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Luis J. Álvarez and Pablo Burriel

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Correspondence address: Alcalá 48, 28014 Madrid, Spain. Email address: ljalv@bde.es.

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Abstract

This paper shows that the standard Calvo model clearly fails to account for the distribution of price durations found in micro data. We propose a novel price setting model that fully captures heterogeneity in individual pricing behavior. Specifically, we assume that there is a continuum of firms that set prices according to a Calvo mechanism, each of them with a possibly different price adjustment parameter. The model is estimated by maximum likelihood and closely matches individual consumer and producer price data. Incorporating estimated price setting rules into a standard DSGE model shows that fully accounting for pricing heterogeneity is crucial to understanding inflation and output dynamics. The standard calibration that assumes within sector homogeneity, as in Carvalho (2006), is at odds with micro data evidence and leads to a substantial distortion of estimates of the real impact of monetary policy.

Keywords: price setting, Calvo model, heterogeneity, hazard rate.

JEL classification: C40, D40, E30.

1 Introduction

Recent years have seen an explosion of theoretical pricing models derived from the optimizing behavior of forward-looking firms in a framework of nominal rigidities and imperfect competition. Despite widespread use of these models, little empirical work has been carried out to link them with micro evidence. To a large extent, this simply reflects the fact that individual price evidence has been scarce and partial,[1] mainly due to the lack of information at the firm level. This state of affairs has changed in the last years, and numerous papers have used the micro data underlying the Consumer Price Index (CPI) and the Producer Price Index (PPI) for different countries.[2]

One of the main conclusions of this new empirical strand of research is that pricing behavior is highly heterogenous across firms. This heterogeneity in the frequency of price adjustments also helps explain the common finding that hazard rates are downward sloping (see Figure 1).[3] This new micro evidence is in sharp contrast with the widespread assumption of homogeneous pricing behavior typically employed in macroeconomic models.

Against this background, an incipient theoretical literature has started to analyze the relevance of pricing heterogeneity in assessing the real and nominal impact of shocks (Carvalho, 2006; Nakamura and Steinsson, 2007). Two conclusions that emerge from this work are as follows. First, models with heterogeneity in price stickiness lead monetary policy to have substantially larger and more persistent real effects than when all firms have the same degree of nominal rigidity. In heterogeneous economies, the response of aggregate variables to shocks is initially largely driven by the more flexible firms. The speed of adjustment slows down through time because aggregate variables are affected to a larger extent by the response of more rigid firms. Second, the quantitative impact of allowing for heterogeneity is quite substantial.

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[1] Among seminal papers, see Stigler and Kindhal (1970) on producer prices or Cecchetti (1986) on consumer prices.

[2] Examples of studies using CPI micro data are Bils and Klenow (2004) for the U.S. and Dhyne et al. (2006) for the euro area. Micro PPI data have also been used, for instance, in Vermeulen et al. (2007) for the euro area and Nakamura and Steinsson (2008) for the U.S. Álvarez (2008) presents a survey of this literature.

[3] A well known result in the failure literature is that a mixture of distributions with nonincreasing failure rates has a decreasing failure rate (see Proschan, 1963, or Appendix 1 for a discrete time expression). In addition, estimates of population hazard functions on consumer prices can be found in Baumgartner et al. (2005), Aucremanne and Dhyne (2005), Fougère et al. (2007), Hoffmann and Kurz-Kim (2010), Fabiani et al. (2006a), Álvarez and Hernando (2006), and Klenow and Krystov (2008). Empirical evidence on producer prices is found in Álvarez et al. (2010) and in Stahl (2005). Estimates for hazard rates at the individual level are presented in Campbell and Eden (2005), Fougère et al. (2007), and Nakamura and Steinsson (2008).

In this paper, we challenge the simplifying assumption made in this growing literature that heterogeneity in pricing behavior can be adequately modeled by simply assuming a finite number of sectors in the economy where all firms in a given sector follow the same pricing mechanism. This assumption of no within-sector heterogeneity is clearly at odds with the empirical evidence on micro data where firm level heterogeneity is pervasive. Indeed, the frequencies of price adjustments are found to differ, among other factors, according to the type of outlet, market competition, or product regulation. To account for the firm level heterogeneity found in individual price data, we introduce a novel pricing model. Specifically, the economy is composed of a continuum of firms that set prices according to a Calvo (1983) mechanism, and each firm is characterized by a possibly different price adjustment parameter.[4] The distribution across the population of Calvo parameters is characterized by a probability density function with few parameters. Interestingly, it is possible to find closed-form expressions for the distribution of observed price durations (or hazard rates), and the estimation of the model is straightforward using standard maximum likelihood techniques.[5]

We assume that firms use a Calvo pricing mechanism for several reasons. First, the Calvo model is analytically simple, easy to estimate, and easily reconciled with the stylized facts. Indeed, Klenow and Kryvtsov (2008) find that, allowing for heterogeneity, individual hazard rates are flat. Second, the Calvo pricing rule is the most widely used in the derivation of New Keynesian Phillips Curves and in DSGE models. Third, Woodford (2009) shows that the Calvo model is a fairly accurate approximation to the solution of a model with state-dependent pricing in a world characterized by moderate levels of information costs. A natural alternative to the Calvo model is the Taylor (1980) model,[6] but this pricing rule is considerably less parsimonious in this context because it requires as many groups of price setters as actual price-spell durations. Other pricing models, such as standard sticky information models (e.g., Mankiw and Reis, 2002; Reis, 2006), imply continuous price adjustment, which is at odds with the available empirical evidence.

