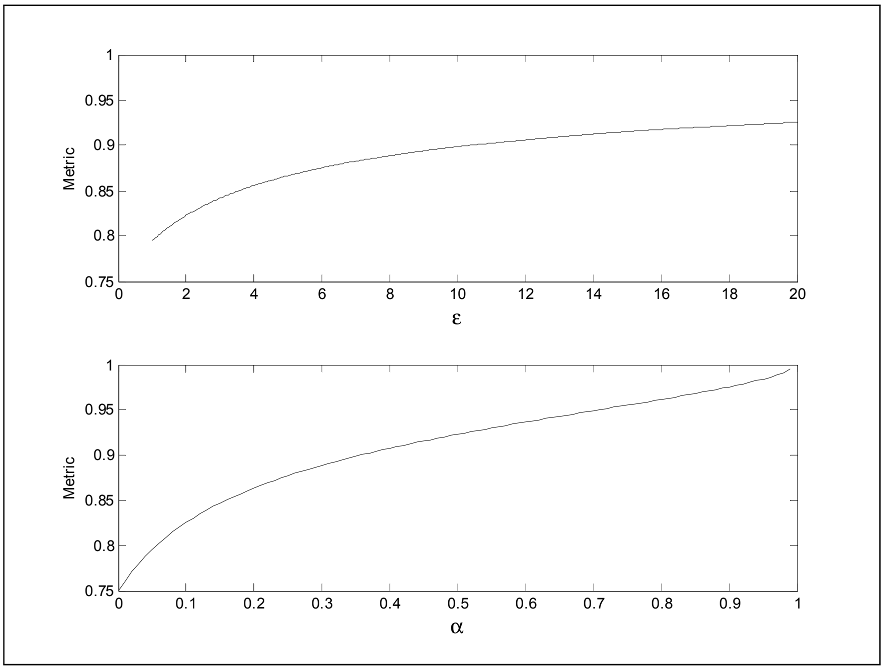

Figure 2: Relationship between the metric and parameters ε and α.

a model for empirical analysis would tend to overestimate the degree of price stickiness. For instance, Smets and Wouters (2003) amend their empirical analysis with a caveat of this kind. Their estimate of the expected lifetime of a price is two and a half years, which is far fetched. Our theoretical result shows that this somewhat puzzling finding might reflect the quantitative consequences of the rental market assumption. Our result sheds also light on a finding by Christiano et al. (2001). Their empirical estimate of the price stickiness parameter in a Calvo style model with capital accumulation and a rental market is 'driven to unity'. They claim that this is an unappealing feature of sticky price models. However, we tend to interpret their finding as an artefact of the rental market assumption.[23]

Of course, the adjustment of the price stickiness parameter that is needed in the rental market model in order to generate the same equilibrium dynamics as in the baseline model depends on the calibration. This is shown in Figure 2. First, if the elasticity of substitution between goods, ε, increases then a price setter is more

[23]It should be noticed, however, that both Smets and Wouters (2003) and Christiano et al. (2001) assume an investment adjustment cost combined with other features that are not present in the models we compare in the present paper.

reluctant to change its price in the baseline model. The reason is that a higher value of ε implies that a firm's price setting decision has a stronger impact on its marginal cost. Therefore, more price stickiness is needed in the rental market model in order to make the two impulse responses coincide. This is shown in the upper panel of Figure 2. Second, an increase in the capital share in the production function, α, has a similar effect: it increases the price setters' reluctance to change their prices in the baseline model. As is shown in the lower panel of Figure 2, the latter implies that more price stickiness is needed in the rental market model in order to generate the same equilibrium dynamics as in the baseline model.

4 Conclusion

We should emphasize the main contribution of our paper and some of the issues that are left for future research. We analyze New-Keynesian models with staggered price setting à la Calvo and a convex adjustment cost in the process of capital accumulation. In the baseline model it is assumed that firms do not have access to a rental market for capital. We compare this model with an alternative specification where a rental market is assumed. Our main finding is that the difference in implied equilibrium dynamics is large and we propose a metric, which gives a precise quantitative meaning to that statement. This theoretical result sheds light on some of the puzzling empirical findings that have been obtained using New-Keynesian models with staggered price setting and a rental market for capital.

Clearly, our model is very simplistic and lacks many aspects that seem to be relevant for investment decisions by firms in the real economy. A natural extension is to introduce convex adjustment costs in investment into the model developed so far. The latter will help producing empirically desirable features like a hump shaped output response to a monetary policy shock. The model presented in this paper is not capable of producing this pattern. However, we conjecture that our main result is robust as long as some restriction on capital accumulation is introduced into the model: the widely used assumption of a rental market for capital does not appear to be innocuous in a model with staggered price setting.

Appendix: Price Setting and Investment

A time t price setter i chooses contingent plans for $\left\{P^*_{t+k}(i), K_{t+k+1}(i), N_{t+k}(i)\right\}_{k=0}^{\infty}$ in order to solve the following problem:[24]

$$\max \sum_{k=0}^{\infty} E_t \left\{Q_{t,t+k}\left[Y_{t+k}(i)P_{t+k}(i) - W_{t+k}N_{t+k}(i) - P_{t+k}I_{t+k}(i)\right]\right\}$$

s.t.

$$\begin{aligned}
Y_{t+k}(i) &= \left(\frac{P_{t+k}(i)}{P_{t+k}}\right)^{-\varepsilon} Y_{t+k}, \\
Y_{t+k}(i) &\leq N_{t+k}(i)^{1-\alpha} K_{t+k}(i)^{\alpha}, \\
I_{t+k}(i) &= I\left(\frac{K_{t+k+1}(i)}{K_{t+k}(i)}\right) K_{t+k}(i), \\
P_t(i) &= P^*_t(i), \\
P_{t+k+1}(i) &= \begin{cases} P^*_{t+k+1}(i) \text{ with prob. } 1-\theta \\ P_{t+k}(i) \text{ with prob. } \theta, \end{cases} \\
& K_t(i) \text{ given.}
\end{aligned}$$

Using the expressions for a firm's nominal marginal cost and the real marginal savings in its labor cost given in equations (12) and (15), respectively, it follows that $P^*_t(i)$ and $K_{t+1}(i)$ must satisfy the first order conditions given in equations (11) and (14), respectively. A firm j that is restricted to change its price at time t solves the same problem, except for the fact that it takes $P_t(j)$ as given.

[24] We use the notation and the definitions that have already been introduced in the main text.

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