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Firm-specific capital and welfare

by

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# Firm-Specific Capital and Welfare\*

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## Abstract

What are the consequences for monetary policy design implied by the fact that price setting and investment takes typically place simultaneously at the firm level? To address this question we analyze simple (constrained) optimal interest rate rules in the context of a dynamic New Keynesian model featuring firm-specific capital accumulation as well as sticky prices and wages à la Calvo. We make the case for Taylor type rules. They are remarkably robust in the sense that their welfare implications do not appear to hinge neither on the specific assumptions regarding capital accumulation that are used in their derivation nor on the particular definition of natural output that is used to construct the output gap. On the other hand we find that rules prescribing that the central bank does not react to any measure of real economic activity are not robust in that sense.

**Keywords:** Monetary Policy, Sticky Prices, Aggregate Investment.

**JEL Classification:** E22, E31, E52

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# 1 Introduction

How does *firm-specific* capital accumulation affect the desirability of alternative arrangements for the conduct of monetary policy? We address this question employing a New Keynesian (NK) framework, i.e. a dynamic stochastic general equilibrium model featuring nominal rigidities combined with monopolistic competition. Specifically, we consider an economic environment with sticky prices and wages à la Calvo (1983). Our model is therefore similar to the one developed in Erceg et al. (2000) except for the fact that we allow for capital accumulation.<sup>1</sup> The welfare criterion is derived from the utility of the representative household, along the lines of Rotemberg and Woodford (1997).

What is the relevance of our analysis? Edge (2003) shows how the work by Rotemberg and Woodford (1997) can be extended to conduct a welfare analysis in the context of a NK model where capital accumulation is endogenous. She assumes, however, that firms have access to a rental market for capital,<sup>2</sup> which is not an innocuous simplification in a NK model, as analyzed in Sveen and Weinke (2003, 2004, 2005a) and Woodford (2003, Ch. 5, 2005).<sup>3</sup> In the present paper we show how a welfare analysis can be conducted in the context of a NK model featuring firm-specific capital accumulation (FS for short). Moreover we explain how and why the conclusions regarding the desirability of monetary policy change if a rental market for capital (RM for short) is assumed instead.

We obtain three results. First, the implied price stickiness is the main difference between FS and RM as far as their welfare implications are concerned. Sveen and Weinke (2005a) show that this is the *only* difference between the two models if atten-

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<sup>1</sup>Erceg et al. (2000) assume that the aggregate capital stock is constant and that there exists a rental market for capital.

<sup>2</sup>Another difference between our work and Edge's is that she assumes frictionless investment whereas we follow Woodford (2003, Ch. 5) in assuming a convex adjustment cost at the firm level.

<sup>3</sup>Schmitt-Grohé and Uribe (2004) argue that both the rental market assumption and the assumption of firm-specific capital are somewhat extreme. However, the work by Altig et al. (2005) suggests that the assumption of firm-specific capital is appealing on empirical grounds.

tion is restricted to a *first* order approximation to the equilibrium dynamics. Here we show that the additional endogenous price stickiness implied by the presence of firm-specific capital (and the lack thereof under RM) is also the key player as far as the welfare implications of the two alternative specifications are concerned. This is interesting and surprising because our welfare criterion, a *second* order approximation to the unconditional expectation of the household's utility, is *not* identical in the two models if we change the price stickiness in one of them in such a way that the first order approximations to the respective equilibrium dynamics would be identical. Optimized interest rate rules therefore prescribe putting relatively more weight on price inflation than on wage inflation under FS, whereas the opposite is true under RM. This is important for the following reason. Suppose that the central bank does not react to any measure of real economic activity. Then using the optimized interest rate rule associated with RM in the FS specification implies a large welfare loss, as we discuss. Let us relate that result to the existing literature. Schmitt-Grohé and Uribe (2005b) show in the context of a rental market model that the relative weight attached to price- and to wage inflation in an optimized interest rate rule depends crucially on which nominal variable is stickier.<sup>4</sup> We show that the difference in policy implications between FS and RM can be understood in an analogous way.

We also analyze Taylor type rules, i.e. interest rate rules prescribing that the central bank reacts to price inflation and to the output gap. Our second result is that these interest rate rules are remarkably robust in the following sense. If the optimized rule implied by one model is used in the other one then the resulting welfare loss is small compared with the outcome under the optimized rule associated with that model. Consequently, the central bank does not need to take a stand on

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<sup>4</sup>In related work Schmitt-Grohé and Uribe (2005a) make the case for price stability as the central goal of optimal monetary policy. They show that desirable outcomes can be implemented by a combination of passive monetary and active fiscal policy. In the present paper we focus exclusively on optimal monetary policy.

which specification of capital accumulation is the empirically more plausible one if it uses a Taylor type rule.

But how should the output gap be defined? So far there is no consensus in the literature on the answer to that question. Neiss and Nelson (2003) and Woodford (2003, Ch. 5) propose two alternative definitions. Our third result is that the difference between these two competing definitions matters very little for the resulting welfare implications and we explain why this is so.

The remainder of the paper is organized as follows. The model is outlined in Section 2. We present the welfare criterion in Section 3. Our results are shown and interpreted in Section 4. Section 5 concludes.

## 2 The Model

### 2.1 Preferences, Market Structure and Technology

#### 2.1.1 Households

The model we use to analyze the implications of firm-specific capital accumulation for monetary policy design is a NK framework with complete financial markets. Throughout the analysis the subscript  $t$  is used to indicate that a variable is dated as of that period. Households maximize expected discounted utility:

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

where  $\beta$  is the subjective discount factor. Moreover  $N_t(h)$  denotes hours worked by household  $h$  and  $C_t$  is a Dixit-Stiglitz consumption aggregate as of that time. Specifically,

$$C_t \equiv \left( \int_0^1 C_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di \right)^{\frac{\varepsilon}{\varepsilon-1}}, \quad (1)$$

where  $\varepsilon$  is the elasticity of substitution between different varieties of goods  $C_t(i)$ . The associated price index is defined as follows:

$$P_t \equiv \left( \int_0^1 P_t(i)^{1-\varepsilon} di \right)^{\frac{1}{1-\varepsilon}}. \quad (2)$$

