Firm-Specific Production Factors in a DSGE Model with Taylor Price Setting

de Walque, Gregory and Smets, Frank and Wouters, Rafael

30 June 2006

Firm-Specific Production Factors in a DSGE Model with Taylor Price Setting*

Gregory de Walque,[a] Frank Smets,[b] and Rafael Wouters[a]
[a]National Bank of Belgium
[b]European Central Bank, CEPR, and Ghent University

Using Bayesian likelihood methods, this paper estimates a dynamic stochastic general equilibrium model with Taylor contracts and firm-specific factors in the goods market on euro-area data. The paper shows how the introduction of firm-specific factors improves the empirical fit of the model and reduces the estimated contract length to a duration of four quarters, which is more consistent with the empirical evidence on average price durations in the euro area. However, in order to obtain this result, the estimated real rigidity is very large, either in the form of a very large constant elasticity of substitution between goods or in the form of an endogenous elasticity of substitution that is very sensitive to the relative price. Finally, the paper also investigates the implications of these estimates for the distribution of prices and quantities across the various goods sectors.

JEL Codes: E1–E3.

1. Introduction

Following the theoretical work of Yun (1996) and Woodford (2003), the New Keynesian Phillips curve, relating inflation to expected future inflation and the marginal cost, has become a popular tool

*We thank Steve Ambler, Guido Ascari, Günter Coenen, Herve Le Bihan, Andy Levin, Jesper Lindé, and members of the Inflation Persistence Network for insightful and stimulating comments. The views expressed in this paper are our own and do not necessarily reflect those of the European Central Bank or the National Bank of Belgium. Author e-mail addresses: gregory.dewalque@nbb.be, frank.smets@ecb.int, rafael.wouters@nbb.be.

for monetary policy analysis. Typically, the elasticity of inflation with respect to changes in the marginal cost is, however, estimated to be very small (e.g., Galí and Gertler 1999; Galí, Gertler, and López-Salido 2001; and Sbordone 2002). In models with constant-returns-to-scale technology, perfectly mobile production factors, and a constant elasticity of substitution between goods, such low estimates imply an implausibly high degree of nominal price stickiness. For example, Smets and Wouters (2003) find that, on average, nominal prices remain fixed for more than two years. This is not in line with existing microevidence that suggests that, on average, prices are sticky for around six months to one year.[1]

In response to these findings, a number of papers have investigated whether the introduction of additional real rigidities, such as frictions in the mobility of capital across firms, can address this apparent mismatch between the macro- and microestimates of the degree of nominal price stickiness. For example, Woodford (2005), Eichenbaum and Fisher (2004), and Altig et al. (2005) show how the introduction of firm-specific capital lowers the elasticity of prices with respect to the real marginal cost for a given degree of price stickiness. This paper focuses on the same issue. Using Bayesian likelihood methods as in Smets and Wouters (2003, 2005), it estimates a dynamic stochastic general equilibrium (DSGE) model with overlapping price and wage contracts as in Taylor (1980) and firm-specific factors in the monopolistically competitive goods market. With the exception of those two features, the specification of the DSGE model is the same as in Smets and Wouters (2005). As in

[1]See the evidence in Bils and Klenow (2004) for the United States and Altissimo, Ehrmann, and Smets (2005) for a summary of the Inflation Persistence Network (IPN) evidence on price stickiness in the euro area.

However, one should be careful with using the microevidence to interpret the macroestimates. Because of indexation and a positive steady-state inflation rate, all prices change all the time. However, only a small fraction of prices are set optimally. The alternative story for introducing a lagged inflation term in the Phillips curve based on the presence of rule-of-thumb price setters is more appealing from this perspective, as it does not imply that all prices change all the time. In that case, the comparison of the Calvo parameter with the microevidence makes more sense. As the reduced-form representations are almost identical, one could still argue that the estimated Calvo parameter is implausibly high.

Smets and Wouters (2005), the model is estimated on quarterly euro-area data from 1974:Q1 to 2002:Q2.[2] The reason for using Taylor contracts is twofold. First, while the simple Calvo model is analytically tractable, its derivation with firm-specific factors and endogenous capital accumulation is nontrivial and cannot be solved in closed form. This complicates the empirical estimation of the full model. The assumption of Taylor contracts facilitates the estimation of a fully specified linearized DSGE model that embeds the pricing decisions of monopolistically competitive price and wage setters and real rigidities such as firm-specific capital and/or labor. Second, the use of Taylor contracts in this DSGE setting makes it easier to analyze the distribution of prices and quantities across the various sectors. This analysis is important to check whether the introduction of real rigidities leads to a realistic distribution of prices and quantities (as in Altig et al. 2005). Our paper is most closely related to that of Coenen and Levin (2004), which also investigates the relative importance of real and nominal rigidities in a world with Taylor contracts. However, the Coenen and Levin (2004) paper focuses on Germany and does not specify the full structural model. Finally, in contrast to most of the papers mentioned above, our paper also analyzes the implications of firm-specific labor markets.

In the rest of this paper, we proceed in several steps. First, we estimate the Taylor contracting specification of the Smets-Wouters DSGE model under the assumption that firms are price takers in the factor markets, i.e., the labor and capital markets, and hence all firms face the same flat marginal cost curve. We compare this specification with the analogous Calvo model and find that the length of the Taylor contracts in the goods market needs to be extremely long (about five years) in order to match the data as well as the Calvo scheme. Though striking, this result is consistent with Dixon and Kara (2006), who show how to compare the mean duration of contracts in both time-dependent price-setting models. In this section, we also show that the standard way of introducing markup shocks in the Calvo model does not work very well with Taylor-type price

[2]As shown in Smets and Wouters (2005), estimation results are quite similar for U.S. data.

setting, and we propose a different way of introducing price-markup shocks.

Next, we reestimate the Taylor contracting models with firm-specific capital and/or firm-specific labor and analyze the impact of these assumptions on the empirical performance of the DSGE model and on the estimated contract length in the goods market. Our main findings are twofold. First, in line with the previous literature, we find that introducing firm-specific capital does lead to a fall in the estimated Taylor contract length in the goods market to a more reasonable length of four quarters. However, the elasticity of substitution between goods of the various price-setting cohorts is estimated to be improbably high. Furthermore, the corresponding price markup is estimated to be smaller than the fixed cost, implying negative profits in steady state. Enforcing a steady-state zero-profit condition leads to a significant deterioration of the empirical fit. At the same time, the estimated elasticity of substitution remains very large. Moving from the traditional Dixit-Stiglitz aggregator toward Kimball's (1995) generalized aggregator helps to solve both problems. In that case, the curvature parameter is estimated to be high, which is a sign that real rigidities are at work, but both the estimated elasticity of substitution and the cost of imposing the above-mentioned zero-profit constraint are sharply reduced. These results are in line with Eichenbaum and Fisher (2004), Coenen and Levin (2004), and Altig et al. (2005). In this context, we also investigate the implications of the various models for the firm-specific supply and pricing decisions, which are straightforward to perform in a Taylor contracting framework.

Finally, we also analyze the impact on empirical performance of introducing firm-specific labor markets. Here the results are less promising in terms of reducing the estimated degree of nominal price stickiness. The reason is that firm-specific labor markets only dampen the price impact of a change in demand for a given degree of nominal price stickiness if the firm-specific labor markets are flexible and the firm-specific wage is responding strongly to changes in the demand for labor. Such wage flexibility is, however, incompatible with the empirical properties of aggregate wage behavior.

The rest of the paper is structured as follows. First, section 2 reviews the estimated DSGE model of Smets and Wouters (2005) and introduces Taylor-type contracting in goods and labor markets.

Next, section 3 explores the impact of introducing firm-specific production factors. The concluding remarks are in section 4.

2. Taylor and Calvo Price Setting with Mobile Production Factors

In this section, we compare the empirical performance of the Taylor price-setting model with the Calvo model estimated in Smets and Wouters (2005), maintaining the assumption of mobile production factors across firms. We first briefly review the Calvo model of Smets and Wouters (2005) and the alternative Taylor specification. Then, we compare the estimates of both models on euro-area data.

2.1 The Smets-Wouters Model with Calvo and Taylor Price Setting

The Smets-Wouters (2005) model contains many frictions that affect both nominal and real decisions of households and firms. Households maximize a nonseparable utility function with two arguments (goods and labor effort) over an infinite life horizon. Consumption appears in the utility function relative to a time-varying external habit variable. Labor is differentiated, so that there is some monopoly power over wages, which results in an explicit wage equation and allows for the introduction of sticky nominal wages à la Calvo (1983). Households rent capital services to firms and decide how much capital to accumulate, taking into account capital adjustment costs.

The main focus in this paper is on the firms' price setting. In the Calvo specification, a continuum of firms produces differentiated goods, decides on labor and capital inputs, and sets prices. Following Calvo (1983), every period, only a fraction $(1 - \xi_p)$ of firms in the monopolistic competitive sector are allowed to reoptimize their price. This fraction is constant over time. Moreover, those firms that are not allowed to reoptimize index their prices to the past inflation rate and the time-varying inflation target of the central bank. An additional important assumption is that all firms are price takers in the factor markets for labor and capital and thus face the same marginal cost. The marginal costs depend on wages, the rental rate of capital, and productivity.

As shown in Smets and Wouters (2005), this leads to the following linearized *inflation equation*:

$$\hat{\pi}_t - \bar{\pi}_t = \frac{\beta}{1+\beta\gamma_p}(E_t\hat{\pi}_{t+1} - \bar{\pi}_t) + \frac{\gamma_p}{1+\beta\gamma_p}(\hat{\pi}_{t-1} - \bar{\pi}_t)$$

$$+ \frac{1}{1+\beta\gamma_p}\frac{(1-\beta\xi_p)(1-\xi_p)}{\xi_p}\hat{s}_t + \eta_t^p \tag{1}$$

$$\hat{s}_t = \alpha\hat{r}_t^k + (1-\alpha)\hat{w}_t - \varepsilon_t^a - (1-\alpha)\gamma t. \tag{2}$$

Parameters α and β are, respectively, the capital share and the household's discount factor. The deviation of inflation $\hat{\pi}_t$ from the target inflation rate $\bar{\pi}_t$ depends on past and expected future inflation deviations and on the current marginal cost (which itself is a function of the rental rate on capital $\hat{r}_t^k$, the real wage $\hat{w}_t$, and the productivity process) that is composed of a deterministic trend in labor efficiency γt and a stochastic component ε_t^a, which is assumed to follow a first-order autoregressive process: $\varepsilon_t^a = \rho_a\varepsilon_{t-1}^a + \eta_t^a$, where η_t^a is an i.i.d.-normal productivity shock. Finally, η_t^p is an i.i.d.-normal price-markup shock. When the degree of indexation to past inflation is zero ($\gamma_p = 0$), this equation reverts to the standard purely forward-looking New Keynesian Phillips curve. When all prices are flexible ($\xi_p = 0$) and the price-markup shock is zero, this equation reduces to the normal condition that, in a flexible-price economy, the real marginal cost is constant.

In the Taylor specification, firms set prices for a fixed number of periods, and price setting is staggered over the duration of the contract, i.e., the number of firms adjusting their price is the same every period.[3] The explicit modeling of the different cohorts in the Taylor model facilitates the introduction of firm-specific capital and labor in the next section, as no aggregation across cohorts is required. It also has the advantage that the cohort-specific output and price levels are directly available, which is important for checking whether

[3]See Coenen and Levin (2004) and Dixon and Kara (2005) for a generalization of the standard Taylor contracting model where different firms may set prices for different lengths of time. See also chapter 2 in Taylor (1993).

the dispersion of output and prices across price-setting cohorts is realistic.

In order to be able to compare the Taylor price-setting model with the Calvo model estimated in Smets and Wouters (2005), we maintain the assumption of partial indexation to lagged inflation and the inflation objective. As discussed in Whelan (2004) and Coenen and Levin (2004), the staggered Taylor contracting model gives rise to the following linearized equations for the newly set optimal price and the general price index:

$$\hat{p}_t^* = \frac{1}{\sum_{i=0}^{n_p-1}\beta^i}\left[\sum_{i=0}^{n_p-1}\beta^i(\hat{s}_{t+i}+\hat{p}_{t+i}) - \sum_{i=0}^{n_p-2}\left((\gamma_p\hat{\pi}_{t+i}+(1-\gamma_p)\bar{\pi}_{t+i+1})\sum_{q=i+1}^{n_p-1}\beta^q\right)\right] + d\varepsilon_t^p \qquad (3)$$

$$\hat{p}_t = \frac{1}{n_p}\sum_{i=0}^{n_p-1}\left(\hat{p}_{t-i}^* + \sum_{q=0}^{i-1}(\gamma_p\hat{\pi}_{t-1-q}+(1-\gamma_p)\bar{\pi}_{t-q})\right) + (1-d)\varepsilon_t^p, \qquad (4)$$

where n_p is the duration of the contract, d is a binary parameter ($d \in \{0,1\}$), and $\varepsilon_t^p = \rho_t^p\varepsilon_{t-1}^p + \eta_t^p$, with η_t^p an i.i.d. shock. We experiment with two ways of introducing the price-markup shocks in the Taylor contracting model. The first method ($d = 1$) is fully analogous with the Calvo model. We assume a time-varying markup in the optimal price-setting equation, which introduces a shock in the linearized price-setting equation (3) as shown above. The second method ($d = 0$) is somewhat more ad hoc. It consists of introducing a shock in the aggregate price equation (4).[4]

[4]This could be justified as a relative price shock to a flexible-price sector that is not explicitly modeled. Of course, such a shortcut ignores the general equilibrium implications (e.g., in terms of labor and capital reallocations).