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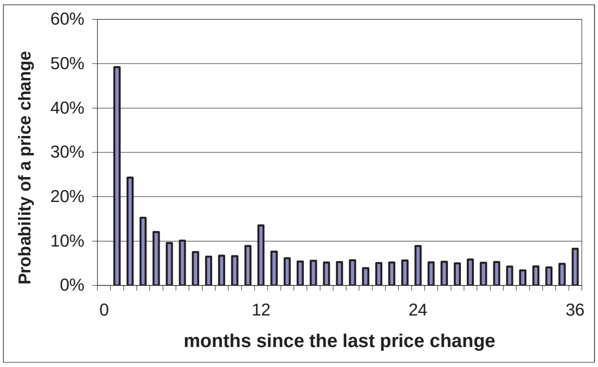
[4] Other models have been proposed in the literature. For instance, Álvarez et al. (2005) and Ikeda and Nishioka (2007) consider a small number of different price setters but do not assume within product price setting homogeneity. Population heterogeneity is modeled in Carvalho (2005) by assuming a large number of different products but no within product heterogeneity. Nakamura and Steinsson (2008) also consider an economy with many different goods. The hazard rate for a given product is proportional to a nonparametric baseline hazard, which is often found to be downward sloping. Fougère et al (2007) consider heterogeneity both at the good and product level.

[5] The method we employ is based on models developed in the biometric literature on women fecundability (see, e.g., Sheps 1964; Weinberg and Gladen 1986; Ecochard and Clayton 2000).

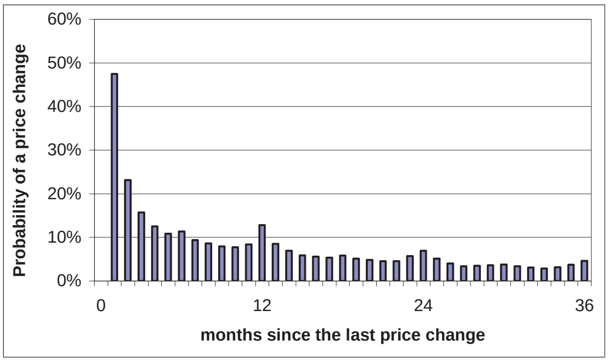
[6] See Álvarez (2008) for a survey of theoretical pricing models and their ability to capture stylized facts found in the empirical literature on price setting behavior at the firm level.

Figure 1: International evidence on decreasing hazard functions for price changes

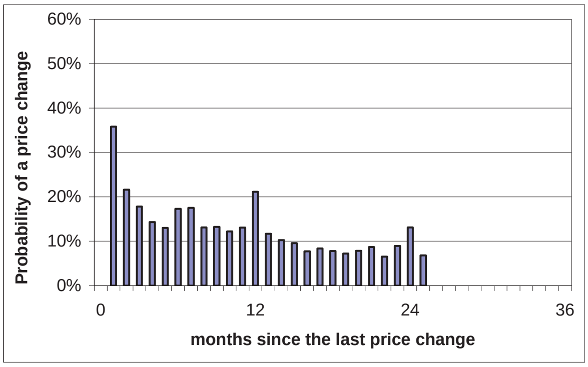
AUSTRIA - CPI



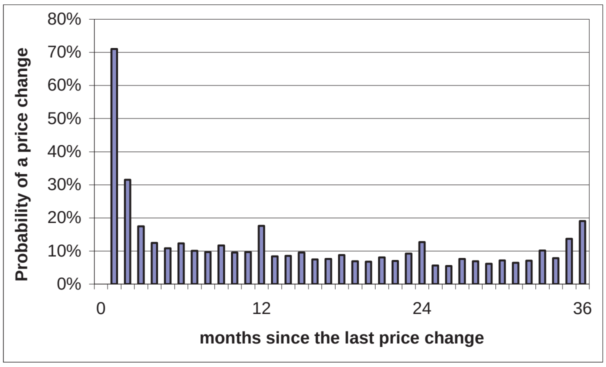
BELGIUM - CPI



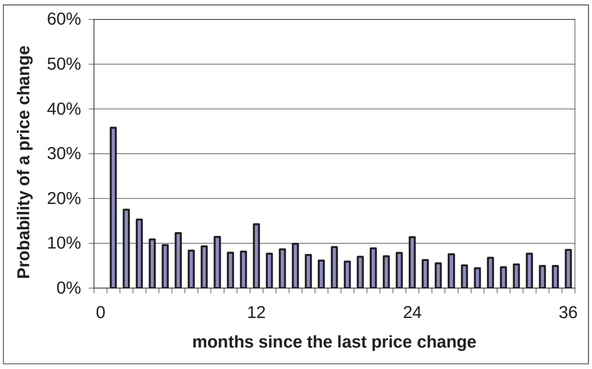
FRANCE - CPI



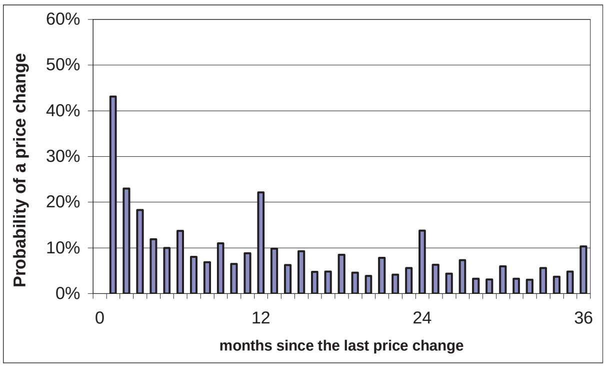
GERMANY - CPI



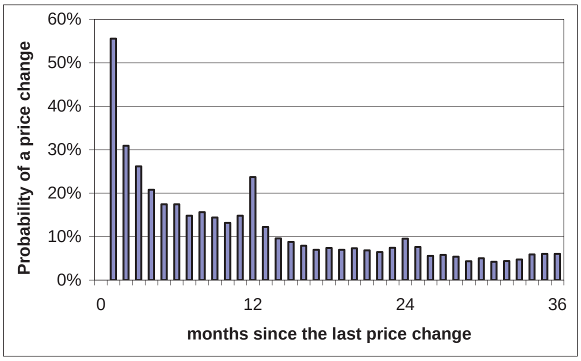
ITALY - CPI



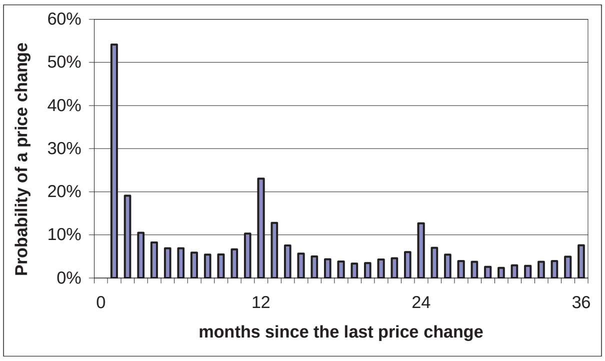
SPAIN - CPI



US - CPI



SPAIN - PPI



This implication still holds if firms differ in the frequency of updating their information set, as in Carvalho (2005). Finally, closed-form expressions for the unconditional hazard function of state-dependent models generally do not exist, which renders their empirical implementation difficult. Moreover, estimated populational hazard rates do not show an upward slope, as in Dotsey et al. (1999).

