Evaluating Calvo-Style Sticky Price Models*

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Abstract

This paper assesses the empirical performance of Calvo-style sticky goods price models. We argue that Calvo-style models in which firms update non-reoptimized prices to lagged inflation are consistent with the aggregate data in a statistical sense. We then investigate whether these models imply plausible degrees of inertia in price setting behavior by firms. We find that these model do, but only if we depart from two auxiliary assumptions made in standard expositions of the Calvo model. These assumptions are that monopolistically competitive firms face a constant elasticity of demand, and capital is homogeneous and can be instantaneously reallocated after a shock. When we relax these assumptions our model is consistent with the view that firms reoptimize prices, on average, once every two quarters.

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1. Introduction

This paper addresses two questions. First, can variants of the Calvo (1983) sticky price model account for the statistical behavior of post-war U.S. inflation rates? Second, can these models succeed statistically with plausible degrees of inertia in pricing setting behavior at the firm level? If we assume that firms update non reoptimized prices to lagged inflation, then the answer to the first question is yes. Our answer to the second question is also yes, but only if we depart from two auxiliary assumptions made in standard expositions of the Calvo model: monopolistically competitive firms face a constant elasticity of demand, and capital is homogeneous and can be instantly reallocated after a shock. Under these assumptions, our estimated model implies that firms reoptimize prices roughly once every two *years*. This finding motivates us to consider a variant of the Calvo model in which the elasticity of demand facing firms is variable and capital is firm-specific. The resulting model is observationally equivalent to the original model in terms of its implications for the aggregate time series used in our analysis. However, inference about how frequently firms reoptimize prices is affected in an important way. The modified model is consistent with the view that firms reoptimize prices on average once every two *quarters*.

Despite ongoing controversies, models embodying sticky prices continue to play a central role in analyses of the monetary transmission mechanism. In time-dependent sticky price models, the number of firms that change prices in any given period is specified exogenously.[1] In state-dependent pricing models, the number of firms that change prices in any given period is determined endogenously.[2] While state-dependent models seem promising, at least to us, they are substantially more difficult to work with than time-dependent models. Perhaps more importantly, empirically plausible versions of time and state-dependent models often generate similar results for many policy experiments that are relevant in moderate inflation economies.[3] Here we take as given the widespread interest in time-dependent models and

[1] Classic models of this sort were developed by Taylor (1980) and Calvo (1983). Modern variants are now central elements of a large class of models. See, for example, Christiano, Eichenbaum and Evans (2005), Erceg, Henderson, and Levon (2000), Gali and Gertler (1999), Rotemberg and Woodford (1997) and Yun (1996).

[2] Important recent examples of state-dependent pricing models include Dotsey, King, and Wolman (1999), Burstein (2002) and Golosov and Lucas (2003).

[3] See, for example, Burstein (2002) and Klenow and Krystov (2003). In contrast, Golosov and Lucas (2003) argue that the shock repsonses in their model are very different from the analog responses in a Calvo-type model. It is not clear whether this would be the case in a version of the Golosov and Lucas model calibrated to the finding in Klenow and Krystov that 90% of monthly US inflation stems solely from fluctuations in the

focus on the empirical properties of Calvo-style models.

We interpret the Calvo price-setting mechanism as capturing firms' responses to various costs of changing prices. The basic idea is that in the presence of these costs, firms fully optimize prices only periodically, and follow simple rules for changing their prices at other times. The type of costs we have in mind are those associated with optimization (e.g., costs associated with information gathering, decision making, negotiation and communication). These costs are different from menu costs, which apply to all price changes.[4] We consider a Calvo-style model, in which firms who do not reoptimize their prices index their prices to lagged inflation. This dynamic indexing scheme implies that inflation depends on its own lag as well as expected future marginal cost. Allowing for such a lag is important for rendering Calvo-style models consistent with the data.[5]

We also allow for the possibility that there is a lag between the time at which firms reoptimize their price plans, and the time at which they implement the new plan. In our model, this lag is equivalent to the assumption that firms reoptimize time prices based on an information set that only includes lagged values of marginal cost. For convenience, we proceed under the "implementation lag" interpretation. We refer to the model with dynamic indexation and an implementation lag as our benchmark model.

We find that allowing for a one-quarter delay in the implementation of new prices and dynamic indexation renders the benchmark model consistent with the aggregate data in a statistical sense. But that does not mean the estimated model makes economic sense. The key question is whether the model implies plausible inertia in price setting behavior by firms. Taken at face value, the answer to this question is no. Specifically, the estimated version of our preferred model implies that firms reoptimize prices, on average, roughly once every two years. This implication seems implausible to us and would justify rejection of the model.

As it turns out, this inference about price inertia at the firm level is warranted only under very special auxiliary assumptions associated with Calvo-style models; namely, that

average size of price changes, as opposed to the fraction of firms who change prices.

[4]Zbaracki, Ritson, Levy, Dutta, and Bergen (2000) provide some microeconomic evidence that costs associated with reoptimization are much more important than menu costs.

[5]See for example Gali and Gertler (1999) or more recently Eichenbaum and Fisher (2004). An alternative way to make inflation depend on lagged inflation is to allow for Gali and Gertler (1999) rule-of-thumb type firms. In a previous version of this paper, Eichenbaum and Fisher (2004), we show that it is difficult to discriminate between the statistical plausibility of Calvo models with dynamic indexing and Calvo models modified to allow for some Gali and Gertler type rule-of-thumb firms.

price setting firms face a constant elasticity of demand and capital is homogeneous and can be instantly reallocated after a shock. These assumptions are typically made for analytic convenience, but neither is compelling on empirical grounds. As for the first assumption, relatively little is known about how the elasticity of demand varies along intermediate good firms' demand curves. So it is important to know how sensitive results are to this assumption. Following Kimball (1995), we allow for the possibility that the elasticity of demand is increasing in a firm's price. The second assumption is clearly counter factual - firms do not rent capital on a period-by-period basis in perfectly competitive economy wide markets. Following Woodford (2003) we allow for the possibility that capital is firm-specific. In this specification, a firm's capital stock can only be augmented with a one-period delay using final goods, subject to adjustment costs. We refer to the model with a non-constant elasticity of demand and firm-specific capital as the modified benchmark model.

We demonstrate that the parameters of the modified benchmark model are not separately identified using aggregate time series data. In particular, we cannot separately identify the frequency with which a firm reoptimizes its price, the nature of demand elasticities, and the degree of capital mobility. Still, we can identify the frequency of re-optimization if we have information about demand elasticities and the degree of capital mobility.

If we assume that capital is firm-specific, and there are empirically plausible costs of adjusting capital, then the model implies a degree of inertia in price re-optimization that is much more plausible than that implied by our benchmark model. Depending on our assumptions about demand elasticities, our measure of inflation, and the sample period under consideration, we infer that firms reoptimize prices once every 2.3 to three quarters. In no case can we reject, at conventional confidence intervals, the hypothesis that firms reoptimize prices once every two quarters.

The paper is organized as follows. We discuss our extended version of the Calvo model in Section 2. In Section 3 we display our econometric strategy for estimating and testing the model. We discuss our data in Section 4. In Section 5 we present our statistical results. In Section 6 we interpret the parameters of the estimated model. Finally, we make brief concluding remarks in Section 7.

2. A Model of Sticky Prices

We present a version of the Calvo sticky goods price model which departs from standard expositions in two important ways. First, we assume that intermediate good firms face a varying elasticity of demand for their output. Second, we assume that capital is firm-specific and can only be augmented with a one-period delay with adjustment costs. Throughout we assume that firms index non reoptimized prices to lagged inflation.

2.1. The Calvo Model with a Varying Elasticity of Demand

At time t, a final good, Y_t, is produced by a perfectly competitive firm. The firm does so by combining a continuum of intermediate goods, indexed by $i \in [0,1]$, using the following technology:

$$\int_0^1 G(Y_{it}/Y_t)di = 1. \tag{1}$$

Here G is increasing, strictly concave, $G(1) = 1$, and Y_{it} denotes the input of intermediate good i. This specification corresponds to the one adopted in Kimball (1995). The standard Dixit-Stiglitz specification corresponds to the special case:

$$G(Y_{it}/Y_t) = (Y_{it}/Y_t)^{(\mu-1)/\mu},\ \mu > 1.$$

We refer to the general version of $G(\cdot)$ as the Kimball specification.

The final good firm chooses Y_t and Y_{it} to maximize profits, $P_tY_t - \int_0^1 P_{it}Y_{it}di$, subject to (1). Here P_t and P_{it} denote the time t price of the final and intermediate good i, respectively. The first order conditions to the firm's problem imply:

$$Y_{it} = Y_t G'^{-1}\left(\frac{P_{it}Y_t}{\lambda_t}\right). \tag{2}$$

Here λ_t, the time t Lagrange multiplier on constraint (1), is given by:

$$\lambda_t = \frac{P_tY_t}{\int G'(Y_{it}/Y_t)\cdot(Y_{it}/Y_t)di}.$$

Throughout, the symbol "$'$" denotes the derivative operator and $G'^{-1}(\cdot)$ denotes the inverse function of $G'(\cdot)$. Our assumptions on $G(\cdot)$ imply that the firm's demand for input Y_{it} is decreasing in its relative price.[6]

Intermediate good $i \in [0,1]$ is produced by a monopolist who uses the following technology:

$$Y_{it} = Z_t K_{it}^{\alpha} H_{it}^{1-\alpha} \tag{3}$$

where $0 < \alpha < 1$. Here, H_{it} and K_{it} denote time t labor and capital services used to produce intermediate good i, respectively. Intermediate good firms rent capital and labor in economy-wide, perfectly competitive factor markets. With this specification, individual firms do not view their own capital stock as predetermined within the period. The variable Z_t denotes possible stochastic disturbances to technology.

