DOCTORAL THESIS

"Essays on Sticky Prices, Aggregate Investment and Monetary Policy"

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Contents

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Barcelona, December 2004 Lutz Weinke

Foreword

How does capital accumulation affect inflation and output dynamics, and what are the consequences for monetary policy? We analyze these questions in a general equilibrium framework with monopolistic competition and staggered price setting.

The first chapter makes progress in explaining the role of capital accumulation for inflation and output dynamics. It is assumed that firms face restrictions regarding both price adjustment and capital accumulation. In this sense capital is firm-specific. The main result is that capital accumulation affects inflation dynamics primarily through its impact on the marginal cost. This mechanism is much simpler than the one implied by the analysis of the problem in the earlier related literature. The reason is that the latter has suffered from a conceptual mistake, as we note.

In the second chapter we compare the model with firm-specific capital 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.

The third chapter analyzes the desirability of alternative arrangements for the conduct of monetary policy. According to the Taylor principle a central bank should adjust the nominal interest rate by more than one-for-one in response to changes in current inflation. Most of the existing literature supports the view that by following this simple recommendation a central bank can avoid being a source of unnecessary fluctuations in economic activity. The third chapter explains why this conclusion is not robust with respect to the modeling of capital accumulation. We also identify some desirable properties interest rate rules. Interestingly, the results suggest a reinterpretation of monetary policy under Volcker and Greenspan: the empirically plausible characterization of monetary policy can explain the stabilization of macroeconomic outcomes observed in the early eighties for the U.S. economy. The Taylor principle in itself cannot.

In summary, we emphasize the importance of modeling a simultaneous price setting and investment decision at the firm level. Both the positive and the normative conclusions regarding the role of capital in a world with nominal rigidities change if attention is restricted to the price setting decision alone. The latter specification has been the standard modeling choice in the existing literature. This convenience is, however, not innocuous, as we show.

Since we wrote and circulated the papers on which my thesis is based other contributions that stress the fruitfulness of assuming firm-specific capital in a model with staggered price setting have mushroomed. I am happy to see the impact of my thesis on the way economists think about capital and prices.

Barcelona, December 2004 Lutz Weinke

The second and third chapter of the Ph.D. thesis were published in this article:
"New Perspectives on Capital, Sticky Prices, and the Taylor Principle"
(with Tommy Sveen), Journal of Economic Theory, 123 (2005), p. 21-39.

In the first footnote (1) of the article "Lumpy Investment, Sticky Prices, and the Monetary Transmission Mechanism" (with Tommy Sveen), Journal of Monetary Economics, 54S (2007), p. 23-36, you will find a note on the origins of the article.

Chapter 1

Pitfalls in the Modeling of Forward-Looking Price Setting and Investment Decisions

Abstract:[1] The first chapter makes progress in explaining the role of capital accumulation for inflation and output dynamics. We follow Woodford (2003, Ch. 5) in assuming Calvo pricing, combined with a convex capital adjustment cost at the firm level. The main result is that capital accumulation affects inflation dynamics primarily through its impact on the marginal cost. This mechanism is much simpler than the one implied by the analysis in Woodford's text. The reason is that his analysis suffers from a conceptual mistake, as we show. The latter has obscured the economic mechanism through which capital affects inflation and output dynamics in the Calvo model, as discussed in Woodford (2004).

1.1 Introduction

By now there exists a large literature studying business cycles using dynamic New-Keynesian (DNK) models, i.e. stochastic general equilibrium models with imperfect competition and nominal rigidities.[2] However, it is generally assumed that labor is the only productive input, or alternatively, that the

[1]The first version of the paper on which this chapter is based has been circulated as Norges Bank Working Paper 2004/1, Oslo, February 11, 2004, http://www.norges-bank.no/publikasjoner/arbeidsnotater/.

[2]See, e.g., Clarida et al. (1999) and Chari et al. (2000).

capital stock in the economy is constant.[3] Woodford (2003, p. 352) comments on these modeling choices: '[...] while this has kept the analysis of the effects of interest rates on aggregate demand quite simple, one may doubt the accuracy of the conclusions obtained, given the obvious importance of variations in investment spending both in business fluctuations generally and in the transmission mechanism for monetary policy in particular.'

DNK models that introduce capital accumulation typically assume a rental market.[4] In the present paper we follow Woodford (2003, Chapt. 5) in assuming firm-specific capital: staggered price setting à la Calvo is combined with a convex capital adjustment cost at the firm level.[5] Along the way we show that the analysis in Woodford's text suffers from a conceptual mistake. In a nutshell: he does not assess correctly over what set of future states of the world an optimizing Calvo price setter forms expectations.[6]

The ultimate goal of the present chapter is to assess the role of endogenous firm-specific capital for inflation and output dynamics. To this end we analyze impulse responses to a shock in the exogenous growth rate of money balances[7] for two cases: the baseline model with endogenous capital (henceforth baseline) and a specification with decreasing returns to scale resulting from a constant capital stock at the firm level (henceforth DRS). We find the

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[3] Erceg et al. (2000) assume a constant aggregate capital stock combined with a rental market for capital, while Sbordone (2002) and Galí et al. (2001) assume constant capital at the firm level.

[4] See, e.g., Yun (1996), Smets and Wouters (2003), Christiano et al. (2004), and Schmitt-Grohé and Uribe (2004). However, Sveen and Weinke (2003, 2004a,b) show that the rental market assumption is not innocuous in a model with staggered price setting.

[5] Since we wrote and circulated the first version of the present chapter there have been other contributions studying firm-specific capital in a Calvo-style model. See, e.g., Altig et al. (2004), Christiano (2004), Eichenbaum and Fisher (2004), and Woodford (2004).

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

[7] In the above mentioned first working paper version of the present chapter we solve the model using an iterative procedure. In this chapter the computationally more efficient algorithm proposed by Woodford (2004) is employed.

following: first, the response of output is larger in the baseline model – both on impact and during the transition period. Second, the inflation dynamics are similar in the two models.

The intuition is surprisingly simple: first, endogenous capital at the firm level affects inflation dynamics primarily through its impact on the marginal cost. The inflation equation, however, changes only to a negligible extent with respect to the one derived by Sbordone (2002) and Galí et al. (2001) under the assumption that the capital stock is constant at the firm level. Second, there are two opposite effects from capital accumulation on the determination of the marginal cost. On the one hand, the additional production triggered by investment demand increases the marginal cost in the baseline model with respect to the DRS specification. On the other hand, the resulting additional capital increases the economy's productive capacity, thereby decreasing the marginal cost. The latter is anticipated by forward-looking price setters. This explains why the two models display similar inflation dynamics even though the output response is consistently larger with endogenous firm-specific capital.

This mechanism is indeed much simpler than the one outlined in Woodford (2003, Ch. 5). His analysis implies that firm-specific capital combined with Calvo pricing results in a substantial change in the dynamic relationship between the average real marginal cost and inflation. This has obscured the economic mechanism through which capital affects inflation and output dynamics, as discussed in Woodford (2004).[8]

The remainder of the chapter is organized as follows: Section 1.2 outlines the baseline model. In particular, it is shown why the price setting prob-

[8] One particularly problematic feature of the inflation equation in Woodford (2003, Ch. 5) is that an increase in expected future marginal cost may result in a decrease in current inflation. Thanks to Larry Christiano for drawing our attention to this point.

lem associated with that structure has not been solved in a correct way in Woodford (2003, Ch. 5). In Section 1.3 we present and interpret our results. Section 1.4 concludes.

1.2 The Model

We follow the general equilibrium structure outlined in Woodford (2003, Ch. 5).[9] There are two sectors, households and firms. Households choose labor supply and consumption demand. They have access to complete financial markets and supply labor in a perfectly competitive market. Firms produce differentiated goods and act under monopolistic competition. They face restrictions on both price adjustment and capital accumulation.

The only aggregate uncertainty comes from the growth rate of money balances, which we assume to follow an $AR(1)$ process:

$$\Delta m_t = \rho_m \Delta m_{t-1} + \varepsilon_t, \tag{1.1}$$

where Δ denotes the difference operator, and m_t is the log of nominal money balances M_t at time t. The autoregressive parameter, ρ_m, is assumed to be strictly positive and less than one. Finally, ε_t is assumed to be *iid* with zero mean and variance σ_ε^2.

1.2.1 Households

A representative household maximizes expected discounted utility:

$$E_t \sum_{k=0}^{\infty} \beta^k U\left(C_{t+k}, N_{t+k}\right), \tag{1.2}$$

[9] His model is more general than ours. However, this is irrelevant for our dicussion of the conceptual mistake in his treatment of optimal price-setting with endogenous capital.

where E_t denotes the expectational operator conditional on information available up to time t. Furthermore, $U(\cdot)$ is period utility, and parameter β is the discount factor. Hours worked in period t are denoted N_t. Finally, $C_t \equiv \left(\int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon}{\varepsilon-1}}$ denotes the time t Dixit-Stiglitz consumption aggregator, and parameter ε is the elasticity of substitution between different varieties of goods $C_t(i)$.

The maximization is subject to a sequence of budget constraints:

$$\int_0^1 P_t(i)\, C_t(i)\, di + E_t\{Q_{t,t+1}D_{t+1}\} \leq D_t + W_t N_t + T_t, \tag{1.3}$$

where $Q_{t,t+1}$ and D_{t+1} denote, respectively, the stochastic discount factor for random nominal payments and the nominal payoff associated with the portfolio held at the end of period t. Moreover, $P_t(i)$ gives the nominal price of variety i at time t, W_t is the nominal wage as of that period, and T_t denotes profits resulting from ownership of firms.

We assume a standard period utility:

$$U(C_t, N_t) = \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\phi}}{1+\phi}, \tag{1.4}$$

where parameter σ denotes household's relative risk aversion, and parameter ϕ can be interpreted as the the inverse of the aggregate Frisch labor supply elasticity.

Cost minimization by households implies that for each variety of goods the consumption demand function reads:

$$C_t^d(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon} C_t, \tag{1.5}$$

where $P_t \equiv \left(\int_0^1 P_t(i)^{1-\varepsilon} di\right)^{\frac{1}{1-\varepsilon}}$ denotes the price index. The latter has the property that the minimum expenditure required to purchase a bundle of goods resulting in C_t units of the composite good is given by $P_t C_t$.

The remaining first order conditions associated with the household's problem are as follows:

$$C_t^{\sigma} N_t^{\phi} = \frac{W_t}{P_t}, \tag{1.6}$$

$$\beta \left(\frac{C_{t+1}}{C_t}\right)^{-\sigma} \left(\frac{P_t}{P_{t+1}}\right) = Q_{t,t+1}. \tag{1.7}$$

The first equation is the optimality condition for labor supply, and the second is a standard intertemporal optimality condition. Finally, let us note that the price of a risk-less one-period bond is given by $R_t^{-1} = E_t Q_{t,t+1}$, where R_t denotes the gross nominal interest rate.

1.2.2 Firms

Firms are indexed on the unit interval. Each firm has access to a Cobb-Douglas production technology:

$$Y_t(i) = K_t(i)^{\alpha} N_t(i)^{1-\alpha}, \tag{1.8}$$

where $K_t(i)$ and $N_t(i)$ denote, respectively, capital holdings and labor input used by firm i in its period t production denoted $Y_t(i)$. Parameter α is the capital share.