Similarly, we introduce Taylor contracting in the wage-setting process. This leads to the following linearized equations for the newly set optimal wage and the average wage:

$$\hat{w}_t^* = \frac{1}{\sum_{i=0}^{n_w-1}\beta^i}\left[\sum_{i=0}^{n_w-1}\beta^i\left(\sigma_l \hat{l}_{i,t+i} + \frac{1}{1-h}(\hat{c}_{t+i} - h\hat{c}_{t+i-1}) - \varepsilon_{t+i}^l\right)\right.$$
$$\left. + \sum_{i=1}^{n_w-1}\left((\hat{\pi}_{t+i} - \gamma_w\hat{\pi}_{t+i-1} - (1-\gamma_w)\bar{\pi}_{t+i})\sum_{q=i}^{n_w-1}\beta^q\right)\right] + d\varepsilon_t^w \tag{5}$$

$$\hat{w}_t = \frac{1}{n_w}\left[\sum_{i=0}^{n_w-1}\hat{w}_{i,t} + \hat{p}_{t-i}\right] - \hat{p}_t + (1-d)\varepsilon_t^w \tag{6}$$

with

$$\hat{w}_{i,t} = \hat{w}_{t-i}^* + \sum_{q=0}^{i-1}(\gamma_w\hat{\pi}_{t-1-q} + (1-\gamma_w)\bar{\pi}_{t-q}) \tag{7}$$

$$\hat{l}_{i,t+i} = \hat{l}_{t+i} - \frac{1+\lambda_w}{\lambda_w}[\hat{w}_{i,t+i} + \hat{p}_t - (\hat{w}_{t+i} + \hat{p}_{t+i})], \tag{8}$$

where n_w is the duration of the wage contract; σ_l represents the inverse elasticity of work effort with respect to real wage; $\hat{l}_t$ is the labor demand described in equation (23) (cf. appendix 2); $\hat{l}_{i,t}$ is the demand for the labor supplied at nominal wage $\hat{w}_{i,t}$ by the households who reoptimized their wage i periods ago; h is the habit parameter; $\hat{c}_t$ is consumption; $\varepsilon_t^l = \rho_t^l\varepsilon_{t-1}^l + \eta_t^l$, with η_t^l an i.i.d. shock to the labor supply; γ_w is the degree of indexation to the lagged wage growth rate; and $\varepsilon_t^w = \rho_t^w\varepsilon_{t-1}^w + \eta_t^w$, *with* η_t^w an i.i.d. wage-markup shock. Finally, λ_w is the wage markup. Note that, as we did for price shocks, wage shocks have been introduced in two different ways.

The rest of the linearized DSGE model is summarized in appendix 2. In sum, irrespective of the pricing specification, the Smets-Wouters (2005) model determines nine endogenous variables: inflation, the real wage, capital, the value of capital, investment, consumption, the short-term nominal interest rate, the rental rate on capital, and hours worked. The stochastic behavior is driven by ten exogenous shocks. Five shocks arise from technology and preference parameters: the total factor productivity shock, the investment-specific technology shock, the preference shock, the labor-supply shock, and the government-spending shock. Those shocks are assumed to follow an autoregressive process of order one. Three shocks can be interpreted as "cost-push" shocks: the price-markup shock, the wage-markup shock, and the equity-premium shock. Those are assumed to follow a white-noise process. And, finally, there are two monetary policy shocks: a permanent inflation target shock and a temporary interest rate shock.

Before discussing the estimation results, it is worth highlighting two issues. First, Dixon and Kara (2006) have argued that a proper comparison of the degree of price stickiness in the Taylor and Calvo model should be based on the average age of the running contracts, rather than on the average frequency of price changes. As is well known, in a Calvo pricing model the average age of the running contracts is computed as

$$(1-\xi_p)\sum_{i=0}^{\infty}\xi_p^i\cdot(i+1)=\frac{1}{1-\xi_p},$$

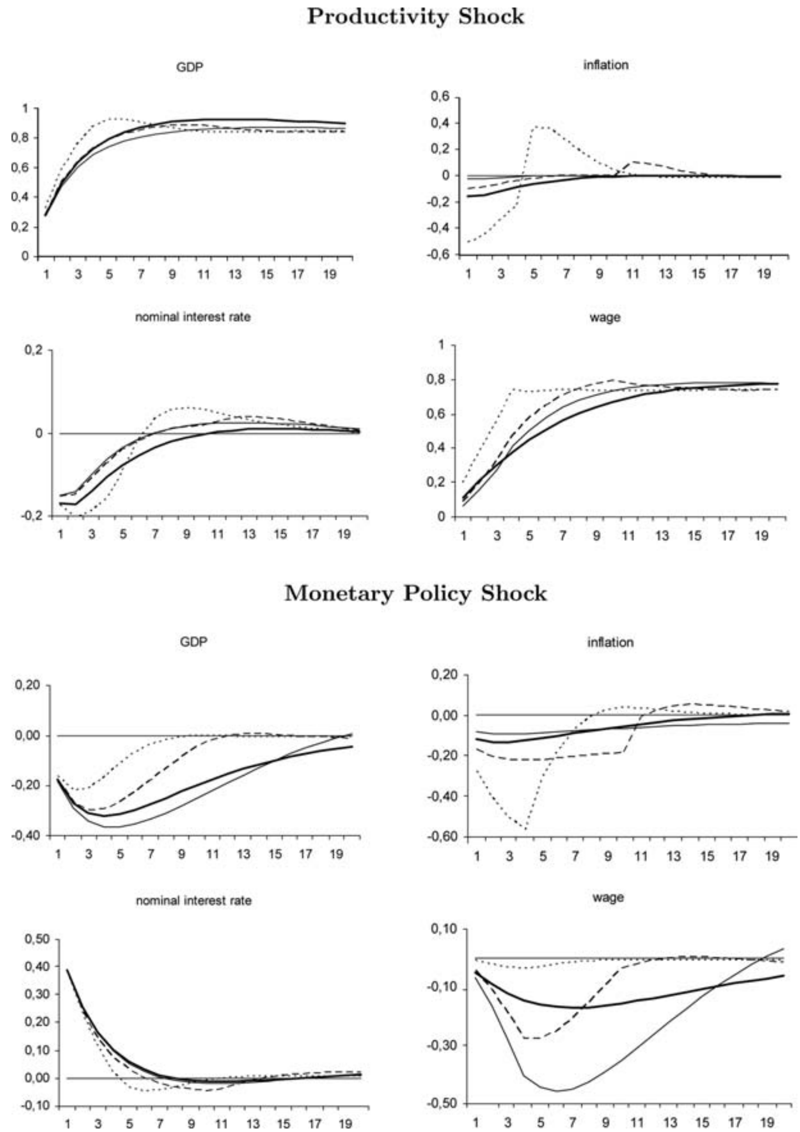
while the corresponding statistic for Taylor contracts is given by

$$\frac{1}{n_p}\sum_{i=1}^{n_p} i=\frac{n_p+1}{2}.$$

Thus, in order to produce the same average contract age as the one implied by a Calvo parameter ξ_p, the Taylor-contract length needs to be $\frac{1+\xi_p}{1-\xi_p}$ periods. The Calvo parameter $\xi_p = 0.9$ estimated in section 2 above therefore implies a long Taylor-contract length of nineteen quarters.

Figure 1 confirms the Dixon and Kara (2006) analysis by comparing the impulse responses to, respectively, a productivity and a monetary policy shock in the baseline Calvo model and four-, ten-, and twenty-quarter Taylor contracting, keeping the other parameters fixed at those estimated for the baseline Calvo model. In this figure the wage contract length n_w is fixed at four quarters. As the duration of the Taylor contract lengthens, the impulse responses appear to approach the outcome under the Calvo model. One needs a very long duration (about twenty quarters) in order to come close to the

Figure 1. Selected Impulse Responses: Calvo versus Taylor Contracts (Baseline Parameters)



Legend: Bold black line: baseline (Calvo) model; full line: 20-quarter Taylor price contract; dashed line: 10-quarter Taylor price contract; dotted line: 4-quarter Taylor price contract.

Calvo model. With shorter Taylor contracts, typically the inflation response becomes larger in size but also less persistent. Conversely, the output and real wage responses are closer to the flexible-price outcome. For example, in response to a monetary policy shock, the response of output is considerably smaller. Moreover, with shorter Taylor contracts, the inflation response changes sign quite abruptly after the length of the contract. This feature is absent in the Calvo specification. As discussed in Whelan (2004), in reduced-form inflation equations, the reversal of the inflation response after the contract length is captured by a negative coefficient on lagged inflation once current and expected future marginal costs are taken into account.

A second issue relates to the way in which the price shocks are introduced. As shown in figure 2, the two ways of introducing price (resp. wage) shocks discussed above generate very different short-run dynamics in response to such shocks. The right-hand panels of figure 2 shows that introducing a persistent shock in the GDP deflator equation (i.e., $d = 0$) allows the Taylor contracting model to mimic most closely the response to a markup shock in the baseline Calvo specification.[5]

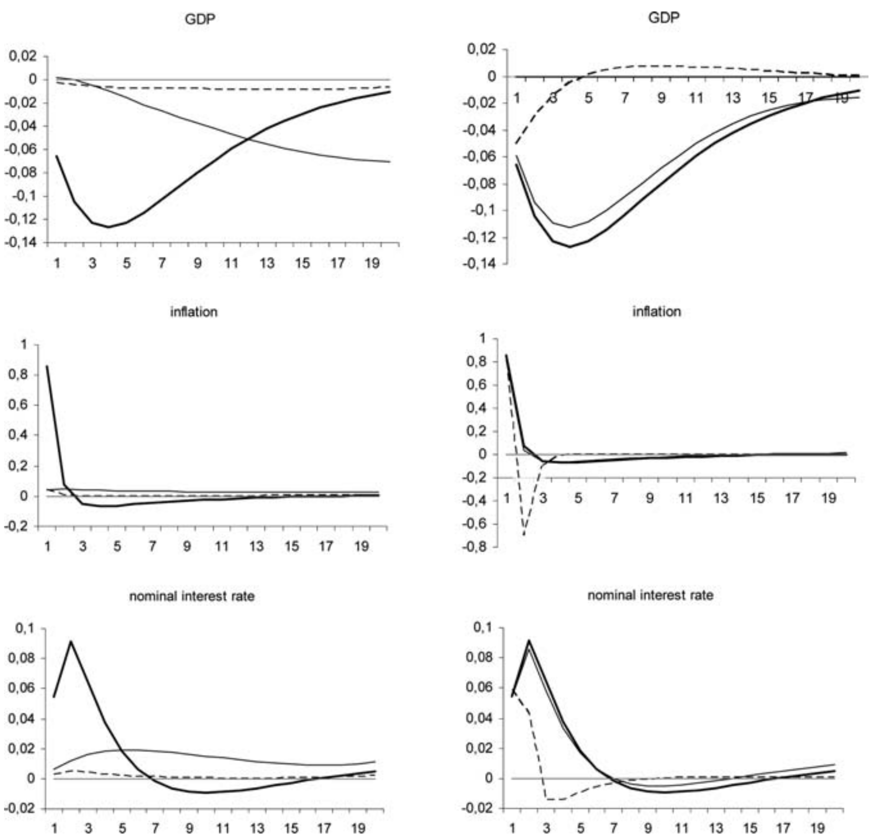
2.2 Estimation Results

We now turn to the main estimation results. The full set of results as well as a description of the euro-area data set and the assumed prior distributions can be found in the appendices. A number of results are worth highlighting. First, we confirm the findings of Smets and Wouters (2005) regarding the Calvo specification. The degree of indexation is rather limited, while the degree of Calvo price stickiness is very large: each period, 89 percent of the firms do not reoptimize their price setting. The average age of the price contract is therefore more than two years (9.1 quarters). Second, as illustrated by figure 3, which plots the log data density of the estimated Taylor model as a function of the contract length, the contract length that maximizes the predictive performance of the Taylor model is nineteen quarters. This again confirms the analysis of Dixon and

[5]The same exercise could actually be run for a wage shock. Since it leads to similar conclusions, we do not reproduce it here.

Figure 2. Impulse Response to a Price Shock in the 20-Quarter Taylor Model for Different Specifications of the Price Shock (Baseline Parameters)

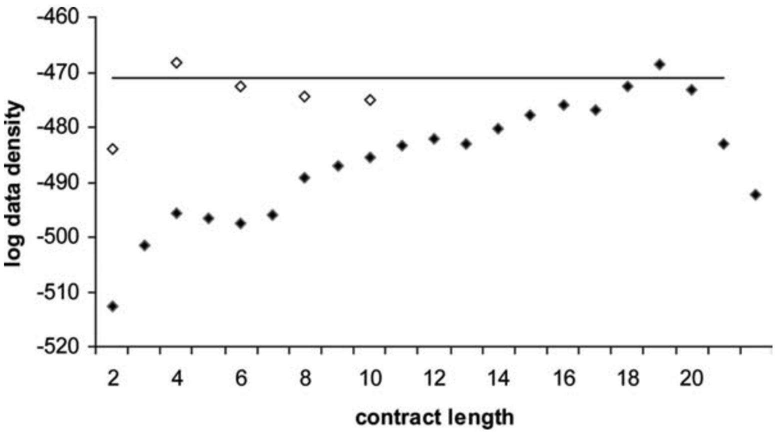
***d* = 1: Price Shock in (3)** **$d = 0$: Price Shock in (4)**



Legend: Bold black line: baseline (Calvo) model; black line: 20-quarter Taylor contract with persistent price shock; dashed line: 20-quarter Taylor contract with i.i.d. price shock.