Profits are distributed to the firms' owners at the end of each time period. Let s_t denote the representative firm's real marginal cost. Given our assumptions on factor markets, all firms have identical marginal costs. Consequently, we do not index s_t by i. Marginal cost depends on the parameter α and factor prices that the firm takes as given. The firm's time t profits are $\left[P_{it}/P_t - s_t\right] P_t Y_{it}$, where P_{it} is the price of intermediate good i.

Intermediate good firms set prices according to a variant of the mechanism spelled out in Calvo (1983). In each period a firm faces a constant probability, $1-\theta$, of being able to reoptimize its nominal price. So, on average, a firm reoptimizes its price every $(1-\theta)^{-1}$ periods. The firm's ability to reoptimize its price is independent across firms and time. For now, we leave open the issue of what information set the firm has when it resets its price.

As in Christiano, Eichenbaum and Evans (2005) we suppose that when a firm does not reoptimize its price, it resets its price according to the dynamic indexing scheme:[7]

$$P_{it} = \pi_{t-1} P_{it-1}. \tag{4}$$

In Eichenbaum and Fisher (2004) we discuss results based on the assumption that firms adopt a static indexing scheme, $P_{it} = \bar{\pi} P_{it-1}$, where $\bar{\pi}$ is the long-run average gross rate

[6] To obtain this result we use the fact that, given our assumptions on G, if $x = G^{'-1}(z)$, then $dG'^{-1}(z)/dz = 1/G''(x)$.

[7] See Christiano, Eichenbaum and Evans (2005) for a discussion of dynamic indexing rules, and a comparison to rules in which firms who don't re-optimize leave their price unchanged or index their price to the unconditional rate of inflation.

of inflation.[8] Interestingly, our point estimate of θ is not much affected by which indexing scheme we work with.

Let P_t^* denote the value of P_{it} set by a firm that can reoptimize its price. In addition, let Y_t^* denote the time t output of this firm. Our notation does not allow P_t^* or Y_t^* to depend on i because all firms who can reoptimize their price at time t choose the same price (see Woodford, (1996) and Yun (1996)). The firm chooses P_t^* to maximize:

$$E_{t-\tau} \sum_{l=0}^{\infty} (\beta\theta)^l \, v_{t+l} \left[P_t^* X_{tl} - s_{t+l} P_{t+l} \right] Y_t^* \tag{5}$$

subject to (2) and

$$X_{tl} = \left\{ \begin{array}{cc} \pi_t \times \pi_{t+1} \times \cdots \times \pi_{t+l-1} & \text{for } l \geq 1 \\ 1 & \text{for } l = 0 \end{array} . \right\}$$

Here, β is a constant between zero and one, $E_{t-\tau}$ denotes the conditional expectations operator given the firm's $t-\tau$ information set, which includes the realization of all model variables dated $t-\tau$ and earlier. In addition, v_{t+l} is the time-varying portion of the firm's discount factor. The intermediate good firm views s_t, P_t, v_t and λ_t as exogenous stochastic processes beyond its control.

Let $p_t^* = P_t^*/P_t$. Log linearizing the first order condition of the firm around the relevant steady state values we obtain:

$$\widehat{p}_t^* = E_{t-\tau} \sum_{l=1}^{\infty} (\beta\theta)^l \, \Delta\hat{\pi}_{t+l} + A E_{t-\tau} \left[\hat{s}_t + \sum_{l=1}^{\infty} (\beta\theta)^l \left(\hat{s}_{t+l} - \hat{s}_{t+l-1} \right) \right] \tag{6}$$

where

$$A = \frac{1 + G''(1)/G'(1)}{2 + G'''(1)/G''(1)}.$$

Throughout, $\hat{x}_t$ denotes the percent deviation of a variable x_t from its steady-state value. For future reference it is useful to write $\hat{s}_t$ as

$$\hat{s}_t = \hat{W}_t - \hat{P}_t - \frac{1}{1-\alpha} \hat{Z}_t + \frac{\alpha}{1-\alpha} \hat{Y}_t - \frac{\alpha}{1-\alpha} \hat{K}_t. \tag{7}$$

[8] This specification is adopted by Erceg, Henderson, and Levin (2000) and Yun (1996), among others.

Note that $\hat{s}_t$ depends only on economy-wide variables, which an individual firm views as beyond its control.

Several features of (6) are worth emphasizing. First, if inflation and real marginal cost are expected to remain constant after time t, then the firm sets $\widehat{p}_t^* = AE_{t-\tau}\hat{s}_t$. That is, the percent deviation in the firm's relative price is a constant markup of the expected deviation of marginal cost from its steady-state value. Second, suppose the firm expects real marginal costs to be higher in the future than at time t. Anticipating those higher future marginal costs, the firm sets $\widehat{p}_t^*$ higher than $AE_{t-\tau}\hat{s}_t$. It does so because it understands that it may not be able to raise its price when higher marginal costs materialize. Third, to avoid declines in its relative price, the firm incorporates expected changes in the inflation rate into $\widehat{p}_t^*$.

The degree to which $\widehat{p}_t^*$ responds to current and future values of $\hat{s}_t$ is increasing in A, which in turn depends on the properties of $G(\cdot)$. One way to interpret A is that it governs the degree of pass-through from a rise in marginal cost to prices. For example, according to (6), a highly persistent 1% increase in time t marginal cost from its steady state value induces the firm to initially raise its relative price by approximately A percent.

A different way to interpret A involves the elasticity of demand for a given intermediate good, $\eta(x) = -G'(x)/(xG''(x))$, where $x = Y_t^*/Y_t$. In the Appendix we show that:

$$A = \frac{1}{\zeta\epsilon + 1}, \tag{8}$$

where $\epsilon = (\tilde{P}/\eta(1))(\partial\eta(1)/\partial\tilde{P})$. The variable ϵ is the percent change in the elasticity of demand due to a one percent change in the relative price of the good, evaluated in steady state. The variable ζ denotes the firm's steady state markup, $\eta(1)/(\eta(1)-1)-1$. In the standard Dixit-Stiglitz case, ϵ is equal to zero and A is equal to one.

Relations (8) and (6) imply that the larger is ϵ, the lower is A and the less responsive is $\widehat{p}_t^*$ to current and future values of $\hat{s}_t$. To understand these relationships, recall that other things being equal, a rise in marginal cost induces a firm to increase its price. A higher value of ϵ means that, for any given rise in its price, the demand curve for the firm's good will be more elastic. So, relative to the case where $\epsilon = 0$, the firm will raise its price by less. As we discuss below, this means that inflation will respond by less to movements in marginal cost.

Zero profits in the final goods sector and our assumptions about the distribution of θ

across firms and time imply:

$$P_tY_t = \int_0^1 P_{it}Y_{it} = (1-\theta)P_t^*Y_{t+l}G'^{-1}\left(\frac{P_t^*Y_t}{\lambda_t}\right) + \theta\bar{\pi}P_{t-1}Y_tG'^{-1}\left(\frac{\bar{\pi}P_{t-1}Y_t}{\lambda_t}\right). \tag{9}$$

Linearizing this relationship around the steady-state values of the variables in (9) yields the standard relationship $\widehat{p}_t^* = \theta\hat{\pi}_t/(1-\theta)$. Combining this equation and (6) we obtain:

$$\Delta\hat{\pi}_t = \beta E_{t-\tau}\Delta\hat{\pi}_{t+1} + \frac{(1-\beta\theta)(1-\theta)}{\theta}AE_{t-\tau}\hat{s}_t. \tag{10}$$

Iterating forward on (10) yields:

$$\Delta\hat{\pi}_t = \frac{(1-\beta\theta)(1-\theta)}{\theta}AE_{t-\tau}\sum_{j=0}^{\infty}\beta^j\hat{s}_{t+j}. \tag{11}$$

Relation (11) makes clear a central prediction of the model: the change in $\hat{\pi}_t$ depends only on firms' expectations of current and future deviations of real marginal cost from its steady state value. The lower is A, i.e., the more sensitive is the elasticity of demand for intermediate goods to price changes, the less responsive is $\Delta\hat{\pi}_t$ to changes in expected values of $\hat{s}_{t+j}$. Similarly, the higher is θ, the smaller will be the response of $\Delta\hat{\pi}_t$ to expected changes in marginal cost. Therefore the version of the Calvo model that we consider in this subsection has two distinct mechanisms that can account for a small response of inflation to movements in marginal cost.

2.2. Firm-specific Capital

Standard variants of the Calvo model assume that firms rent capital and purchase labor services in perfectly competitive economy-wide markets. Woodford (2003) has proposed a variant of the Calvo model in which capital is firm-specific. In this specification, a firm's capital can only be augmented with a one-period delay using final goods, subject to adjustment costs. These assumptions imply that, unlike the case in which capital is not firm-specific, intermediate good firms do not view marginal costs as being beyond their ability to control. We show that this change allows the model to account for the time series behavior of inflation with less inertia in firms' pricing plans, i.e., lower values of θ.