Requiring optimal allocation of any spending on the available goods implies that consumption expenditure can be written as  $P_t C_t$ . Household  $h$ 's period utility is given by the following function:

$$U(C_t, N_t(h)) = \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t(h)^{1+\phi}}{1+\phi}, \quad (3)$$

where parameter  $\sigma$  denotes the household's relative risk aversion and parameter  $\phi$  can be interpreted as the the inverse of the Frisch aggregate labor supply elasticity. Our assumptions of separable preferences combined with complete financial markets imply that the heterogeneity across households in their hours worked does not translate into consumption heterogeneity. This is reflected in our notation. Each household is assumed to be the monopolistically competitive supplier of its differentiated type of labor,  $N_t(h)$ . We also assume staggered wage setting à la Erceg et al. (2000), i.e. each firm faces a constant and exogenous probability,  $\theta_w$ , of getting to reoptimize its wage in any given period. Optimizing behavior on the part of firms implies that demand for type  $h$  labor,  $N_t^d(h)$ , is given by:

$$N_t^d(h) = \left( \frac{W_t(h)}{W_t} \right)^{-\varepsilon_N} N_t^d, \quad (4)$$

where  $W_t(h)$  denotes the nominal wage posted by household  $h$  and  $\varepsilon_N$  gives the elasticity of substitution between different types of labor. Finally,  $W_t$  and  $N_t^d$  denote, respectively, the aggregate nominal wage and aggregate labor demand. They are defined as the corresponding aggregate prices and quantities for goods.

Under standard assumptions the relevant budget constraint prescribes that the present value of all expenditures cannot be greater than the value of a household's initial assets and the present value of its income. The latter derives from wage payments and profits resulting from ownership of firms net of taxes.<sup>5</sup> We assume that there are only lump sum taxes and the only role of the government is to levy these taxes to finance subsidies in goods and factor markets which render the steady state of our model Pareto optimal. This assumption in turn is needed to compute our welfare criterion up to the second order using a first order approximation to the equilibrium dynamics.

For future reference let us note two implications of households' optimizing behavior. First, we obtain a stochastic discount factor for random nominal payments,  $Q_{t,t+1}$ , from a standard intertemporal optimality condition:

$$\beta \left( \frac{C_{t+1}}{C_t} \right)^{-\sigma} \left( \frac{P_t}{P_{t+1}} \right) = Q_{t,t+1}. \quad (5)$$

The stochastic discount factor is linked to the gross nominal interest rate,  $R_t$ , by the relationship  $E_t \{Q_{t,t+1}\} = R_t^{-1}$  which holds in equilibrium.

Second, under our assumptions the first order condition for wage setting reads:

$$E_t \left\{ \sum_{k=0}^{\infty} (\beta \theta_w)^k N_{t+k}^d(h) C_{t+k}^\sigma \left[ \frac{W_t(h)}{P_{t+k}} - MRS_{t+k}(h) \right] \right\} = 0, \quad (6)$$

where  $MRS_t(h) \equiv N_t(h)^\phi C_t^\sigma$  is the (negative of the) marginal rate of substitution of consumption for leisure of household  $h$ .

### 2.1.2 Firms

There is a continuum of firms and each of them is the monopolistically competitive producer of a differentiated good. Each firm  $i$  is assumed to maximize its market

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<sup>5</sup>For details see Woodford (2003, Ch. 2).



value,

$$\max \sum_{k=0}^{\infty} E_t \{Q_{t,t+k} \Phi_{t+k}(i)\},$$

where we have used the notation  $\Phi_t(i)$  for firm  $i$ 's cash flows. The maximization is subject to the following constraints.

Each firm  $i$  has access to a Cobb-Douglas technology:

$$Y_t(i) = A_t K_t(i)^\alpha N_t(i)^{1-\alpha}, \quad (7)$$

where parameter  $\alpha$  measures the capital share in the production function. Aggregate technology is given by  $A_t$  and  $K_t(i)$  and  $N_t(i)$  denote, respectively, firm  $i$ 's capital stock and labor input used in its production  $Y_t(i)$ . As in Erceg et al. (2000) technology shocks are assumed to be the only source of aggregate uncertainty in our model.<sup>6</sup> Specifically, we consider a stationary AR(1) process for the log of technology:

$$a_t = \rho_a a_{t-1} + \varepsilon_t, \quad (8)$$

where parameter  $\rho_a \in (0, 1)$  and  $\varepsilon_t$  is assumed to be *iid*.

Firms face three additional restrictions. First, we assume Calvo (1983) pricing, i.e. each firm faces a constant and exogenous probability,  $\theta$ , of getting to reoptimize its price in any given period. Second, we follow Woodford (2003, Ch. 5) in assuming that investment at the firm level is restricted in the following way:

$$I_t(i) = I \left( \frac{K_{t+1}(i)}{K_t(i)} \right) K_t(i). \quad (9)$$

In the last equation  $I_t(i)$  denotes the amount of the composite good<sup>7</sup> necessary to change firm  $i$ 's capital stock from  $K_t(i)$  to  $K_{t+1}(i)$  one period later. Moreover,

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<sup>6</sup>Of course, the extent to which technology shocks are an important source behind the observable business cycle fluctuations is the topic of an ongoing debate. See, e.g., Galí and Rabanal (2004).

<sup>7</sup>We assume that the elasticity of substitution is the same as in the consumption aggregate.

function  $I(\cdot)$  is assumed to satisfy the following:  $I(1) = \delta$ ,  $I'(1) = 1$ , and  $I''(1) = \epsilon_\psi$ . Parameter  $\delta$  denotes the depreciation rate and  $\epsilon_\psi > 0$  measures the convex capital adjustment cost in a log-linear approximation to the equilibrium dynamics. Third, cost minimization by firms and households implies that demand for each individual good  $i$  can be written as follows:

$$Y_t^d(i) = \left( \frac{P_t(i)}{P_t} \right)^{-\varepsilon} Y_t^d, \quad (10)$$

where  $Y_t^d$  denotes aggregate demand which is given by:

$$Y_t^d \equiv C_t + I_t, \quad (11)$$

and  $I_t \equiv \int_0^1 I_t(i) di$  denotes aggregate investment demand. A firm's cash flows,  $\Phi_t(i)$ , are therefore given by the following expression:

$$\Phi_t(i) = Y_t^d(i)P_t(i) - W_tN_t(i) - P_tI_t(i). \quad (12)$$

For future reference let us mention two implications of optimizing behavior at the firm level. First, firm  $i$ 's first order condition for capital accumulation reads:

$$\frac{dI_t(i)}{dK_{t+1}(i)}P_t = E_t \left\{ Q_{t,t+1} \left[ MS_{t+1}(i) - \frac{dI_{t+1}(i)}{dK_{t+1}(i)}P_{t+1} \right] \right\}, \quad (13)$$

where  $MS_t(i) \equiv \frac{W_tMPK_t(i)}{MPL_t(i)}$  is the marginal return to firm  $i$ 's capital. Second, let us note that under our assumptions firm  $i$ 's first order condition for price setting reads:

$$\sum_{k=0}^{\infty} \theta^k E_t \left\{ Q_{t,t+k} Y_{t+k}^d(i) [P_t^*(i) - MC_{t+k}^m(i)] \right\} = 0, \quad (14)$$

where  $MC_t^m(i) \equiv \frac{W_t}{MPL_t(i)}$  measures the nominal marginal cost and  $MPL_t(i)$  is the marginal product of labor of firm  $i$ .