Kara (2006) discussed above. A Calvo parameter of 0.9 implies an average length of the contracts of about nineteen quarters. Third, we confirm (results not shown) that, in line with the impulse responses shown in figure 2, the specification with the persistent price shock in the GDP price equation ($d = 0$) does best in terms of empirical

Figure 3. Log Data Density for Taylor Contracting Models with Different Lengths



Legend: The black line represents the log data density in the baseline Calvo model; black diamonds denote the Taylor model with mobile production factors and a persistent price shock in the GDP price; white diamonds denote the same model but with nonmobile capital, zero profits, and endogenous markup (see section 4.4).

performance. For example, the log data density of the estimated model with ten-quarter Taylor contracts improves by ninety points relative to the specification with a persistent price shock in the optimal price-setting equation. Similar improvements are found for other contract lengths. Moreover, the empirical performance also improves significantly by allowing for persistence in the price shocks.[6]

Table 1 compares some of the estimated parameters across various Taylor models and the Calvo model. While most of the other parameters are estimated to be very similar, it is noteworthy that the estimated degree of indexation rises quite significantly as the assumed Taylor contracts become shorter. Possibly, this reflects the need to overcome the negative dependence on past inflation in the standard Taylor contract. Next we turn to the introduction of firm-specific factors in the Taylor model.

[6]Similar findings have been found for various specifications of the wage shock. For that reason, we consider a persistent wage shock in the average wage equation for all the estimations performed in the rest of the paper.

Table 1. Comparing the Calvo Model with Taylor Contracting Models

	Calvo	4-Q Tayl.	8-Q Tayl.	10-Q Tayl.	19-Q Tayl.
Log Data Densities					
	−471.113	−495.566	−489.174	−485.483	−468.469
Selection of Estimated Parameter Outcomes					
ρ_a	0.991	0.980	0.982	0.962	0.983
	(0.006)	(0.007)	(0.006)	(0.006)	(0.006)
σ_a	0.653	0.615	0.682	0.619	0.622
	(0.093)	(0.068)	(0.085)	(0.076)	(0.085)
ρ_p	0	0.995	0.995	0.912	0.934
	(–)	(0.004)	(0.004)	(0.016)	(0.018)
σ_p	0.207	0.406	0.323	0.277	0.229
	(0.019)	(0.030)	(0.023)	(0.020)	(0.016)
ρ_w	0	0.973	0.966	0.881	0.955
	(–)	(0.012)	(0.014)	(0.017)	(0.012)
σ_w	0.250	0.4386	0.453	0.461	0.454
	(0.021)	(0.031)	(0.034)	(0.031)	(0.035)
γ_w	0.388	0.313	0.397	0.351	0.460
	(0.197)	(0.166)	(0.205)	(0.206)	(0.188)
γ_p	0.178	0.859	0.463	0.436	0.273
	(0.096)	(0.150)	(0.130)	(0.116)	(0.074)
A	9.1 Q	2.5 Q	4.5 Q	5.5 Q	10 Q

Note: ρ_a, ρ_p, and ρ_w are the persistence parameters associated with the productivity, the price, and the wage shock, respectively; σ_a, σ_p, and σ_w are the standard error of the productivity, the price, and the wage shock, respectively; γ_w and γ_p are, respectively, the wage and price indexation parameters; A is the average age of the price contract.

3. Firm-Specific Production Factors and Taylor Contracts

3.1 Modeling Firm-Specific Factors

So far the model includes all kinds of adjustment costs such as those related to the accumulation of new capital, to changes in prices and wages, and to changes in capacity utilization, but shifting capital or labor from one firm to another is assumed to be costless (see Danthine and Donaldson 2002). The latter assumption is clearly not fully realistic. In this section we instead assume that production factors are firm specific, i.e., the cost of moving them across firms is extremely high. Although this is also an extreme assumption, it may be more realistic. The objective is to investigate the implications of introducing this additional real rigidity on the estimated degree of nominal price stickiness and the overall empirical performance of the Taylor contracting model. As shown in Coenen and Levin (2004) for the Taylor model and Woodford (2003, 2005), Eichenbaum and Fisher (2004), and Altig et al. (2005) for the Calvo model, the introduction of firm-specific capital reduces the sensitivity of inflation with respect to its driving variables. Similarly, Woodford (2003, 2005) shows that firm-specific labor may also help reduce price variations and may lead to higher inflation persistence.

In the case of firm-specific factors, the key equations of the linearized model governing the decision of a firm belonging to the cohort j (with $j \in [1, n_p]$), which reoptimizes its price in period t, are given by

$$\hat{p}_t^*(j) = \frac{1}{\sum_{i=0}^{n_p-1} \beta^i} \left[\sum_{i=0}^{n_p-1} \beta^i (\hat{s}_{t+i}(j) + \hat{p}_{t+i}) - \sum_{i=0}^{n_p-2} \left((\gamma_p \hat{\pi}_{t+i} + (1-\gamma_p)\bar{\pi}_{t+i+1}) \sum_{q=i+1}^{n_p-1} \beta^q \right) \right] \tag{3b}$$

$$\hat{p}_t = \frac{1}{n_p} \sum_{i=0}^{n_p-1} \hat{p}_t(j-i) + \varepsilon_t^p \tag{4b}$$

$$\hat{s}_{t+i}(j) = \alpha\hat{\rho}_{t+i}(j) + (1-\alpha)\hat{w}_{t+i}(j) - \hat{\varepsilon}^a_{t+i} - (1-\alpha)\gamma t \tag{9}$$

$$\hat{Y}_{t+i}(j) = \hat{Y}_{t+i} - \frac{1+\lambda_p}{\lambda_p}(\hat{p}_{t+i}(j) - \hat{p}_{t+i}) \tag{10}$$

$$\hat{p}_{t+i}(j) = \hat{p}^*_t(j) + \sum_{q=0}^{i-1}(\gamma_p\bar{\pi}_{t-1-q} + (1-\gamma_p)\bar{\pi}_{t-q}) \tag{11}$$

with

$$\frac{\partial\hat{\rho}_{t+i}(j)}{\partial\hat{Y}_{t+i}(j)} > 0 \quad \text{and} \quad \frac{\partial\hat{w}_{t+i}(j)}{\partial\hat{Y}_{t+i}(j)} > 0, \tag{12}$$

where $\hat{\rho}_t(j)$ is the "shadow rental rate of capital services,"[7] and λ_p is the price markup so that $\frac{1+\lambda_p}{\lambda_p}$ is the elasticity of substitution between goods. The main difference with equations (3) and (4) is that the introduction of firm-specific factors implies that firms no longer share the same marginal cost. Instead, a firm's marginal cost and its optimal price will depend on the demand for its output. A higher demand for its output implies that the firm will have a higher demand for the firm-specific input factors, which in turn will lead to a rise in the firm-specific wage costs and capital rental rate. Because this demand will be affected by the pricing behavior of the firm's competitors, the optimal price will also depend on the pricing decisions of the competitors.

The net effect of this interaction will be to dampen the price effects of various shocks. Consider, for example, an unexpected demand expansion. Compared to the case of homogenous marginal costs across firms, the first price mover will increase its price by less because, everything else being equal, the associated fall in the relative demand for its goods leads to a fall in its relative marginal cost. This, in turn, reduces the incentive to raise prices. This relative marginal cost effect is absent when factors are mobile across firms and, as a result, firms face the same marginal cost irrespective of their output levels. From this example it is clear that the

[7]Indeed, we left aside the assumption of a rental market for capital services. Each firm builds its own capital stock. The "shadow rental rate of capital services" is the rental rate of capital services such that the firm would hire the same quantity of capital services in an economy with a market for capital services as it does in the economy with firm-specific capital.

extent to which variations in firm-specific marginal costs will reduce the amplitude of price variations will depend on the combination of two elasticities: (i) the elasticity of substitution between the goods produced by the firm and those produced by its competitors, which will govern how sensitive relative demand for a firm's goods is to changes in its relative price (see equation [4b]); (ii) the elasticity of the individual firm's marginal cost with respect to changes in the demand for its products (see equation [4b]). With a Cobb-Douglas production function, the latter elasticity will mainly depend on the elasticity of the supply of the factors with respect to changes in the factor prices. In brief, the combination of a steep firm-specific marginal cost curve and high demand elasticity will maximize the relative marginal cost effect and minimize the price effects, thereby reducing the need for a high estimated degree of nominal price stickiness.

Before turning to a quantitative analysis of these effects in the next sections, it is worth examining in somewhat more detail the determinants of the partial derivatives in equation (12) in each of the two factor markets (capital and labor). Consider first firm-specific capital. Given the one-period time-to-build assumption in capital accumulation, the firm-specific capital stock is given within the quarter. As a result, when the demand faced by the firm increases, production can only be adjusted by either increasing the labor/capital ratio or by increasing the rate of capital utilization. Both actions will tend to increase the cost of capital services. It is, however, also clear that when the firm can increase the utilization of capital at a constant marginal cost, the effect of an increase in demand on the cost of capital will be zero. In this case, the supply of capital services is infinitely elastic at a rental price that equals the marginal cost of changing capital utilization and, as a result, the first elasticity in equation (12) will be zero. In the estimations reported below, the marginal cost of changing capital utilization is indeed high, so that in effect there is nearly no possibility to change capital utilization. Over time, the firm can adjust its capital stock subject to adjustment costs. This implies that the firm's marginal cost depends on its capital stock, which itself depends on previous pricing and investment decisions of the firm. As a result, the capital stock, the value of capital, and investment will also be firm specific. In the case of a Calvo model, Woodford (2005) and Christiano (2004) show

how the linearized model can still be solved in terms of aggregate variables, without solving for the whole distribution of the capital stock over the different firms. This linearization is, however, complicated and remains model specific. With staggered Taylor contracts, it is straightforward to model the cohorts of firms characterized by the same price separately. The key linearized equations governing the investment decision for a firm belonging to the jth cohort are then

$$\hat{K}_t(j) = (1-\tau)\hat{K}_{t-1}(j) + \tau\hat{I}_{t-1}(j) + \tau\varepsilon_{t-1}^I \tag{13}$$

$$\hat{I}_t(j) = \frac{1}{1+\beta}\hat{I}_{t-1}(j) + \frac{\beta}{1+\beta}E_t\hat{I}_{t+1}(j) + \frac{1/\varphi}{1+\beta}\hat{Q}_t(j) + \varepsilon_t^I \tag{14}$$

$$\begin{aligned}\hat{Q}_t(j) = {} & -(\hat{R}_t - \hat{\pi}_{t+1}) + \frac{1-\tau}{1-\tau+\bar{\rho}}E_t\hat{Q}_{t+1}(j) \\ & + \frac{\bar{\rho}}{1-\tau+\bar{\rho}}E_t\hat{\rho}_{t+1}(j) + \eta_t^Q,\end{aligned} \tag{15}$$

where $\hat{K}_t(j)$, $\hat{I}_t(j)$, and $\hat{Q}_t(j)$ are, respectively, the capital stock, investment, and the Tobin's Q for each of the firms belonging to the jth price-setting cohort. Parameter τ is the depreciation rate of capital, and $\bar{\rho}$ is the shadow rental rate of capital discussed above, so that $\beta = 1/(1-\tau+\bar{\rho})$. Parameter φ depends on the investment adjustment-cost function.[8]

Consider next firm-specific monopolistic competitive labor markets. In this case each firm requires a specific type of labor that cannot be used in other firms. Moreover, within each firm-specific labor market, we allow for Taylor-type staggered wage setting. The following linearized equations display how a worker belonging to the fth wage-setting cohort (with $f \in [1, n_w]$) optimizes its wage in

[8] As in the baseline model, there are two aggregate investment shocks: ε_t^I, which is an investment technology shock, and η_t^Q, which is meant to capture stochastic variations in the external finance premium. The first one is assumed to follow an AR(1) process with an i.i.d.-normal error term and the second is assumed to be i.i.d.-normal distributed.

period t for the labor it rents to the firms of the jth price-setting cohort (with $j \in [1, n_p]$):

$$\hat{w}_t^*(f,j) = \frac{1}{\sum_{i=0}^{n_w-1}\beta^i} \times \left[\sum_{i=0}^{n_w-1}\beta^i\left(\sigma_l \hat{l}_{t+i}(f,j) + \frac{1}{1-h}(\hat{c}_{t+i} - h\hat{c}_{t+i-1}) - \varepsilon_{t+i}^l\right) + \sum_{i=1}^{n_w-1}\left((\hat{\pi}_{t+i} - \gamma_w\hat{\pi}_{t+i-1} - (1-\gamma_w)\bar{\pi}_{t+i})\sum_{q=i}^{n_w-1}\beta^q\right)\right] \tag{5b}$$

$$\hat{w}_t(j) = \frac{1}{n_w}\left[\sum_{i=0}^{n_w-1}\hat{w}_t(f-i,j) + \hat{p}_{t-i}\right] - \hat{p}_t + \varepsilon_t^w \tag{6b}$$

$$\hat{w}_{t+i}(f,j) = \hat{w}_t^*(f,j) + \sum_{q=0}^{i-1}(\gamma_w\hat{\pi}_{t-1-q} + (1-\gamma_w)\bar{\pi}_{t-q}) \tag{7b}$$

$$\hat{l}_{t+i}(f,j) = \hat{l}_{t+i}(j) - \frac{1+\lambda_w}{\lambda_w}(\hat{w}_{t+i}(f,j) + \hat{p}_t - (\hat{w}_{t+i}(j) + \hat{p}_{t+i})) \tag{8b}$$

$$\hat{l}_t(j) = -\hat{w}_t(j) + (1+\psi)\hat{\rho}_t(j) + \hat{K}_{t-1}(j). \tag{23b}$$

It directly appears from these equations that there is now a labor market for each cohort of firms. Contrarily to the homogeneous labor setting, the labor demand of (cohort of) firm(s) j (equation [23b]) directly affects the optimal wage chosen by the worker f (equation [5b]) and, consequently, the cohort-specific average wage (equation [6b]). When $\gamma_w = 0$, real wages do not depend on the lagged inflation rate.[9]

Due to the staggered wage setting, it is not so simple to see how changes in the demand for the firm's output will affect the firm-specific wage cost (equation [12]). A number of intuitive statements can, however, be made. First, higher wage stickiness as captured by the length of the typical wage contract will tend to reduce the

[9]Parameter ψ is the inverse of the elasticity of the capital-utilization cost function.

response of wages to demand. As a result, high wage stickiness is likely to reduce the impact of firm-specific labor markets on the estimated degree of nominal price stickiness. In contrast, with flexible wages, the relative wage effect may be quite substantial, contributing to large changes in relative marginal cost of the firm and thereby dampening the relative price effects discussed above. Second, this effect is likely to be larger the higher the demand elasticity of labor (as captured by a lower labor-market markup parameter) and the higher the elasticity of labor supply. Concerning the latter, if labor supply is infinitely elastic, wages will again tend to be very sticky and, as a result, relative wage costs will not respond very much to changes in relative demand, even in the case of firm-specific labor markets.