The basic intuition for this claim can be described as follows. With firm-specific capital, a firm's marginal cost depends partly on economy-wide factors such as the real wage rate and the aggregate level of technology. However, because its stock of capital is predetermined, a firm's marginal cost is also an increasing function of its output. Consider a shock that raises the economy-wide component of marginal cost, such as a rise in the real wage rate. Other things equal, a firm that is re-optimizing its price will respond by planning to raise its price. However, this rise in price reduces output, which leads to a countervailing fall in marginal cost. Therefore, the firm will plan to raise its price by less than it would have were capital not predetermined. The presence of adjustment costs implies that the firm will only slowly adjust its stock of capital. Consequently, the dynamic effects stemming from adjustment costs reinforce the effects of predetermined capital on firms' pricing decisions.

To be concrete, we now briefly describe a version of Woodford's (2003) model in which final output is produced using the Kimball (1995) specification (see (1)). We refer the reader to the Appendix for details. The model is identical to the one described in the previous subsection except for the nature of capital. At time t, firm i's capital, K_{it}, is given. The firm can augment its capital by purchasing time t output of the final good sector. But it does so subject to convex capital adjustment costs. Specifically, increasing capital to K_{it+1} in period $t+1$ requires time t investment, I_{it}, satisfying:

$$I_{it} = Q\left(\frac{K_{it+1}}{K_{it}}\right) K_{it}. \tag{12}$$

The function $Q(\cdot)$ satisfies the following properties: $Q(1) = \delta$, $Q'(1) = 1$ and $Q''(1) = \psi$, where $0 < \delta < 1$ and $\psi \geq 0$. In non-stochastic steady state, investment is equal to δ times the steady-state capital stock. Therefore, we can interpret δ as the steady-state rate of capital depreciation. The parameter ψ controls the degree of adjustment costs. For simplicity, we assume that capital decisions are made subject to the same timing constraints as price decisions. Specifically, we assume I_{it} is chosen at time $t - \tau$. When $\tau = 1$, this assumption coincides with the corresponding assumption in Christiano, Eichenbaum and Evans (2005).

The average marginal cost across firms is $s_t = \int_0^1 s_{it} di$, where s_{it} is the relevant measure of marginal cost entering into firm i's pricing decisions. In the Appendix we show that the marginal cost for firm i satisfies:

$$\hat{s}_{it} = \hat{s}_t + \frac{\alpha}{1-\alpha}\left[\hat{Y}_{it} - \hat{Y}_t\right] - \frac{\alpha}{1-\alpha}\left[\hat{K}_{it} - \hat{K}_t\right].$$

Here, $\hat{s}_t$ is given by (7). Unlike the case in which capital is firm-specific, firm i's marginal cost is not beyond its control.[9] Instead, $\hat{s}_{it}$ is an increasing function of firm i's output relative to economy wide output and a decreasing function of firm i's capital stock relative to the economy-wide stock of capital.

With firm specific capital, the analog to (10) is:

$$\Delta\hat{\pi}_t = \beta E_{t-\tau}\Delta\hat{\pi}_{t+1} + \frac{(1-\beta\theta)(1-\theta)}{\theta} \cdot A \cdot D \cdot E_{t-\tau}\hat{s}_t, \tag{13}$$

where A is defined as in (8) and D is a function of the underlying parameters of the model (see the Appendix). For simplicity, we summarize this relationship as:

$$D = d(\beta, \alpha, \delta, \psi, \theta, \zeta, \epsilon). \tag{14}$$

For the parameter values that we consider, $D \leq 1$. So, for any given value of θ, firm-specific capital, like a non-constant elasticity of demand, reduces the response of $\hat{\pi}_t$ to movements in $\hat{s}_t$. So firm-specific capital gives rise to an additional mechanism that generates a small response of inflation to movements in $\hat{s}_t$.

In the Appendix we show that when adjustment costs approach infinity, that is, as ψ approaches infinity, then:

$$D \rightarrow \frac{1}{1+\bar{\eta}\alpha A/(1-\alpha)}.$$

Under Dixit-Stiglitz, $A = 1$ and $\bar{\eta} = \mu$, in which case D corresponds to the coefficient in the model considered by Sbordone (2002) and Galí, Gertler and López-Salido (2001). The key characteristic of that model is that each firm has a fixed stock of firm-specific capital.

3. Econometric Methodology

We now discuss our strategy for estimating and testing our variant of the Calvo model. Our strategy corresponds to the one pioneered by Hansen (1982) and Hansen and Singleton (1982) and applied to the Calvo model by Galí and Gertler (1999) and Galí, Gertler and López-Salido (2001). The idea is to exploit the fact that in *any* model incorporating Calvo pricing, certain restrictions must hold. We can analyze and test these restrictions without

[9] Without firm specific capital, $\hat{Y}_{it} = \hat{Y}_t$, and $\hat{K}_{it} = \hat{K}_t$, and $\hat{s}_{it} = \hat{s}_t$.

making assumptions about other aspects of the economy. The specific test that we use is based on Hansen's (1982) 'J statistic'.[10] An alternative to our strategy is to embed the Calvo pricing model within a fully articulated general equilibrium model. One could then estimate and test the model using maximum likelihood methods. Two interesting examples of this approach include Linde (2002) and Smets and Wouters (2003).

To derive the testable implications of the Calvo model, it is convenient to focus on the model with static indexation and define the random variable:

$$\xi_{t+1} = \Delta\hat{\pi}_t - \beta\Delta\hat{\pi}_{t+1} - \frac{(1-\beta\theta)(1-\theta)}{\theta} \cdot A \cdot D \cdot \hat{s}_t. \tag{15}$$

Since $\hat{\pi}_t$ is in agents' time $t-\tau$ information sets, (13) can be written as:

$$E_{t-\tau}\xi_{t+1}(\sigma) = 0,$$

where σ denotes the structural parameters of the model. It follows that:

$$E\xi_{t+1}(\sigma)X_{t-\tau} = 0 \tag{16}$$

for any k dimensional vector $X_{t-\tau}$ in agents' time $t-\tau$ information sets. We exploit (16) to estimate the true value of σ, σ_0, and test the over-identifying restrictions of the model using Hansen's (1982) Generalized Method of Moments procedure.[11]

Our estimate of σ is:

$$\hat{\sigma} = \arg\min_{\sigma} J_T(\sigma), \tag{17}$$

where

$$J_T(\sigma) = g_T(\sigma)' W_T g_T(\sigma) \tag{18}$$

and

$$g_T(\sigma) = (\frac{1}{T}) \sum_{t=1}^{T} \left[\xi_{t+1}(\sigma)X_{t-\tau}\right]. \tag{19}$$

[10] A possible shortcoming of tests based on the J statistic is that they may have low power against specific alternatives. Gali and Gertler (1999) argue that this is the case when the Calvo model is confronted with the possibility that some firms adopt backward-looking 'rule of thumb' rules for setting prices. In the Eichenbaum and Fisher (2004) we incorporate this type of firm into our analysis and test for their presence.

[11] We require that $\{\hat{\pi}_t, \hat{s}_t, X_t\}$ is a stationary and ergodic process.

Here, T denotes the size of our sample and W_T is a symmetric positive definite matrix that can depend on sample information. The choice of W_T that minimizes the asymptotic covariance matrix of $\hat{\sigma}$ is a consistent estimate of the spectral density matrix of $\{\xi_{t+1}(\sigma_0)X_{t-\tau}\}$ at frequency zero. Our theory implies that $\xi_{t+1}(\sigma)X_{t-\tau}$ has a moving average representation of order τ. So we choose W_T^{-1} to be a consistent estimate of

$$\sum_{k=-\tau}^{\tau} E[\xi_{t+1+k}(\sigma)X_{t+k-\tau}][\xi_{t+1+k}(\sigma)X_{t+k-\tau}]'. \tag{20}$$

The minimized value of the GMM criterion function, J_T, is asymptotically distributed as a chi-squared random variable with degrees of freedom equal to the difference between the number of unconditional moment restrictions imposed (k) and the number of parameters being estimated.[12] We impose the restriction that $\psi_{t+1}(\sigma)X_{t-\tau}$ has an MA(τ) representation when we construct our estimate of W_T^{-1}.[13]

Relations (15) and (17) - (19) imply that θ, A and D are not separately identified. We can only identify the reduced form parameter:

$$c = A \cdot D \cdot \frac{(1-\beta\theta)(1-\theta)}{\theta}. \tag{21}$$

However, given any estimate of $c, \hat{c}$, and assumed values for A and D, we can deduce the implied value of θ. When capital is not firm-specific, $D = 1$, and we can derive θ from the relation

$$A = \frac{\theta\hat{c}}{(1-\beta\theta)(1-\theta)}. \tag{22}$$

Here A is a function of ζ and ϵ. When capital is firm-specific, we can deduce θ using (14) and

$$A = \frac{\theta\hat{c}}{D(1-\beta\theta)(1-\theta)}. \tag{23}$$

The previous discussion implies that, given priors about a key subset of the model's structural parameters and the nature of capital markets, we can deduce the degree of inertia

[12] According to relation (11), $\hat{\pi}_t$ is predetermined at time $t-\tau$. If we were only interested in assessing the hypothesis that inflation is predetermined at time $t-\tau$, we could test whether any variable dated between time $t-\tau$ and t has explanatory power for time t inflation.