In order to evaluate the importance of heterogeneity in price setting on the real impact of nominal shocks, the estimated fully heterogenous Calvo model is used to calibrate an otherwise standard DSGE model. Our two main results are: (1) Incorporating estimated price-setting rules into an otherwise standard DSGE model shows that fully accounting for pricing heterogeneity is crucial to understanding inflation and output dynamics; and (2) The standard calibration that assumes within sector homogeneity, as in Carvalho (2006), leads to an underestimation of the share of both very sticky and very flexible price setters and, as a result, a substantial distortion in the estimates of the real impact of monetary policy. Our fully heterogeneous Calvo model is found to involve a faster initial adjustment of flexible price setters, which tends to limit the impact of monetary policy, and a slower subsequent adjustment, which tends to lead to a higher impact of nominal disturbances. Importantly, the net result of these two effects, in general, is indeterminate.

After this introduction, the structure of the paper is as follows. Section 2 presents the fully heterogenous Calvo model, which is estimated in Section 3 by standard maximum likelihood methods using Spanish producer and consumer price data. In Section 4, we present the macroeconomic implications of heterogeneity in price setting including estimated pricing rules into an otherwise standard DSGE model. Conclusions are presented in Section 5.

2 The fully heterogeneous Calvo model

Heterogeneity in the frequency of price adjustments across different dimensions (e.g., products, cities, or types of outlets) suggests building a model with an infinite number of price setters. Under the additional assumption of Calvo pricing, we obtain the fully heterogeneous Calvo [FHC] model in which:

(1) Each individual sets prices according to a Calvo mechanism, so that the individual survival and hazard functions are given by

$$\begin{aligned} S(k) &= \Pr(X > k/\theta) = \theta^{k-1} \quad k = 1, 2, 3, ... \\ h(k) &= (1-\theta). \end{aligned}$$

(2) There is an infinite number of price setters, each with a different no-price adjustment parameter (θ). The distribution over θ across the population has

a general pdf $f(\theta)$. We derive the general expressions of the survival and hazard functions of this model and then obtain closed-form expressions under several assumption regarding the distribution describing heterogeneity.

2.1 General case

In the FHC model, the population survival function is a simple function of the moments of the distribution over the Calvo parameter

$$S(k) = \int_0^1 S(k/\theta) f(\theta)\, d\theta = \int_0^1 \theta^{k-1} f(\theta)\, d\theta = E\left(\theta^{k-1}\right),$$

which implies the population hazard rate

$$h(k) = 1 - \frac{E\left(\theta^{k}\right)}{E\left(\theta^{k-1}\right)}.$$

Alternative expressions can be obtained by making a parameter transformation. In fact, $\mu = -\log\theta$, which implies $\theta = e^{-\mu}$, yields $S(k) = \Pr(X > k/\mu) = e^{-\mu(k-1)}$, so that

$$S(k) = \int_0^1 \Pr(X > k/\mu)\, g(\mu)\, d\mu = \int_0^1 e^{-\mu(k-1)} g(\mu)\, d\mu = mgf_{\mu}\left[-(k-1)\right],$$

where mgf_{μ} is the moment-generating function of the distribution of μ (alternatively, this is the Laplace transform of the distribution for μ). The distribution over θ can be easily derived on the basis of the distribution over μ by a simple change of variable.

The corresponding population hazard rate is then given by

$$h(k) = 1 - \frac{mgf_{\mu}\left[-k\right]}{mgf_{\mu}\left[-(k-1)\right]}.$$

These expressions are valid for any distribution over θ. To be operational, though, they require particular forms for the distribution describing heterogeneity.

2.2 Particular cases

The Calvo parameter is bounded between 0 and 1, so a natural assumption is to consider that the distribution over the adjustment parameter is a beta of the first kind, which has as pdf

$$f\left(\theta/p,q\right)=\frac{\theta^{p-1}\left(1-\theta\right)^{q-1}}{B\left(p,q\right)},$$

where $B(p,q)$ is the beta function.

This assumption leads to a beta Calvo model [BC]. This distribution is very flexible in the shapes it accommodates. In particular, the distribution is symmetric if $p=q$ and right or left skewed otherwise. The standard uniform distribution is obtained if $p=q=1$.

The corresponding survival function of the BC model is

$$\begin{aligned} S\left(k;p,q\right) &= \int_0^1 \Pr\left(X>k/\theta\right) f\left(\theta/p,q\right) d\theta = \int_0^1 \theta^{k-1}\frac{\theta^{p-1}\left(1-\theta\right)^{q-1}}{B\left(p,q\right)} d\theta \\ &= \frac{B\left(p+k-1,q\right)}{B\left(p,q\right)}, \end{aligned}$$

and the hazard rate is

$$h\left(k;p,q\right)=\frac{B\left(p+k-1,q+1\right)}{B\left(p+k-1,q\right)}=\frac{q}{p+q+k-1};$$

so, the hazard rate is a decreasing function of the time since the last price change (k) and its inverse is a linear function of k.

Alternative closed-form expressions can be obtained by using the family of distributions proposed by Hougaard (1984, 1986). This family of distributions $H_{\varepsilon}(k;\alpha,$ $(k;\alpha,\beta,\gamma)$ has only three parameters and has the desirable property of having a simple moment-generating function

$$mgf_{\mu}\left(k;\alpha,\beta,\gamma\right)=\exp\left\{-\frac{\beta}{\alpha}\left[\left(\gamma-k\right)^{\alpha}-\gamma^{\alpha}\right]\right\}.$$

We assume that μ follows a Hougaard distribution $H_{\mu}\left(k;\alpha,\beta,\gamma\right)$. Because $\mu=-\log\theta$, we denote the distribution over the Calvo parameter θ as log Hougaard and the resulting mixture model as Log Hougaard Calvo [LHC]. The Hougaard family of distributions nests other distributions used in the literature. The positive-stable distribution is obtained if $\gamma=0$, the gamma distribution if $\alpha=0$, and the inverse Gaussian distribution if $\alpha=0.5$.