3.2 Alternative Models

In this section we illustrate the discussion above by displaying how the output, the marginal cost, and the price of the first price-setting cohort respond to a monetary policy shock. We compare the benchmark model with mobile production factors (hereafter denoted MKL) with the following three models:

1. A model with homogeneous capital and firm-specific labor market (hereafter denoted NML).

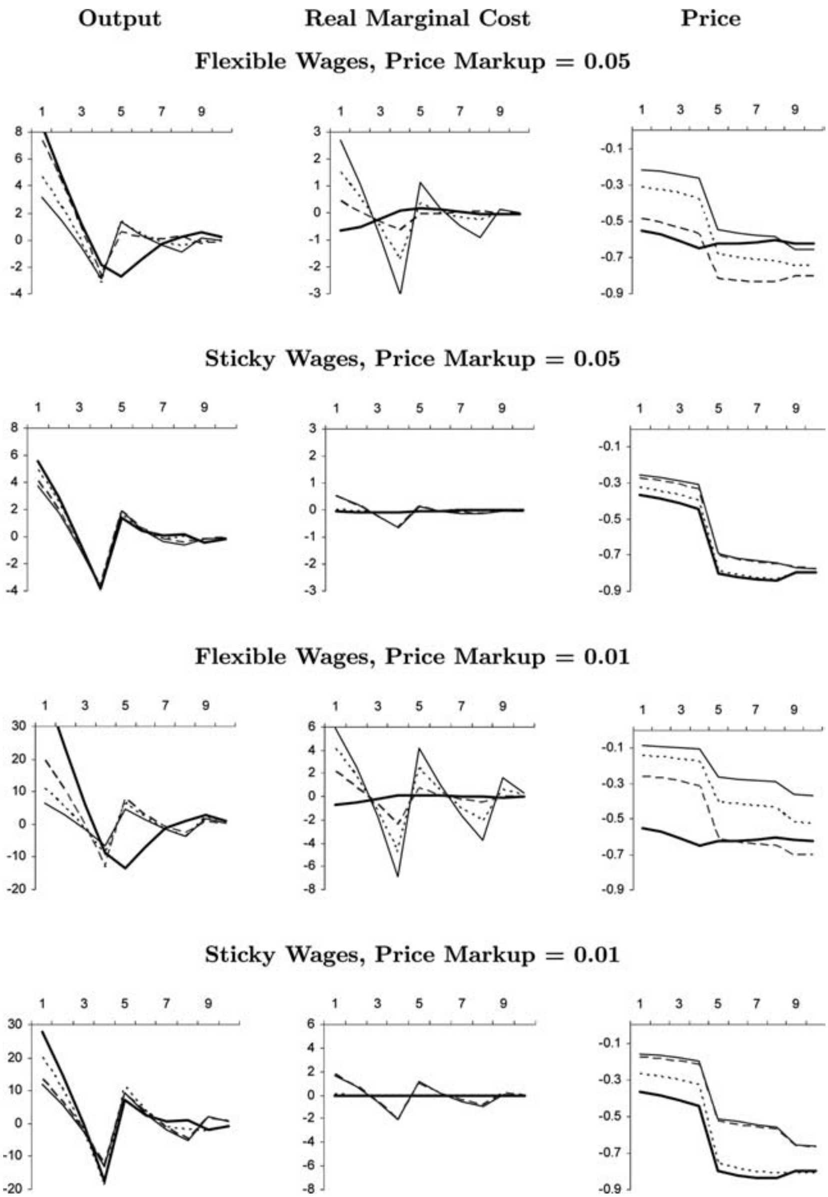
2. A model with firm-specific capital and homogeneous labor (hereafter denoted NMK).

3. A model with firm-specific capital and labor (hereafter denoted NMKL).

Moreover, for each of those models we consider four cases corresponding to flexible and sticky wages and low (0.01) and high (0.05) markups in the goods market.[10] Figure 4 shows the responses of

[10]This corresponds to demand elasticities of 21 and 101, respectively. The latter is the one estimated by Altig et al. (2005). Furthermore, one needs rather high substitution elasticities to observe significant differences between the homogeneous marginal cost model and its firm-specific production-factors counterparts. So, for demand elasticities below 10, there is nearly no difference between the MKL model and the NML, NMK, and NMKL ones. This indicates again the importance of a very elastic demand curve.

Figure 4. The Effect of a Monetary Policy Shock on Output, Marginal Cost, and Price of the First Cohort in the Three Considered Models



Legend: Bold black line: MKL; black line: NMKL; dashed line: NMK; dotted line: NML the cohort that is allowed to change its price in the period of the monetary policy shock. In this figure we assume that the length of the price and wage contracts is four quarters. The rest of the parameters are those estimated for the benchmark Taylor model (MKL) with the corresponding contract length. Responses are displayed for the first ten quarters following the shock, i.e., prices are reoptimized three times by the considered cohort in the time span considered, at periods 1, 5, and 9.

Several points are worth noting. First, introducing firm-specific factors always reduces the initial impact on prices and output, while it increases the impact on the marginal cost. As discussed above, with firm-specific production factors, price-setting firms internalize the fact that large price responses lead to large variations in marginal costs and therefore lower their initial price response. Second, the introduction of firm-specific factors increases the persistence of price changes, in particular, when wages are flexible. While in the case of mobile production factors with flexible wages, the initial price decrease is partially reversed after four quarters; prices continue to decrease five and nine quarters after the initial shock when factors are firm specific. Third, in the case with mobile factors (MKL—the bold black curve in figure 4), it is clear that prices and marginal cost are not affected by changes in the demand elasticity, while the firm's output is very much affected. On the contrary, for all the models with at least one nonmobile production factor, price responses decrease, while marginal cost variations increase with a higher demand elasticity.

Finally, as long as wages are considered to be flexible, a firm-specific labor market is the device that leads to the largest reactions in marginal cost. It is also worth noting that the combination of a firm-specific labor market and firm-specific capital brings more reaction in the marginal cost than the respective effect of each assumption separately.[11] However, as soon as wages become sticky, firm-specific labor markets do not generate much more variability in marginal cost. In this case, it is striking that the responses of the NMK and NMKL models get very close to each other.

[11] This is actually much in line with the findings of Matheron (2005) in a Calvo price-flexible wage setting with firm-specific capital and labor.

3.3 Estimation

In this section we reestimate the model with firm-specific production factors to investigate the effects on the empirical performance of the model. Sbordone (2002) and Galí, Gertler, and López-Salido (2001) show that considering capital as a fixed factor that cannot be moved across firms does indeed reduce the estimated degree of nominal price stickiness in U.S. data. In particular, it reduces the implied duration of nominal contracts from an implausibly high number of more than two years to a duration of typically less than a year. Altig et al. (2005) reach the same conclusion in a richer setup where firms endogenously determine their capital stock. In this section, we extend this analysis to the case of firm-specific labor markets and test whether similar results are obtained in the context of Taylor contracts.

Table 2 reports the log data densities of the three models considered above and their flexible/sticky wages variants for various price-contract lengths. A higher log data density implies a better empirical fit in terms of the model's one-step-ahead prediction performance.

The following findings are noteworthy. First, in almost all cases, the data prefer the sticky-wage version over the flexible-wage version.

Table 2. Log Data Densities for the Three Models Considered and Their Variants

	2-Q Taylor	**4-Q Taylor**	**6-Q Taylor**	**8-Q Taylor**
Flexible Wages				
NML	–520.21	–481.86	–492.87	–490.16
NMKL	–484.92	–479.56	–481.87	–485.23
NMK	–486.50	–480.68	–482.16	–481.97
Sticky Wages (4-Quarter Taylor Contract)				
NML	–512.50	–490.19	–484.72	–480.54
NMKL	–484.46	–466.10	–475.80	–477.23
NMK	–479.11	–464.92	–473.17	–474.30

This is not surprising, as sticky wages are better able to capture the empirical persistence in wage developments. In what follows, we therefore focus on the sticky-wage models. Second, with sticky wages, the data prefer the model with firm-specific capital but mobile labor. The introduction of firm-specific labor markets does not help the empirical fit of the model. The main reason for this result is that, as argued before, in order for firm-specific labor markets to help in explaining price and inflation persistence, one needs a strong response of wages to changes in demand. But this is in contrast to the observed persistence in wage developments. On the other hand, as we do not observe the rental rate of capital, no such empirical constraint is relevant for the introduction of firm-specific capital. Finally, introducing firm-specific capital does indeed reduce the contract length that fits the data best. While the log data density is maximized at a contract length of nineteen quarters in the case of homogeneous production factors, it is maximized at only four quarters when capital cannot move across firms. This is clearly displayed in figure 3 (even though it is shown for a variant model with endogenous markup developed in section 4.4 below). As clarified by Dixon and Kara (2006), this is equivalent in terms of price duration to a Calvo probability of not reoptimizing equal to 0.6. This confirms the findings of Galí, Gertler, and López-Salido (2001) and Altig et al. (2005). Moreover, it turns out that the four-quarter Taylor contracting model with firm-specific capital performs as well as the nineteen-quarter Taylor contracting model with mobile capital.

In line with these results, in the rest of the paper we will focus on the model with firm-specific capital, homogeneous labor, and sticky wages. Table 3 presents a selection of the parameters estimated for this model with various contract lengths. Note that, in comparison to the case with homogeneous production factors, we also estimate the elasticity of substitution between the goods of the various cohorts. A number of findings are worth noting. First, allowing for firm-specific capital leads to a drop in the estimated degree of indexation to past inflation in the goods sector. In comparison with results displayed in table 1, in this case the parameter drops back to the low level estimated for the Calvo model and does not appear to be significantly different from zero. Second, as discussed in Coenen and Levin (2004), one advantage of the Taylor price setting is that the price-markup parameter is identified and therefore can

Table 3. A Selection of Estimated Parameters for the Taylor Contract Models with Firm-Specific Capital (NMK)

	2-Q Taylor	4-Q Taylor	6-Q Taylor	8-Q Taylor
σ_p	0.216	0.225	0.232	0.230
	(0.016)	(0.016)	(0.019)	(0.017)
ρ_p	0.997	0.979	0.863	0.802
	(0.002)	(0.029)	(0.124)	(0.085)
$1+\phi$	1.616	1.515	1.522	1.520
	(0.093)	(0.138)	(0.111)	(0.100)
λ_p	0.0008	0.004	0.008	0.016
	(0.0003)	(0.0015)	(0.003)	(0.006)
γ_p	0.067	0.093	0.149	0.220
	(0.070)	(0.077)	(0.094)	(0.102)
γ_w	0.403	0.463	0.547	0.436
	(0.195)	(0.210)	(0.232)	(0.231)

Note: ρ_p is the persistence parameter associated to the price shock; σ_p is the standard error of the price shock; γ_w and γ_p are, respectively, the wage and price indexation parameters; ϕ is the share of the fixed cost; λ_p is the price markup.

be estimated. In contrast, with Calvo price setting, the model with firm-specific factors is observationally equivalent to its counterpart with homogeneous production factors. Table 3 shows that one needs a very high elasticity of substitution (or a low markup) to match the Calvo model in terms of empirical performance. It is also interesting to note that the estimated price markup increases with the length of the price contract, showing the substitutability between nominal and real rigidities. Finally, the persistence parameter of the price shock significantly decreases with the length of the price contract.

For the four-quarter price-contract model, the estimated parameter for the price markup is 0.004, which implies an extremely high elasticity of substitution of about 250. This clearly indicates that one needs large real rigidities in order to compensate for the reduction in

Table 4. Estimated Models with Constrained and/or Endogenous Demand Elasticity (Some Selected Parameters)

	$\phi = \lambda_p$ and $\epsilon = 0$	$\phi = \lambda_p$ and $\epsilon \neq 0$
Log Data Density	−479.671	−468.344
σ_p	0.208	0.178
	(0.015)	(0.013)
ρ_p	0.829	0.539
	(0.086)	(0.056)
σ_a	1.099	0.650
	(0.153)	(0.088)
ρ_a	0.960	0.981
	(0.011)	(0.007)
$\lambda_p = \phi$	0.006	0.489
	(0.001)	(0.128)
$\frac{\epsilon}{1+\epsilon}$	0	0.986
	–	(0.004)

Note: ρ_a and ρ_p are the persistence parameters associated with the productivity and the price shock, respectively; σ_a and σ_p are the standard error of the productivity and the price shock, respectively; γ_w and γ_p are, respectively, the wage and price indexation parameters; ϕ is the share of the fixed cost; λ_p and λ_w are, respectively, the price and the wage markup; ϵ is the curvature parameter.

price stickiness. However, this implies that the estimated fixed cost in production ($1 + \phi$ stands at 1.515) very much exceeds the profit margin, implying negative profits in steady state.