[13] We could allow for higher-order serial correlation in the error term than the theory implies. But as we show in the Eichenbaum and Fisher (2004), doing so reduces the power of our statistical tests.

in price optimization (θ) required to render the extended Calvo model consistent with the aggregate time series data.

4. Data

Our benchmark sample period is 1959:1 - 2001:4. Numerous observers have argued that there was an important change in the nature of monetary policy with the advent of the Volker disinflation in the early 1980s. It is also often argued that the Federal Reserve's operating procedures were different before 1980 and after 1982. Accordingly, we re-estimate the model over the two distinct subsamples used in Galí, López-Salido and Vallés (2003): 1959:1-1979:2 and 1982:3- 2001:4. We report results for two measures of inflation: the GDP deflator and the price deflator for personal consumption expenditures.[14] We measure $\hat{\pi}_t$ as the difference between actual time t inflation and the sample average of inflation.

In the case where capital is not firm-specific, real marginal cost is equal to the real product wage divided by the marginal product of labor. Production function (3) implies that real marginal cost is proportional to labor's share in national income, $W_t H_t/(P_t Y_t)$, where W_t is the nominal wage. In practice, we measure $W_t H_t$ as nominal labor compensation in the non-farm business sector. Our measure of $P_t Y_t$ is nominal output of the non-farm business sector. The variable $\hat{s}_t$ is measured as the difference between the log of the time t value of our measure of labor's share in national income and its sample average. This is a standard measure of $\hat{s}_t$ which has been used by Galí and Gertler (1999), Galí et. al. (2001), and Sbordone (2002). We demonstrate in the Appendix that this is the correct measure of $\hat{s}_t$ even when capital is firm-specific.

Rotemberg and Woodford (1999) discuss possible corrections to this measure that are appropriate for different assumptions about technology. These corrections include those that take into account a non-constant elasticity of factor substitution between capital and labor and the presence of overhead costs and labor adjustment costs. We redid our analysis for these alternative measures of marginal costs and found that they do not affect the qualitative nature of our results.[15]

[14] All data sources are listed in the Appendix. We also considered the price deflator for the non-farm business sector and the consumer price index (CPI) and found that our key results are insensitive to the use of these alternative measures.

[15] See also Gagnon and Khan (2004) who study versions of the Calvo model under different assumptions about marginal cost.

Consider next the instrument vector $X_{t-\tau}$. Let Z_t denote the four-dimensional vector consisting of the time t value of real marginal cost, quadratically detrended real GDP, inflation, and the growth rate of nominal wages in the non-farm business sector. Our benchmark specification of $X_{t-\tau}$ is given by[16]

$$X_{t-\tau} = \{1, Z_{t-\tau,}\xi_{t-\tau}\}'. \tag{24}$$

We include lagged values of ξ_t, defined in (15), because we found that doing so increased the power of our statistical tests (see below). We also redo our analysis using an alternative specification of $X_{t-\tau}$ given by

$$X_{t-\tau} = \{1, \mu_{t-\tau}, \mu_{t-\tau-1}, \mu_{t-\tau-2}\}'. \tag{25}$$

Here $\mu_{t-\tau}$ is the time $t-\tau$ shock to monetary policy as identified in Altig, Christiano, Eichenbaum, and Linde (2005).[17]

5. Empirical Results

To facilitate comparisons with the literature, we report point estimates of θ corresponding to the identifying assumption that capital is not firm specific and $G(\cdot)$ in (1) is of the Dixit-Stiglitz form. Eichenbaum and Fisher (2004) display results for the version of the model in which there are no delays in implementing new optimal price decisions ($\tau = 0$). They show that the overidentifying restrictions of this version of the model are strongly rejected. This

[16] Gali and Gertler (1999) use an instrument list consisting of a constant and lagged values of Z_t, where the latter is augmented to include an index of commodity prices and the spread between the annual interest rate on the ten year Treasury Bond and three month bill. We redo our basic analysis, setting X_t to $\{1, Z_{t-j}, j = 0,1,2,3\}'$ and $\{1, Z_{t-j}, j = 1,2,3,4\}$. Gali et..al. (2001) adopt the same specification as we do but set $X_t = \{1, Z_{t-j}, j = 1,2,3,4\}$. It turns out that the point estimates are similar across different specifications of X_t, including the one used in this paper. However, using a larger set of instruments leads to misleading inference about the plausibility of the overidentifying restrictions implied by the model. Specifically, often we cannot reject the model with a larger set of instruments on the basis of the J_T statistic, but we can do so with the smaller set of instruments.

[17] This measure of the monetary policy shock is identified as the residual in the regression of the federal funds rate on four lags of itself, current and four lagged values of the log of the price of investment goods, the log of labor productivity, the change in the log of the GDP deflator, the log of capacity utilization, the log of per capita hours worked, the log of the ratio of consumption to GDP, the log of the ratio of investment to GDP, and four lags of the log of velocity, defined as the GDP deflator plus the log of GDP minus the log of the monetary aggregate, MZM.

result holds both when we test and estimate the model over the whole sample period and when we allow for a sample break in 1979.

We now report the results of estimating our model when $\tau = 1$. This value of τ implies that ξ_{t+1} has an MA(1) representation (see 20). We impose this restriction on our estimator of W_T because it improves the power of our statistical tests (see Eichenbaum and Fisher (2004)). Panel A of Table 1 reports our results with the benchmark instruments, (24). We note two key results. First, regardless of which sample period we consider or which measure of inflation we use, there is virtually no statistical evidence against the model. Second, θ is estimated with reasonable precision with the point estimates ranging from a low of 0.83 to a high of 0.89. This corresponds to firms re-optimizing prices on average every six to nine quarters, an interval of time which seems implausible high.

Panel B reports our results when we use monetary policy shocks as instruments, (25). Again there is very little statistical evidence against the model. The point estimates of θ are somewhat lower than those that we obtain using the benchmark instruments. However taking sampling uncertainty into account, we conclude that our estimates are robust to either of the two instrument lists that we use. Christiano, Eichenbaum and Evans (2005) report a point estimate of θ equal to 0.60, with a standard error of 0.08. Their estimation strategy is different than the one we use here. Specifically, they choose model parameters to minimize the distance between model and VAR based dynamic responses to a monetary policy shock. Our estimation strategy involves matching different moments of the data. In addition, our benchmark instrument list does not take a stand on which shocks are driving the data.

6. Interpreting Our Estimated Model

In Section 5 we argued that there is little statistical evidence against the Calvo model with dynamic indexation and a one-period implementation lag. However, the estimated degree of inertia in price re-optimization implied by the model is implausibly large. Taken at face value, these findings indicate that the Calvo model can be rescued statistically, but not in any interesting economic sense. However, this conclusion follows only under the maintained assumptions that firms face a constant elasticity of demand ($A = 1$) and that capital is not firm-specific ($D = 1$). In this section we explore the sensitivity of inference about θ to these assumptions. Specifically, we analyze the quantitative trade-off between θ, the nature of capital markets, and the variability of the elasticity of demand for intermediate goods, ϵ.

Recall that the relation between the reduced form parameter c and the underlying parameters of the model is given by expressions (14) and (21) - (23). Suppose we have an estimate of c and values for $(\beta, \alpha, \delta, \zeta)$. In the case where capital is not firm-specific, these equations reduce to one equation in two unknowns, θ and ϵ. When capital is firm-specific, we have two equations in three unknowns θ, ψ and ϵ. In general, different values of ψ and ϵ imply different values of θ that are consistent with a given estimate of c.

To explore the nature of these trade-offs, we proceed as follows. We set the share of capital in the production function, α, to 1/3, the quarterly depreciation rate of capital, δ, to 0.025, the markup, ζ, equal to 10% and the quarterly discount rate, β, to 0.99. We consider three values for ϵ: 0, 10 and 33. The latter two values of ϵ encompass the calibration used by Dotsey and King (2005). Table 2 summarizes the implications of the different values of ϵ for how much a flexible price firm changes price in response to a change in marginal cost, holding all economy-wide variables constant. We report this statistic for two values of the adjustment cost parameter, ψ (two and three). For convenience we concentrate on the benchmark case of $\psi = 3$. A value of ϵ equal to zero corresponds to the Dixit - Stiglitz case. In this cases it is optimal for a firm to raise its price by 100 percent of an increase in marginal cost. The case of $\epsilon = 10$ is consistent with the symmetric translog specification of Bergin and Feenstra (2000). Here it is optimal for a firm to raise its price by 50 percent of an increase in marginal cost. The case of ϵ equal to 33 is the benchmark value considered in Kimball (1995). Here it is optimal for a firm to raise its price by 23 percent of an increase in marginal cost.

When firm capital is not firm-specific, $D = 1$ and the parameter ψ does not appear in the model. For the firm-specific capital case, we consider three values of ψ. First, we assume that $\psi = 0$. This assumption allows us to disentangle the impact of pre-determined firm-specific capital per se from the effect of capital adjustment costs. The other two values are ψ equal to two and three. The latter value is emphasized in Woodford (2003).