### 2.1.3 Market clearing

Clearing of the labor market requires for each type of labor  $h$ :

$$N_t(h) = N_t^d(h). \quad (15)$$

Likewise, market clearing for each variety  $i$  requires at each point in time,

$$Y_t(i) = C_t^d(i) + I_t^d(i), \quad (16)$$

where  $C_t^d(i)$  is consumption demand for good  $i$  while  $I_t^d(i)$  denotes investment demand for that good. To close the model we need to specify monetary policy. We will come back to that point.

## 2.2 Some Linearized Equilibrium Conditions

The starting point of our welfare analysis is a linear approximation to the equilibrium dynamics around a steady state with zero inflation. Since the details of the linearization have been developed elsewhere<sup>8</sup> we just briefly mention the resulting equilibrium conditions. In what follows all variables are expressed in terms of logs and we ignore constants throughout. Let us already note that the linearized equilibrium conditions are identical for FS and RM, except for the respective inflation equations.

The Euler equation reads:

$$c_t = E_t c_{t+1} - \frac{1}{\sigma} (i_t - E_t \pi_{t+1} - \rho), \quad (17)$$

where  $\rho \equiv -\log \beta$  is the time discount rate. We have also used the notation  $i_t \equiv \log(R_t)$  for the nominal interest rate and  $\pi_t \equiv \log\left(\frac{P_t}{P_{t-1}}\right)$  for inflation.

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<sup>8</sup>See, e.g., Erceg et al. (2000), Svein and Weinke (2005a) and Woodford (2005).

The law of motion of capital is obtained from averaging and aggregating optimizing investment decisions on the part of firms. This implies:

$$\Delta k_{t+1} = \beta E_t \Delta k_{t+2} + \frac{1}{\epsilon_\psi} [(1 - \beta(1 - \delta)) E_t m s_{t+1} - (i_t - E_t \pi_{t+1} - \rho)], \quad (18)$$

where  $K_t \equiv \int_0^1 K_t(i) di$  denotes aggregate capital, and  $MS_t \equiv \int_0^1 MS_t(i) di$  measures the average real marginal return to capital.

Up to the first order aggregate production is pinned down by aggregate labor, capital and technology:

$$y_t = a_t + \alpha k_t + (1 - \alpha) n_t. \quad (19)$$

As in Erceg et al. (2000) the wage inflation equation results from averaging and aggregating optimal wage setting decisions on the part of households. It takes the following simple form:

$$\omega_t = \beta E_t \omega_{t+1} + \lambda_\omega (mrs_t - rw_t), \quad (20)$$

where  $\omega_t \equiv \log\left(\frac{W_t}{W_{t-1}}\right)$  denotes wage inflation,  $MRS_t \equiv \int_0^1 MRS_t(h) dh$  gives the average marginal rate of substitution of consumption for leisure and  $RW_t \equiv \int_0^1 \frac{W_t(h)}{P_t} dh$  denotes average real wage. Parameter  $\lambda_\omega$  takes the value  $\frac{(1-\beta\theta_w)(1-\theta_w)}{\theta_w} \frac{1}{1+\eta\epsilon_N}$ .

The price inflation equation associated with FS takes the familiar form:

$$\pi_t = \beta E_t \pi_{t+1} + \lambda mc_t, \quad (21)$$

where  $MC_t \equiv \int_0^1 \frac{MC_t^n(i)}{P_t} di$  denotes the average real marginal cost. The only difference with respect to the one implied by RM is that the coefficient premultiplying the real marginal cost,  $\lambda$ , is now computed numerically, as discussed in Woodford (2005). In RM parameter  $\lambda$  takes its standard value  $\frac{(1-\beta\theta)(1-\theta)}{\theta}$ .

The goods market clearing equation reflects our assumption that there are subsi-

dies offsetting the distortions associated with monopolistic competition in goods and labor markets. This implies that the steady state of our model is Pareto efficient. Specifically, we have:

$$y_t = \zeta c_t + \frac{1 - \zeta}{\delta} [k_{t+1} - (1 - \delta) k_t], \quad (22)$$

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

Let us now mention the values which we assign to the model parameters in most of the quantitative analysis that we are going to conduct. The coefficient of autocorrelation in the process of technology,  $\rho_a$ , is assumed to take the value 0.95. We set the capital share  $\alpha = 0.36$ . Our choice for the risk aversion parameter  $\sigma$  is 2. The elasticity of substitution between goods  $\varepsilon$  is set to 11. Our baseline value for the Calvo parameter for price setting,  $\theta_p$ , is 0.75 and we assume the same value for its wage setting counterpart  $\theta_w$ . The rate of capital depreciation,  $\delta$ , is assumed to be equal to 0.025 and we set  $\epsilon_\psi = 3$ . These parameter values are justified in Sveen and Weinke (2005a), Erceg et al. (2000) and the references therein. Finally, we set the elasticity of substitution between different types of labor  $\varepsilon_N$  equal to 6, a conventional value in the empirically plausible range range between 4, as in Erceg et al. (2000), and 21 which is the value assumed in Altig et al. (2005).

### 3 Welfare

We follow Erceg et al. (2000) and let the policymaker's period welfare function be the unweighted average of households' period utility:

$$W_t \equiv U(C_t) + \int_0^1 V(N_t(h)) dh = U(C_t) + E_h \{V(N_t(h))\}. \quad (23)$$

In what follows we introduce our welfare criterion and use it to compare the implications of FS and RM for monetary policy design.