Each firm i makes an investment decision at any point in time with the resulting additional capital becoming productive one period after the investment decision is made. As in Woodford (2003, Ch. 5) we assume the following: first, the investment good is a Dixit-Stiglitz aggregate of all of the goods in the economy with the same constant elasticity of substitution as in the consumption aggregate. Second, firms face a convex adjustment cost of changing their capital holdings. Given firm i's time t capital stock $K_t(i)$ the amount of the composite good $I_t(i)$ that has to be purchased by that firm at this point in time in order to have a capital stock $K_{t+1}(i)$ in place in the next period is given by:

$$I_t(i) = I\left(\frac{K_{t+1}(i)}{K_t(i)}\right) K_t(i). \tag{1.9}$$

Function $I(\cdot)$ has the following characteristics: $I(1) = \delta$, $I'(1) = 1$, and $I''(1) = \epsilon_\psi$. Parameter δ denotes the depreciation rate. Eichenbaum and Fisher (2004) interpret parameter ϵ_ψ as the elasticity of the investment to capital ratio with respect to Tobin's q, evaluated in steady state. Parameter ϵ_ψ is assumed to be strictly larger than zero and it measures the convex capital adjustment cost in a log-linear approximation to the equilibrium dynamics.

Firms post sticky prices à la Calvo (1983), i.e. each period a measure $(1-\theta)$ is randomly selected. Those firms change their prices and the remaining firms post their last period's nominal prices. Cost minimization by firms and households implies that demand for each individual good i in period t can be written as follows:

$$Y_t^d(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon} Y_t^d, \tag{1.10}$$

where $Y_t^d \equiv C_t + I_t$ denotes aggregate time t demand, and $I_t \equiv \int_0^1 I_t(i)\, di$ is aggregate time t investment demand.

With probability θ^k a price that was chosen at time t will still be posted at time $t+k$. When setting a new price $P_t^*(i)$ in period t firm i maximizes the current value of its dividend stream over the expected lifetime of the chosen price. Formally, given $K_t(i)$ a time t price setter 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:[10]

$$\max \sum_{k=0}^{\infty} E_t \left\{Q_{t,t+k} \left[Y_{t+k}^{d}(i) P_{t+k}(i) - W_{t+k} N_{t+k}(i) - P_{t+k} I_{t+k}(i)\right]\right\} \quad (1.11)$$

s.t.

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

The implied first order condition for capital accumulation reads:

$$\frac{dI_t(i)}{dK_{t+1}(i)} P_t = E_t \left\{Q_{t,t+1} \left[MS_{t+1}(i) - \frac{dI_{t+1}(i)}{dK_{t+1}(i)} P_{t+1}\right]\right\}, \quad (1.12)$$

where $MS_{t+1}(i)$ denotes the nominal marginal savings in firm i's labor cost associated with having one additional unit of capital in place in period $t+1$. The intuition behind the last equation is the following: the marginal cost of installing an additional unit of capital at time t (including the adjustment cost) is equalized to the expected discounted marginal contribution to the firm's value associated with having that additional unit of capital in place at point in time $t+1$. The latter is given by the marginal return from using it for production, $MS_{t+1}(i)$, and selling the remaining capital after depreciation (net of the change in the time $t+1$ adjustment cost that is associated with the time t investment decision). As has been emphasized by Woodford (2003, Ch. 5), the relevant measure of the marginal return to capital is the marginal savings in a firm's labor cost: firms are demand constrained and hence the

[10] 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.

return from having an additional unit of capital in place results from the fact that this allows to produce the quantity that happens to be demanded using less labor.

The following relationship holds true:

$$MS_t(i) = W_t \frac{MPK_t(i)}{MPL_t(i)}, \tag{1.13}$$

where $MPK_t(i)$ and $MPL_t(i)$ denote, respectively, the marginal product of capital and labor of firm i in period t.

The first order condition for price setting is given by:

$$\sum_{k=0}^{\infty} \theta^k E_t \left\{ Q_{t,t+k} Y_{t+k}^d(i) \left[P_t^*(i) - \mu MC_{t+k}(i) \right] \right\} = 0, \tag{1.14}$$

where $\mu \equiv \frac{\varepsilon}{\varepsilon - 1}$ is the frictionless mark-up over marginal costs, and $MC_t(i)$ denotes the nominal marginal cost of firm i in period t. The latter is given by:

$$MC_t(i) = \frac{W_t}{MPL_t(i)}. \tag{1.15}$$

Equation (1.14) is the familiar first order condition implied by the Calvo model: optimizing price setters behave in a forward-looking manner, i.e. they take into account not only current but also future expected marginal costs in those states of the world where the chosen price is still posted.[11] The only non-standard feature in equation (1.14) is that capital affects labor productivity and hence a firm's marginal cost. This aspect of a firm's price setting decision results in an intricate problem. As we argue next, the latter has not been solved in a correct way in Woodford (2003, Ch. 5).

[11] We follow a large literature on the Calvo model in using the notation E_t in equation (1.14) to indicate an expectation that is conditional on the time t state of the world, but integrating only over those future states in which firm i has not reset its price since period t. Woodford (2004) uses $\widehat{E}_t^i$ in order to denote this expectation.

1.2.3 A Short Note on Woodford's Conceptual Mistake

To fix ideas we represent firm i's price setting problem at time t by a simple tree, which consists of the states of the world that are consistent with the current state S. This is shown in Figure 1. Equations (1.14) and (1.15) prescribe that the relevant capital holdings are associated with those states of the world where the newly set price is still posted. We refer to these states as the Calvo states. In Figure 1 they are assumed to correspond to nodes S, $S0$, $S00$,... in the tree. Firm i's capital stock at node S is predetermined.

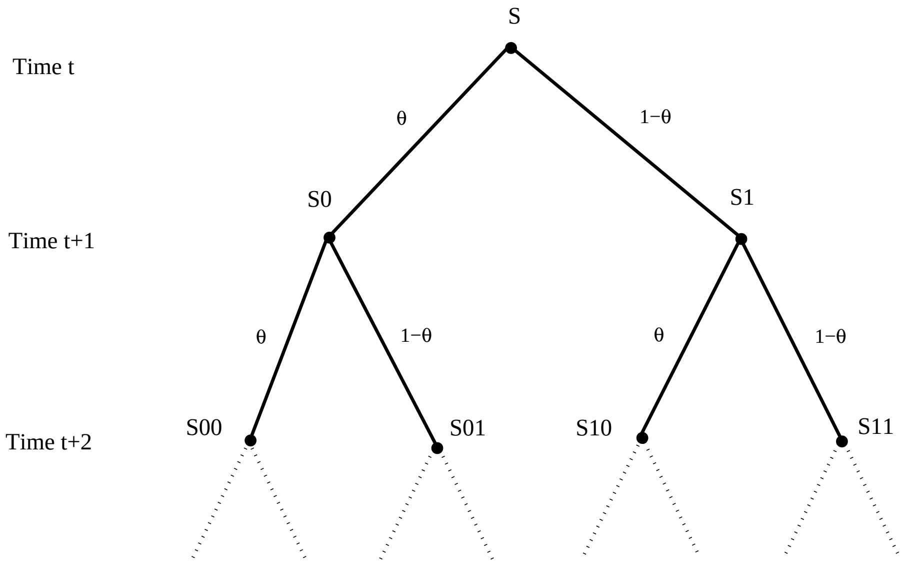

Figure 1: Price setting with firm-specific capital accumulation.

The conceptual mistake in Woodford (2003, pp. 688 - 690) is that he computes firm i's time t expectation of its future capital holdings in the Calvo states without acknowledging that this expectation depends on that firm's time t expectation regarding its future *optimally* chosen prices. Specifically, he restricts attention to firm i's time t expectation of its future relative prices in the Calvo states. This is not correct, as we show next.

Clearly, it is enough to show that firm i's time t expectation regarding one of its future capital holdings in the Calvo states is computed in an incorrect way. To this end we consider firm i's time t choice of its next period's capital stock. Equations (1.12) and (1.13) state that this choice takes rationally into account that firm i's time $t+1$ price might be *optimally* chosen. But this means that the *possibility* of choosing a new price in period $t+1$ affects a price setter's time t investment decision and hence its time $t+1$ capital stock, *in particular*, if node S0 is reached at point in time $t+1$. Therefore, firm i's time t expectation regarding its capital holdings in the Calvo states does depend on its time t expectation regarding future *optimally* chosen prices, as we have claimed.

1.2.4 Market Clearing

Clearing of the labor market requires that hours worked, N_t, are given by the following equation, which holds for all t:

$$N_t = \int_0^1 N_t(i)\, di. \tag{1.16}$$

Moreover, it is useful to define time t aggregate capital $K_t \equiv \int_0^1 K_t(i)\, di$ and auxiliary variable $Y_t \equiv K_t^{\alpha} N_t^{1-\alpha}$.[12]

For each variety i supply, $Y_t(i)$, must equal demand:

$$Y_t(i) = C_t^d(i) + I_t^d(i), \tag{1.17}$$

where $I_t^d(i)$ denotes investment demand for good i.

[12] The difference between Y_t and aggregate output in the economy is of the second order.

1.2.5 Linearized Equilibrium Conditions

We restrict attention to a log-linear approximation to the equilibrium dynamics around a steady state with zero inflation. In what follows, the percent deviation of a variable with respect to its steady state value is denoted by a hat.

Households

Log-linearizing and rearranging the first order condition (1.7) we obtain the household's Euler equation:

$$\widehat{C}_t = E_t\widehat{C}_{t+1} - \frac{1}{\sigma}\left(i_t - E_t\pi_{t+1} - \rho\right), \tag{1.18}$$

where i_t denotes the time t nominal interest rate, and $\pi_t \equiv \log\left(\frac{P_t}{P_{t-1}}\right)$ is the rate of inflation. Finally, the time discount rate is given by $\rho \equiv -\log\beta$.

Log-linearizing the household's labor supply equation (1.6) results in:

$$\widehat{\left(\frac{W_t}{P_t}\right)} = \phi\widehat{N}_t + \sigma\widehat{C}_t. \tag{1.19}$$

For convenience, we just assume a standard demand for real balances $\frac{M_t}{P_t}$:

$$\widehat{\left(\frac{M_t}{P_t}\right)} = \widehat{Y}_t - \eta\left(i_t - \rho\right), \tag{1.20}$$

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

Firms

We log-linearize the first order condition for investment (1.12) and average over all firms in the economy.[13] Combining the resulting relationship with the

[13] For details see Woodford (2003, Ch. 5).

Euler equation (1.18) we obtain the following law of motion of the aggregate capital stock:

$$\begin{aligned}\Delta K_{t+1} &= \beta E_t \Delta K_{t+2} + \frac{1}{\epsilon_\psi} E_t \left\{ (1-\beta(1-\delta)) \widehat{ms}_{t+1} \right. \\ &\quad \left. - (i_t - E_t \pi_{t+1} - \rho) \right\}. \end{aligned} \tag{1.21}$$

where $ms_t \equiv \int_0^1 \frac{MS_t(i)}{P_t} di$ denotes the average real marginal savings in labor costs at time t.

The inflation equation is derived from averaging optimal price setting decisions and aggregating prices via the price index. A natural starting point is the log-linearized real marginal cost at the firm level. The latter reads:

$$\widehat{mc}_t(i) = \widehat{mc}_t - \frac{\varepsilon\alpha}{1-\alpha} \widehat{p}_t(i) - \frac{\alpha}{1-\alpha} \widehat{k}_t(i), \tag{1.22}$$

where $k_t(i) \equiv \frac{K_t(i)}{K_t}$ and $mc_t \equiv \int_0^1 \frac{MC_t(i)}{P_t} di$ denotes the average time t real marginal cost in the economy.