The parameter ψ is related to the elasticity of the investment-to-capital ratio with respect to Tobin's q, evaluated in steady state. As shown in the Appendix, for our model this elasticity is equal to $1/(\delta\psi)$. With $\delta = 0.025$ and $\psi = 3$, this elasticity is equal to 13.3.[18] Gilchrist and Himmelberg (1995) estimate the dependence of (I/K) on q using firm level data from the manufacturing sector over the period 1985 to 1989. Based on all the firms in

[18]If we set ψ equal to 2, then this this elasticity is equal to 20. See Table 2.

their sample, they estimate that $\partial(I/K)/\partial q = 0.183$. Using the mean values of q and I/K reported in their Appendix, this finding implies that the elasticity of I/K with respect to q is equal to 12.1. This elasticity is close to the value of 13.3 implied by our model when $\psi = 3$. In practice calibrating ψ to imply an elasticity of 12.1 has virtually no effect on our results.

An elasticity of 13.3 is somewhat high relative to those reported in the literature based on aggregate data (see Christiano and Fisher 1998). From this perspective, a value of ψ equal to three is a conservative choice, since we would have to assume a larger value to obtain elasticities closer to those reported in Christiano and Fisher (1998) and a higher value of ψ magnifies the quantitative effects associated with firm-specific capital.

Finally, in results not reported here, we also consider the case of ψ equal to infinity. In this case, the elasticity of the investment-to-capital ratio with respect to Tobin's q is equal to zero. This case corresponds to Sbordone's (2002) assumption that capital is firm-specific and cannot be augmented over time. As it turns out, raising ψ from three to infinity has very little impact on our findings.

A different way to assess the magnitude of ψ is to calculate how long it would take a firm to close the gap between its actual capital stock and its steady state capital stock. To this end we consider an individual firm whose initial capital stock is 1% higher than its steady state capital stock. We calculate how long it takes the firm to close fifty percent of the gap between its actual and steady state capital stock under the assumption that all aggregate variables remain at their steady state values. We refer to this statistic as the half-life of the gap between actual and steady state capital. We consider both the flexible price case and the case in which the firm is subject to Calvo style price setting frictions.[19] In the flexible price case firms still have monopoly power but they can adjust prices in every period and there is no uncertainty. In this case we report the actual half-life. In the sticky price case we assume that the firm can reoptimize its price in the initial period. In future periods it has a constant probability, $1-\theta$, of being able to reoptimize its price. In this case we report the expected half-life of the gap between actual and steady state capital

Table 2 reports our results for two different values of ψ (two and three), $\delta = 0.025$ and different values of ϵ. For the sticky price case we set $\theta = 0.72$. We now discuss our main findings. First, the half-life for the flexible price case ranges from 3.7 quarters, when $\epsilon = 0$,

[19] See the Appendix for the details of how we calculate these half-lives.

to 2.1 quarters, when ϵ is 33. To understand the dependency of the half-life on ϵ, suppose that the firm's initial capital stock exceeds its steady state capital stock. This assumption implies that the firm's marginal cost is lower than its steady state value. So the firm will set its price lower than its steady state value. The flexible price version of equation (6) and (8) implies that the larger is ϵ (the smaller is A), the less the firm will lower its price. Consequently the firm will sell less than the analog firm with a smaller ϵ. This consideration implies that the firm with the larger ϵ desires a smaller capital stock and converges more quickly to its steady state capital stock than the analog firm with a smaller ϵ. Second, the full sample results in Gilchrist and Himmelberg's (1995) imply that for a purely competitive flexible price firm, the half-life of the gap between actual and steady state capital is roughly 2 years, which lies at the lower end of the flexible price case half-lives reported in Table 2.

Third, the expected half-life for the sticky price case ranges from four quarters when $\epsilon = 0$, to 2.3 quarters, when ϵ is 33. These half-lives are somewhat higher than the analog half-lives for the flexible price case. The intuition for this result can be described as follows. In our experiment the firm can reoptimize its price when confronted with its initial high capital stock. Other things equal, the firm would like to lower its price and converge to its old capital stock from above. With Calvo pricing frictions, the firm faces uncertainty about when it can next change its price. This effect causes a forward looking firm to lower its initial price by less than a flexible price firm would because it does not want to be saddled with a low price for a long time. This consideration alone suggests the sticky price firm will converge to steady state more quickly than a flexible price firm. However, the fact that the firm only changes prices with probably of $(1 - \theta)$ dominates the expected half-life calculation. The net result is that the expected half-life of the gap between actual and steady state capital for the sticky price firm is somewhat lower than the analog half-life for a flexible price firm. Finally, Table 2 reports the expected half-lives for the case of $\psi = 2$. Not surprisingly, a smaller value for ψ lowers the half-lives.

The previous discussion indicates that our assumed value of ψ generates implications in line with existing results in the literature. Table 3 reports results based on estimates of c implied by Panel A of Table 1 (the benchmark instruments). The values in square brackets represent 95% confidence intervals.[20] Since our findings are similar for the two inflation

[20] These intervals were calculated as follows. Using the information from Table 1, we construct a 95% confidence interval for c. Then, for the different specifications of our model, we compute the values of θ that correspond to the lower and upper values of the confidence intervals for c. Using these values of θ, we

measures, we focus on the GDP deflator case. Three key results emerge from Table 3. First, as anticipated, θ is a declining function of ϵ. For example, when capital is not firm-specific, the point estimate of θ falls from 0.88 to 0.76 as ϵ rises from the benchmark value of 0 to 33. This fall corresponds to a decline in the average frequency at which firms reoptimize prices from roughly two years to one year. Second, for any given value of ϵ, θ decreases if we assume that capital is firm-specific. For $\psi = 3$, our point estimate of θ is less than 0.75 (a re-optimization rate of at least one year) regardless of which value of ϵ we work with. By comparing the case of $\psi = 0$ and $\psi = 3$, we see that the fall in θ is partly attributable to the effect of predetermined capital per se and partly to the effect of capital adjustment costs. As mentioned above, assuming larger adjustment costs than ψ has very little impact on inference regarding θ. Third, conditional on the presence of firm-specific capital, there is only marginal evidence against the null hypothesis that firms reoptimize prices every half-year.[21]

Table 4 reports the analog statistics calculated for values of c estimated allowing for a break in the sample period. The qualitative results from Table 3 are very robust to this change: allowing for a non-constant elasticity of demand or firm-specific capital leads to lower values of θ. Perhaps more importantly, the reported values of θ are lower than those reported in either Table 1 or Table 3. It is useful to focus on the case in which capital is firm-specific. With $\psi = 3$, our point estimate of θ is substantially lower than 0.75, varying from a low of 0.56 to a high of 0.67, depending on the value of ϵ we assume. Therefore the average amount of time between price re-optimization ranges from 2.3 to roughly three quarters. In no case can we reject the hypothesis that firms reoptimize prices on average every two quarters.

We conclude by briefly discussing the relationship of our results to recent findings in the literature regarding the degree of price stickiness based on microeconomic data. Blinder, Canetti, Lebow, and Rudd (1998) survey actual price setters to assess the plausibility of alternative theories of price stickiness. From our perspective, their key finding is that among firms reporting regular price reviews, annual reviews are by far the most common. This finding is consistent with our results regarding the average time between price re-optimization (see Table 3). Indeed our point estimates of this statistic with the firm specific capital model are all smaller than one year.

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computed the corresponding lower and upper values of $1/(1-\theta)$.

[21] The confidence intervals for the statistic $1/(1-\theta)$ are asymmetric. Because of the nonlinear nature of this function, the right hand tails of the reported confidence intervals are very large.

Much of the recent empirical literature that uses micro data to look at price stickiness emphasizes the frequency at which prices change. For example, Blinder et. al. (1998) also report that the median time between price changes among the firms that they survey is roughly three quarters. Golosov and Lucas (2003) and Klenow and Krystov (2003) report that roughly 21.9% and 24.8%, respectively, of prices of items in the CPI basket remain unchanged each month.[22]

Comparing our variants of the Calvo model with these findings is delicate. At one level, the models in this paper imply that prices change *too* frequently relative to the micro data. This is because with price indexation, all prices are changing all the time. An even more subtle difficulty is that just because firms are changing prices does not mean that they have reoptimized those prices: a subset of the price changes being recorded could reflect various forms of time-dependent price updating rules. So, in principle, our model could be consistent with findings that prices change all the time.

Despite these difficulties, we think that it is still useful to compare the average frequency with which firms reoptimize prices in the estimated version of our model with the findings in Golosov and Lucas (2003) and Klenow and Krystov (2003). The idea is not to match their exact numbers since the conceptual experiments are different. Instead the comparison is meant as a rough additional check on the plausibility of our parameter estimates. Golosov and Lucas' estimates imply that firms change prices once every 1.9 quarters, while Klenow and Krystov's estimates imply that firms change prices roughly every $1.7 - 1.8$ quarters. Table 8 indicates that, based on the GDP deflator, in the version of the model with firm specific capital and $\psi = 3$, we can never reject the hypothesis that firms reoptimize prices, on average, every 1.8 quarters. With the PCE deflator, we can never reject the hypothesis that firms reoptimize prices, on average, every 1.9 quarters. In this limited sense, the degree of inertia in price setting implied by our model seems plausible in light of the findings in Golosov and Lucas and Klenow and Krystov.