### 3.1 Welfare with Firm-Specific Capital

The main technical novelty in the present paper is that we extend the work by Rotemberg and Woodford (1997) and conduct a welfare analysis in the context of a model with firm-specific capital.<sup>9</sup> Our welfare criterion is the unconditional expected value of the period welfare function.<sup>10</sup> In Appendix A we derive the following expression:

$$\begin{aligned}
E \left\{ \frac{W_t - W_t^*}{\bar{U}_C \bar{C}} \right\} &\simeq E \left\{ \Omega_1^{FS} (y_t^2 - (y_t^*)^2) + \Omega_2^{FS} (c_t^2 - (c_t^*)^2) + \Omega_3^{FS} (i_t^2 - (i_t^*)^2) \right. \\
&\quad + \Omega_4^{FS} \left( (\Delta k_{t+1})^2 - (\Delta k_{t+1}^*)^2 \right) + \Omega_5^{FS} (n_t^2 - (n_t^*)^2) \\
&\quad \left. + \Omega_6^{FS} \Delta_t + \Omega_7^{FS} \lambda_t + \Omega_8^{FS} \kappa_t + \Omega_9^{FS} \kappa_{t+1} + \Omega_{10}^{FS} \psi_t \right\} + tip, \quad (24)
\end{aligned}$$

where superscript "\*" indicates an equilibrium value associated with having flexible prices and wages. Terms independent of policy are denoted *tip*. A bar indicates the steady state value of the original variable and  $U_C$  is the marginal utility of consumption. Moreover we have used the following definitions:  $\Delta_t \equiv Var_i \widehat{p}_t(i)$ ,  $\kappa_t \equiv Var_i k_t(i)$ ,  $\psi_t \equiv Cov_i(\widehat{p}_t(i), k_t(i))$  and  $\lambda_t \equiv Var_h \widehat{w}_t(h)$ , where  $\widehat{P}_t(i) \equiv \frac{P_t(i)}{\bar{P}_t}$  and  $\widehat{W}_t(h) \equiv \frac{W_t(h)}{\bar{W}_t}$  denote, respectively, firm  $i$ 's relative to average price and household  $h$ 's relative to average nominal wage. Parameters  $\Omega_1^{FS}$  to  $\Omega_{10}^{FS}$  are functions of the structural parameters of our model. They are defined in Appendix A. The key complication that we have to face is to calculate of the cross-sectional variances of prices and capital holdings at each point in time, as well as their covariance. We

<sup>9</sup>The proof that the method of Rotemberg and Woodford (1997) can be applied to the problem at hand carries over from Edge's (2003) to our work because the relevant steady states properties of the two models are identical.

<sup>10</sup>Maximizing that function is equivalent to maximizing  $E \left\{ \sum_{t=0}^{\infty} W_t \right\}$ .

make one key observation which allows us to overcome that difficulty. Woodford's (2005) linearized rules for price setting and investment can be used to compute the relevant second moments with the accuracy that we need for our second order approximation to welfare. The details are explained in Appendix A.

### 3.2 Welfare with a Rental Market for Capital

In the rental market case the welfare criterion reads,

$$\begin{aligned}
E \left\{ \frac{W_t - W_t^*}{\bar{U}_C \bar{C}} \right\} &\simeq E \left\{ \Omega_1^{RM} (y_t^2 - (y_t^*)^2) + \Omega_2^{RM} (c_t^2 - (c_t^*)^2) + \Omega_3^{RM} (i_t^2 - (i_t^*)^2) \right. \\
&\quad + \Omega_4^{RM} \left( (\Delta k_{t+1})^2 - (\Delta k_{t+1}^*)^2 \right) + \Omega_5^{RM} (n_t^2 - (n_t^*)^2) \\
&\quad \left. + \Omega_6^{RM} \Delta_t + \Omega_7^{RM} \lambda_t \right\} + tip, \tag{25}
\end{aligned}$$

as we show in Appendix B where we also define parameters  $\Omega_1^{RM}$  to  $\Omega_7^{RM}$ . Compared with FS the analysis is greatly simplified in that case by the fact that the capital labor ratio is constant across firms, as discussed in Edge (2003).

## 4 Results

We consider two prominent families of monetary policy rules. Our ultimate goal is to explain how and why the associated constrained optimal values of the policy parameters change in each case depending on whether or not a rental market for capital is assumed.

## 4.1 The Welfare Consequences of Responding to Price and to Wage Inflation

We start by considering interest rate rules of the following kind,

$$r_t = \rho + \tau_r (r_{t-1} - \rho) + \tau_s [\tau_\omega \omega_t + (1 - \tau_\omega) \pi_t], \quad (26)$$

where parameter  $\tau_s$  measures the overall responsiveness of the nominal interest rate to changes in inflation, whereas  $\tau_\omega$  is the relative weight put on wage inflation. The weight on price inflation is therefore given by  $(1 - \tau_\omega)$ . Finally, parameter  $\tau_r$  denotes the interest rate smoothing coefficient. We analyze constrained optimal rules, i.e. we restrict attention to a particular subset of possible parameter values that parametrize the rule. Specifically, we consider only positive parameter values and moreover we require parameter  $\tau_\omega$  to be less or equal to one.

We compare the optimized interest rate rules under FS and RM. In each case we report the optimized coefficients entering the interest rate rule as well as the associated welfare loss. We follow Erceg et al. (2000) and measure the latter as a fraction of Pareto-optimal consumption, divided by the productivity innovation variance.<sup>11</sup> The results are shown in Table 1.

Table 1: Price and Wage Inflation Rule

Parameter	FS	RM
$\tau_r$	1.0156	0.9396
$\tau_s$	2.1501	4.7857
$\tau_\omega$	0.4419	0.7205
Welfare	-8.7105	-8.6403

<sup>11</sup>Let us give a concrete example for the interpretation of the welfare numbers in our tables. Suppose the productivity innovation variance is  $0.01^2$ . Then, the number  $-10$  for welfare would mean that the representative household would be willing to give up  $10 \times 0.01^2 \times 100 = 0.1$  percentage points of steady state (Pareto optimal) consumption in order to avoid the business cycle cost associated with the presence of the nominal rigidities in our model.