We refer to $\widehat{k}_t(i)$ as firm i's capital gap at time t. The intuition behind equation (1.22) is the following: for a zero capital gap a firm that posts a higher than average price faces a lower than average marginal cost due to the implied increase in its marginal product of labor. This is reflected in the second term, and it is exactly as in Sbordone (2002) and Galí et al. (2001) for models with decreasing returns to scale and labor as the only variable input in production. With capital accumulation there is an extra effect coming from the firm's capital stock, which corresponds to the last term. Conditional on posting the average price in the economy a firm that has a higher than average capital stock in place faces a lower than average marginal cost. The reason is that the marginal product of labor increases with the capital stock used by the firm.

Invoking equations (1.14) and (1.22) the optimal relative price of firm i

at time t, $p_t^*(i) \equiv \frac{P_t^*(i)}{P_t}$, can be log-linearized as:

$$\widehat{p_t^*}(i) = \sum_{k=1}^{\infty} (\beta\theta)^k E_t \pi_{t+k} + \xi \sum_{k=0}^{\infty} (\beta\theta)^k E_t \widehat{mc}_{t+k} - \psi \sum_{k=0}^{\infty} (\beta\theta)^k E_t \widehat{k}_{t+k}(i), \tag{1.23}$$

where $\xi \equiv \frac{(1-\beta\theta)(1-\alpha)}{1-\alpha+\varepsilon\alpha}$, and $\psi \equiv \frac{(1-\beta\theta)\alpha}{1-\alpha+\varepsilon\alpha}$.[14] Hence, in addition to the usual 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 (random) lifetime of the chosen price.

Woodford (2004) shows that the associated inflation equation takes the following simple form:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa\, \widehat{mc}_t, \tag{1.24}$$

where κ is a parameter which he computes numerically.[15]

Finally, we note that the aggregate production function is given by:

$$\widehat{Y}_t = \alpha \widehat{K}_t + (1-\alpha)\widehat{N}_t. \tag{1.25}$$

Market clearing

Since equation (1.17) holds for each variety in the economy we are entitled to integrate on both sides. Log-linearizing the resulting equation we obtain the aggregate goods market clearing condition:

$$\widehat{Y}_t = \zeta \widehat{C}_t + (1-\zeta)\frac{1}{\delta}\left[\widehat{K}_{t+1} - (1-\delta)\widehat{K}_t\right], \tag{1.26}$$

where $\zeta \equiv \frac{\rho+\delta(1-\alpha)}{\rho+\delta}$ denotes the steady state consumption to output ratio. The steady state capital to output ratio is given by $(1-\zeta)\frac{1}{\delta}$.

[14] The variables in (1.23) are constant in the steady state.

[15] See the Appendix for an outline of the Woodford (2004) solution.

1.3 Equilibrium Dynamics

Given the specification of monetary policy in (1.1), the equilibrium processes for the nominal interest rate, consumption, real wage, real balances, capital, inflation, output, and hours are given by equations (1.18), (1.19), (1.20), (1.21), (1.24), (1.25), and (1.26). The relevant average marginal products entering the average real marginal cost and marginal savings in labor costs are obtained from $Y_t \equiv K_t^{\alpha} N_t^{1-\alpha}$. We analyze impulse responses to a positive one standard deviation shock in the growth rate of money balances.

1.3.1 Calibration

The period length is one quarter. We choose $\epsilon_{\psi} = 3$, as suggested by Woodford (2003, Ch. 5) and the references herein. The intertemporal elasticity of substitution is given by $\frac{1}{\sigma}$. Assuming $\sigma = 2$ is in line with empirical estimates.[16] Consistent with a unit labor supply elasticity, we assume $\phi = 1$. The semi-elasticity of demand for real balances with respect to the nominal interest rate, η, is set to unity implying an empirically plausible value of about 0.05 for the interest rate elasticity. The capital share in the production function, α, is 0.36. We set $\beta = 0.99$ implying an average annual real return of about 4 percent. Setting $\theta = 0.75$ means that the average lifetime of a price is equal to one year. Consistent with the estimated autoregressive process for M1 in the United States we assume $\rho_m = 0.5$ and $\sigma_{\varepsilon}^2 = 0.1$.[17] Setting $\varepsilon = 11$ implies a frictionless markup of 10 percent.[18]

[16] See, e.g., Basu and Kimball (2003) and the references herein.

[17] Our calibration of parameters ϕ, α, β, θ, ρ_m, and σ_{ε}^2 is justified in Galí (2003) and the references herein.

[18] This is consistent with the estimate in Galí et al. (2001).

1.3.2 Results

We compare the responses to a monetary policy shock for the baseline model and a specification with decreasing returns to scale resulting from a constant capital stock at the firm level. The result is shown is Figure 2: first, output is higher in the former – both on impact and during the transition period. Second, the inflation dynamics are similar in the two models.

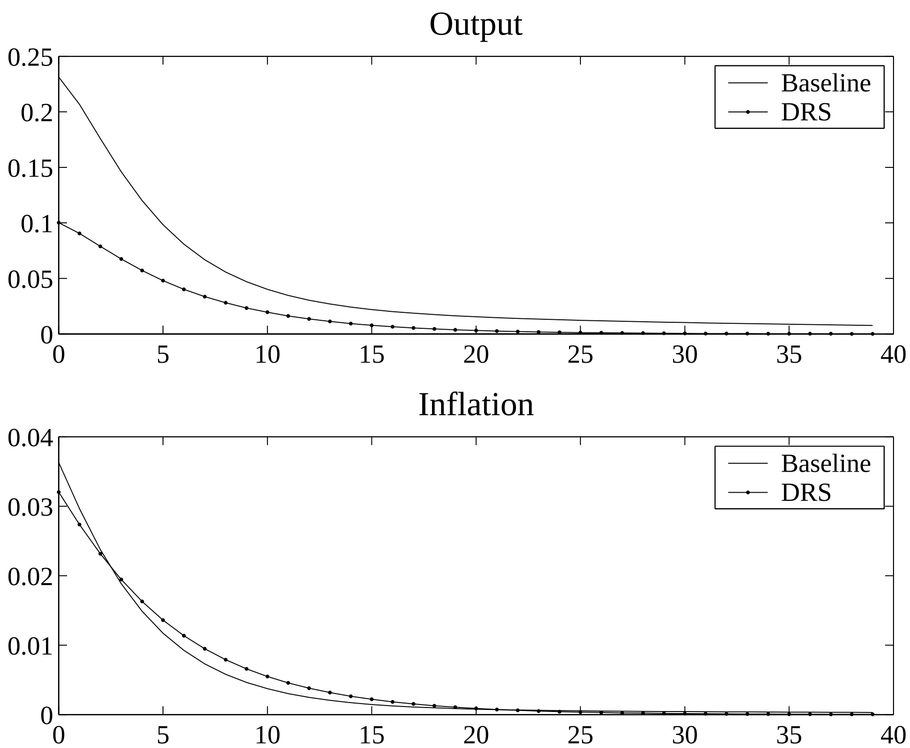

Figure 2: Endogenous firm-specific capital vs. fixed capital.

Let us develop the intuition behind our result. We start by observing that firm-specific capital affects inflation dynamics primarily through its impact on the marginal cost. The form of the inflation equation, however, is only affected to some negligible extent by the feature of capital accumulation at the firm level: if κ in equation (1.24) is approximated by the coefficient premultiplying the marginal cost in the inflation equation associated with the DRS specification,[19] then the resulting loss in accuracy is negligible, as shown in Figure 3.[20] The reason is as follows. To the extent that there exists a capital adjustment cost the firm's investment decision is forward-looking. If the planning horizon for the investment decision is long enough, then price setters and non-price setters do not make very different investment decisions, on average. The fact that they face the same probabilities of being allowed or restricted to change their prices over the relevant planning horizon leads to a small difference in their current investment decisions and, more generally, in their expected investment policies.

Next we note that there are two counteracting effects from capital accumulation on the determination of the marginal cost. On the one hand, investment spending adds to aggregate demand, thereby implying higher production and an increase in the marginal cost in response to the shock. On the other hand, the additional capital resulting from investment spending in one period increases the economy's productive capacity in subsequent periods. This implies a decrease in marginal costs.

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[19]Sbordone (2002) and Galí et al. (2001) show that this coefficient takes the following form: $\frac{(1-\beta\theta)(1-\theta)}{\theta}\frac{1-\alpha}{1+\alpha(\varepsilon-1)}$.

[20]We acknowledge a tiny difference between the baseline impulse responses reported in the first working paper version of the present chapter and the ones shown in Figures 2 and 3. This is, however, negligible: for each variable the maximum difference is more than eight times smaller than the corresponding maximum difference in Figure 3. The reason for why we formerly did not choose an even higher accuracy lies in the lack of computational efficiency of the iterative procedure that we used to solve the model.

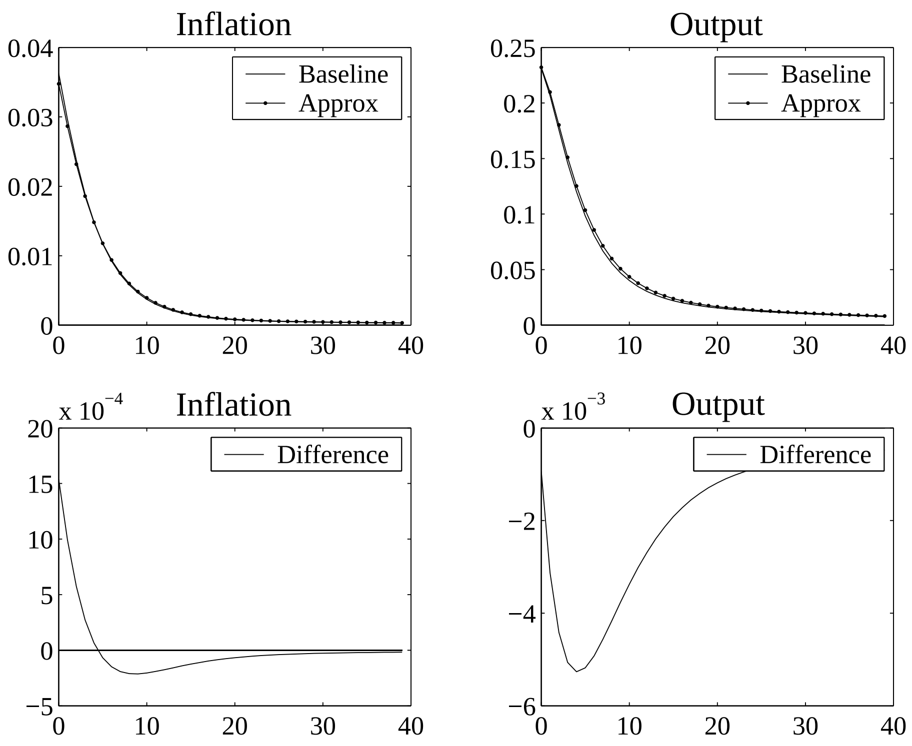

Figure 3: Capital works through the marginal cost.

The intuition behind the results shown in Figure 2 is therefore surprisingly simple. First, firm-specific capital affects inflation dynamics primarily through its impact on the marginal cost. Second, there are two counteracting effects from endogenous capital accumulation on the determination of the marginal cost. The latter is anticipated by forward-looking price setters. This explains why the baseline model and the DRS specification display similar inflation dynamics even though the output response is consistently larger in the former.