Integrating over all the previous evidence, including Blinder et. al.'s (1998) evidence on how frequently firms review price plans, we infer that the version of our model with firm-specific capital and a non-constant elasticity of demand can be reconciled with the

[22] Golosov and Lucas (2003) look at disaagregated CPI data from the greater New York area. Klenow and Krystov (2003) use disaggregated CPI data from New York, Chicago, and Los Angeles. Klenow and Krystov also report that roughly 90% of the variance in monthly inflation stems solely from fluctuations in the average size of price changes. This last finding is inconsistent with a large class of state dependent pricing models.

macro data without requiring implausible degrees of rigidities in price setting behavior at the micro level. Of course we are not claiming that our variant of the Calvo model is literally 'true'. There are some obvious aspects of the model that are counterfactual, such as the implication that some firms never reoptimize prices. Nevertheless, the degree of inertia in price re-optimization implied by the estimated version of our model does not seem implausible relative to existing findings in the literature.

7. Conclusion

This paper assesses the empirical performance of Calvo-style models of sticky goods prices. We argue that Calvo-style models with a one-quarter delay in the implementation of new prices and dynamic indexation are consistent with the aggregate data in a statistical sense. A separate question is whether estimated versions of the model imply plausible inertia in price setting behavior by firms. On the face of it, the answer to this question is no: our benchmark model implies that firms reoptimize prices roughly once every seven quarters.

However, this conclusion is not warranted once we abandon two special auxiliary assumptions associated with standard expositions of the Calvo model: (i) monopolistically competitive firms face a constant elasticity of demand and (ii) capital is homogeneous and can be instantaneously reallocated after a shock. Once we abandon these assumptions, the estimated model implies a degree of inertia in price re-optimization that is much more plausible. Specifically, it is consistent with the hypothesis that firms reoptimize prices at least once every two quarters. This result holds even though the model is observationally equivalent to the original model in terms of its implications for the time series data on inflation.

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8. Appendix

This appendix describes our data sources, how to interpret the parameter A, the model with firm-specific capital and a varying elasticity of demand for intermediate goods, how to assess the magnitude of the adjustment cost parameter, ψ, and how to compute half-lives of capital adjustment.

8.1. Data

Our data are from the Haver Analytics database. For each data series below, we provide a brief description and, in parenthesis, the Haver codes for the series used.

- Price measures: GDP deflator is the ratio of nominal GDP (GDP) and real chain-weighted GDP (GDPH); personal consumption expenditures deflator (JCBM2).
- Real marginal cost: Share of labor income in nominal output for the non-farm business sector, which is proportional to the Bureau of Labor Statistics measure of nominal unit labor costs divided by the non-farm business deflator (LXNFU/LXNFI).
- Instruments: Quadratically detrended real GDP is the residual of a linear regression of real GDP (GDPH) on a constant, t and t^2; inflation is the first difference of the log of the price measures; growth rate of nominal wages is the first difference of the log of nominal compensation in the non-farm business sector (LXNFC).

8.2. Interpreting A

Recall that the elasticity of demand for a given intermediate good is:

$$\eta(x) = -\frac{G'(x)}{xG''(x)} \tag{26}$$

where

$$x = \frac{Y^*}{Y}. \tag{27}$$

The coefficient A can be written:

$$A = \frac{1 - 1/\bar{\eta}}{2 + G'''(1)/G''(1)} \tag{28}$$

where $\bar{\eta} = -G'(1)/G''(1)$ is the steady state elasticity of demand. In steady state an intermediate good firm sets price as a markup over marginal cost, where the markup, ζ, is $\bar{\eta}/(\bar{\eta} - 1) - 1$.

Many authors have considered the value of:

$$\epsilon = \frac{P^*}{\eta(x)} \frac{\partial \eta(x)}{\partial P^*} \bigg|_{x=1}.$$

This is the percent change in the elasticity of demand due to a one percent change in the own price at the steady state. The value of ϵ can be derived in terms of A and $\bar{\eta}$ (or ζ) using (2), (26), (27), and (28)

$$\epsilon = \left[\frac{P^*}{\eta(x)} \frac{\partial \eta(x)}{\partial x} \frac{\partial x}{\partial \tilde{Y}} \frac{\partial \tilde{Y}}{\partial P^*} \right]_{x=1} = 1 + \bar{\eta} \left[\frac{1 - 1/\bar{\eta}}{A} - 1 \right] = 1 + \frac{1+\zeta}{\zeta} \left[\frac{1}{(1+\zeta)A} - 1 \right].$$

Under Dixit-Stiglitz, if $A = 1$ then $\epsilon = 0$. This is to be expected: under Dixit-Stiglitz, the markup is constant. Solving for A using the last equality in the above expression, we find:

$$A = \frac{1}{\zeta \epsilon + 1}.$$

8.3. Solving the model with Kimball aggretation and firm-specific capital

In this section we describe the solution to the model with firm-specific capital and the Kimball specification of the final good technology. Our derivation follows Christiano (2004) and Woodford (2004), who consider firm- specific capital with the Dixit-Stiglitz specification. The model is identical to the one described in section 2.1 except that, in addition to the usual Calvo price-setting, at each date $t - \tau$ all intermediate good firms choose date $t + 1$ capital subject to adjustment costs.[23] Labor continues to be hired in economy-wide competitive labor markets. Firms take all aggregate variables as given, including the return on risk-free one-period real bonds, R_t. Below we focus on the static indexation case. The derivation under dynamic indexation is similar.

The objective of a randomly chosen intermediate firm i at date $t - \tau$, before it knows whether it can reoptimize its price, is to maximize the expected present value of profit:

$$E_{t-\tau} \sum_{j=0}^{\infty} \Lambda_{t+j} \left[P_{i,t+j} Y_{i,t+j} - W_{t+j} Y_{i,t+j}^{1/(1-\alpha)} A_{t+j}^{-1/(1-\alpha)} K_{i,t+j}^{-\alpha/(1-\alpha)} - P_{t+j} I_{i,t+j} \right] \tag{29}$$

subject to (2) and (12). Here $\Lambda_{t+j} = \prod_{l=0}^{\infty} \pi_{t+j+1}/R_{t+j}$ and I_{t+j} is the investment of the i'th intermediate firm. In (29), we have substituted out for labor using the production function. Also, we have assumed, without loss of generality, that the price of investment goods is the same as that for consumption.

Marginal cost at firm i is given by:

$$s_{it} = \frac{W_t}{P_t} \frac{1}{(1-\alpha) Z_t K_{it}^{\alpha} H_{it}^{-\alpha}}.$$

Linearizing average marginal cost, $s_t = \int_0^1 s_{it} di$, we find:

$$\hat{s}_t = \int_0^1 \hat{s}_{i,t} di$$

[23] In practice we only require that it be made *at least* τ periods before date t. Assuming otherwise complicates the analysis in a manner described below.

$$= \hat{W}_{t+j} - \hat{P}_{t+j} - \frac{1}{1-\alpha}\hat{A}_{t+j} + \frac{\alpha}{1-\alpha}\hat{Y}_{t+j} - \frac{\alpha}{1-\alpha}\hat{K}_t.$$

It follows that:

$$\hat{s}_{it} = \hat{s}_t + \frac{\alpha}{1-\alpha}\left[\hat{Y}_{it} - \hat{Y}_t\right] - \frac{\alpha}{1-\alpha}\left[\hat{K}_{it} - \hat{K}_t\right].$$

Linearizing the first order condition associated with the price choice (in the event that it can reoptimize its price) and substituting for the real marginal cost of firm i, $\hat{s}_{it}$:

$$\hat{E}^i_{t-\tau}\sum_{j=0}^{\infty}(\beta\theta)^j\left[(1+\xi A\bar{\eta})\,\hat{p}_{it+j} - A\hat{s}_{t+j} + \xi A\hat{k}_{it+j}\right] = 0 \tag{30}$$

where A is defined in (8), $\hat{k}_{it} \equiv \left[\hat{K}_{it} - \hat{K}_t\right]$, $\xi \equiv \alpha/(1-\alpha)$, $p_{it+j} \equiv P_{it+j}/P_{t+j}$, and $\widehat{x}$ denotes percent deviation of x from its steady state value. Also, $\hat{E}^i_{t-\tau}X_{it+k}$ denotes the expectation of the random variable X_{it+k}, conditional on date $t-\tau$ information and on the event that the i'th firm optimizes its price in period t, but not in any period after that, up to and including $t+k$.

Linearizing the first order condition for the choice of $t+1$ capital (regardless of whether the firm can reoptimize its price or not):

$$E_{t-\tau}\left[Q(L)\hat{k}_{it+2}\right] = \Xi E_{t-\tau}\hat{p}_{it+1}, \tag{31}$$

where

$$\begin{aligned} Q(L) &= \beta - \phi L + L^2, \\ \phi &= 1 + \beta + (1-\beta(1-\delta))\frac{1}{1-\alpha}\frac{1}{\psi}, \\ \Xi &= (1-\beta(1-\delta))\,\bar{\eta}\frac{1}{1-\alpha}\frac{1}{\psi}. \end{aligned}$$

Here L is the lag operator. Also, $E_{t-\tau}$ denotes the expectation operator, conditional on date $t-\tau$ information, where the expectation integrates over all possible continuation histories associated with the date $t-\tau$ information, including histories in which firm i reoptimizes its price. A comparable expression is derived in Woodford (2003, p. 689).