In order to circumvent this problem, one may simply impose the zero-profit condition in steady state. The estimation result obtained for the four-quarter price-contract model is displayed in the first column of table 4. The empirical cost of imposing the constraint is rather high, about 15 in log data density. Furthermore, the estimated demand elasticity remains very high at about 167. Note also that the constraint leads to a much larger estimated standard error of the productivity shock.

3.4 Endogenous Price Markup

Following Eichenbaum and Fisher (2004) and Coenen and Levin (2004), we can consider a model with an endogenous markup, whereby the optimal markup is a function of the relative price as in Kimball (1995). Replacing the Dixit-Stiglitz aggregator with the homogeneous-degree-one aggregator considered by Kimball (1995), the linearized optimal price equation (3b) becomes

$$\hat{p}_t^*(j) = \frac{1}{\sum_{i=0}^{n_p-1}\beta^i}\left[\frac{1}{1+\lambda_p\cdot\epsilon}\sum_{i=0}^{n_p-1}\beta^i\hat{s}_{t+i}(j) + \sum_{i=0}^{n_p-1}\beta^i\hat{p}_{t+i} - \sum_{i=0}^{n_p-2}\left((\gamma_p\hat{\bar{\pi}}_{t+i} + (1-\gamma_p)\bar{\pi}_{t+i+1})\sum_{q=i+1}^{n_p-1}\beta^q\right)\right], \tag{16}$$

where ϵ represents the deviation from the steady-state demand elasticity following a change in the relative price, while λ_p is the steady-state markup:[12]

$$\epsilon = \frac{\partial\left(\frac{1+\lambda_p(z)}{\lambda_p(z)}\right)}{\partial p^*}\cdot\frac{p^*}{\frac{1+\lambda_p(z)}{\lambda_p(z)}}\Bigg|_{z=1} \tag{17}$$

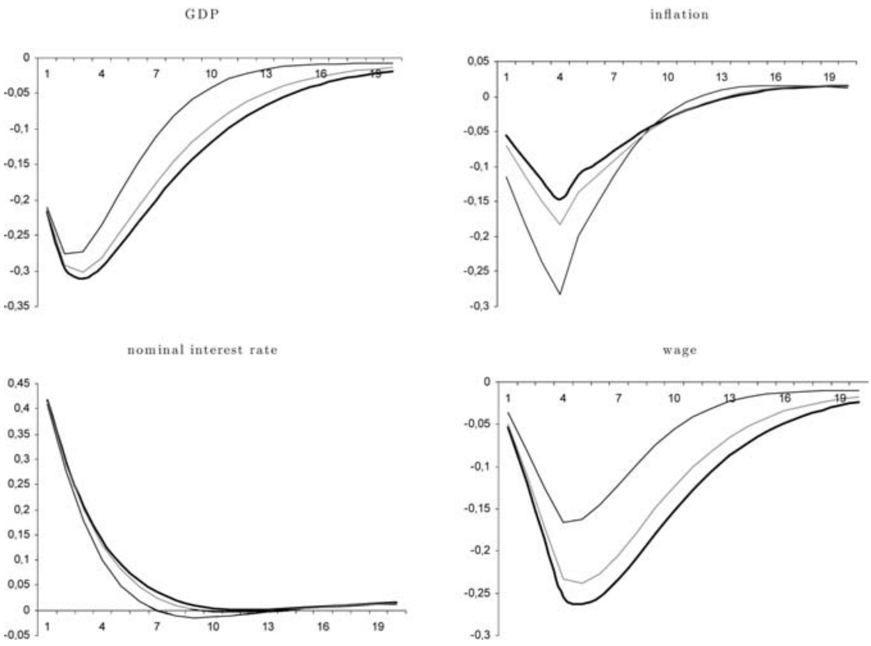
This elasticity plays the same role as the elasticity of substitution: the larger it is, the less the optimal price is sensitive to changes in the marginal cost. In this sense, having $\epsilon > 0$ can help to reduce the estimate for the demand elasticity to a more realistic level.

In order to illustrate this mechanism, figure 5 displays the reactions of aggregate output, inflation, the real wage, and the interest rate after a monetary policy shock for a model with an endogenous price markup. As benchmark, we use the four-quarter price-contract model with constant price markup estimated in table 3

[12] Of course, the Dixit-Stiglitz aggregator corresponds to the case where ϵ is equal to zero.

Figure 5. Assessing the Substitutability between the Steady State Demand Elasticity and the Curvature Parameter

Monetary Policy Shock



Legend: Bold black line: estimated 4-quarter NMK model with fixed markup; black line: $\lambda_p = 0.5$ and $\epsilon = 20$; gray line: $\lambda_p = 0.5$ and $\epsilon = 60$.

and we compare it with the model integrating both the zero-profit constraint and the endogenous price markup. For the latter model, we use the parameters estimated for the benchmark, except for the steady-state markup, λ_p, which is fixed at 0.5, while different values are used for the curvature parameter ϵ: 20 and 60. It is clear from figure 5 that an endogenous price markup that is very sensitive to the relative price can produce the same effect on aggregate variables as a very small constant price markup.

The next step is to reestimate the NMK model with four-quarter price and wage Taylor contracts but adding the modifications discussed above, i.e., imposing the price markup to equate the share of the fixed cost ($\phi = \lambda_p$) and allowing ϵ to be different from zero.

The results are displayed in column 2 of table 4. When the share of the fixed cost is forced to equate the markup, shifting from a final good production function with a constant price markup to one with a price markup declining in the relative price, the estimated steady-state price markup becomes much larger, implying a demand elasticity of about 3. This helps to reduce the cost of the constraint, and the log data density is improved by 11. The very high estimated curvature parameter ϵ (about 70) reveals the need for real rigidities.

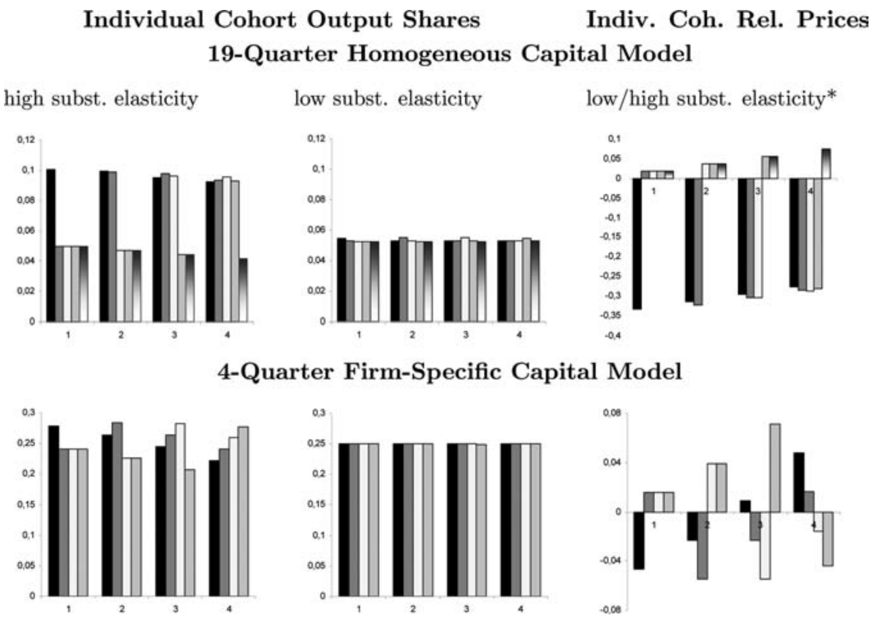
3.5 Comparing Models

Based on the log data density of the estimated models, we are not able to discriminate between the model with homogeneous capital and very long price contracts and the model with firm-specific capital, endogenous markup, and short price contracts. We are then somewhat in the same position as Altig et al. (2005), who have to compare two models that are observationally equivalent from a macroeconomic point of view. These authors reject the model with homogeneous capital for two reasons. First, it implies a price stickiness not in line with microevidence, and second, it generates too-high volatility in cohort-specific output shares. In this section we compare the various models in terms of their implied behavior of cohort-specific output shares and relative prices. The latter allows us to confront the models also with the microevidence on firms' price setting, which finds that price changes are typically large.

Figure 6 compares the evolution of the output share (as a percentage deviation from the steady state) of the first four cohorts of firms during the first four periods following a monetary policy shock and the corresponding relative price changes. We run this comparison for four models: (i) the four-quarter Taylor contracting model with nonmobile capital and a high elasticity of substitution (table 3, column 2); (ii) its variant with constrained elasticity of substitution and endogenous markup (table 4, column 2); (iii) the nineteen-quarter Taylor contracting model with mobile capital and an elasticity of substitution equal to 250; and (iv) the same model with a substitution elasticity of 3.

First, focusing on the evolution of the relative prices in these models, we observe that relative prices vary much more across cohorts in the homogeneous factor model than in the model with

Figure 6. Output Shares and Relative Prices for the First Four Periods after a Monetary Policy Shock in Homogeneous and Firm-Specific Capital Models



Legend: Columns from left to right are for cohort 1 to cohort 4. Column 5 is for the fifteen cohorts that have not yet had the opportunity to reoptimize their price.
*See footnote 18.

firm-specific capital.[13] There are two reasons for such a higher volatility: (i) the fact that the marginal cost is independent of firm-specific output and (ii) the length of the price contract, which implies that only a small fraction of firms can actually change their price. The corollary of this high relative price variability is a much larger variability in the market shares of firms in the model with

[13]Note that the relative prices are displayed only for the model with firm-specific capital and endogenous markup and for the model with mobile capital. Indeed, in the case of mobile capital, the relative prices are not influenced by the subsitution elasticity. For the two models with firm-specific capital, the numbers for relative prices are extremely close, and showing them twice would prove redundant.

homogeneous capital and a high substitution elasticity. In that case, the first cohort to reset optimally its price nearly doubles its share in production. Even though this result is less extreme than the one presented in Altig et al. (2005),[14] such a high variability in output shares following a monetary policy shock is empirically implausible. However, reducing the huge elasticity of substitution to the level consistent with a zero-profit condition, we observe that the variability of the market share becomes quite small in both models, which weakens the argument made by Altig et al. (2005) in favor of the model with firm-specific capital. Furthermore, it is also clear from figure 6 that the model with firm-specific capital fails to reproduce the large price changes observed at the microlevel.

To conclude this section, the introduction of firm-specific capital helps to reconcile the macro models with the microevidence concerning the frequency of the price changes. However, the mechanism for this achievement is entirely based on a very strong reaction of the marginal cost to output changes, which implies very small relative price variations. Such small relative price changes are incompatible with the microevidence, which typically finds that the average size of price changes is quite large.

4. Conclusions

In this paper we have introduced firm-specific production factors in a model with price and wage Taylor contracts. For this type of exercise, Taylor contracts present a twofold advantage over Calvo-type contracts: (i) firm-specific production factors can be introduced and handled explicitly and (ii) the individual firm variables can be analyzed explicitly. This allows a comparison of the implications of the various assumptions concerning the firm-specificity of production factors not only for aggregate variables but also for cross-firm variability.

Our main results are threefold. First, in line with existing literature, we show that introducing firm-specific capital reduces the estimated duration of price contracts from an implausible nineteen

[14] In their model, with their estimated parameters, at the fourth period after the monetary policy shock, 57 percent of the firms produce 180 percent of the global output, leaving the remaining firms with a negative output.

quarters to an empirically more plausible four quarters. Firm-specific production factors make the marginal costs of individual firms steep and very reactive to output changes. Since individual firms' output depends on their relative prices, firms will hesitate to make large price adjustments. Second, introducing firm-specific labor markets does not help in improving the empirical performance of the model. The main reason is that observed wages are sticky, and therefore large variations in firm-specific wages, which help in generating steep marginal costs, are empirically implausible. Overall, it thus appears that rigidities in the reallocation of capital across firms rather than rigidities in the labor market are a more plausible real friction for reducing the estimated degree of nominal price stickiness. Third, in order to obtain this outcome, one needs a very high demand elasticity, implying implausibly large variations in the demand faced by the firms throughout the length of the contract. Imposing the zero-profit condition drastically reduces the estimated demand elasticity and leads to a corresponding reduction in the volatility of output across firms. However, in this case, the need for important real rigidities becomes evident through a high estimated curvature of the demand curve.

To compare the respective merits of the models with mobile production factors (flat marginal cost) and firm-specific production factors (increasing marginal cost), it is important to remember the main findings emerging from microdata on firms' pricing behavior: price changes are at the same time frequent and large (cf. Bils and Klenow 2004; Angeloni et al. 2006). The model with flat marginal costs does lead to large price changes but requires a high degree of nominal stickiness to reproduce inflation persistence. The introduction of firm-specific marginal cost does lead to less nominal stickiness but implies small relative price variations across firms. It thus seems that, so far, neither model can simultaneously satisfy both stylized facts. Altig et al. (2005) favor the model with firm-specific marginal cost on the basis of the argument that it produces less-extreme variations in output shares after an exogenous shock. We have, however, shown that this outcome relies heavily on the price-contract length and on the very large demand elasticity. Introducing additional curvature in the demand function as in Kimball (1995) significantly reduces the variability of output shares in the model with flat marginal costs. Overall, we therefore conclude that other elements such as the presence of firm-specific shocks will have to be introduced to match all the important microstylized facts. Further research on the relationship between prices, output, and marginal costs at the firm level would be very useful in this respect.