Substituting this moment-generating function in the population-survival function for the FHC model, we have the survival of the LHC model

$$S(k;\alpha,\beta,\gamma)=\exp\left\{-\frac{\beta}{\alpha}\left[(\gamma+(k-1))^{\alpha}-\gamma^{\alpha}\right]\right\},$$

and its population hazard rate is given by

$$h(k;\alpha,\beta,\gamma)=1-\frac{\exp\left\{-\frac{\beta}{\alpha}\left[(\gamma+k)^{\alpha}-\gamma^{\alpha}\right]\right\}}{\exp\left\{-\frac{\beta}{\alpha}\left[(\gamma+(k-1))^{\alpha}-\gamma^{\alpha}\right]\right\}}.$$

3 Empirical results

In this section, we estimate the fully heterogeneous Calvo model proposed above using Spanish PPI and CPI micro data. Specifically, we estimate by standard maximum likelihood methods the Beta Calvo model and the Log Hougaard Calvo models for which closed-form expressions are available. For comparison purposes, we also estimate the standard Calvo model.

The log-likelihood function for the fully heterogeneous Calvo model above, allowing for censoring,[7] is given by:

$$l(y;\alpha,\beta,\gamma)=\sum_{i=NC}\log\left[S(k;\alpha,\beta,\gamma)-S(k+1;\alpha,\beta,\gamma)\right]+\sum_{i=C}\log\left[S(k;\alpha,\beta,\gamma)\right],$$

where $S(k;\alpha,\beta,\gamma)$ represents the survival function and NC and C refer to noncensored and censored price spells, respectively. Models are selected on the basis of four model selection criteria: the Akaike Information criterion (AIC), the Bayesian Information Criterion (BIC), and two statistics measuring the quadratic distances between empirical and fitted probability mass functions (qd_f) and hazard functions (qd_h). Criteria are computed as follows:

$$AIC=-2\log\left[L(\widehat{\Psi})\right]+2d \qquad BIC=-2\log\left[L(\widehat{\Psi})\right]+d\log(n)$$

$$qd_f=\sum_{k=1}^{\max k}\frac{\left(f_k^{\text{empirical}}-f_k^{\text{fitted}}\right)^2}{f_k^{\text{empirical}}} \qquad qd_h=\sum_{k=1}^{\max k}\frac{\left(h_k^{\text{empirical}}-h_k^{\text{fitted}}\right)^2}{h_k^{\text{empirical}}}$$

where d is the number of estimated parameters, n is the number of observations,

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[7] In what follows, we do not take into account left-censored observations. For ease of exposition, we refer to right-censored observations simply as censored observations.

and $L(\widehat{\Psi})$ is the value of the likelihood at its maximum.

Table 1: Selection of models

	Producer prices				**Consumer prices**			
Model	**AIC**	**BIC**	**qd f**	**qd h**	**AIC**	**BIC**	**qd f**	**qd h**
Standard Calvo [C]	1153457	1153460	1.23	69.2	891611	891614	0.58	57.1
Within sector homogenous Calvo [WSHC]	--	--	0.68	7.28	--	--	0.94	1.41
Fully heterogeneous Calvo [FHC]:								
Beta Calvo [BC]	927590	927611	0.11	1.34	790396	790417	0.07	1.46
Gamma Calvo [GC]	926793	926813	0.10	1.33	790371	790391	0.07	1.46
Inverse Gaussian Calvo [IGC]	923108	923129	0.17	1.90	**782477**	**782497**	0.05	1.00
Positive Stable Calvo [PSC]	**910213**	**910234**	0.08	0.75	782499	782519	0.05	1.03
Hougaard Calvo [HC]	910215	910246	**0.08**	**0.75**	782477	782508	**0.05**	**0.978**

The estimation is performed using micro data on producer and consumer prices.[8] The data set on producer prices contains over 1.6 million price records for a seven-year period (November 1991 to February 1999) and covers over 99 percent of the production value of the PPI, including 244.864 price spells by 26.965 firms. The data set on consumer prices contains over 1.1 million price records for a nine-year period (1993–2001) and covers around 70 percent of the expenditure of the CPI basket, including 179.673 price spells by 12.494 firms.

Table 1 shows the values of the different model selection criteria, and Table 2 shows the estimation results. The standard Calvo model clearly has the worst performance. AIC and BIC selection criteria show that the best performing model for producer prices is the positive stable Calvo, whereas for consumer prices it is the inverse Gaussian Calvo. The log Hougaard Calvo model, which nests them, has a marginally better fit in terms of quadratic distances than these models, although the additional parameter hardly improves the likelihood. Figure 2 confirms these results by comparing the fitted and empirical probability mass and hazard functions

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[8] Detailed descriptions of the data sets are provided in Álvarez et al. (2010) for the PPI and Álvarez and Hernando (2006) for the CPI.

for the best performing model and the standard Calvo one.[9]

Table 2: Estimation of price-setting models

Model	Producer prices				Consumer prices			
	theta			**LL**	**theta**			**LL**
Standard Calvo [C]	0.82			-576727	0.83			-445804
	(0.00)				(0.00)			
	p	**q**		**LL**	**p**	**q**		**LL**
Beta Calvo [BC]	0.49	0.54		-463793	1.34	0.91		-395196
	(0.00)	(0.00)			(0.01)	(0.01)		
	a	**b**	**g**	**LL**	**a**	**b**	**g**	**LL**
Gamma Calvo [GC]	0.00	0.54	0.33	-463394	0.00	0.91	1.29	-395183
		(0.00)	(0.00)			(0.01)	(0.01)	
Inverse Gaussian Calvo [IGC]	0.50	0.30	0.00	-461552	0.50	0.30	0.00	-391236
		(0.00)	(0.00)			(0.00)	(0.00)	
Positive Stable Calvo [PSC]	0.38	0.28	0.00	-455104	0.51	0.29	0.00	-391247
	(0.00)	(0.00)			(0.00)	(0.01)		
Hougaard Calvo [HC]	0.38	0.28	0.00	-455104	0.50	0.30	0.00	-391236
	(0.00)	(0.00)	(0.00)		(0.00)	(0.00)	(0.00)	

Note: LL, a, b and g denote Log-likelihood, α, β and γ . Standard errors shown within parentheses.