Linearizing the zero profit condition for final good producers yields:

$$\hat{\pi}_t = \frac{1-\theta}{\theta}\hat{p}^*_t. \tag{32}$$

Here, $\hat{p}^*_t$ is the percent deviation from steady state of the average optimized relative price set in period t.

Following Christiano (2004) and Woodford (2004), we solve (30) and (31) using the method of undetermined coefficients and combine this solution with (32) to derive the reduced form inflation equation. We posit that the price chosen by price-optimizing firms is:

$$\hat{p}^*_{it} = \hat{p}^*_t - \nu\hat{k}_{it}, \tag{33}$$

where ν is a number to be determined and $\hat{p}_t^*$ is a function of aggregate variables only, which is also to be determined. Note that, according to our assumptions, the variables on the right hand side of (33) are known when the price decision is made at $t-\tau$. The capital decision of a firm is assumed to satisfy:

$$\hat{k}_{it+1} = \kappa_1 \hat{k}_{it} + \kappa_2 E_{t-\tau} \hat{p}_{it}, \tag{34}$$

where κ_1 and κ_2 are to be determined. Here, the variable $\hat{p}_{it}$ denotes the i'th firm's price, whether optimized or not. If the firm is not reoptimizing at date $t-\tau$, then $\hat{p}_{it}$ is not in the information set used to choose $\hat{k}_{it+1}$. This is why we have $E_{t-\tau}$ in (34).

The requirement that (33) and (34) must be satisfied for all possible realizations of $\hat{p}_t^*$, $\hat{k}_{it}$, and $E_{t-\tau}\hat{p}_{it}$ implies the unknown coefficients, κ_1, κ_2, and ν must satisfy the following three equations, subject to $|\kappa_1| < 1$:

$$\begin{aligned}
1 - \left[\phi + (1-\theta)\,\nu\,(\beta\kappa_2 - \Xi)\right]\kappa_1 + \beta\kappa_1^2 &= 0 \\
\Xi\theta + \left[\phi - \beta\,(\theta+\kappa_1) - (1-\theta)\,\Xi\nu\right]\kappa_2 + \beta\,(1-\theta)\,\nu\kappa_2^2 &= 0 \\
\frac{\xi A\,(1-\beta\theta)}{(1+\bar{\eta}\xi A)\,(1-\beta\theta\kappa_1) + \xi A\beta\theta\kappa_2} - \nu &= 0.
\end{aligned}$$

Christiano (2004) incorporates industry-specific labor in this model. Except for this difference, these three equations are equivalent to analogous equations he derives under the assumption of a constant elasticity of demand, $A = 1$.

Following Christiano (2004), we can derive an expression for $\hat{p}_t^*$ using the linearized first order conditions as well as (33) and (34):

$$\hat{p}_t^* = \sum_{j=1}^{\infty} (\beta\theta)^j E_{t-\tau}\hat{\pi}_{t+j} + \frac{(1-\beta\theta\kappa_1)\,(1-\beta\theta)}{(1+\bar{\eta}\xi A)\,(1-\beta\theta\kappa_1) + \xi A\beta\theta\kappa_2} \sum_{j=0}^{\infty} (\beta\theta)^j\, E_{t-\tau}\hat{s}_{t+j}.$$

By substituting this expression into (32), we obtain the following equation relating inflation to average marginal cost:

$$\hat{\pi}_t = \beta E_{t-\tau}\hat{\pi}_{t+1} + \frac{1-\theta}{\theta}\,(1-\beta\theta)\,A \cdot D E_{t-\tau}\hat{s}_t$$

where

$$D = \frac{(1-\beta\theta\kappa_1)}{(1+\bar{\eta}\xi A)\,(1-\beta\theta\kappa_1) + \xi A\beta\theta\kappa_2}.$$

When adjustment costs go to infinity, that is as $\psi \to \infty$, then $\kappa_1 \to 1$ and $\kappa_2 \to 0$. In this case it is easy to see that:

$$D \to \frac{1}{1+\bar{\eta}\xi A}.$$

Under Dixit-Stiglitz, $A = 1$ and $\bar{\eta} = \mu$, in which case D corresponds to the coefficient derived by Sbordone (2002) for her model of constant capital.

When there are no adjustment costs ($\psi = 0$) it is easy to verify that

$$\kappa_1 = 0, \quad \kappa_2 = -\tilde{\Xi}/\tilde{\phi}, \quad \nu = \xi A\,(1-\beta\theta)\,/\left[(1+\bar{\eta}\xi A) + \xi A\beta\theta\kappa_2\right]$$

where $\tilde{\Xi} = (1 - \beta(1-\delta))\,\bar{\eta}/(1-\alpha)$ and $\tilde{\phi} = 1 + \beta + (1 - \beta(1-\delta))/(1-\alpha)$. In this case:

$$D = \frac{1}{(1 + \bar{\eta}\xi A) - \xi A \beta \theta \tilde{\Xi}/\tilde{\phi}}.$$

8.4. Interpreting the Adjustment Cost Parameter, ψ

In the model without capital rental markets, what is an empirically plausible value for the capital adjustment cost parameter, ψ? Typically, the magnitude of capital adjustment costs is assessed by considering its implications for the elasticity of the investment-capital ratio with respect to Tobin's q. To do this in our model, we assume the existence of a competitive stock market in which claims on the profits of intermediate good firms are traded. Under our assumptions, in general, intermediate good firms will be valued differently.

Tobin's q for firm i is defined as:

$$q_{it} = \frac{P_{K_i' t}}{P_{It}}$$

where $P_{K_i' t}$ denotes the marginal value of capital at firm i installed at the beginning of time $t+1$ and P_{It} is the price of investment goods, which is unity, since investment and consumption goods are both derived from the composite final good. Profit maximization implies the value of a marginal unit of installed capital is equal to its cost. That is:

$$P_{K' t} = \frac{P_{I,t}}{MPI_t} = \frac{1}{MPI_t}$$

where $MPI_t = dK_{it+1}/dI_t$ is the marginal product of investment in producing installed date $t = 1$ capital. The marginal product of investment can be derived by differentiating equation (12). Under the assumption that $K_{i,t}$ is predetermined at date t this yields $dK_{it+1}/d\left(I_{it}/K_{it}\right) = K_{it}/Q'\left(K_{it+1}/K_{it}\right)$. It follows that:

$$q_{it} = \frac{Q'\left(\frac{K_{it+1}}{K_{it}}\right)}{K_{it}}. \tag{35}$$

The desired elasticity may be derived by differentiation of (35) and (12). Differentiating (35) yields $dK_{it+1}/dq_{it} = K_{it}/Q''\left(K_{it+1}/K_{it}\right)$ and (12) implies $d\left(I_{it}/K_{it}\right)/dK_{it+1} = Q'\left(K_{it+1}/K_{it}\right)/K_{it}$. Therefore, the elasticity of I_{it}/K_{it} with respect to q_{it} is:

$$\frac{q_{it}}{I_{it}/K_{it}} \frac{d(I_{it}/K_{it})}{dq_{it}} = \frac{q_{it}}{I_{it}/K_{it}} \frac{\partial I_{it}/K_{it}}{\partial K_{it+1}} \cdot \frac{\partial K_{it+1}}{\partial q_{it}} = \frac{q_{it}}{I_{it}/K_{it}} \frac{Q'\left(\frac{K_{it+1}}{K_{it}}\right)}{Q''\left(\frac{K_{it+1}}{K_{it}}\right)}.$$

Evaluating the expression on the right hand side of the second equality above in steady state:

$$\frac{q}{I/K} \frac{d(I/K)}{\partial q} = \frac{1}{\delta \psi}, \tag{36}$$

where we have dropped subscripts to denote steady state values of variables. Equation (36) follows since $Q'(1) = 1$, $Q''(1) = \psi$, $q = 1$, and $I/K = \delta$.

8.5. Calculating Capital Adjustment Half-lives

Consider the half-life of capital adjustment with perfect competition, predetermined capital, and capital adjustment costs. The linear approximation around steady state of the optimal accumulation equation for the respresentative firm is:

$$\begin{aligned} \hat{k}_{n+1} &= \rho \hat{k}_t \\ &= \rho^n \hat{k}_0 \end{aligned}$$

where

$$\begin{aligned} \rho &= -2\left[b + \mathrm{sqrt}(b^2 - 4\beta)\right]/\beta \\ b &= -\phi - \Xi \frac{\alpha}{1-\alpha} \times \frac{1}{1/A + \alpha(1+\zeta)/(1-\alpha)}. \end{aligned}$$

The half-life capital stock is $\hat{k}_0/2$. Therefore the half-life in quarters, n^*, is:

$$n^* = -4\ln(2)/\ln(\rho).$$

The specification at the end of the detalied description of the model solution above has Calvo price-setting with capital predetermined, but no other capital adjustment costs. Equations (34) and (33) can be simulated to show the expected half-life in this case is always less than a quarter.