1.4 Conclusion

The present chapter makes progress in explaining the economic mechanism through which capital accumulation affects inflation and output dynamics. We use a Calvo-style model with a convex capital adjustment cost at the firm level. Our main finding is that firm-specific capital accumulation affects primarily the determination of the marginal cost. The form of the inflation equation, however, changes only to a negligible extent compared with a model where the capital stock at the firm level is assumed to be constant. Combined with the fact that investment demand has counteracting effects on the determination of the marginal cost this leads to a surprisingly simple intuition for the associated inflation and output dynamics. This economic mechanism has been obscured by a conceptual mistake in Woodford (2003, Ch. 5), as we show.

In related work Sveen and Weinke (2003, 2004a,b) find that the convenient and widely used alternative modeling choice of assuming a rental market for capital is not innocuous. Hence, it is worthwhile modeling a simultaneous price setting and investment decision at the firm level. This highlights the importance of the insights developed in the first chapter, as also documented by the results in Altig et al. (2004), Christiano (2004), Eichenbaum and Fisher (2004), and Woodford (2004).

Appendix: Inflation Dynamics

Woodford (2004) posits that the price chosen by a Calvo price setter i is:

$$\widehat{p}_t^* (i) = \widehat{p}_t^* - \tau_1 \widehat{k}_t (i) , \qquad \text{(A1)}$$

where τ_1 is an unknown parameter. He further assumes that the investment decision of any firm j satisfies:

$$\widehat{k}_{t+1} (j) = \tau_2 \widehat{k}_t (j) + \tau_3 \widehat{p}_t (j) , \qquad \text{(A2)}$$

where τ_2 and τ_3 are two additional unknown parameters.

Finally, he invokes the relationship between the log-linearized average newly set price, $\widehat{p}_t^*$, and inflation, π_t:

$$\pi_t = \frac{1-\theta}{\theta} \widehat{p}_t^* . \qquad \text{(A3)}$$

Combined with the first-order conditions for price setting and investment it is possible to pin down the unknown coefficients τ_1, τ_2, and τ_3 and to derive the inflation equation (2.5), along the lines outlined in Woodford (2004).

References

Altig, David, Lawrence J. Christiano, Martin Eichenbaum, and Jesper Linde (2004): "Firm-Specific Capital, Nominal Rigidities, and the Business Cycle", mimeo.

Basu, Susanto, and Miles S. Kimball (2003): "Investment Planning Costs and the Effects of Fiscal and Monetary Policy", mimeo.

Calvo, Guillermo (1983): "Staggered Prices in a Utility Maximizing Framework", *Journal of Monetary Economics*, 12(3), 383-398.

Casares, Miguel (2002), "Time-to-Build Approach in a Sticky Price, Sticky Wage Optimizing Monetary Model", European Central Bank Working Paper No. 147.

Chari, V. V., Patrick J. Kehoe, and Ellen R. McGratten (2000): "Sticky Price Models of the Business Cycle: Can the Contract Multiplier Solve the Persistence Problem", *Econometrica*, 68, 1151-1179.

Christiano, Lawrence J. (2004): "Firm-Specific Capital and Aggregate Inflation Dynamics in Woodford's Model", mimeo.

Christiano, Lawrence J., Martin Eichenbaum, and Charles Evans (2004): "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy", forthcoming in *Journal of Political Economy*.

Clarida, Richard, Jordi Galí, and Mark Gertler (1999): "The Science of Monetary Policy: a New Keynesian Perspective", *Journal of Economic Literature*, 37(4), 1661-1707.

Eichenbaum, Martin and Jonas D. M. Fisher (2004): "Evaluating the Calvo Model of Sticky Prices", NBER Working Paper 10617.

Erceg, Christopher J., Dale W. Henderson, and Andrew T. Levin (2000): "Optimal Monetary Policy with Staggered Wage and Price Contracts", *Journal of Monetary Economics*, 46(2), 281-313.

Galí, Jordi (2003): "New Perspectives on Monetary Policy, Inflation, and the Business Cycle", in M. Dewatripont, L. Hansen, and S. Turnovsky (editors), *Advances in Economics and Econometrics*, Volume III, 151-197, Cambridge University Press.

Galí, Jordi, Mark Gertler, and David López-Salido (2001): "European Inflation Dynamics", *European Economic Review*, 45(7), 1237-1270.

Sbordone, Argia M. (2002): "Prices and Unit Labor Costs: A New Test of Price Stickiness", *Journal of Monetary Economics*, 49, 265-292.

Smets, F. and R. Wouters (2003): "An Estimated Stochastic Dynamic General Equilibrium Model of the Euro Area", *Journal of the European Economic Association*, 1, 1123-1175.

Schmitt-Grohé, Stephanie, and Martin Uribe (2004): "Optimal Simple and Implementable Monetary and Fiscal Rules", NBER Working Paper 10253.

Sveen, Tommy, and Lutz Weinke (2003): "Inflation and Output Dynamics with Firm-owned Capital", Universitat Pompeu Fabra Working Paper No. 702.

Sveen, Tommy, and Lutz Weinke (2004a): "New Perspectives on Capital and Sticky Prices", Norges Bank Working Paper 2004/3.

Sveen, Tommy, and Lutz Weinke (2004b): "Firm-Specific Investment, Sticky Prices, and the Taylor Principle", Norges Bank Working Paper 2004/12.

Woodford, Michael (2003): *Interest and Prices: Foundations of a Theory of Monetary Policy*, Princeton University Press.

Woodford, Michael (2004): "Inflation and Output Dynamics with Firm-Specific Investment", Princeton University, mimeo.

Chapter 2

New Perspectives on Capital and Sticky Prices

Abstract:[1] We model capital accumulation in a dynamic New-Keynesian model with staggered price setting à la Calvo. Capital is assumed to be firm-specific, as analyzed in the first chapter. We now compare this model with an alternative specification where households accumulate capital and rent it to firms. The difference in implied equilibrium dynamics is large, as justified by 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.

2.1 Introduction

In the field of New-Keynesian macroeconomics there has been recent interest in models with staggered price setting that allow for capital accumulation.[2] The main reason is that many research questions can only be addressed if capital accumulation is taken into account.[3] Moreover, it has been argued

[1]The first version of the paper on which this chapter is based has been circulated as Norges Bank Working Paper 2004/3, Oslo, February 23, 2004, http://www.norges-bank.no/publikasjoner/arbeidsnotater/.

[2]For an early contribution see, e.g., Yun (1996).

[3]See, e.g., Galí et al. (2004). 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.

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.[4] 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 chapter fills that gap in the existing literature: the rental market case is compared with a baseline model with firm-specific capital. In both models staggered price setting à la Calvo is combined with 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 to a shock in the exogenous growth rate of money balances.

The 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

[4]Christiano et al. (2004) 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.

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 (2002) 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]

It is obvious that the theoretical insights developed in this chapter can be used to explain why the econometrician tends to overestimate the price stickiness in actual economies if aggregate data are analyzed through the lense of a dynamic New-Keynesian model featuring a rental market for capital. Therefore not surprisingly, Altig et al. (2004) and Eichenbaum and Fisher (2004) find that assuming firm-specific capital results in estimated values of

[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.

the Calvo parameter that appear to be in line with the micro evidence. It also follows from our results that some of the puzzling empirical findings in Christiano et al. (2004) and Smets and Wouters (2003) might be interpreted as an artefact of assuming staggered price setting combined with a rental market for capital.

The remainder of the chapter is organized as follows: Section 2.2 outlines the baseline model and the rental market specification. In Section 2.3 we conduct the above mentioned simulation exercise and interpret the results. Section 2.4 concludes.

2.2 Theoretical Framework

2.2.1 Firm-Specific Capital

The model with firm-specific capital has already been developed in the first chapter. As a reminder we just summarize the relevant log-linearized equilibrium conditions. The household's Euler equation:

$$\widehat{C}_t = E_t\widehat{C}_{t+1} - \frac{1}{\sigma}\left(i_t - E_t\pi_{t+1} - \rho\right). \tag{2.1}$$

The household's labor supply equation:

$$\widehat{\left(\frac{W_t}{P_t}\right)} = \phi\widehat{N}_t + \sigma\widehat{C}_t. \tag{2.2}$$

Demand for real balances:

$$\widehat{\left(\frac{M_t}{P_t}\right)} = \widehat{Y}_t - \eta\left(i_t - \rho\right). \tag{2.3}$$

Law of motion of the aggregate capital stock:

$$\begin{aligned}\Delta K_{t+1} &= \beta E_t\Delta K_{t+2} + \frac{1}{\epsilon_\psi}E_t\left\{(1-\beta(1-\delta))\widehat{ms}_{t+1}\right. \\ &\quad \left. - \left(i_t - E_t\pi_{t+1} - \rho\right)\right\}. \end{aligned} \tag{2.4}$$

Inflation equation:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa \, \widehat{mc}_t. \tag{2.5}$$

Aggregate production function:

$$\widehat{Y}_t = \alpha \widehat{K}_t + (1-\alpha) \, \widehat{N}_t. \tag{2.6}$$

Aggregate goods market clearing:

$$\widehat{Y}_t = \zeta \widehat{C}_t + (1-\zeta) \frac{1}{\delta} \left[\widehat{K}_{t+1} - (1-\delta) \, \widehat{K}_t \right]. \tag{2.7}$$

Monetary Policy:

$$\Delta m_t = \rho_m \Delta m_{t-1} + \varepsilon_t. \tag{2.8}$$

Again, the marginal products entering the average real marginal cost and marginal savings in labor costs are to be obtained from $Y_t \equiv K_t^{\alpha} N_t^{1-\alpha}$.

2.2.2 Rental Market for Capital

We now assume that the representative household accumulates the capital stock and rents it to intermediate goods firms. This is the only change with respect to the specification with firm-specific capital. The household maximizes the objective function given in (1.2) subject to the following sequences of constraints:

$$\begin{aligned} P_t \left(C_t + I_t \right) + E_t \left\{ Q_{t,t+1} D_{t+1} \right\} &\leq D_t + W_t N_t + R_t^k K_t + T_t, && (2.9) \\ I_t &= I \left(\frac{K_{t+1}}{K_t} \right) K_t. && (2.10) \end{aligned}$$

Again, function $I(\cdot)$ is assumed to have the characteristics outlined in the first chapter. 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 (1.6) and (1.7), respectively. The first order condition associated with the household's investment decision is:

$$\frac{dI_t}{dK_{t+1}}P_t = E_t\left\{Q_{t,t+1}\left[R^k_{t+1} - \frac{dI_{t+1}}{dK_{t+1}}P_{t+1}\right]\right\}. \tag{2.11}$$

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:

$$R^k_t = W_t\frac{MPK_t}{MPL_t}. \tag{2.12}$$

Log-linearizing equation (2.11) and invoking (2.1) we recover the same log-linearized law of motion of capital as the one given in equation (2.4). 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 therefore takes the following standard form:

$$\pi_t = \beta E_t\pi_{t+1} + \lambda\widehat{mc}_t, \tag{2.13}$$

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.[8]

[8] See Galí (2004) et al. for a detailed development of a Calvo- style model with a rental market for capital.

2.3 Results

Both the baseline model with firm-specific capital and the alternative rental market specification are calibrated as discussed in the first chapter.[9]

For both models we analyze impulse responses associated with a positive one standard deviation shock to the growth rate of money balances.