3.1 Generalized Calvo pricing

Another stylized fact of the international empirical evidence on hazard functions is that population hazard functions are characterized by local modes at durations of 12, 24, 36, ... months, suggesting that a fraction of firms apply annual pricing rules. This is also in line with the results of surveys on pricing behavior (Álvarez and Hernando 2007; Blinder 1991; Fabiani et al. 2006b), which find that a substantial share of firms tend to review and change their prices on a yearly basis.

Here, we extend the Calvo pricing rule in a novel way to try to capture these local modes, which we call a Generalized Calvo pricing rule [GC]. Firms have a constant conditional probability of changing prices $(1-\theta_c)$, as in the standard Calvo model, although this probability may be different for prices that have remained constant for an integer number of years $(1-\theta_a)$.

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[9] The empirical and fitted probability mass functions rates suggest that there is a nonnegligible number of price setters with very high durations (3 percent over 4 years). However, there is substantial evidence in this regard. For instance, Levy and Young (2004) document that the price of Coke was 5¢ from 1886 until 1959. Carlton (1986) reports that it is not unusual in some industries for prices to individual buyers to remain unchanged for several years. Gopinath and Rigodon (2008) find that, using a monthly sample spanning 12 years, around 30 percent of goods have constant prices over their entire life.

Figure 2.1: Empirical vs fitted hazard function.

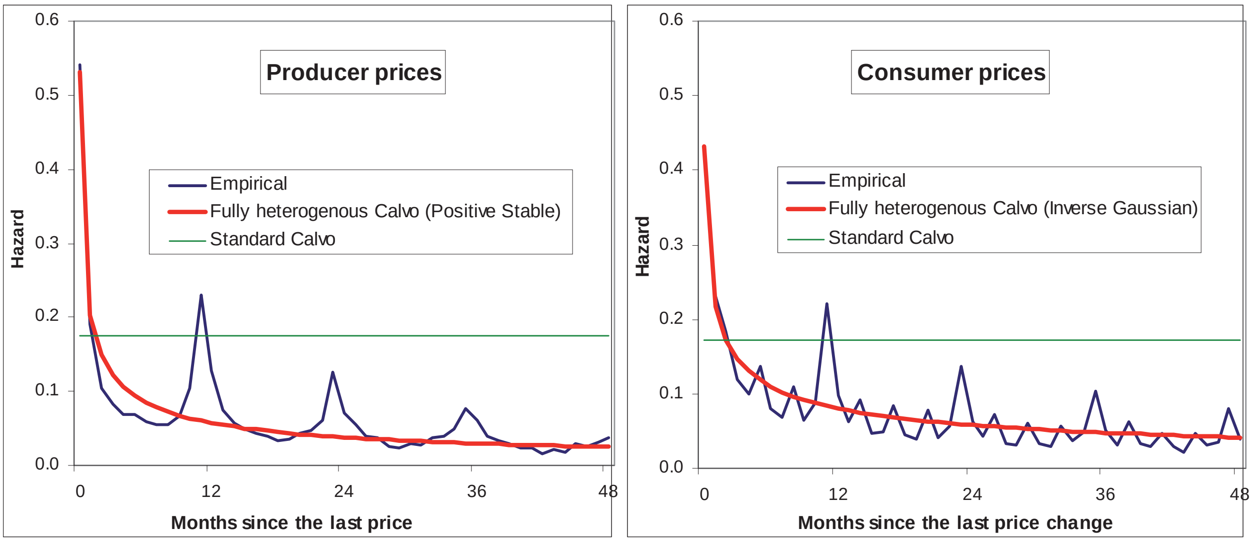


Figure 2.2: Empirical vs fitted frequency function.