Finally, note that in this paper and in contrast to Coenen and Levin (2004), we did not allow for heterogeneity in the contract length. Such heterogeneity is another important stylized fact of the microdata. Moreover, such heterogeneity could help explain the tension between the finding of macropersistence and microflexibility to the extent that the presence of sectors with long price durations can have a disproportionately large effect on the aggregate inflation behavior (Dixon and Kara 2005). Further research along these lines would be worthwhile.

Appendix 1. Data Appendix

All data are taken from the Area Wide Model (AWM) database from the European Central Bank (see Fagan, Henry, and Mestre 2005). Investment includes both private and public investment expenditures. The sample contains data from 1970:Q2 to 2002:Q2, and the first fifteen quarters are used to initialize the Kalman filter. Real variables are deflated with their own deflator. Inflation is calculated as the first difference of the log GDP deflator. In the absence of data on hours worked, we use total employment data for the euro area. As explained in Smets and Wouters (2003), we therefore use for the euro-area model an auxiliary observation equation linking labor services in the model and observed employment based on a Calvo mechanism for the hiring decision of firms. The series are updated for the most recent period using growth rates for the corresponding series published in the ECB's *Monthly Bulletin*. Consumption, investment, GDP, wages, and hours/employment are expressed in 100 times the log. The interest rate and inflation rate are expressed on a quarterly basis corresponding with their appearance in the model (in the graphs the series are translated on an annual basis).

Appendix 2. Model Appendix

This appendix describes the other linearized equations of the Smets-Wouters model (2003, 2004).

Indexation of nominal wages results in the following *real wage equation*:

$$\begin{aligned}\hat{w}_t = {} & \frac{\beta}{1+\beta}E_t\hat{w}_{t+1} + \frac{1}{1+\beta}\hat{w}_{t-1} + \frac{\beta}{1+\beta}(E_t\hat{\pi}_{t+1} - \bar{\pi}_t) \\ & - \frac{1+\beta\gamma_w}{1+\beta}(\hat{\pi}_t - \bar{\pi}_t) + \frac{\gamma_w}{1+\beta}(\hat{\pi}_{t-1} - \bar{\pi}_t) \\ & - \frac{1}{1+\beta}\frac{(1-\beta\xi_w)(1-\xi_w)}{\left(1+\frac{(1+\lambda_w)\sigma_l}{\lambda_w}\right)\xi_w} \\ & \times \left[\hat{w}_t - \sigma_l\hat{l}_t - \frac{1}{1-h}(\hat{c}_t - h\hat{c}_{t-1}) + \varepsilon_t^l\right] + \eta_t^w. \qquad (18)\end{aligned}$$

The real wage $\hat{w}_t$ is a function of expected and past real wages and the expected, current, and past inflation rate where the relative weight depends on the degree of indexation γ_w to lagged inflation of the nonoptimized wages. When $\gamma_w = 0$, real wages do not depend on the lagged inflation rate. There is a negative effect of the deviation of the actual real wage from the wage that would prevail in a flexible labor market. The size of this effect will be greater, the smaller the degree of wage stickiness (ξ_w), the lower the demand elasticity for labor (higher markup λ_w), and the lower the inverse elasticity of labor supply (σ_l) or the flatter the labor supply curve. ε_t^l is a preference shock representing a shock to the labor supply and is assumed to follow a first-order autoregressive process with an i.i.d.-normal error term: $\varepsilon_t^l = \rho_l\varepsilon_{t-1}^l + \eta_t^l$. In contrast, η_t^w is assumed to be an i.i.d.-normal wage-markup shock.

The dynamics of *aggregate consumption* are given by

$$\begin{aligned}\hat{c}_t = {} & \frac{h}{1+h}\hat{c}_{t-1} + \frac{1}{1+h}E_t\hat{c}_{t+1} + \frac{\sigma_c - 1}{\sigma_c(1+\lambda_w)(1+h)}(\hat{l}_t - E_t\hat{l}_{t+1}) \\ & - \frac{1-h}{(1+h)\sigma_c}(\hat{R}_t - E_t\hat{\pi}_{t+1} + \varepsilon_t^b). \qquad (19)\end{aligned}$$

Consumption $\hat{c}_t$ depends on the ex ante real interest rate ($\hat{R}_t - E_t\hat{\pi}_{t+1}$) and, with external habit formation, on a weighted average of past and expected future consumption. When $h = 0$, only the traditional forward-looking term is maintained. In addition, due to the nonseparability of the utility function, consumption will also depend on expected employment growth $(E_t\hat{l}_{t+1} - \hat{l}_t)$. When the elasticity of intertemporal substitution (for constant labor) is smaller than one ($\sigma_c > 1$), consumption and labor supply are complements. Finally, ε_t^b, represents a preference shock affecting the discount rate that determines the intertemporal substitution decisions of households. This shock is assumed to follow a first-order autoregressive process with an i.i.d.-normal error term: $\varepsilon_t^b = \rho_b\varepsilon_{t-1}^b + \eta_t^b$.

The *investment equation* is given by

$$\hat{I}_t = \frac{1}{1+\beta}\hat{I}_{t-1} + \frac{\beta}{1+\beta}E_t\hat{I}_{t+1} + \frac{1/\varphi}{1+\beta}\hat{Q}_t + \varepsilon_t^I, \tag{20}$$

where $\varphi = \bar{S}''$ depends on the adjustment-cost function (S) and β is the discount factor applied by the households. As discussed in Christiano, Eichenbaum, and Evans (2005), modeling the capital adjustment costs as a function of the change in investment rather than its level introduces additional dynamics in the investment equation, which is useful in capturing the hump-shaped response of investment to various shocks, including monetary policy shocks. A positive shock to the investment-specific technology, ε_t^I, increases investment in the same way as an increase in the value of the existing capital stock $\hat{Q}_t$. This investment shock is also assumed to follow a first-order autoregressive process with an i.i.d.-normal error term: $\varepsilon_t^I = \rho_I\varepsilon_{t-1}^I + \eta_t^I$.

The corresponding Q *equation* is given by

$$\hat{Q}_t = -(\hat{R}_t - \hat{\pi}_{t+1}) + \frac{1-\tau}{1-\tau+\bar{r}^k}E_t\hat{Q}_{t+1} + \frac{\bar{r}^k}{1-\tau+\bar{r}^k}E_t\hat{r}_{t+1}^k + \eta_t^Q, \tag{21}$$

where τ stands for the depreciation rate and $\bar{r}^k$ for the rental rate of capital so that $\beta = 1/(1-\tau+\bar{r}^k)$. The current value of the capital stock depends negatively on the ex ante real interest rate and positively on its expected future value and the expected rental rate. The introduction of a shock to the required rate of return on equity investment, η_t^Q, is meant as a shortcut to capture changes in the cost of capital that may be due to stochastic variations in the external finance premium. We assume that this equity premium shock follows an i.i.d.-normal process. In a fully fledged model, the production of capital goods and the associated investment process could be modeled in a separate sector. In such a case, imperfect information between the capital-producing borrowers and the financial intermediaries could give rise to a stochastic external finance premium. Here, we implicitly assume that the deviation between the two returns can be captured by a stochastic shock, whereas the steady-state distortion due to such informational frictions is zero.

The *capital accumulation equation* becomes a function not only of the flow of investment but also of the relative efficiency of these investment expenditures as captured by the investment-specific technology shock:

$$\hat{K}_t = (1-\tau)\hat{K}_{t-1} + \tau\hat{I}_{t-1} + \tau\varepsilon^I_{t-1}. \tag{22}$$

The equalization of marginal cost implies that, for a given installed capital stock, *labor demand* depends negatively on the real wage (with a unit elasticity) and positively on the rental rate of capital:

$$\hat{l}_t = -\hat{w}_t + (1+\psi)\hat{r}^k_t + \hat{K}_{t-1}, \tag{23}$$

where $\psi = \frac{\psi'(1)}{\psi''(1)}$ is the inverse of the elasticity of the capital-utilization cost function.

The *goods market equilibrium condition* can be written as

$$\hat{Y}_t = (1-\tau k_y - g_y)\hat{c}_t + \tau k_y \hat{I}_t + g_y \varepsilon^g_t + +k_y \frac{1-\beta(1-\tau)}{\beta}\psi\hat{r}^k_t \tag{24a}$$

$$= \phi\big[\alpha(\hat{K}_{t-1} + \psi\hat{r}^k_t) + (1-\alpha)(\hat{l}_t + \gamma t\big] - (\phi-1)\gamma t, \tag{24b}$$

where k_y is the steady-state capital-output ratio, g_y is the steady-state government-spending-output ratio, and ϕ is one plus the share of the fixed cost in production. We assume that the government-spending shock follows a first-order autoregressive process with an i.i.d.-normal error term: $\varepsilon^g_t = \rho_g \varepsilon^g_{t-1} + \eta^g_t$.

Finally, the model is closed by adding the following empirical *monetary policy reaction function*:

$$\begin{aligned}\hat{R}_t = {} & \bar{\pi}_t + \rho(\hat{R}_{t-1} - \bar{\pi}_{t-1}) \\ & + (1-\rho)\left[r_\pi(\hat{\pi}_{t-1} - \bar{\pi}_{t-1}) + r_Y(\hat{Y}_{t-1} - \hat{Y}^p_{t-1})\right] \qquad (25) \\ & + r_{\Delta\pi}\left[(\hat{\pi}_t - \bar{\pi}_t) - (\hat{\pi}_{t-1} - \bar{\pi}_{t-1})\right] \\ & + r_{\Delta Y}\left[(\hat{Y}_t - \hat{Y}^p_t) - (\hat{Y}_{t-1} - \hat{Y}^p_{t-1})\right] + \eta^R_t. \qquad (26)\end{aligned}$$

The monetary authorities follow a generalized Taylor rule by gradually responding to deviations of lagged inflation from an inflation objective and the lagged output gap defined as the difference between actual and potential output. Consistently with the DSGE model, potential output is defined as the level of output that would prevail under flexible price and wages in the absence of the three "cost-push" shocks. The parameter ρ captures the degree of interest rate smoothing. In addition, there is also a short-run feedback from the current changes in inflation and the output gap. Finally, we assume that there are two monetary policy shocks: one is a temporary i.i.d.-normal interest rate shock (η^R_t) also denoted a monetary policy shock; the other is a permanent shock to the inflation objective ($\bar{\pi}_t$), which is assumed to follow a nonstationary process ($\bar{\pi}_t = \bar{\pi}_{t-1} + \eta^\pi_t$). The dynamic specification of the reaction function is such that changes in the inflation objective are immediately and without cost reflected in actual inflation and the interest rate if there is no exogenous persistence in the inflation process.

Appendix 3. Description of the Priors

Some parameters are fixed. They are principally parameters related to the steady-state values of the state variables. The discount factor β is calibrated at 0.99, corresponding with an annual steady-state real interest rate of 4 percent. The depreciation rate τ is set at 0.025, so that the annual capital depreciation is equal to 10 percent. The steady-state share of capital income is fixed at $\alpha = 0.24$. The share of steady-state consumption in total output is assumed equal to 0.65, and the share of steady-state investment is assumed equal to 0.17.

The priors on the other parameters are displayed in tables 5–8 in the next appendix. The first column is the description of the parameter, the second column shows the prior distribution, and the next two columns give, respectively, the prior mean and standard error. Most of the priors are the same as in Smets and Wouters (2003). However, there is an important difference to note regarding the capital-utilization adjustment-cost parameter (ψ). Instead of estimating $\frac{1}{\psi}$ with a prior [normal 0.2 0.075], we now estimate $cz = \frac{\psi}{1+\psi}$ with a prior [beta 0.5 0.25], which actually corresponds to a much looser prior since it allows for values of the elasticity of the capital utilization cost function between 0.1 and 10. Some new parameters appear: the price and wage markups, which are given a rather loose prior of [beta 0.25 0.15], and the curvature parameter, which is estimated via $eps = \frac{\epsilon}{1+\epsilon}$ with a prior of [beta 0.85 0.1]. The latter allows for values of parameter ϵ between 1.5 and 100.

For the rest, as in Smets and Wouters (2003), the persistence parameters are given a normal prior distribution with a mean of 0.85 and a standard error of 0.10. The variance of the shocks is assumed to follow an inverted gamma distribution with two degrees of freedom.

Appendix 4. Parameter Estimates for the Main Models

The Metropolis-Hastings algorithm has been run with 250,000 draws. Convergence is assessed with the help of cumsum graphs and using the Brooks and Gelman (1998) uni- and multivariate tests performed by the Dynare software.