In the Calvo-style model with the Kimball (1995) aggregator and firm-specific capital, the half-life of capital adjustment can be simulated as follows. Let $\hat{k}_0 = 0.01$ and evaluate (33) with $\hat{p}^*_n = 0$, $\forall\ n \geq 0$. The latter equality holds since we are considering one firm out of a continuum, so that the effect of the deviation on the average optimal price is always zero. Simulate capital going forward, using (34) and, update the firm's expected price by averaging across outcomes next period using (33):

$$\hat{p}_{in} = \theta \hat{p}_{in-1} - (1-\theta)\nu \hat{k}_{in-1}.$$

Then, n^* is defined as the first n such that $\hat{k}_{n+1} \leq \hat{k}_0/2$.

Table 1: Estimates of the Sticky Price Model

Inflation Measure	Full Sample θ	Full Sample J_T	1959:1-1979:2 θ	1959:1-1979:2 J_T	1982:3-2001:4 θ	1982:3-2001:4 J_T
			Benchmark Instruments			
GDP Deflator	0.88	2.65	0.86	0.89	0.83	6.33
	(0.05)	[0.62]	(0.09)	[0.93]	(0.05)	[0.18]
PCE Deflator	0.86	4.98	0.84	2.05	0.83	5.61
	(0.05)	[0.29]	(0.08)	[0.73]	(0.06)	[0.23]
			Monetary Policy Shocks as Instruments			
GDP Deflator	0.79	1.88	0.77	1.46	0.80	3.66
	(0.07)	[0.60]	(0.12)	[0.69]	(0.08)	[0.30]
PCE Deflator	0.76	3.64	0.77	1.80	0.78	0.55
	(0.04)	[0.30]	(0.07)	[0.61]	(0.11)	[0.91]

Notes: This table considers the case where firms that do not reoptimize their price plans use the updating scheme: $P_{it} = \pi_{t-1} P_{it-1}$. The J_T statistics are distributed as χ^2 random variables with 3 degrees of freedom. Standard errors in parentheses. P-values in brackets.

Table 2: Interpreting Adjustment Costs and the Kimball (1995) Parameter

Adjustment Cost (ψ)	Kimball Parameter (ϵ)	q-Elasticity	Adjustment Half-Life ($\theta = 0.7$)	Adjustment Half-Life (Flexible Prices)	Price Pass Through (A)
3	0	13.3	4.0	3.7	1
	10	13.3	3.0	2.7	0.50
	33	13.3	2.3	2.1	0.23
2	0	20.0	3.3	3.0	1
	10	20.0	2.5	2.2	0.50
	33	20.0	1.8	1.7	0.23

Note: q-Elasticity – elasticity of investment with respect to Tobin's q; adjustment half-lives are measure in years; Price Pass Through – change in prices as a fraction of change in marginal cost.

Table 3: Frequency of Re-optimization: Full Sample Results

		Rental Market for Capital		Firm-Specific Capital $\psi = 0$		$\psi = 3$	
Deflator	ϵ	θ	$\frac{1}{1-\theta}$	θ	$\frac{1}{1-\theta}$	θ	$\frac{1}{1-\theta}$
GDP	**0**	**0.88**	**8.3**	**0.83**	**5.9**	**0.72**	**3.6**
		$[0.78, 0.98]$	$[4.5, 50.0]$	$[0.65, 0.97]$	$[2.9, 33.3]$	$[0.53, 0.95]$	$[2.1, 20.0]$
	10	**0.83**	**5.9**	**0.79**	**4.8**	**0.70**	**3.3**
		$[0.70, 0.96]$	$[3.3, 25.0]$	$[0.60, 0.96]$	$[2.5, 25.0]$	$[0.51, 0.94]$	$[2.0, 16.7]$
	33	**0.76**	**4.2**	**0.72**	**3.6**	**0.66**	**2.9**
		$[0.60, 0.95]$	$[2.5, 20.0]$	$[0.52, 0.94]$	$[2.1, 16.7]$	$[0.46, 0.93]$	$[1.9, 14.3]$
PCE	**0**	**0.86**	**7.1**	**0.80**	**5.0**	**0.69**	**3.2**
		$[0.77, 0.96]$	$[4.3, 25.0]$	$[0.62, 0.95]$	$[2.6, 20.0]$	$[0.51, 0.91]$	$[2.0, 11.0]$
	10	**0.81**	**5.3**	**0.76**	**4.2**	**0.67**	**3.0**
		$[0.68, 0.94]$	$[3.1, 16.7]$	$[0.57, 0.93]$	$[2.3, 14.3]$	$[0.49, 0.90]$	$[2.0, 10.0]$
	33	**0.73**	**3.7**	**0.69**	**3.2**	**0.63**	**2.7**
		$[0.57, 0.91]$	$[2.3, 11.1]$	$[0.49, 0.91]$	$[2.0, 11.1]$	$[0.44, 0.88]$	$[1.8, 8.3]$

Note: Estimates based on labor's share equal to 2/3, a 10% markup and a 2.5% quarterly depreciation rate.

Table 4: Frequency of Re-optimization: Sub-Sample Results

Panel A: 1959:1-1979:2

		Rental Market for Capital		Firm-Specific Capital $\psi = 0$		Firm-Specific Capital $\psi = 3$	
Deflator	ϵ	θ	$\frac{1}{1-\theta}$	θ	$\frac{1}{1-\theta}$	θ	$\frac{1}{1-\theta}$
GDP	**0**	**0.86**	**7.1**	**0.79**	**4.8**	**0.67**	**3.0**
		$[0.73, 0.98]$	$[3.7, 50.0]$	$[0.56, 0.98]$	$[2.3, 50.0]$	$[0.45, 0.96]$	$[1.8, 25.0]$
	10	**0.80**	**5.0**	**0.75**	**4.0**	**0.65**	**2.9**
		$[0.64, 0.97]$	$[2.8, 33.3]$	$[0.50, 0.97]$	$[2.0, 33.3]$	$[0.43, 0.96]$	$[1.8, 25.0]$
	33	**0.72**	**3.6**	**0.68**	**3.1**	**0.61**	**2.6**
		$[0.52, 0.96]$	$[2.1, 25.0]$	$[0.43, 0.96]$	$[1.8, 20.0]$	$[0.38, 0.94]$	$[1.6, 16.7]$
PCE	**0**	**0.84**	**6.3**	**0.80**	**5.0**	**0.65**	**2.9**
		$[0.75, 0.94]$	$[4.0, 16.7]$	$[0.62, 0.95]$	$[2.6, 20.0]$	$[0.48, 0.89]$	$[1.9, 9.1]$
	10	**0.78**	**4.6**	**0.76**	**4.2**	**0.63**	**2.7**
		$[0.66, 0.91]$	$[2.9, 11.1]$	$[0.57, 0.93]$	$[2.3, 14.3]$	$[0.46, 0.86]$	$[1.9, 6.7]$
	33	**0.70**	**3.3**	**0.69**	**3.2**	**0.59**	**2.4**
		$[0.55, 0.87]$	$[2.2, 7.7]$	$[0.49, 0.91]$	$[2.0, 11.1]$	$[0.41, 0.82]$	$[1.7, 5.6]$

Panel B: 1982:3-2001:4

		Rental Market for Capital		Firm-Specific Capital $\psi = 0$		Firm-Specific Capital $\psi = 3$	
Deflator	ϵ	θ	$\frac{1}{1-\theta}$	θ	$\frac{1}{1-\theta}$	θ	$\frac{1}{1-\theta}$
GDP	**0**	**0.83**	**5.9**	**0.75**	**4.0**	**0.63**	**2.7**
		$[0.73, 0.93]$	$[3.7, 14.3]$	$[0.56, 0.92]$	$[2.3, 12.5]$	$[0.45, 0.85]$	$[1.8, 6.7]$
	10	**0.77**	**4.4**	**0.70**	**3.3**	**0.60**	**2.5**
		$[0.64, 0.90]$	$[2.8, 10.0]$	$[0.51, 0.90]$	$[2.0, 10.0]$	$[0.43, 0.84]$	$[1.8, 6.2]$
	33	**0.68**	**3.1**	**0.62**	**2.6**	**0.56**	**2.3**
		$[0.52, 0.86]$	$[2.1, 7.1]$	$[0.43, 0.85]$	$[1.8, 6.7]$	$[0.38, 0.81]$	$[1.6, 5.3]$
PCE	**0**	**0.83**	**5.9**	**0.80**	**5.0**	**0.63**	**2.7**
		$[0.71, 0.95]$	$[3.5, 20.0]$	$[0.62, 0.95]$	$[2.6, 20.0]$	$[0.43, 0.91]$	$[1.8, 11.1]$
	10	**0.77**	**4.4**	**0.76**	**4.2**	**0.60**	**2.5**
		$[0.62, 0.92]$	$[2.6, 12.5]$	$[0.57, 0.93]$	$[2.3, 14.3]$	$[0.41, 0.89]$	$[1.7, 9.1]$
	33	**0.68**	**3.1**	**0.69**	**3.2**	**0.56**	**2.3**
		$[0.50, 0.89]$	$[2.0, 9.1]$	$[0.49, 0.91]$	$[2.0, 11.1]$	$[0.36, 0.85]$	$[1.6, 6.7]$

Note: Estimates based on labor's share equal to 2/3, a 10% markup, and a 2.5% quarterly depreciation rate.