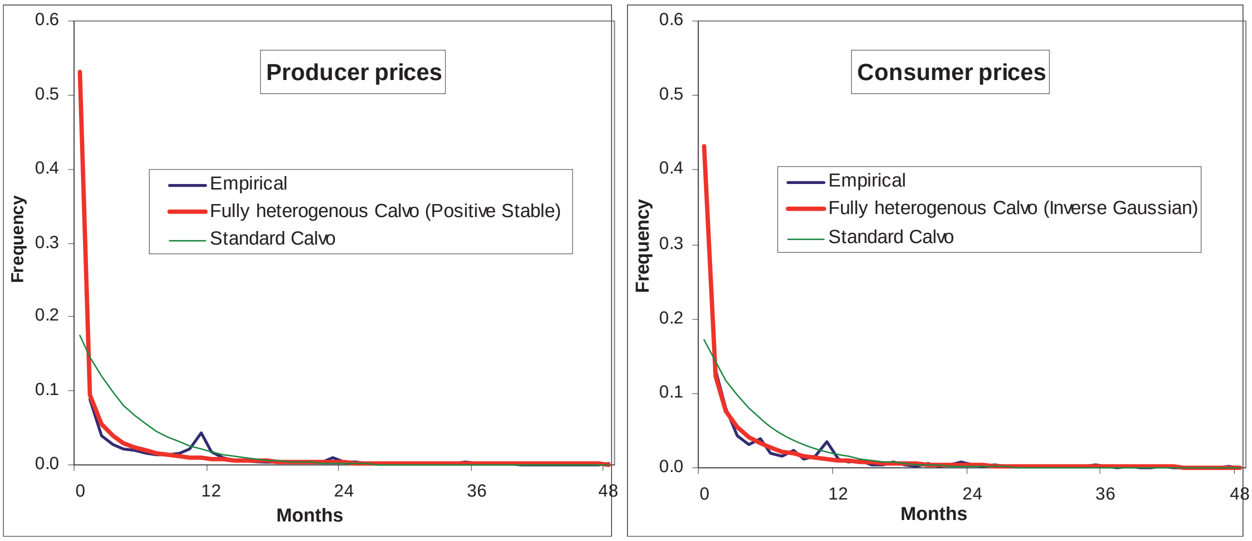
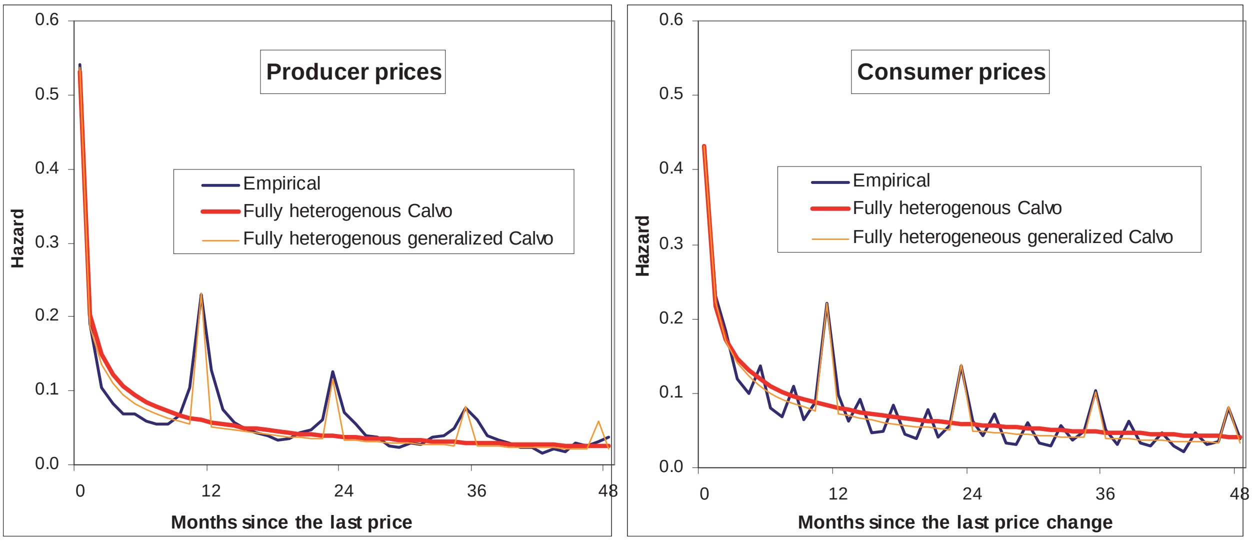


Figure 3: Hazard function: FH Calvo vs FH generalized Calvo



The hazard rate for an agent i using this price-setting rule is:

$$h^{i}(k/\theta_c, \theta_a) = (1 - \theta_{c,i})^{1-d}(1 - \theta_{a,i})^{d},$$

where, if monthly data are used, $d = 1\ if\ k = 12, 24, 36...$ and 0 otherwise.

We consider that there is an infinite number of price setters, each with a different pair of parameters (θ_c, θ_a). We assume that the bivariate distribution over (θ_c, θ_a) is the product of marginal distributions over θ_c and θ_a. In the empirical applications, these distributions are assumed to be Log Hougaard $H(\alpha_c, \beta_c, \gamma_c)$, and $H(\alpha_a, \beta_a, \gamma_a)$.

Estimation results, reported in Table 3, show that this model performs better than the fully heterogeneous Calvo according to the different model selection criteria, although differences are small (Figure 3). This is due to the fact that, although there is some annual price-setting behavior reflected in the spikes of the hazard functions, this represents a small percentage of the population of price setters. In particular, the accumulated difference between the fitted density function of the fully heterogeneous Calvo and the heterogeneous generalized Calvo for annual points is only 3 percent in the PPI case and 4 percent in the CPI case.

Table 3: Robustness—fully heterogeneous generalized Calvo model

	Producer prices				**Consumer prices**			
Monthly parameters	**ac**	**bc**	**gc**		**ac**	**bc**	**gc**	
	0.34	0.26	0.00		0.41	0.32	0.06	
	(0.00)	(0.00)	(0.00)		(0.00)	(0.00)	(0.00)	
Annual parameters	**aa**	**ba**	**ga**		**aa**	**ba**	**ga**	
	0.00	0.24	0.51		0.12	0.31	0.83	
	(0.01)	(0.00)	(0.00)		(0.27)	(0.10)	(0.23)	
	AIC	**BIC**	**qd f**	**qd h**	**AIC**	**BIC**	**qd f**	**qd h**
	895,800	895,863	0.04	0.53	776,507	776,567	0.02	0.52

Note: a, b, and g denote α, β, and γ. Standard errors shown within parenthesis.

4 Fully accounting for heterogeneity in a DSGE model

To analyze the macroeconomic implications of the fully heterogeneous Calvo model,[10] we incorporate it into an otherwise standard DSGE model.[11] In the tradition of the simplest New Keynesian sticky price models, the demand side of the model con-

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[10] A related issue of interest is the macroeconomic implications of the fully heterogeneous generalized Calvo model. We leave this analysis for further research.

[11] The model we use is very similar to Carvalho (2006)

sists of an intertemporal IS equation, derived from optimal consumer choices, and a Taylor rule with interest rate smoothing, according to which the central bank sets short-run nominal interest rates. In the supply side, there is a continuum of good producers, each composed of j monopolistically competitive firms. For tractability reasons, we discretize the continuum distribution implied by the estimated fully heterogeneous Calvo model into k different groups.[12] Each of these groups follows a Calvo pricing mechanism but with a possibly different no price-adjustment parameter θ_k. A competitive distribution sector puts together intermediate sectoral goods (Y_{kjt}) into a final good (Y_t), which is sold to consumers at price (P_t). Firms in the distribution sector solve the following maximization problem

$$\max_{Y_{kjt}} P_t Y_t - \int_0^1 P_{kjt} Y_{kjt}\, dk$$

$$\text{s.t.} \quad : \quad Y_t = \left[\int_0^1 f(k) \int_0^1 Y_{kjt}^{\frac{\varepsilon-1}{\varepsilon}}\, dj dk \right]^{\frac{\varepsilon}{\varepsilon-1}},$$

and the demand for intermediate goods is a function of aggregate demand and relative prices:

$$\begin{aligned} Y_{kjt} &= \left(\frac{P_{kjt}}{P_t} \right)^{-\varepsilon} Y_t \\ P_t &= \left[\int_0^1 f(k) \int_0^1 P_{kjt}^{1-\varepsilon} dj dk \right]^{\frac{1}{1-\varepsilon}}, \end{aligned}$$

where ε is the elasticity of substitution between output varieties,[13] P_{kjt} the price of intermediate good j of sector k, and $f(k)$ is the density of firms in group k.