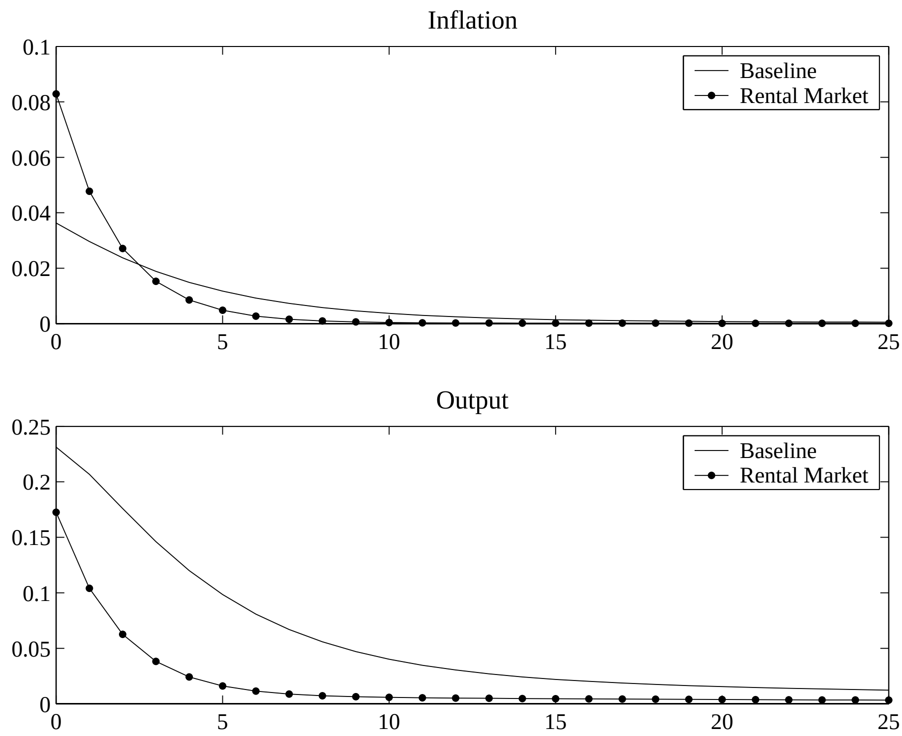

Figure 1: Endogenous firm-specific capital vs. rental market.

[9]It should be noted that in both cases we need to assign values to exactly the same set of structural parameters.

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 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. 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 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. (2004). 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.[10] From our theoretical results it is also plain that the estimated price stickiness must be considerably smaller, if the aggregate data are analyzed using a DNK model with firm-specific capital. This is confirmed by the empirical results in Altig et al. (2004) and Eichenbaum and Fisher (2004).[11]

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 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

[10] It should be noticed, however, that both Smets and Wouters (2003) and Christiano et al. (2004) assume an investment adjustment cost combined with other features that are not present in the models we compare in the present paper.

[11] It should be noted, however, that both Altig et al. (2004) and Eichenbaum and Fisher (2004) tend to overstate the conflict between micro evidence on price adjustments and empirical estimates of price stickiness obtained from macro data. They only quote the part of the relevant micro literature which suggests an extremely high frequency of price adjustment at the firm level. In the third chapter we will come back to the micro evidence on price adjustment.

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.

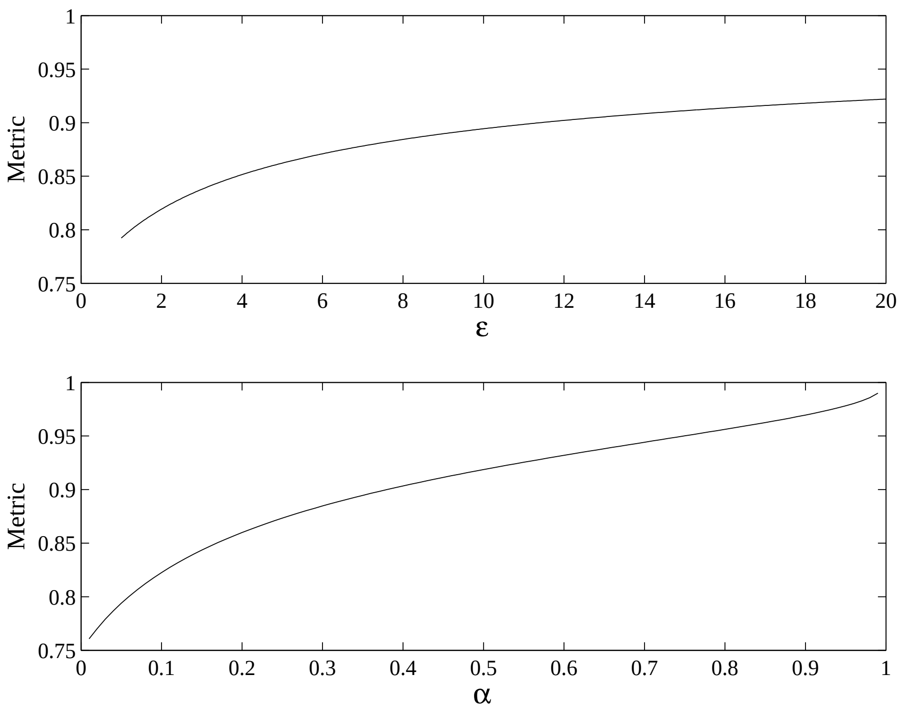

Figure 2: Implied price stickiness is a useful metric.

2.4 Conclusion

We should emphasize the main contribution of the present chapter 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.

References

Altig, David, Lawrence J. Christiano, Martin Eichenbaum, and Jesper Lindé (2004): "Firm-Specific Capital, Nominal Rigidities, and the Business Cycle", mimeo.

Basu, Susanto and Miles S. Kimball (2003): "Investment Planning Costs and the Effects of Fiscal and Monetary Policy", mimeo.

Calvo, Guillermo (1983): "Staggered Prices in a Utility Maximizing Framework", Journal of Monetary Economics, 12(3), 383-398.

Casares, Miguel (2002): "Time-to-Build Approach in a Sticky Price, Sticky Wage Optimizing Monetary Model", European Central Bank Working Paper No. 147.

Christiano, Lawrence J., Martin Eichenbaum, and Charles Evans (2004): "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy", forthcoming in *Journal of Political Economy.*

Clarida, Richard, Jordi Galí, and Mark Gertler (1999): "The Science of Monetary Policy: A New Keynesian Perspective", *Journal of Economic Literature*, 37(4), 1661-1707.

Edge, Rochelle M. (2000): "Time-to-Build, Time-to-Plan, Habit Persistence, and the Liqidity Effect", International Finance Discussion Papers No. 673.

Eichenbaum, Martin and Jonas D. M. Fisher (2004): "Evaluating the Calvo Model of Sticky Prices", NBER Working Paper 10617.

Erceg, Christopher J., Dale W. Henderson, and Andrew T. Levin (2000): "Optimal Monetary Policy with Staggered Wage and Price Contracts", *Journal of Monetary Economics*, 46(2), 281-313.

Galí, Jordi (2003): "New Perspectives on Monetary Policy, Inflation, and the Business Cycle", in M. Dewatripont, L. Hansen, and S. Turnovsky (editors), *Advances in Economics and Econometrics*, Volume III, 151-197, Cambridge University Press.

Galí, Jordi, Mark Gertler, and David López-Salido (2001): "European Inflation Dynamics", *European Economic Review*, (45)7, 1237-1270.

Galí, Jordi, David López-Salido, and Javier Vallés (2004): "Rule-of-Thumb Consumers and the Design of Interest Rate Rules", forthcoming in *Journal of Money, Credit, and Banking.*

Sbordone, Argia M. (2002): "Prices and Unit Labor Costs: A New Test of Price Stickiness", *Journal of Monetary Economics*, 49, 265-292.

Smets, Frank and Raf Wouters (2003): "An Estimated Stochastic Dynamic General Equilibrium Model of the Euro Area", *Journal of the European Economic Association*, 1(5), 1123-1175.

Sveen, Tommy and Lutz Weinke (2003): "Inflation and Output Dynamics with Firm-owned Capital", Universitat Pompeu Fabra Working Paper No. 702.

Sveen, Tommy and Lutz Weinke (2004): "Pitfalls in the Modeling of Forward-Looking Price Setting and Investment Decisions", Norges Bank Working Paper No. 2004/1.

Woodford, Michael (1996): "Control of Public Debt: A Requirement for Price Stability?", NBER Working Paper No. 5684.

Woodford, Michael (2003): *Interest and Prices: Foundations of a Theory of Monetary Policy*, Princeton University Press.

Yun, Tack (1996): "Nominal Price Rigidity, Money Supply Endogeneity, and Business Cycles", *Journal of Monetary Economics*, 37(2), 345-370.

Chapter 3

Firm-Specific Investment, Sticky Prices and the Taylor Principle

Abstract:[1] According to the Taylor principle a central bank should adjust the nominal interest rate by more than one-for-one in response to changes in current inflation. Most of the existing literature supports the view that by following this simple recommendation a central bank can avoid being a source of unnecessary fluctuations in economic activity. The present chapter shows that this conclusion is not robust with respect to the modeling of capital accumulation. We use our insights to discuss the desirability of alternative interest rate rules. Our results suggest a reinterpretation of monetary policy under Volcker and Greenspan: The empirically plausible characterization of monetary policy can explain the stabilization of macroeconomic outcomes observed in the early eighties for the US economy. The Taylor principle in itself cannot.

3.1 Introduction

According to the Taylor principle a central bank should follow an active monetary policy, i.e. it should adjust the nominal interest rate by more than one-for-one in response to changes in current inflation. Simple interest rate

[1]The first version of the paper on which this chapter is based has been circulated as Norges Bank Working Paper 2004/10, Oslo, September 10, 2004, http://www.norges-bank.no/publikasjoner/arbeidsnotater/.

rules consistent with that recommendation guarantee determinacy, i.e. local uniqueness of rational expectations equilibrium (REE), in many dynamic New-Keynesian (DNK) models.[2] Given its apparent robustness Clarida et al. (2000), and a large subsequent literature, use the Taylor principle to judge the conduct of monetary policy in practice.

In the present chapter we reassess the usefulness of the Taylor principle. Again, we consider a DNK model featuring firm-specific investment. Surprisingly, we find that an active monetary policy is *not* a sufficient condition for determinacy. This is interesting because most of the existing literature supports the view that the Taylor principle is robust with respect to the modeling of capital accumulation. An exception is Dupor (2001). His result that a passive interest rate rule is required to guarantee determinacy appears, however, to be specific to the continuous time framework he employs. In a discrete-time model Galí et al. (2004) find that it is not endogenous capital *per se* that challenges the Taylor principle.[3]

How is it possible that we reach a different conclusion in the present paper? The answer is that the convenient and widely used assumption of a rental market for capital is not innocuous: it hides an indeterminacy problem. The intuition is as follows. Current investment increases current marginal cost, but it lowers marginal cost in the future. A central bank that follows the Taylor principle therefore tends to decrease future real interest rates in the aftermath of an investment boom. Hence, to the extent that investment

[2] See, e.g., Taylor (1999) and Woodford (2001).