Regardless of whether FS or RM is used the implied optimized rule prescribes to adjust the nominal interest rate in response to changes in both wage inflation and price inflation. That seems intuitive: both kinds of inflation are costly in welfare terms since we model two nominal rigidities. Interestingly, the optimized rule prescribes to react relatively more to price inflation in FS whereas the opposite holds true in RM. Our intuition is as follows. We observe two things. First, Sveen and Weinke (2005a) show that price stickiness can be used to measure the difference between RM and FS, if attention is restricted to a *first* order approximation to the equilibrium dynamics: the feature of firm-specific capital implies that price setters internalize the consequences of their price setting decisions for the marginal cost they face. That makes them more reluctant to change their prices in FS than under RM.<sup>12</sup> Specifically, we show in our 2005a paper that a value of about 0.9 is needed in RM in order to obtain equivalence with FS if the value 0.75 is assigned to the price stickiness parameter in the latter case and all the remaining parameters are held constant at conventional values. Put differently, the rental market assumption turns off the *endogenous* price stickiness which is implied by the alternative specification with firm-specific capital. Second, it is a well understood property of many New Keynesian models that the central bank achieves the most desirable welfare outcome if it cares relatively more about the nominal variable which is relatively stickier.<sup>13</sup> Combining these two observations the previous finding seems intuitive. Since the rental market assumption eliminates the endogenous part of the price stickiness the central bank should care relatively more about wage inflation in that model. The reason is endogenous wage stickiness. That feature is common to FS and RM: in both models households internalize the consequences of their wage setting decisions for the marginal disutility of labor they face. On the other hand, if firm-specific

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<sup>12</sup>This kind of intuition has been originally developed in Sbordone (2002) and Galí et al. (2001) in the context of models where capital is assumed to be a constant factor. For an early model featuring differences in the marginal cost across firms see Woodford (1996).

<sup>13</sup>See, e.g., Aoki (2001) and Benigno (2003).

capital is taken into account then the implied endogenous price stickiness is strong enough to make it worthwhile for the central bank to care relatively more about price inflation.

So far our intuition relies on a finding, namely our price stickiness metric, which has been obtained in the context of a first order approximation to the equilibrium dynamics. This kind of intuition could easily be misleading for our purposes here. The reason is that the second order approximation to the household’s expected utility, our welfare criterion, is not equivalent in both models if we just change the price stickiness in such a way that the two models would be identical up to the first order. We therefore challenge our intuition by conducting the following experiment whose results are shown in Table 2.

Table 2: Robustness I: Rules from the RM Model Used in FS

Parameter	RM rule with $\theta = 0.75$	RM rule with $\theta = 0.90$
$\tau_r$	0.9396	1.0162
$\tau_s$	4.7857	0.5082
$\tau_\omega$	0.7205	0.3288
Welfare	-11.2425	-9.0250

We compute welfare in FS as implied by the optimized policy rule in RM under the baseline calibration. The welfare loss increases by 29.1% with respect to the outcome under the optimized rule for FS. Now we compute constrained optimal policy in RM for a price stickiness parameter equal to 0.9. The implied optimized rule looks similar to the one associated with FS under the baseline calibration. Specifically, the rule prescribes to react relatively more to price inflation than to wage inflation. Moreover, the increase in welfare loss which obtains if that rule is used in FS is just 3.6%, which we regard as being negligible. The last result suggests that our price stickiness metric is useful from a welfare point of view.<sup>14</sup>

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<sup>14</sup>In principle, whether or not the price stickiness metric is useful to tell the difference in welfare

To further illustrate the macroeconomic consequences of three different monetary policy rules in Tables 1 and 2 we construct impulse responses to a one standard deviation shock to productivity for price inflation and wage inflation. They are shown in Figure 1. Under the baseline calibration the optimal simple rule for FS implies that price inflation is stabilized relatively more than it is the case if the optimized rule for RM is used instead. However, if the price stickiness parameter is set to 0.9 in RM then the implied optimized rule delivers an outcome in FS that is almost identical to the one under the optimized rule for that model.

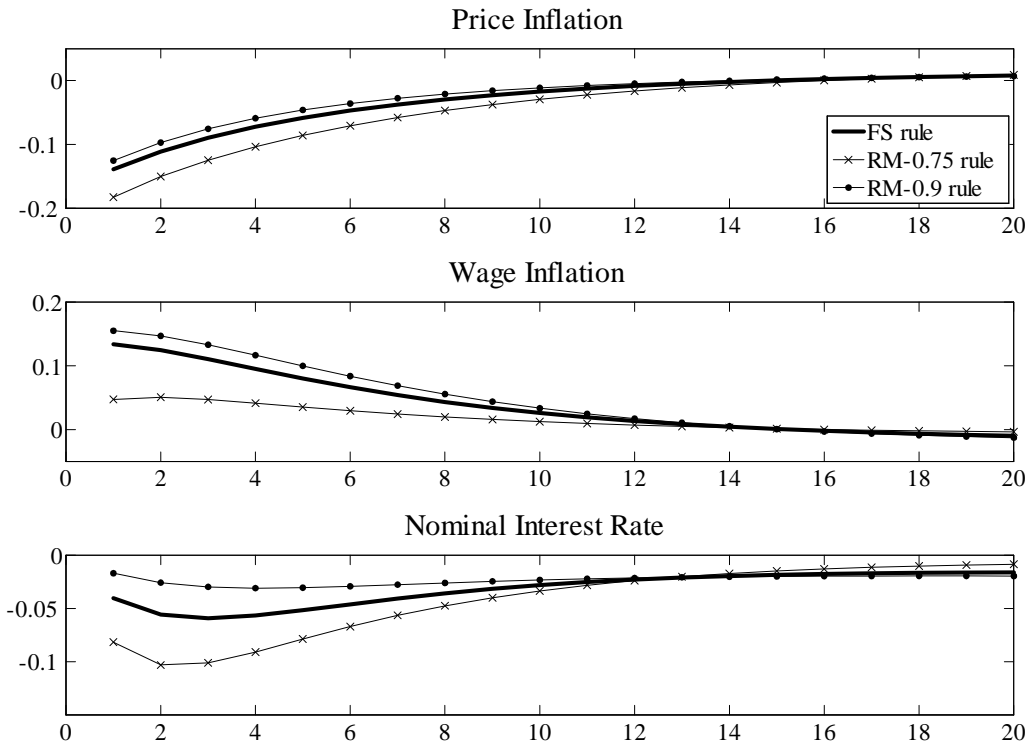


Figure 1: Impulse responses to a technology shock with different price and wage inflation rules.

implications between FS and RM could depend on the specification of monetary policy. For all the policies we consider, however, our metric turns out to be useful.