In the productive sectors, each firm j from group k produces an intermediate good Y_{kjt}, using a linear production function in labor (L_{kjt}). Each firm faces an isoelastic demand and sets its optimal price (X_{kjt}) by solving the following maximization problem

$$\max_{X_{kjt}} \mathbb{E}_t \sum_{s=0}^{\infty} [\beta\theta_k]^s \frac{Y_{t+s}^{-\sigma}}{P_{t+s}} \left\{ X_{kjt} - P_{kt+s} mc_{kt+s} \right\} Y_{kjt+s}$$

$$\text{s.t.} \quad : \quad Y_{kjt} = L_{kjt}; \quad Y_{kjt+s} = \left(\frac{X_{kjt}}{P_{t+s}} \right)^{-\varepsilon} Y_{t+s},$$

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[12] Maximum likelihood estimation does not require any discretization, but this is needed to simulate the DSGE model. In the macro empirical analysis, we consider 500 groups.

[13] Using different within and between elasticities of substitution does not qualitatively change the results.

where the real marginal cost $mc_{kt} = L_{kt}^{\frac{1}{\varphi}} Y_t^{\sigma}$, X_{kjt} is the optimal price, β is the discount factor, $\frac{1}{\varphi}$ is the inverse of Frisch labor supply elasticity, and σ is the intertemporal elasticity of substitution of consumption.

The relative optimal price x_{kt} is given by:

$$x_{kt} = \frac{X_{kt}}{P_{kt}} = \frac{\mathbb{E}_t \sum\limits_{\tau=0}^{\infty} [\beta\theta_k]^s \, Y_{t+s}^{1-\sigma} \left(\frac{\Pi_{kt,t+s}}{\Pi_{t,t+s}^{1-\varepsilon}}\right) \left(\frac{\varepsilon}{\varepsilon-1}\right) mc_{kt+s}}{\mathbb{E}_t \sum\limits_{\tau=0}^{\infty} [\beta\theta_k]^s \, Y_{t+s}^{1-\sigma} \, \Pi_{t,t+s}^{\varepsilon-1},}$$

where $\Pi_{kt,t+s} = \prod_{h=1}^{s} \Pi_{kt+h}$ and $\Pi_{kt} = \frac{P_{kt}}{P_{kt-1}}$ are the sectoral inflation rates. The aggregate sectoral price index evolves as:

$$P_{kt}^{1-\varepsilon} = (1-\theta_k) \, X_{kt}^{1-\varepsilon} + \theta_k P_{kt-1}^{1-\varepsilon}.$$

The (log-linearized) equilibrium of the model is characterized by 2k+3 equations: the New Keynesian Phillips Curves and the output demand for the k groups, the aggregate NKPC, the IS curve, and the Taylor rule:[14]

$$\text{k groups NKPCs } \widehat{\Pi}_{kt} = \beta \mathbb{E}_t \widehat{\Pi}_{kt+1} + \frac{(1-\theta_k)\,[1-\beta\theta_k]}{\theta_k} \left[\sigma \widehat{Y}_t + \frac{1}{\varphi} \widehat{Y}_{kt} \right]$$

$$\text{k groups output demands: } \widehat{Y}_{kt} = \widehat{Y}_t - \varepsilon \widehat{p}_{kt}$$

$$\text{Aggregate NKPC: } \widehat{\Pi}_t = \beta \mathbb{E}_t \widehat{\Pi}_{t+1} + \psi\sigma \widehat{Y}_t + \frac{1}{\varphi} \int_0^1 f(k) \, \frac{(1-\theta_k)\,[1-\beta\theta_k]}{\theta_k} \widehat{Y}_{kt} dk$$

$$\text{IS curve: } \widehat{Y}_t = -\frac{1}{\sigma} \mathbb{E}_t \left(\widehat{I}_t - \widehat{\Pi}_{t+1} \right) + \mathbb{E}_t \widehat{Y}_{t+1}$$

$$\text{Taylor rule: } \widehat{I}_t = \gamma_I \widehat{I}_{t-1} + \left(1-\gamma_I\right) \left(\gamma_{\Pi} \widehat{\Pi}_t + \gamma_y \widehat{Y}_t \right) + m_t$$

where $\psi = \int_0^1 f(k) \frac{(1-\theta_k)[1-\beta\theta_k]}{\theta_k} dk$, $\widehat{I}_t$ is the nominal interest rate, and m_t represents a monetary shock. We redefine the variables as log deviations from steady state; that is, $\widehat{var}_t = \log var_t - \log var$, where var is the steady-state value for the variable var_t.

The calibration used is very standard and similar to Carvalho (2006), except for price-setting rules, which are obtained on the basis of the estimated fully heterogeneous Calvo model (Table 2). Note that the time unit in the model is one