[3] Lubik (2003) obtains a similar result. He finds that determinacy obtains under an active monetary policy, if conventional values are assigned to both the capital adjustment cost and the price stickiness parameter. His results are, however, extremely sensitive with respect to the choice of the capital adjustment cost parameter. Carlstrom and Fuerst (2003) find that forward-looking interest rate rules do generally not guarantee determinacy in a DNK model with capital accumulation. They do not challenge, however, the usefulness of the Taylor principle.

is forward-looking, the expectation of such a boom could potentially become self-fulfilling. Whether this possibility materializes, or not, depends on the degree of price stickiness. With sufficiently high price stickiness REE is indeterminate, as we will discuss. The last aspect is crucial for the fact that the rental market assumption hides an indeterminacy problem. As we show in Sveen and Weinke (2003, 2004b) the difference between a specification with firm-specific capital and an alternative formulation with a rental market boils down to a difference in implied price stickiness:[4] for any given exogenous restriction on price adjustment there is less price stickiness, if a rental market for capital is assumed.[5] Importantly, with a rental market for capital the resulting price stickiness will generally be too low to make the indeterminacy issue appear to be relevant from a practical point of view.[6] This conclusion changes if capital is assumed to be firm-specific: if a central bank respects the Taylor principle and follows a rule according to which the nominal interest rate is set as a function of inflation only, then indeterminacy appears to be the regular case.

Based on our results we reinterpret the conduct of monetary policy under Volcker and Greenspan. The analyzes in Clarida et al. (2000) and Lubik and Schorfheide (2004) suggest that the estimated change from a passive to an active monetary policy explains *in itself* the observed stabilization of economic outcomes. We amend their interpretation with a caveat: active monetary policy appears to guarantee desirable macroeconomic outcomes only if it is

[4]The intuition is analog to the one that explains the difference in implied inflation dynamics resulting from assuming either constant returns to scale or decreasing returns to scale in a DNK model, along the lines discussed in Sbordone (2002) and Galí et al. (2001).

[5]The difference in implied price stickiness is therefore a useful metric: Sveen and Weinke (2004b) show that, for a standard calibration of the two models, one needs a Calvo parameter of about 0.9 in the rental market model in order to obtain the equilibrium dynamics resulting form a value of 0.75 in the model with firm-specific capital.

[6]Carlstrom and Fuerst (2003) note that 'if prices are extremely sticky' the Taylor principle is no longer sufficient for determinacy.

supplemented by interest rate smoothing, and/or some responsiveness of the nominal interest rate to a measure of economic activity. This is precisely the characterization of monetary policy which is empirically plausible under the Volcker-Greenspan tenure.[7]

The remainder of the chapter is organized as follows: Section 3.2 outlines the model. Section 3.3 presents our results. In particular, we answer the following three questions. Why is the Taylor principle not sufficient for determinacy in a model with capital accumulation? Why is price stickiness crucial for the indeterminacy issue? Why do interest rate smoothing and responsiveness of the nominal interest rate to economic activity help guaranteeing determinacy? Section 3.4 concludes.

3.2 The Model

We reconsider the DNK model with firm-specific capital. There are two differences with respect to the framework developed in the first chapter: First, we now assume that the only source of aggregate uncertainty derives from sunspots according to which economic agents coordinate on a particular equilibrium. Second, monetary policy is specified by assuming an interest rate rule. The remaining log-linearized equilibrium conditions are the same as stated in equations (2.1),(2.2),(2.4),(2.5),(2.6), (2.7). The average real marginal cost and marginal savings in labor costs are again obtained in the same way as analyzed in the first chapter.

[7]For a comprehensive review of the relevant empirical literature on interest rate rules, see, e.g., Woodford (2003, Ch. 1).

3.3 Results

Our goal is to explore what are desirable features of interest rate rules in the sense that they guarantee determinacy. Importantly, the theoretical framework developed so far can be used to explain why some rules are more desirable than others, as we will see. Finally, we will show that our results are also useful from a positive point of view. They call for a reinterpretation of the conduct of U.S. monetary policy under Volcker and Greenspan.

3.3.1 A Simple Interest Rate Rule

Consider a simple rule according to which the nominal interest rate is set as a function of current inflation:

$$i_t = \rho + \tau_\pi \pi_t. \tag{3.1}$$

We ask what combinations of values for the inflation response coefficient, τ_π, and the price stickiness parameter, θ, result in a determinate equilibrium. The result is shown in Figure 1 for the model with firm-specific capital: a large range of parameter values that meet the Taylor principle are inconsistent with determinacy.[8] An inflation response coefficient, τ_π, strictly larger than one is necessary but *not* sufficient for determinacy. Next we develop the intuition behind this result.

We focus on the role of capital accumulation for equilibrium dynamics. Let us start by conducting a thought experiment. Suppose a sunspot hits the economy and firms increase their investment spending without any change in the economy's fundamentals justifying it. Could this investment boom be potentially consistent with equilibrium? The answer is yes and the reason

[8] There is also a standard indeterminacy region in Figure 1. The latter is associated with the case where the Taylor principle is not met. As one may expect, the dimension of the standard indeterminacy is one.

is simple. Investment has counteracting effects on the determination of the marginal cost. It increases current marginal cost but it reduces marginal cost in subsequent periods. The resulting inflation dynamics inherit the U-shaped marginal cost pattern. In particular, there will be some period of deflation in the aftermath of the investment boom. To the extent that the central bank follows the Taylor principle, the associated real interest rate will therefore drop in the deflationary period. The latter could potentially result in a drop in the long real interest rate relevant for investment.[9] If the drop is sufficiently large, then it may rationalize the investment boom ex post.[10]

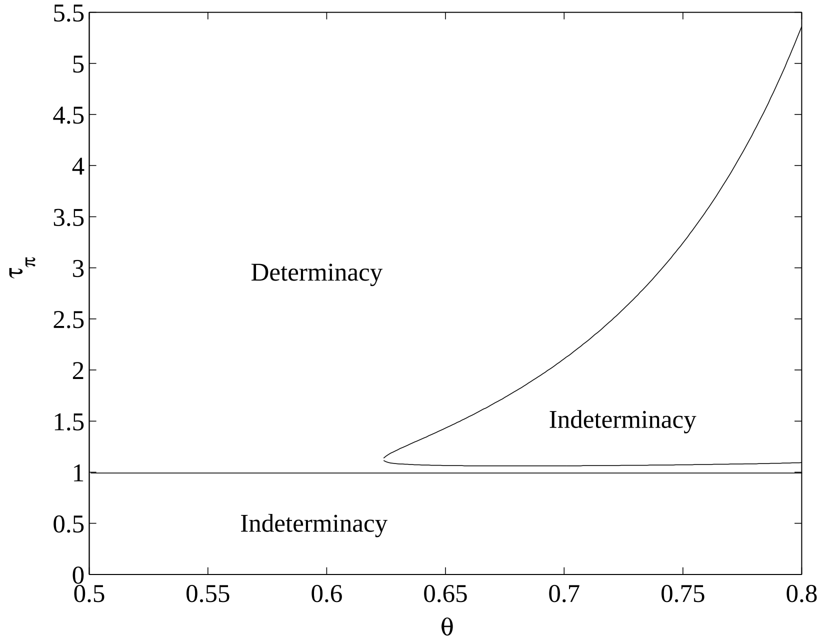

Figure 1: A simple interest rate rule.

[9]The long real rate relevant for investment can be written as: $rr_t^{long} = \rho + E_t \sum_{k=0}^{\infty} \beta^k \left(rr_{t+k} - \rho \right)$, which is obvious from eqaution (2.4).

[10]The reason for the word 'sufficiently' is that the average marginal savings in labor costs will also tend to decrease in the considered economic situation. We will come back to this point.

Whether this possibility materializes, or not, depends on both the price stickiness parameter, θ, and the inflation response coefficient, τ_π, as shown in Figure 1.[11] In order to disentangle the respective roles of the two parameters it is useful to take a detour. Let us consider, for a moment, an economy which is identical to the one with endogenous firm-specific capital, except for the fact that capital accumulation at the firm level is assumed to follow an exogenous stochastic process. The latter is common to all firms and, specifically, it is assumed to take the following form: $\widehat{K}_{t+1} = (1-\delta)\,\widehat{K}_t + e_t$, where e_t is *i.i.d.* with zero mean. The inflation equation resulting from that set of assumptions reads: $\pi_t = \beta E_t \pi_{t+1} + \xi\ \widehat{mc}_t$, with $\xi \equiv \lambda \frac{1-\alpha}{1+\alpha(\varepsilon-1)}$.[12] The latter equation differs from the one implied by the model with endogenous firm-specific capital. However, this difference is negligible, as we show and discuss in Sveen and Weinke (2004a). The simple exogenous investment economy is therefore a useful apparatus to analyze the economic mechanisms behind the results shown in Figure 1. First, we turn to the role of price stickiness. To this end we study impulse responses associated with a 10% increase in exogenous investment spending relative to its steady state level. The inflation response coefficient, τ_π, is set to 1.1, implying that the Taylor principle is met.

[11]The indeterminacy region associated with the case where the Taylor principle is met does not lend itself for a simulation of the sunspot since the dimension of indeterminacy is two. For a discussion of the last point see Galí (1997) and the references herein. Therefore, our thought experiment illustartes only one from among a continuum of possible responses of the endogenous variables to a sunspot shock. In doing so it highlights, however, the key economic mechanism behind our results, namely the role of investment spending for the marginal cost dynamics.

[12]It should be noted that this equation takes the same form as the one implied by assuming a constant capital stock at the firm level, as analyzed in Sbordone (2002) and Galí et al. (2001).

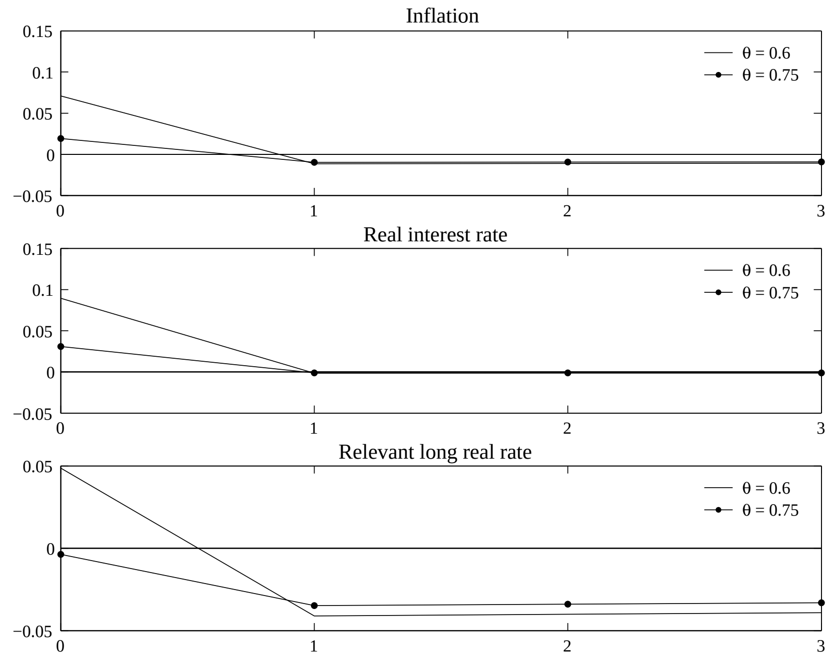

Figure 2: The role of the price stickiness parameter.

As shown in Figure 2, the assumed degree of price stickiness is critical for the response of the long real rate. For a value of the price stickiness parameter, θ, equal to 0.6 the long real rate increases on impact, whereas it decreases if a value of 0.75 is assigned to this parameter. The more forward-looking price setting is the less do prices increase on impact. The reason is as follows. With higher price stickiness the expected future reduction in marginal cost resulting from the investment shock affects current price setting more strongly.[13] Hence, higher price stickiness dampens the increase in the current real interest rate on impact. If the current real rate is sufficiently stable, then

[13]Clearly, the degree of price stickiness affects not only the forward-lookingness of price setting but also the extent to which the marginal cost changes after the shock. However, our simulation results justify the simple intuition given in the text.

the long real rate drops on impact.