Next we consider the welfare implications of interest rate rules prescribing that the central bank adjusts the nominal interest rate not only in response to nominal variables but also as a function of a measure of real economic activity.

## 4.2 The Welfare Consequences of Taylor Type Rules

We now turn to the welfare implications of Taylor type rules,

$$r_t = \rho + \tau_r (r_{t-1} - \rho) + \tau_s [\tau_y y_t^{gap} + (1 - \tau_y) \pi_t], \quad (27)$$

where parameter  $\tau_y$  denotes the relative weight put on the output gap. The resulting weight on price inflation is therefore given by  $(1 - \tau_y)$ . The output gap,  $y_t^{gap}$ , is generally defined as the difference between the equilibrium output in an economy with frictions and natural output, i.e. the equilibrium output that would obtain in the absence of nominal frictions. In the context of a model featuring endogenous capital accumulation Woodford (2003, Ch. 5) proposes to refine the notion of natural output in the following way. He uses the equilibrium output that would obtain if the nominal rigidities were absent and expected to be absent in the future but taking as given the capital stock resulting from optimizing investment behavior in the past in an environment *with* the nominal rigidities present. Woodford argues that this measure of natural output is more closely related to equilibrium determination than the alternative measure which has been used by Neiss and Nelson (2003). Under their definition natural output is the equilibrium output that would obtain if nominal rigidities were not only currently absent and expected to be absent in the future but had also been absent *in the past*. Indeed, intuitively, the Neiss and Nelson definition of natural output appears to be a bit artificial. We find, however, that from a practical point of view it does not matter for the design of constrained optimal interest rate rules which concept of natural output is used to compute the output

gap. We will come back to this point. Before that let us consider some welfare implications of Taylor type rules using Woodford’s definition of the output gap.<sup>15</sup> The results are shown in Table 3.

Table 3: Taylor-type rule with Woodford Output Gap

Parameter	FS	RM
$\tau_r$	1.0043	1.3723
$\tau_s$	0.0715	0.5173
$\tau_y$	1.0000	0.6678
Welfare	-8.7850	-8.6552

The optimal rule implied by FS prescribes a zero weight on price inflation. On the other hand, under RM, we find that the central bank should attach some weight to both price inflation and the output gap. More importantly, however, the loss is negligible if we compute welfare in FS using the optimized rule implied by RM. We therefore argue that Taylor type rules are very robust. The results are shown in table 4.

Table 4: Robustness II: Rules from the RM Model Used in FS

Parameter	RM rule with $\theta = 0.75$	RM rule with $\theta = 0.90$
$\tau_r$	1.3723	1.0105
$\tau_s$	0.5173	0.0577
$\tau_y$	0.6678	0.3983
Welfare	-9.0712	-8.8861

As the last table also indicates the welfare loss associated with using the rule implied by RM in FS can be further reduced if the price stickiness is adjusted in RM

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<sup>15</sup>Our computational strategy to calculate natural output under Woodford’s definition is straightforward. First, we calculate the parameters of the linear function mapping aggregate capital and technology into equilibrium aggregate output in an environment *without* any nominal frictions present. Second, we take the equilibrium value of aggregate capital as implied by FS (or by RM when we study that case) combine it with the the level of technology and compute Woodford’s natural output invoking the above mapping.

in such a way that both models would be identical up to the first order. Once again, our price stickiness metric turns out to be useful. The policy implications of RM are surprisingly accurate if an upward biased estimate of the price stickiness parameter (of the kind that the econometrician actually obtains if she looks at the data through the lens of that model) is used in the analysis. Somewhat surprisingly, however, the optimal relative weight attached to the output gap in RM becomes *smaller* (and hence less in line with the corresponding value implied by FS) if the price stickiness is increased. That feature appears, however, to be specific to Woodford’s definition of natural output, as we are going to see next.

Finally, we analyze Taylor type rules using Neiss and Nelson’s (2003) definition of the output gap. Our results are reported in table 5.

Table 5: Taylor-Type Rule with Neiss and Nelson Output Gap

Parameter	FS	RM
$\tau_r$	1.0055	1.4523
$\tau_s$	0.0628	0.3556
$\tau_y$	1.0000	0.6676
Welfare	-8.7510	-8.7485

Overall, optimized rules implied by FS and RM are very similar to the ones obtained before under Woodford’s definition of the output gap. In particular, we find again that under RM the optimized rule prescribes to react to both inflation and the output gap, whereas a zero weight is attached to inflation under the optimized rule associated with FS. We also confirm our previous finding that Taylor type rules are very robust. If the optimized rule implied by RM is used under FS then the resulting welfare loss is negligible and, moreover, the loss can be further reduced if the price stickiness parameter is adjusted in RM according to our metric. The results are shown in table 6.

Table 6: Robustness III: Rules from the RM Model Used in FS

Parameter	RM rule with $\theta = 0.75$	RM rule with $\theta = 0.90$
$\tau_r$	1.4523	1.0069
$\tau_s$	0.3556	0.0396
$\tau_y$	0.6676	0.9983
Welfare	-9.2120	-8.7810

There is only one (small) difference with respect to the previous analysis of Taylor type rules featuring an output gap à la Woodford. Under the Neiss and Nelson definition the resulting interest rate rules become more similar between FS and RM if we adjust the price stickiness in RM as prescribed by our metric.<sup>16</sup>

Our intuition for why the particular definition of the output gap that is used in the analysis of optimal monetary policy matters so little is simple. The capital stock does not change much at business-cycle frequencies and the *difference* between the change in capital implied by a model with and without nominal rigidities present is even less important.

Regardless of the definition of the output gap Taylor type rules appear to be very robust. The output gap is of course not directly observable. However, our results stress the importance of constructing (theory consistent) observable measures of that variable.

## 5 Conclusion

The present paper makes progress in explaining the welfare consequences of firm-specific capital accumulation. We analyze (constrained) optimal interest rate rules prescribing that the nominal interest rate is set as a function of a small number of

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<sup>16</sup>The finding that, if anything, small details of the optimized interest rate rules change depending on which measure of the output gap is used is also confirmed by further robustness checks that we have conducted experimenting with alternative interest rate rules.

macroeconomic variables. Our results suggest that Taylor type interest rate rules are very robust. Their welfare implications do not appear to hinge neither on the specific assumptions regarding capital accumulation that are used in their derivation nor on the particular definition of natural output that is used to construct the output gap.