Table 5. Baseline Calvo Model (Table 1, First Column)

Marginal Likelihood:
Laplace Approximation: −471.113
Modified Harmonic Mean: −470.407

	Prior Distribution			Estimated Posterior Mode and Mean				Posterior Sample Based				
	Type	Mean	St. Error	Mode	St. Error	Mean	St. Error	5%	10%	50%	90%	95%
St. Dev. of the Shocks												
Productivity Shock	Inv. Gamma	0.250	2 d.f.	0.654	0.094	0.672	0.098	0.533	0.556	0.661	0.802	0.848
Inflation Obj. Shock	Inv. Gamma	0.050	2 d.f.	0.109	0.014	0.113	0.015	0.090	0.095	0.113	0.132	0.138
Cons. Pref. Shock	Inv. Gamma	0.250	2 d.f.	0.194	0.044	0.215	0.051	0.147	0.158	0.207	0.282	0.311
Gov. Spend. Shock	Inv. Gamma	0.250	2 d.f.	0.346	0.023	0.350	0.023	0.315	0.322	0.349	0.380	0.389
Lab. Supl. Shock	Inv. Gamma	0.250	2 d.f.	1.846	0.499	1.985	0.510	1.285	1.394	1.913	2.675	2.925
Investment Shock	Inv. Gamma	0.250	2 d.f.	0.228	0.046	0.232	0.049	0.163	0.175	0.226	0.295	0.319
Interest Rate Shock	Inv. Gamma	0.250	2 d.f.	0.142	0.018	0.144	0.017	0.118	0.123	0.144	0.166	0.174
Equity Premium Shock	Inv. Gamma	0.250	2 d.f.	0.564	0.052	0.565	0.058	0.471	0.491	0.563	0.639	0.663
Price Shock	Inv. Gamma	0.250	2 d.f.	0.207	0.019	0.211	0.020	0.182	0.188	0.210	0.236	0.245
Wage Shock	Inv. Gamma	0.250	2 d.f.	0.209	0.021	0.255	0.024	0.218	0.226	0.254	0.287	0.297
Persistence Parameters												
Productivity Shock	Beta	0.850	0.100	0.991	0.007	0.990	0.007	0.978	0.982	0.992	0.997	0.998
Cons. Pref. Shock	Beta	0.850	0.100	0.890	0.020	0.896	0.023	0.856	0.866	0.897	0.924	0.931
Gov. Spend. Shock	Beta	0.850	0.100	0.994	0.006	0.984	0.011	0.963	0.969	0.987	0.996	0.997
Lab. Supl. Shock	Beta	0.850	0.100	0.979	0.008	0.978	0.009	0.963	0.967	0.979	0.989	0.991
Investment Shock	Beta	0.850	0.100	0.995	0.005	0.988	0.009	0.970	0.976	0.990	0.997	0.998

(continued)

Table 5. (continued). Baseline Calvo Model (Table 1, First Column)

Marginal Likelihood:
Laplace Approximation: −471.113
Modified Harmonic Mean: −470.407

	Prior Distribution			Estimated Posterior Mode and Mean				Posterior Sample Based				
	Type	**Mean**	**St. Error**	**Mode**	**St. Error**	**Mean**	**St. Error**	**5%**	**10%**	**50%**	**90%**	**95%**
Miscellaneous												
Invest. Adj. Cost	Normal	4.000	1.500	5.501	1.014	5.765	1.031	4.159	4.470	5.710	7.131	7.551
Hsehold. Rel. Risk Aversion	Normal	1.000	0.375	2.254	0.309	2.109	0.307	1.597	1.707	2.112	2.508	2.620
Consumption Habit	Beta	0.700	0.100	0.483	0.053	0.502	0.051	0.419	0.438	0.502	0.567	0.585
Labor Utility	Normal	2.000	0.750	1.323	0.869	1.397	0.700	0.393	0.518	1.331	2.353	2.655
Calvo Employment	Beta	0.500	0.100	0.654	0.046	0.654	0.043	0.581	0.598	0.656	0.709	0.723
Calvo Wage	Beta	0.750	0.050	0.712	0.046	0.699	0.049	0.620	0.637	0.700	0.758	0.777
Calvo Price	Beta	0.750	0.050	0.891	0.014	0.890	0.012	0.870	0.874	0.889	0.905	0.910
Indexation Wage	Beta	0.500	0.250	0.389	0.197	0.381	0.183	0.098	0.146	0.369	0.627	0.704
Indexation Price	Beta	0.500	0.250	0.178	0.096	0.184	0.087	0.052	0.075	0.177	0.303	0.339
Cap. Util. Adj. Cost	Beta	0.500	0.250	0.815	0.105	0.850	0.078	0.711	0.745	0.856	0.949	0.967
Fixed Cost	Normal	1.250	0.125	1.715	0.104	1.740	0.104	1.561	1.604	1.743	1.869	1.905
Trend	Normal	0.400	0.025	0.331	0.027	0.324	0.023	0.288	0.295	0.323	0.354	0.363
Policy Rule Parameters												
r Inflation	Normal	1.500	0.100	1.510	0.102	1.529	0.100	1.364	1.399	1.528	1.658	1.694
r d(inflation)	Normal	0.300	0.100	0.101	0.049	0.115	0.047	0.037	0.053	0.115	0.177	0.193
r Lagged Interest Rate	Beta	0.750	0.050	0.901	0.017	0.895	0.018	0.863	0.871	0.896	0.918	0.924
r Output	Beta	0.125	0.050	0.069	0.034	0.092	0.038	0.038	0.046	0.087	0.145	0.162
r d(output)	Beta	0.063	0.050	0.127	0.034	0.132	0.034	0.078	0.090	0.130	0.176	0.191

Table 6. MK Model, 19-Quarter Price Contract (Table 1, Last Column)

Marginal Likelihood:
Laplace Approximation: −468.469
Modified Harmonic Mean: −467.496

	Prior Distribution			Estimated Posterior Mode and Mean				Posterior Sample Based				
	Type	**Mean**	**St. Error**	**Mode**	**St. Error**	**Mean**	**St. Error**	**5%**	**10%**	**50%**	**90%**	**95%**
St. Dev. of the Shocks												
Productivity Shock	Inv. Gamma	0.250	2 d.f.	0.622	0.085	0.636	0.091	0.508	0.531	0.625	0.758	0.805
Inflation Obj. Shock	Inv. Gamma	0.050	2 d.f.	0.104	0.017	0.110	0.018	0.083	0.088	0.109	0.134	0.141
Cons. Pref. Shock	Inv. Gamma	0.250	2 d.f.	0.162	0.028	0.188	0.038	0.136	0.144	0.182	0.237	0.254
Gov. Spend. Shock	Inv. Gamma	0.250	2 d.f.	0.346	0.023	0.349	0.024	0.312	0.320	0.348	0.381	0.390
Lab. Supl. Shock	Inv. Gamma	0.250	2 d.f.	0.324	0.173	0.694	0.393	0.232	0.275	0.628	1.174	1.367
Investment Shock	Inv. Gamma	0.250	2 d.f.	0.205	0.039	0.203	0.041	0.146	0.155	0.198	0.259	0.280
Interest Rate Shock	Inv. Gamma	0.250	2 d.f.	0.158	0.017	0.157	0.020	0.128	0.134	0.156	0.182	0.192
Equity Premium Shock	Inv. Gamma	0.250	2 d.f.	0.557	0.052	0.563	0.059	0.469	0.489	0.562	0.638	0.660
Price Shock	Inv. Gamma	0.250	2 d.f.	0.229	0.016	0.233	0.018	0.206	0.211	0.231	0.256	0.263
Wage Shock	Inv. Gamma	0.250	2 d.f.	0.454	0.035	0.459	0.037	0.404	0.414	0.455	0.509	0.525
Persistence Parameters												
Productivity Shock	Beta	0.850	0.100	0.983	0.006	0.981	0.007	0.969	0.972	0.982	0.990	0.992
Cons. Pref. Shock	Beta	0.850	0.100	0.907	0.017	0.900	0.021	0.866	0.874	0.902	0.925	0.930
Gov. Spend. Shock	Beta	0.850	0.100	0.990	0.009	0.983	0.010	0.963	0.968	0.985	0.995	0.997
Lab. Supl. Shock	Beta	0.850	0.100	0.904	0.067	0.888	0.084	0.713	0.778	0.911	0.969	0.976
Investment Shock	Beta	0.850	0.100	0.993	0.005	0.983	0.015	0.947	0.965	0.987	0.995	0.996
Price Shock	Beta	0.850	0.100	0.934	0.018	0.932	0.021	0.896	0.906	0.933	0.957	0.964
Wage Shock	Beta	0.850	0.100	0.955	0.013	0.950	0.017	0.917	0.928	0.953	0.968	0.972

(continued)

Table 6. (continued). MK Model, 19-Quarter Price Contract (Table 1, Last Column)

Marginal Likelihood:
Laplace Approximation: −468.469
Modified Harmonic Mean: −467.496

	Prior Distribution			Estimated Posterior Mode and Mean				Posterior Sample Based				
	Type	**Mean**	**St. Error**	**Mode**	**St. Error**	**Mean**	**St. Error**	**5%**	**10%**	**50%**	**90%**	**95%**
Miscellaneous												
Invest. Adj. Cost	Normal	4.000	1.500	6.543	1.032	6.396	1.036	4.736	5.084	6.364	7.770	8.155
Hsehold. Rel. Risk Aversion	Normal	1.000	0.375	2.085	0.274	1.986	0.282	1.522	1.622	1.992	2.337	2.450
Consumption Habit	Beta	0.700	0.100	0.340	0.049	0.376	0.054	0.291	0.308	0.375	0.445	0.468
Labor Utility	Normal	2.000	0.750	0.495	0.334	0.701	0.335	0.236	0.309	0.662	1.149	1.317
Calvo Employment	Beta	0.500	0.100	0.645	0.043	0.639	0.042	0.568	0.585	0.640	0.692	0.707
Indexation Wage	Beta	0.500	0.250	0.461	0.188	0.470	0.189	0.163	0.226	0.464	0.727	0.795
Indexation Price	Beta	0.500	0.250	0.273	0.074	0.274	0.078	0.146	0.173	0.276	0.372	0.398
Cap. Util. Adj. Cost	Beta	0.500	0.250	0.825	0.080	0.819	0.080	0.680	0.712	0.824	0.921	0.946
Fixed Cost	Normal	1.250	0.125	1.573	0.099	1.577	0.098	1.421	1.452	1.574	1.707	1.743
Wage Markup	Beta	0.250	0.150	0.206	0.123	0.279	0.124	0.105	0.132	0.264	0.445	0.512
Trend	Normal	0.400	0.025	0.394	0.023	0.391	0.022	0.354	0.362	0.390	0.419	0.427
Policy Rule Parameters												
r Inflation	Normal	1.500	0.100	1.562	0.084	1.575	0.082	1.443	1.470	1.574	1.683	1.714
r d(inflation)	Normal	0.300	0.100	0.197	0.046	0.200	0.048	0.123	0.139	0.199	0.263	0.281
r Lagged Interest Rate	Beta	0.750	0.050	0.869	0.018	0.862	0.020	0.828	0.836	0.864	0.887	0.893
r Output	Beta	0.125	0.050	0.094	0.026	0.101	0.028	0.058	0.066	0.099	0.139	0.151
r d(output)	Beta	0.063	0.050	0.185	0.048	0.193	0.052	0.112	0.128	0.190	0.260	0.282

Table 7. NMK Model, 4-Quarter Price Contract, $\phi \neq \lambda_p$ and $\varepsilon = 0$ (Table 3, Column 2)

Marginal Likelihood:
Laplace Approximation: −464.920
Modified Harmonic Mean: −463.902

	Prior Distribution			Estimated Posterior Mode and Mean				Posterior Sample Based				
	Type	**Mean**	**St. Error**	**Mode**	**St. Error**	**Mean**	**St. Error**	**5%**	**10%**	**50%**	**90%**	**95%**
St. Dev. of the Shocks												
Productivity Shock	Inv. Gamma	0.250	2 d.f.	0.655	0.092	0.680	0.092	0.544	0.569	0.672	0.803	0.845
Inflation Obj. Shock	Inv. Gamma	0.050	2 d.f.	0.129	0.016	0.133	0.016	0.107	0.112	0.132	0.154	0.160
Cons. Pref. Shock	Inv. Gamma	0.250	2 d.f.	0.138	0.026	0.164	0.032	0.120	0.127	0.159	0.207	0.224
Gov. Spend. Shock	Inv. Gamma	0.250	2 d.f.	0.347	0.023	0.351	0.023	0.316	0.323	0.350	0.380	0.389
Lab. Supl. Shock	Inv. Gamma	0.250	2 d.f.	0.284	0.112	0.512	0.331	0.204	0.231	0.414	0.898	1.069
Investment Shock	Inv. Gamma	0.250	2 d.f.	0.254	0.049	0.247	0.048	0.177	0.190	0.243	0.310	0.333
Interest Rate Shock	Inv. Gamma	0.250	2 d.f.	0.131	0.015	0.135	0.015	0.112	0.117	0.135	0.155	0.161
Equity Premium Shock	Inv. Gamma	0.250	2 d.f.	0.537	0.053	0.538	0.057	0.445	0.465	0.537	0.612	0.634
Price Shock	Inv. Gamma	0.250	2 d.f.	0.225	0.016	0.227	0.018	0.199	0.205	0.225	0.250	0.257
Wage Shock	Inv. Gamma	0.250	2 d.f.	0.441	0.035	0.449	0.035	0.395	0.406	0.447	0.495	0.512
Persistence Parameters												
Productivity Shock	Beta	0.850	0.100	0.979	0.009	0.979	0.008	0.964	0.968	0.979	0.988	0.990
Cons. Pref. Shock	Beta	0.850	0.100	0.922	0.019	0.914	0.016	0.885	0.892	0.915	0.934	0.938
Gov. Spend. Shock	Beta	0.850	0.100	0.992	0.009	0.984	0.010	0.965	0.971	0.986	0.995	0.997
Lab. Supl. Shock	Beta	0.850	0.100	0.882	0.087	0.855	0.098	0.668	0.718	0.874	0.965	0.976
Investment Shock	Beta	0.850	0.100	0.997	0.003	0.991	0.007	0.977	0.982	0.993	0.998	0.999
Price Shock	Beta	0.850	0.100	0.979	0.029	0.947	0.045	0.851	0.878	0.961	0.987	0.991
Wage Shock	Beta	0.850	0.100	0.959	0.011	0.954	0.014	0.929	0.937	0.956	0.970	0.974

(*continued*)