This insight from the simple exogenous investment economy helps understanding the role of price stickiness for indeterminacy in the model with endogenous firm-specific capital. Indeed, under an interest rate rule that respects the Taylor principle, a price stickiness parameter, θ, of about 0.63 is needed to obtain indeterminacy, as shown in Figure 1. This value corresponds to an average lifetime of a price of less than 3 quarters. Of course, the exact extent to which prices are sticky in actual economies remains controversial. However, a value of θ as high as 0.75 is often considered to be empirically plausible.[14]

Second, we analyze the role of the inflation response coefficient, τ_π, for the results shown in Figure 1. In order to gather the intuition behind our findings we reconsider the simple exogenous investment economy. The price stickiness parameter, θ, is set to 0.75 and we analyze impulse responses associated with an investment shock, as specified above. If the inflation response coefficient, τ_π, is set to 1.1, then the long real rate drops on impact, while the opposite holds true for a parameter value of 4. This is shown in Figure 3.

We have outlined already the intuition for why the long real rate drops on impact for empirically plausible specifications of the inflation response coefficient and the price stickiness parameter. The apparently counterintuitive finding in Figure 3 is that the impact response of the long real rate changes sign for a very aggressive monetary policy rule. This is, however, for a simple reason. We observe that the central bank is more effective in reducing future deflation than in reducing current inflation: an increase in the response parameter decreases future deflation, which in itself tends to

[14]The micro evidence on price adjustments is mixed. Golosov and Lucas (2003) suggest that firms change prices on average about every 2 quarters. Baudry et al. (2004) find, however, a value of 3 quarters, while the analysis conducted in Aucremanne and Dhyne (2004) suggests 5 quarters.

increase current inflation. Hence, if monetary policy is sufficiently aggressive and future expected deflation is low, then the relevant long real interest rate must increase rather than decrease on impact in response to an investment shock.

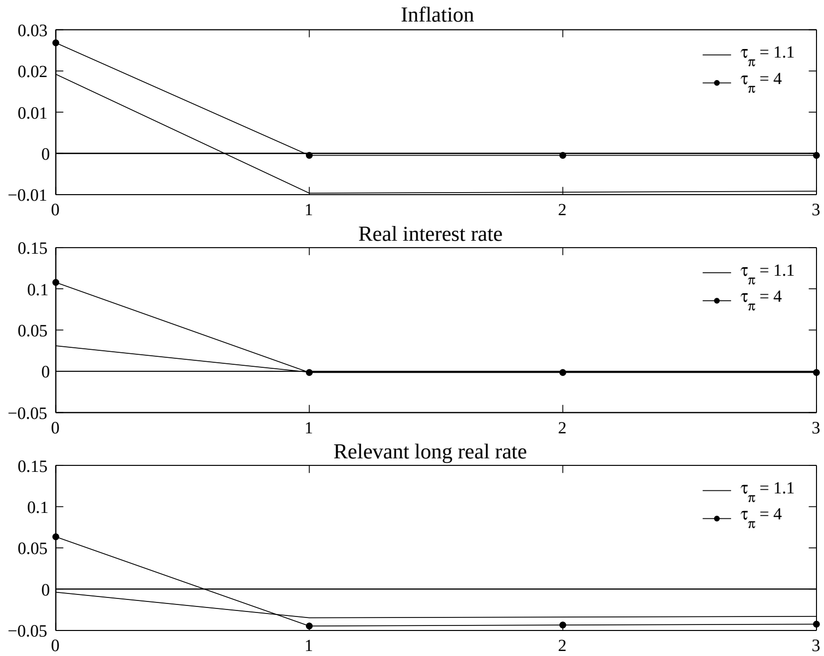

Figure 3: The role of the inflation response coefficient.

Once more, the simple exogenous investment economy helps understanding the results in Figure 1. Indeed, we find that from among the rules which meet the Taylor principle very aggressive rules and intermediate rules, as measured by the relative size of the respective inflation response coefficients, have crucially different properties: the former rules guarantee determinacy, whereas the latter do not.[15] A maybe somewhat surprising result in Figure

[15]Obviously, this claim is conditional on a specification of the price stickiness parameter that we have previously characterized as being empirically plausible.

1 is that there also exists a determinacy region associated with rules that respect the Taylor principle but prescribe a very gentle interest rate response to inflation. Our explanation is as follows. If the long real rate does not change by much then the drop in marginal savings associated with an investment boom will render REE determinate.

What is the relevance of our indeterminacy results? In related literature Edge and Rudd (2002) and Røisland (2003) make the case against too gentle interest rate rules, while Orphanides (2001) points out that too aggressive interst rate rules are undesirable.[16]

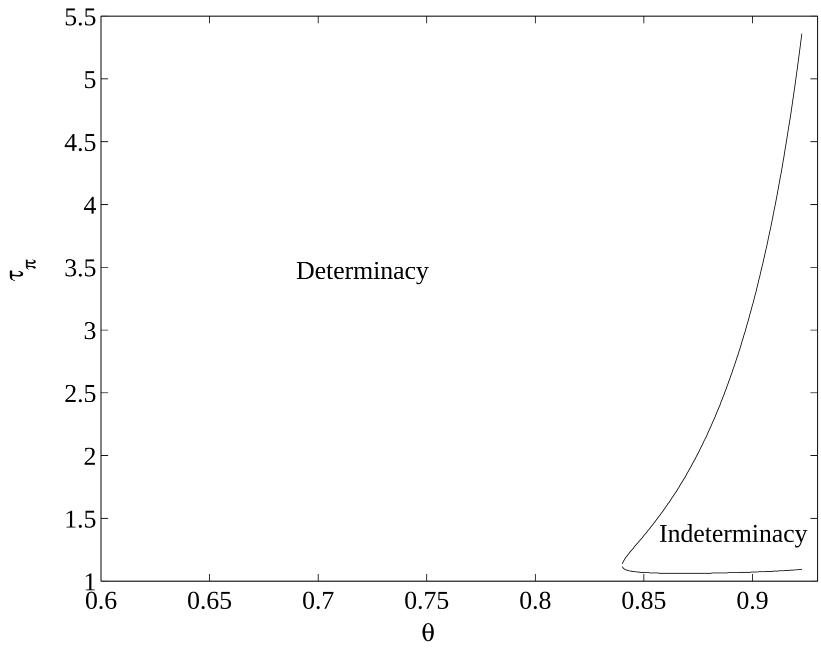

Figure 4: Indeterminacy and the rental market.

[16]Edge and Rudd (2002) and Røisland (2003) obtain their results from a simple observation: taxes are paid on nominal capital income, which calls for a strengthening of the Taylor principle. On the other hand, Orphanides (2001) argues that very aggressive interest rate rules have the undesirable property of amplifying mistakes in the conduct of monetary policy.

Combining their findings with ours we conclude that the Taylor principle is a poor guide for the design of monetary policy. As we have argued, forward-looking price setting is one key economic mechanism behind our results. Indeed, to the extent that a rental market for capital is assumed price setting is not forward-looking enough to imply indeterminacy, unless extreme assumptions regarding the frequency of price adjustment are made. This is shown in Figure 4.[17] These findings are consistent with those reported by Carlstrom and Fuerst (2003).

In summary, abstracting from capital accumulation, i.e. considering only consumption demand, which does not produce any counteracting effects for the determination of the marginal cost, or using the rental market assumption, which reduces the implied price stickiness in the model, obscures the fact that the Taylor principle is not a useful guide for the design of monetary policy. What form should simple interest rate rules then take in order to prevent the central bank from becoming a source of macroeconomic instability?

3.3.2 More Prominent Interest Rate Rules

We analyze the desirabilty of some interest rate rules that have been proposed in the literature, either on normative grounds or as an empirically relevant description of the conduct of monetary policy in practice. As in the previous section our criterion to assess the performance of a particular interest rate rule is whether or not it guarantees determinacy.

[17] Recently, Benhabib and Eusepi (2004) have shown that in a rental market model with Calvo pricing global multiplicities cannot be ruled out by the Taylor principle. Hence, there are more instability issues than Figure 4 appears to suggest.

Responding to Economic Activity

Let us consider first the indeterminacy regions associated with an interest rate rule that allows for an output response, in the spirit of Taylor (1993):

$$i_t = \rho + \tau_\pi \pi_t + \tau_y \widehat{Y}_t. \tag{3.2}$$

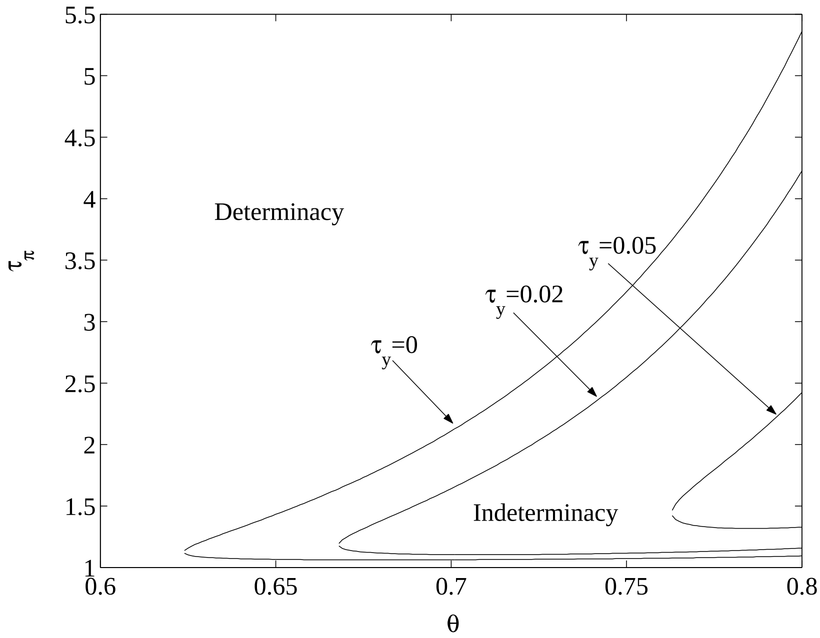

Figure 5: Indeterminacy when responding to economic activity.

A relatively small size of the output response coefficient is sufficient to reduce dramatically the importance of the indeterminacy issue, as shown in Figure 5. The intuition is straightforward from the thought experiment of an investment boom. The latter is associated with an increase in current output. If the central bank reacts with its interest rate instrument directly to this, then the impact of current investment spending on future marginal cost will generally not result in a monetary policy which would justify an investment boom ex post. The last result amends a recent finding by Schmitt-Grohé and Uribe (2004) with a caveat. They study the welfare properties of alternative interest rate rules across a rich variety of DNK models. Using a second order approximation they argue that responding to output is costly in welfare terms.[18] However, based on our analysis, reacting to some measure of real activity will generally prevent the central bank from becoming a source of unnecessary fluctuations in the economy. This aspect is absent in their analysis, just because the rental market assumption hides a relevant indeterminacy problem. Of course, an obvious question is whether or not there exist alternative interest rate rules which have the property of guaranteeing determinacy (at a possibly smaller welfare cost).

Interest Rate Smoothing

Let us analyze next the performance of interest rate rules which take the following form:

$$i_t = \rho_i i_{t-1} + (1-\rho_i)(\rho + \tau_\pi \pi_t)\,. \tag{3.3}$$

With interest rate smoothing the definition of the Taylor principle becomes that monetary policy should be active *in the long run*. In a model without capital the so defined Taylor principle guarantees determincay. This means that the particular value of the interest rate smoothing coefficient, $\rho_i \in (0,1)$, is irrelevant for indeterminacy, as long as the inflation response coefficient, τ_π, is strictly larger than one. Schmitt-Grohé and Uribe (2004) argue that this insight is robust with respect to the modeling of capital accumulation.