# Appendix A: Welfare with Firm-Specific Capital

We approximate the utility of the representative household up to the second order. In what follows, we make frequent use of two rules:

$$\frac{A_t - \bar{A}}{\bar{A}} \simeq a_t + \frac{1}{2}a_t^2, \quad (\text{A1})$$

where  $a_t \equiv \ln\left(\frac{A_t}{\bar{A}}\right)$ . Moreover, if  $A_t = \left(\int_0^1 A_t(i)^\gamma di\right)^{\frac{1}{\gamma}}$  then:

$$a_t \simeq E_i a_t(i) + \frac{1}{2}\gamma \text{Var}_i a_t(i). \quad (\text{A2})$$

As we have already mentioned in the text the policymaker's period welfare function reads:

$$W_t \equiv U(C_t) + \int_0^1 V(N_t(h)) dh = U(C_t) + E_h \{V(N_t(h))\}. \quad (\text{A3})$$

Now we compute a second-order Taylor expansion of period welfare:

$$\begin{aligned} W_t &\simeq \bar{W} + \bar{U}_C (C_t - \bar{C}) + \bar{V}_N E_h \{(N_t(h) - \bar{N})\} \\ &\quad + \frac{1}{2}\bar{U}_{CC} (C_t - \bar{C})^2 + \frac{1}{2}\bar{V}_{NN} E_h \{(N_t(h) - \bar{N})^2\} \\ &= \bar{W} + \bar{U}_C \bar{C} \left(c_t + \frac{1}{2}c_t^2\right) - \bar{V}_N \bar{N} E_h \left\{n_t(h) + \frac{1}{2}n_t(h)^2\right\} \\ &\quad - \frac{1}{2}\bar{U}_{CC} \bar{C}^2 c_t^2 + \frac{1}{2}\bar{V}_{NN} \bar{N}^2 E_h \{n_t(h)^2\}. \end{aligned} \quad (\text{A4})$$

Next we show how the linear terms in consumption and employment in the last equation can be approximated up to the second order. We start by analyzing the consumption portion of welfare. To this end we invoke the resource constraint.

## A1: The Resource Constraint With Convex Adjustment Cost

The resource constraint reads:

$$Y_t = C_t + I_t. \quad (\text{A5})$$

Up to the second order the following relationship holds true:

$$c_t + \frac{1}{2}c_t^2 \simeq \frac{1}{\zeta} \left( y_t + \frac{1}{2}y_t^2 \right) - \frac{1-\zeta}{\zeta} \left( i_t + \frac{1}{2}i_t^2 \right). \quad (\text{A6})$$

Next we analyze the investment portion of the resource constraint. Our starting point is a second order approximation to aggregate investment:

$$i_t \simeq E_i \{i_t(i)\} + \frac{1}{2}Var_i \{i_t(i)\}. \quad (\text{A7})$$

Approximating firm level investment up to the second order yields:

$$i_t(i) \simeq \frac{1}{\delta} \left[ k_{t+1}(i) - (1-\delta)k_t(i) + \frac{1}{2} \left( \varepsilon_\psi - \frac{1-\delta}{\delta} \right) (k_{t+1}(i) - k_t(i))^2 \right]. \quad (\text{A8})$$

Next we invoke the result by Woodford (2005) according to which the linearized pricing and investment rules in our model can be written as follows:

$$\widehat{p}_t^*(i) = \widehat{p}_t^* - \tau_1 \widehat{k}_t(i), \quad (\text{A9})$$

$$\widehat{k}_{t+1}(j) = \tau_2 \widehat{k}_t(j) + \tau_3 \widehat{p}_t(j), \quad (\text{A10})$$

where  $\tau_1$ ,  $\tau_2$  and  $\tau_3$  are parameter that can be computed numerically. We have also used the notation  $\widehat{K}_t(i) \equiv \frac{K_t(i)}{K_t}$  for firm  $i$ 's relative to average capital stock. Using these results we can write a second order approximation to aggregate investment as

follows:

$$\begin{aligned}
i_t \simeq & \frac{1}{\delta} [k_{t+1} - (1 - \delta) k_t] + \frac{1}{2} \frac{1}{\delta} \left( \varepsilon_\psi - \frac{1 - \delta}{\delta} \right) (k_{t+1} - k_t)^2 \\
& + \frac{1}{2} \frac{1}{\delta} \left( \varepsilon_\psi - \frac{2}{\delta} \right) \kappa_{t+1} \\
& + \frac{1}{2} \frac{1}{\delta} \left[ 1 - \delta - \frac{(1 - \delta)^2}{\delta} + \left( \varepsilon_\psi - \frac{1 - \delta}{\delta} \right) (1 - 2\tau_2) \right] \kappa_t \\
& - \frac{\tau_3 \varepsilon_\psi \delta - (1 - \delta) \tau_3}{\delta^2} \psi_t.
\end{aligned} \tag{A11}$$

Next we analyze the labor portion of welfare.

## A2: Aggregate Labor

Approximating  $E_h n_t(h)$  up to the second order yields:

$$\begin{aligned}
E_h n_t(h) \simeq & \frac{1}{1 - \alpha} (y_t - x_t) - \frac{1}{1 - \alpha} \alpha k_t + \frac{1}{2} \frac{1 - \alpha + \frac{\alpha(\varepsilon - 1)}{1 - \alpha}}{1 - \alpha} \varepsilon \Delta_t \\
& + \frac{1}{2} \frac{\alpha}{(1 - \alpha)^2} \kappa_t + \frac{\alpha \varepsilon}{(1 - \alpha)^2} \psi_t \\
& - \frac{1}{2} (\varepsilon_N - 1) \varepsilon_N \lambda_t.
\end{aligned} \tag{A12}$$

We also note that  $E_h \{n_t(h)^2\}$  can be written as:

$$\begin{aligned}
E_h \{n_t(h)^2\} & = \text{var}_h n_t(h) + (E_h n_t(h))^2 \\
& = \varepsilon_N^2 \lambda_t + n_t^2.
\end{aligned} \tag{A13}$$