Table 7. (continued). NMK Model, 4-Quarter Price Contract, $\phi \neq \lambda_p$ and $\varepsilon = 0$ (Table 3, Column 2)

Marginal Likelihood:
Laplace Approximation: −468.469
Modified Harmonic Mean: −467.496

	Prior Distribution			Estimated Posterior Mode and Mean				Posterior Sample Based				
	Type	**Mean**	**St. Error**	**Mode**	**St. Error**	**Mean**	**St. Error**	**5%**	**10%**	**50%**	**90%**	**95%**
Miscellaneous												
Invest. Adj. Cost	Normal	4.000	1.500	6.261	1.029	6.221	1.025	4.620	4.930	6.177	7.585	7.986
Hsehold. Rel. Risk Aversion	Normal	1.000	0.375	2.083	0.285	1.956	0.282	1.485	1.594	1.960	2.311	2.413
Consumption Habit	Beta	0.700	0.100	0.348	0.048	0.388	0.055	0.302	0.320	0.387	0.459	0.483
Labor Utility	Normal	2.000	0.750	0.892	0.648	1.267	0.597	0.459	0.583	1.179	2.070	2.382
Calvo Employment	Beta	0.500	0.100	0.650	0.043	0.650	0.038	0.585	0.602	0.652	0.698	0.709
Indexation Wage	Beta	0.500	0.250	0.463	0.210	0.511	0.191	0.190	0.257	0.513	0.764	0.827
Indexation Price	Beta	0.500	0.250	0.093	0.077	0.113	0.065	0.024	0.035	0.103	0.201	0.233
Cap. Util. Adj. Cost	Beta	0.500	0.250	0.834	0.113	0.867	0.070	0.744	0.772	0.873	0.955	0.971
Fixed Cost	Normal	1.250	0.125	1.515	0.138	1.482	0.104	1.313	1.349	1.482	1.616	1.654
Price Markup	Beta	0.250	0.150	0.004	0.002	0.005	0.001	0.003	0.003	0.005	0.007	0.007
Wage Markup	Beta	0.250	0.150	0.280	0.139	0.345	0.125	0.163	0.196	0.334	0.513	0.576
Curvature Parameter	Beta	0.850	0.100									
Trend	Normal	0.400	0.025	0.398	0.023	0.400	0.023	0.364	0.371	0.400	0.429	0.437
Policy Rule Parameters												
r Inflation	Normal	1.500	0.100	1.536	0.083	1.556	0.081	1.429	1.454	1.553	1.661	1.695
r d(inflation)	Normal	0.300	0.100	0.172	0.045	0.183	0.046	0.107	0.124	0.183	0.242	0.259
r Lagged Interest Rate	Beta	0.750	0.050	0.868	0.017	0.861	0.018	0.829	0.837	0.862	0.883	0.889
r Output	Beta	0.125	0.050	0.114	0.027	0.106	0.027	0.066	0.074	0.104	0.142	0.153
r d(output)	Beta	0.063	0.050	0.114	0.035	0.120	0.036	0.064	0.075	0.119	0.168	0.183

Table 8. NMK Model, 4-Quarter Price Contract, $\phi = \lambda_p$ and $\varepsilon \neq 0$ (Table 4, Column 2)

Marginal Likelihood:
Laplace Approximation: −468.344
Modified Harmonic Mean: −467.130

	Prior Distribution			Estimated Posterior Mode and Mean				Posterior Sample Based				
	Type	**Mean**	**St. Error**	**Mode**	**St. Error**	**Mean**	**St. Error**	**5%**	**10%**	**50%**	**90%**	**95%**
St. Dev. of the Shocks												
Productivity Shock	Inv. Gamma	0.250	2 d.f.	0.650	0.088	0.659	0.089	0.528	0.552	0.651	0.778	0.820
Inflation Obj. Shock	Inv. Gamma	0.050	2 d.f.	0.130	0.017	0.130	0.017	0.102	0.108	0.129	0.152	0.159
Cons. Pref. Shock	Inv. Gamma	0.250	2 d.f.	0.144	0.024	0.168	0.033	0.124	0.132	0.163	0.211	0.229
Gov. Spend. Shock	Inv. Gamma	0.250	2 d.f.	0.347	0.023	0.350	0.023	0.314	0.321	0.349	0.380	0.389
Lab. Supl. Shock	Inv. Gamma	0.250	2 d.f.	0.286	0.115	0.511	0.289	0.205	0.234	0.420	0.934	1.125
Investment Shock	Inv. Gamma	0.250	2 d.f.	0.250	0.048	0.249	0.051	0.177	0.189	0.243	0.316	0.342
Interest Rate Shock	Inv. Gamma	0.250	2 d.f.	0.130	0.015	0.137	0.016	0.112	0.117	0.136	0.158	0.165
Equity Premium Shock	Inv. Gamma	0.250	2 d.f.	0.538	0.054	0.536	0.057	0.442	0.463	0.535	0.608	0.628
Price Shock	Inv. Gamma	0.250	2 d.f.	0.178	0.013	0.184	0.014	0.162	0.166	0.183	0.202	0.207
Wage Shock	Inv. Gamma	0.250	2 d.f.	0.437	0.033	0.448	0.035	0.395	0.406	0.446	0.493	0.507
Persistence Parameters												
Productivity Shock	Beta	0.850	0.100	0.981	0.007	0.978	0.008	0.964	0.968	0.979	0.988	0.990
Cons. Pref. Shock	Beta	0.850	0.100	0.917	0.013	0.912	0.017	0.882	0.890	0.913	0.931	0.936
Gov. Spend. Shock	Beta	0.850	0.100	0.994	0.006	0.983	0.013	0.959	0.967	0.986	0.996	0.997
Lab. Supl. Shock	Beta	0.850	0.100	0.892	0.093	0.850	0.101	0.656	0.707	0.870	0.963	0.975
Investment Shock	Beta	0.850	0.100	0.996	0.004	0.990	0.008	0.975	0.980	0.992	0.998	0.998
Price Shock	Beta	0.850	0.100	0.539	0.056	0.544	0.060	0.443	0.467	0.547	0.617	0.639
Wage Shock	Beta	0.850	0.100	0.956	0.013	0.954	0.015	0.927	0.935	0.956	0.971	0.975

(continued)

Table 8. (continued). NMK Model, 4-Quarter Price Contract, $\phi = \lambda_p$ and $\varepsilon \neq 0$ (Table 4, Column 2)

Marginal Likelihood:
Laplace Approximation: −468.344
Modified Harmonic Mean: −467.130

	Prior Distribution			Estimated Posterior Mode and Mean				Posterior Sample Based				
	Type	**Mean**	**St. Error**	**Mode**	**St. Error**	**Mean**	**St. Error**	**5%**	**10%**	**50%**	**90%**	**95%**
Miscellaneous												
Invest. Adj. Cost	Normal	4.000	1.500	6.327	1.032	6.376	1.034	4.753	5.078	6.335	7.733	8.140
Hsehold. Rel. Risk Aversion	Normal	1.000	0.375	2.111	0.261	1.983	0.283	1.510	1.618	1.987	2.344	2.447
Consumption Habit	Beta	0.700	0.100	0.356	0.049	0.388	0.053	0.303	0.321	0.386	0.458	0.480
Labor Utility	Normal	2.000	0.750	1.124	0.614	1.250	0.578	0.440	0.565	1.178	2.033	2.313
Calvo Employment	Beta	0.500	0.100	0.643	0.040	0.641	0.039	0.574	0.590	0.643	0.690	0.702
Indexation Wage	Beta	0.500	0.250	0.562	0.210	0.533	0.193	0.205	0.274	0.537	0.788	0.846
Indexation Price	Beta	0.500	0.250	0.121	0.096	0.156	0.085	0.034	0.052	0.146	0.274	0.313
Cap. Util. Adj. Cost	Beta	0.500	0.250	0.812	0.080	0.844	0.073	0.719	0.747	0.848	0.938	0.958
Fixed Cost	Normal	1.250	0.125									
Price Markup	Beta	0.250	0.150	0.489	0.098	0.530	0.100	0.370	0.403	0.526	0.660	0.701
Wage Markup	Beta	0.250	0.150	0.288	0.117	0.332	0.122	0.152	0.184	0.319	0.495	0.551
Curvature Parameter	Beta	0.850	0.100	0.986	0.004	0.984	0.006	0.973	0.977	0.984	0.990	0.991
Trend	Normal	0.400	0.025	0.399	0.022	0.395	0.022	0.359	0.367	0.395	0.424	0.432
Policy Rule Parameters												
r Inflation	Normal	1.500	0.100	1.535	0.081	1.552	0.080	1.424	1.452	1.551	1.655	1.686
r d(inflation)	Normal	0.300	0.100	0.175	0.044	0.185	0.046	0.110	0.126	0.184	0.243	0.260
r Lagged Interest Rate	Beta	0.750	0.050	0.866	0.017	0.862	0.018	0.830	0.838	0.863	0.884	0.890
r Output	Beta	0.125	0.050	0.115	0.026	0.112	0.027	0.070	0.078	0.110	0.147	0.158
r d(output)	Beta	0.063	0.050	0.117	0.034	0.128	0.037	0.070	0.081	0.126	0.176	0.192

References

Altig, D., L. Christiano, M. Eichenbaum, and J. Lindé. 2005. "Firm-Specific Capital, Nominal Rigidities and the Business Cycle." NBER Working Paper No. 11034.

Altissimo, F., M. Ehrmann, and F. Smets. 2005. "Inflation Persistence and Price Setting in the Euro Area: A Summary of the IPN Evidence." Mimeo, European Central Bank.

Angeloni, I., L. Aucremanne, M. Ehrmann, J. Galí, A. Levin, and F. Smets. 2006. "New Evidence on Inflation Persistence and Price Stickiness in the Euro Area: Implications for Macro Modelling." *Journal of the European Economic Association* 4 (2–3): 562–74.

Bils, M., and P. Klenow. 2004. "Some Evidence on the Importance of Sticky Prices." *Journal of Political Economy* 112 (5): 947–85.

Brooks, S., and A. Gelman. 1998. "General Methods for Monitoring Convergence of Iterative Simulations." *Journal of Computational and Graphical Statistics* 7 (4): 434–56.

Calvo, G. 1983. "Staggered Prices in a Utility-Maximizing Framework." *Journal of Monetary Economics* 12 (3): 383–98.

Christiano, L. 2004. "Firm-Specific Capital and Aggregate Inflation Dynamics in Woodford's Model." Mimeo, Northwestern University.

Christiano, L., M. Eichenbaum, and C. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." *Journal of Political Economy* 113 (1): 1–46.

Coenen, G., and A. Levin. 2004. "Identifying the Influences of Nominal and Real Rigidities in Aggregate Price Setting Behaviour." ECB Working Paper No. 418.

Danthine, J.-P., and J. Donaldson. 2002. "A Note on NNS Models: Introducing Physical Capital: Avoiding Rationing." *Economic Letters* 77 (3): 433–37.

Dixon, H., and E. Kara. 2005. "Persistence and Nominal Inertia in a Generalized Taylor Economy: How Longer Contracts Dominate Shorter Contracts." ECB Working Paper No. 489.

———. 2006. "How to Compare Taylor and Calvo Contracts: A Comment on Michael Kiley." *Journal of Money, Credit, and Banking* 38 (4): 1119–26.

Eichenbaum, M., and J. Fisher. 2004. "Evaluating the Calvo Model of Sticky Prices." NBER Working Paper No. 10617.

Fagan, G., J. Henry, and R. Mestre. 2005. "An Area-Wide Model (AWM) for the Euro Area." *Economic Modelling* 22 (1): 39–59.

Galí, J., and M. Gertler. 1999. "Inflation Dynamics: A Structural Econometric Analysis." *Journal of Monetary Economics* 44 (2): 195–222.

Galí, J., M. Gertler, and J. D. López-Salido. 2001. "European Inflation Dynamics." *European Economic Review* 45 (7): 1237–70.

Kimball, M. 1995. "The Quantitative Analytics of the Basic Neomonetarist Model." *Journal of Money, Credit, and Banking* 27 (4): 1241–77.

Matheron, J. 2005. "Firm-Specific Labor versus Firm-Specific Capital: Implication for the Euro Data New Phillips Curve." Unpublished Manuscript, Banque de France.

Sbordone, A. 2002. "Price and Unit Labor Costs: A New Test of Price Stickiness." *Journal of Monetary Economics* 49 (2): 265–92.

Smets, F., and R. Wouters. 2003. "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area." *Journal of the European Economic Association* 1 (5): 1123–75.

———. 2004. "Shocks and Frictions in US Business Cycle Fluctuations: A Bayesian DSGE Approach." Mimeo.

———. 2005. "Comparing Shocks and Frictions in US and Euro Area Business Cycle: A Bayesian DSGE Approach." *Journal of Applied Econometrics* 20 (2): 161–83.

Taylor, J. 1980. "Aggregate Dynamics and Staggered Contracts." *Journal of Political Economy* 88 (1): 1–24.

Taylor, J. 1993. *Macroeconomic Policy in a World Economy: From Econometric Design to Practical Considerations.* New York: W. W. Norton.

Whelan, K. 2004. "Staggered Price Contracts and Inflation Persistence: Some General Results." ECB Working Paper No. 417.

Woodford, M. 2003. *Interest and Prices: Foundations of a Theory of Monetary Policy.* Princeton, NJ: Princeton University Press.

———. 2005. "Firm-Specific Capital and the New Keynesian Phillips Curve." *International Journal of Central Banking* 1 (2): 1–46.

Yun, T. 1996. "Nominal Price Rigidity, Money Supply Endogeneity, and Business Cycles." *Journal of Monetary Economics* 37 (2): 345–70.