[18]It should be noted that the analysis in Schmitt-Grohé and Uribe (2004) does not imply that it would be costly in welfare terms to respond to some output gap measure. However, it is unclear *a priori* how natural output should be defined in a model with endogenous capital, as discussed in Woodford (2003, Ch. 5).

We find, however, that the role of interest rate smoothing changes substantially if capital is firm-specific. This is shown in Figure 6. For a value of τ_π strictly larger than one it is not true that determincy would obtain for all $\rho_i \in (0, 1)$.[19] To our best knowledge this observation is new in the literature.[20]

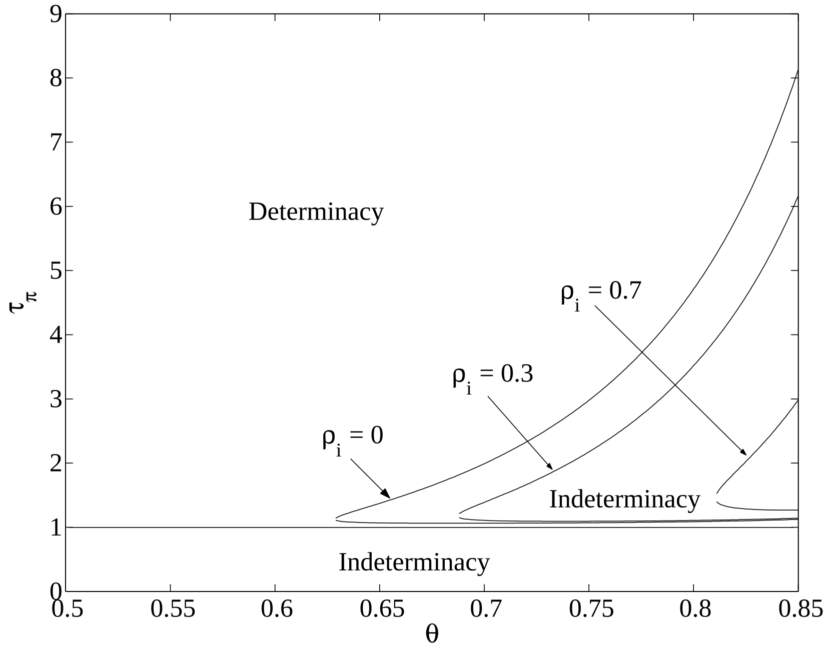

Figure 6: Indeterminacy with interest rate smoothing.

[19]This is, again, conditional on what we have characterized as an empirically plausible specification of price stickiness.

[20]In particular, the focus in Benhabib et al. (2003) is different from ours. They conduct a global analysis and make the case for super-inertial rules (i.e. rules where i_t on the left hand side of equation (3.3) is replaced by Δi_t, and Δ is the first-difference operator). Rules of this type have also been advocated based on local analysis. See, e.g., Rotemberg and Woodford (1999).

The intuition behind this finding is in line with our previous interpretations of the model. Let us reconsider the thought experiment of an investment boom that is not justified by a change in the economy's fundamentals. To the extent that the central bank behaves in a backward-looking manner the initial increase in inflation associated with the boom will keep being relevant for the determination of future (real) rates. Hence, indeterminacy can be ruled out in this case: the future expected reduction in marginal cost associated with the investment boom does not dominate the determination of the long rate relevant for investment. We therefore find that interest rate smoothing and responding to real activity are both desirable properties of interest rate rules, in the sense that they help guranteeing determinacy. Clearly, a second order approximation to the equilibrium dynamics is required in order to tell which one of the two features is preferable from a welfare point of view. This is an interesting line for future research.[21]

Our results regarding the desirability of alternative arrangements for the conduct of monetary policy are also interesting from a positive point of view. The analyzes in Clarida et al. (2000) and Lubik and Schorfheide (2004) appear to imply that the estimated change from a passive to an active monetary policy explains *in itself* the stabilization of macroeconomic outcomes in the U.S. that has been observed in the early 1980's. We take the occurrence of self-fulfilling expectations, or lack thereof, as a possible explanation for the observed reduction in macroeconomic instability under the Volcker-Greenspan tenure.[22] However, viewed through the lense of a DNK

[21]It should be emphasized that the results from such an analysis are not trivial given the findings in Schmitt-Grohé and Uribe (2004). The reason is that a rental market model and a specification with firm-specific capital do not just differ in the inflation equation if the order of approximation to the equilibrium dynamics is higher than one.

[22]For a discussion of alternative hypotheses that explain this change in macroeconomic outcomes, see Lubik and Schorfheide (2004).

model with firm-specific capital, the interpretation of their empirical results changes: active monetary policy appears to guarantee desirable macroeconomic outcomes only if it is supplemented by interest rate smoothing, and/or some responsiveness of the nominal interest rate to a measure of economic activity. Interestingly, this is precisely the characterization of monetary policy which is empirically plausible under the Volcker-Greenspan tenure.

3.4 Conclusion

According to the Taylor principle a central bank should adjust the nominal interest rate by more than one-for-one in response to changes in current inflation. This recommendation is generally believed to be a useful guide for the design of monetary policy. We find, however, that by following the Taylor principle a central bank does not necessarily avoid becoming a source of marcoeconomic instability. More importantly, to the extent that a central bank adjusts the nominal interest rate in response to inflation *only*, indeterminacy appears to be the regular case. This challenges much of the conventional wisdom regarding desirable features of interest rate rules.

The reason for why our results differ from those that have been obtained in the existing literature lies in the fact that we model a simultaneous price setting and investment decision at the firm level, instead of focusing on the price setting decision alone. Our results follow from an interaction of two economic mechanisms: forward-lookingness in investment and in price setting. In explaining these mechanisms we build on our earlier work where Sveen and Weinke (2003, 2004a,b) solve and discuss models with firm-specific capital and Calvo pricing.

Based on our insights we make the case for interest rate rules prescribing that the central bank should allow for some interest rate smoothing and/or react to some measure of economic activity. We also use our theoretical results to reinterpret the empirical estimates in Clarida et al. (2000) and Lubik and Schorfheide (2004). It is not plausible that active monetary policy *in itself* would have stabilized the economy. Our interpretation is that the whole design of monetary policy is crucial: active monetary policy appears to guarantee desirable macroeconomic outcomes only if it is supplemented by interest rate smoothing, and/or some responsiveness of the nominal interest rate to a measure of economic activity. This interpretation is consistent with both our theory and their empirical estimates.

References

Aucremanne, Luc, and Emmanuel Dhyne (2004): "How Frequently do Prices Change? Evidence Based on the Micro Data Underlying the Belgian CPI", European Central Bank Working Paper No. 331.

Basu, Susanto, and Miles S. Kimball (2003): "Investment Planning Costs and the Effects of Fiscal and Monetary Policy", mimeo.

Baudry, Laurent, Hervé Le Bihan, Patrick Sevestre, and Sylvie Tarrieu (2004): "Price Rigidity. Evidence from the French CPI Micro-Data", European Central Bank Working Paper No. 331.

Benhabib, Jess, and Stefano Eusepi (2004): "The Design of Monetary and Fiscal Policy: A Global Perspective", mimeo.

Benhabib, Jess, Stephanie Schmitt-Grohé, and Martin Uribe (2003): "Backward-Looking Interest-Rate Rules, Interest-Rate Smoothing, and Macroeconomic Instability", *Journal of Money, Credit, and Banking*, 35(6), 1379-1412.

Calvo, Guillermo (1983): "Staggered Prices in a Utility Maximizing Framework", *Journal of Monetary Economics*, 12(3), 383-398.

Carlstrom, Charles T., and Timothy S. Fuerst (2003): "Investment and Interest Rate Policy: A Discrete Time Analysis", Federal Reserve Bank of Cleveland Working Paper 03/20.

Clarida, Richard, Jordi Galí, and Mark Gertler (2000): "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory", *Quarterly Journal of Economics*, 115(1), 147–80.

Dupor, Bill (2001): "Investment and Interest Rate Policy", *Journal of Economic Theory*, 98 May, 85-113.

Edge, Rochelle M., and Jeremy B. Rudd (2002): "Taxation and the Taylor Principle", Federal Reserve Board, Finance and Economics Discussion Series No. 2002-51.

Galí, Jordi (1997): "Solving Linear Dynamic Models with Sunspot Equilibria: A Note", mimeo, New York University.

Galí, Jordi, Mark Gertler, and David López-Salido (2001): "European Inflation Dynamics", *European Economic Review*, 45(7), 1237-1270.

Galí, Jordi, David López-Salido, and Javier Vallés (2004): "Rule-of-Thumb Consumers and the Design of Interest Rate Rules", forthcoming in *Journal of Money, Credit, and Banking.*

Golosov, M., and R.E. Lucas, Jr. (2003): "Menu Costs and Phillips Curves", NBER Working Paper 10187.

Lubik, Thomas A. (2003): "Investment Spending, Equilibrium Indeterminacy, and the Interactions of Monetary and Fiscal Policy", mimeo, Johns Hopkins University.

Lubik, Thomas A., and Frank Schorfheide (2004): "Testing for Indeterminacy: An Application to U.S. Monetary Policy", *American Economic Review*, 94(1), 190-217.

Orphanides, Athanasios (2001): "Monetary Policy Rules Based on Real-Time Data", *American Economic Review*, 91(4), 964-985.

Rotemberg, Julio, and Michael Woodford (1999): "Interest-Rate Rules in an Estimated Sticky-Price Model", in John B. Taylor, ed., *Monetary Policy Rules*, Chicago: University of Chicago Press, 57–119.

Røisland, Øistein (2003): "Capital Income Taxation, Equilibrium Determinacy, and the Taylor Principle", *Economics Letters*, 81, 147-153.

Sbordone, Argia M. (2002): “Prices and Unit Labor Costs: A New Test of Price Stickiness”, *Journal of Monetary Economics*, 49(2), 265-292.

Schmitt-Grohé, Stephanie, and Martin Uribe (2004): “Optimal Simple and Implementable Monetary and Fiscal Rules”, NBER Working Paper 10253.

Sveen, Tommy, and Lutz Weinke (2003): “Inflation and Output Dynamics with Firm-owned Capital”, Universitat Pompeu Fabra Working Paper 702.

Sveen, Tommy, and Lutz Weinke (2004a): “Pitfalls in the Modelling of Forward-Looking Price Setting and Investment Decisions”, Central Bank of Norway (Norges Bank) Working Paper 2004/1.

Sveen, Tommy, and Lutz Weinke (2004b): “New Perspectives on Capital and Sticky Prices”, Central Bank of Norway (Norges Bank) Working Paper 2004/3.

Taylor, John B. (1993): “Discretion versus Policy Rules in Practice”, *Carnegie-Rochester Conference Series on Public Policy*, 39, 195-214.

Taylor, John B. (1999): “A Historical Analysis of Monetary Policy Rules”, in John B. Taylor, ed., *Monetary Policy Rules*, Chicago: University of Chicago Press, 319-341.

Woodford, Michael (2001): “The Taylor Rule and Optimal Monetary Policy”, *American Economic Review*, 91(2), 232-237.

Woodford, Michael (2003): *Interest and Prices: Foundations of a Theory of Monetary Policy*, Princeton: Princeton University Press.

Woodford, Michael (2004): “Inflation and Output Dynamics with Firm-specific Capital”, mimeo, Princeton University.