### A3: The Welfare Function

Now we combine equations (A6), (A11), (A12) and (A13) with (A4) and note that the linear terms in the resulting expression cancel except for the ones in current and next period's aggregate capital. The economic reason is that the steady state of our model is Pareto optimal, as analyzed in Rotemberg and Woodford (1997). In order to eliminate next period's aggregate capital we write our welfare criterion as  $E \{ \sum_{t=0}^{\infty} W_t \}$ . This allows us to invoke a result by Edge (2003). She shows that the terms in aggregate capital in that expression cancel except for the initial one which is independent of policy. Deriving the welfare associated with flexible prices and wages,  $W_t^*$ , in an analogous way and subtracting the resulting expression from  $W_t$  we therefore obtain:

$$\begin{aligned}
 E \left\{ \frac{W_t - W_t^*}{\bar{U}_C \bar{C}} \right\} &\simeq E \left\{ \Omega_1^{FS} (y_t^2 - (y_t^*)^2) + \Omega_2^{FS} (c_t^2 - (c_t^*)^2) + \Omega_3^{FS} (i_t^2 - (i_t^*)^2) \right. \\
 &\quad + \Omega_4^{FS} \left( (\Delta k_{t+1})^2 - (\Delta k_{t+1}^*)^2 \right) + \Omega_5^{FS} (n_t^2 - (n_t^*)^2) + \Omega_6^{FS} \Delta_t \\
 &\quad \left. + \Omega_7^{FS} \lambda_t + \Omega_8^{FS} \kappa_t + \Omega_9^{FS} \kappa_{t+1} + \Omega_{10}^{FS} \psi_t \right\} + tip, \tag{A14}
 \end{aligned}$$

where the following coefficients have been used:

$$\begin{aligned}
 \Omega_1^{FS} &\equiv \frac{1}{2} \frac{1}{\zeta}, \quad \Omega_2^{FS} \equiv \frac{\sigma}{2}, \quad \Omega_3^{FS} \equiv \frac{1}{2} \frac{1 - \zeta}{\zeta}, \\
 \Omega_4^{FS} &\equiv -\frac{1}{2} \frac{1 - \zeta}{\delta} \left( \varepsilon_\psi - \frac{1 - \delta}{\delta} \right), \quad \Omega_5^{FS} \equiv -\frac{1}{2} \frac{1 - \alpha}{\zeta} (1 + \phi), \\
 \Omega_6^{FS} &\equiv -\frac{1}{2} \frac{\varepsilon (1 - \alpha) + \alpha \varepsilon}{\zeta (1 - \alpha)}, \quad \Omega_7^{FS} \equiv -\frac{1}{2} \frac{(1 - \alpha) \varepsilon_N}{\zeta} (1 + \phi \varepsilon_N), \\
 \Omega_8^{FS} &\equiv -\frac{1}{2} \left\{ \frac{1 - \zeta}{\delta} \left[ (1 - \delta) \left( 1 - \frac{1 - \delta}{\delta} \right) + \left( \varepsilon_\psi - \frac{1 - \delta}{\delta} \right) (1 - 2\tau_2) \right] - \frac{1}{2} \frac{1 - \alpha}{\zeta (1 - \alpha)} \right\}, \\
 \Omega_9^{FS} &\equiv -\frac{1}{2} \frac{1 - \zeta}{\delta} \left( \varepsilon_\psi - \frac{2}{\delta} \right), \quad \Omega_{10}^{FS} \equiv \frac{1}{\zeta} \left( (1 - \zeta) \frac{\tau_3 \varepsilon_\psi \delta - (1 - \delta) \tau_3}{\delta^2} - \frac{\alpha \varepsilon}{1 - \alpha} \right).
 \end{aligned}$$

This is the expression stated in the text.

#### A4: Recursive Formulation for the Variance/Covariance Terms

Next we derive recursive formulations for the variance/covariance terms. Using again the pricing and investment rules mentioned above we arrive at the following expressions:

$$\Delta_t = \theta_p \Delta_{t-1} + (1 - \theta_p) \tau_1^2 \kappa_t + \frac{\theta_p}{1 - \theta_p} \pi_t^2, \quad (\text{A15})$$

$$\kappa_t = \tau_2^2 \kappa_{t-1} + \tau_3^2 \Delta_{t-1}, \quad (\text{A16})$$

$$\psi_t = \theta_p \tau_2 \psi_{t-1} + \theta_p \tau_3 \Delta_{t-1} - \tau_1 (1 - \theta_p) \kappa_t, \quad (\text{A17})$$

$$\lambda_t = \theta_w \lambda_{t-1} + \frac{\theta_w}{1 - \theta_w} (\Delta w_t)^2. \quad (\text{A18})$$

## Appendix B: Welfare with Rental Market

In the rental market case the analysis is greatly simplified by that fact that the capital labor ratio is constant across firms, as discussed in Edge (2003). The resulting welfare criterion reads:

$$\begin{aligned}
 E \left\{ \frac{W_t - W_t^*}{\bar{U}_C \bar{C}} \right\} &\simeq E \left\{ \Omega_1^{RM} (y_t^2 - (y_t^*)^2) + \Omega_2^{RM} (c_t^2 - (c_t^*)^2) + \Omega_3^{RM} (i_t^2 - (i_t^*)^2) \right. \\
 &+ \Omega_4^{RM} \left( (\Delta k_{t+1})^2 - (\Delta k_{t+1}^*)^2 \right) + \Omega_5^{RM} (n_t^2 - (n_t^*)^2) + \Omega_6^{RM} \Delta_t \\
 &\left. + \Omega_7^{RM} \lambda_t \right\} + tip, \tag{A19}
 \end{aligned}$$

where

$$\begin{aligned}
 \Omega_1^{RM} &\equiv \Omega_1^{FS}, \\
 \Omega_2^{RM} &\equiv \Omega_2^{FS}, \\
 \Omega_3^{RM} &\equiv \Omega_3^{FS}, \\
 \Omega_4^{RM} &\equiv \Omega_4^{FS}, \\
 \Omega_5^{RM} &\equiv \Omega_5^{FS}, \\
 \Omega_6^{RM} &\equiv -\frac{1}{2} \frac{\varepsilon}{\zeta}, \\
 \Omega_7^{RM} &\equiv \Omega_7^{FS}.
 \end{aligned}$$

Finally, the variance terms can be written in a recursive manner:

$$\Delta_t = \theta_p \Delta_{t-1} + \frac{\theta_p}{1 - \theta_p} \pi_t^2, \tag{A20}$$

$$\lambda_t = \theta_w \lambda_{t-1} + \frac{\theta_w}{1 - \theta_w} (\Delta w_t)^2, \tag{A21}$$

as discussed in Wooford (2003, Ch, 6) and Erceg et al. (2000).

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