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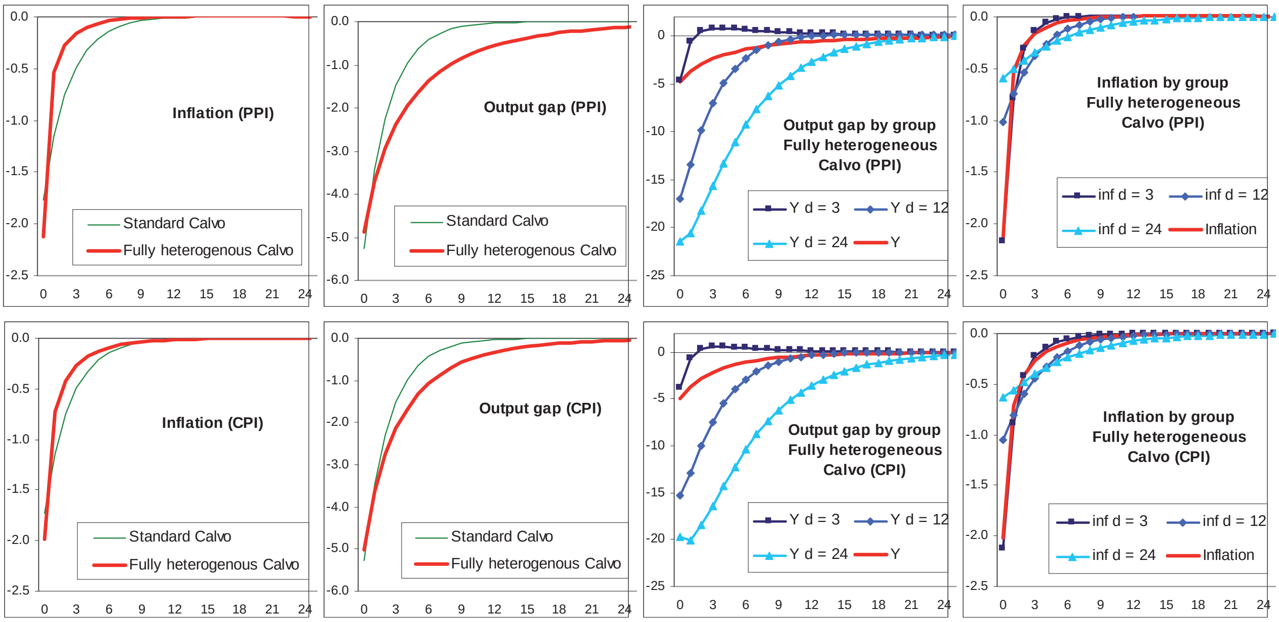
[14] This has been derived under the assumption of a zero steady-state level of inflation, as is standard in the NKPC literature. An appendix with the full derivation of the nonlinear model is available from the authors upon request.

month. Accordingly, the Taylor rule coefficient on the lagged nominal interest rate is γ_I=0.91; on the inflation rate is γ_Π=1.53, and on the output gap is γ_y=0.93/12;[15] the consumer's discount rate β=0.9975, to have a steady-state (annualized) nominal interest rate of 3 percent, the elasticity of labor supply φ=1.5, the elasticity of substitution between intermediate varieties ε=11, and the intertemporal elasticity of consumption σ=1.[16]

Figure 4: Impulse response functions to a monetary shock



To highlight the implications of incorporating price heterogeneity into an otherwise standard model, we undertake the following exercise. We compute the impulse response functions to a nominal shock of the calibrated model under two alternative price-setting mechanisms: a standard Calvo price-setting rule, where the probability of adjusting prices is equal across all firms in the economy, and the fully heterogeneous Calvo model, where the probability of price adjustment is different for each of the k groups into which the log Hougaard distribution has been discretized.

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[15] This is divided by 12 to correct for the fact that the estimates in the literature are based on annualized inflation and interest rates (Rudebusch 2002).

[16] We have considered an alternative calibration with lower real rigidities ($\varphi = 0.5$ and $\varepsilon = 5$). Results are qualitatively similar.

Parameters of these price-setting rules are derived from the estimates in Table 2.

Table 4: Comparison of the impact of a monetary shock across price-setting models

	Output gap		**Inflation**		**Sacrifice ratio**	
Producer prices	Initial	Accumulated	Initial	Accumulated	Initial	Accumulated
Standard Calvo [C]	-5.3	-15.2	-1.8	-5.1	3.0	3.0
Fully heterogeneous Calvo [FHC]	-4.9	-28.3	-2.1	-3.2	2.3	8.8
Within sector homogenous Calvo [WSHC]	-5.7	-23.8	-1.3	-3.9	4.5	6.2
Consumer prices	Initial	Accumulated	Initial	Accumulated	Initial	Accumulated
Standard Calvo [C]	-5.3	-15.5	-1.7	-5.1	3.1	3.1
Fully heterogeneous Calvo [FHC]	-5.0	-22.8	-2.0	-4.0	2.5	5.7
Within sector homogenous Calvo [WSHC]	-6.5	-40.8	-0.4	-1.4	15.2	28.4

The LHS panel of Figure 4 represents the impulse response functions of the output gap and the inflation rate to a one standard deviation monetary shock. Results with PPI data are reported in the top row and those with CPI data in the bottom row. These impulse responses show that output in the fully heterogeneous Calvo model falls to a larger extent and is more persistent than in the standard Calvo one, whereas inflation falls to a lesser extent and returns more quickly to its steady state. That is, the fully heterogeneous economy is more flexible on impact but more persistent thereafter. These differences reflect the distortions introduced by the standard Calvo model in which the probability of adjusting prices is constant. Specifically, the standard Calvo model substantially underestimates both the fraction of firms with very flexible and very rigid prices, although it overestimates the share of firms with prices spells of intermediate duration (Figure 5.1).[17]

The RHS panel of Figure 4 compares the impulse responses of aggregate output gap and inflation with those for three different groups of firms with average price duration of one quarter, one year, and two years, respectively. Very flexible price setters are able to quickly reoptimize prices after the shock, so they do not need to adjust production much (dark blue line), while the more rigid firms take much longer to correct their prices and therefore are penalized to a larger extent in terms of lost demand (lighter blue lines).The RHS panel of Figure 4 also shows that the behavior of aggregate variables is influenced differently by each group over time. In heterogeneous economies, the response of aggregate variables to a shock is initially driven by the more flexible price setters because most price changes are undertaken

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[17] In fact, in the micro data and the fully heterogenous economy around 60 percent of firms change their prices every quarter, whereas only 30 percent in the standard Calvo case. However, in the micro data and the fully heterogeneous economy around 6 percent of firms keep their prices unchanged for more than two years, while only 1 percent do it in the standard Calvo case.

by those firms. As time passes, aggregate variables are dominated by more rigid firms, and the speed of adjustment slows down through time. These results are confirmed in Table 4 in which the initial and accumulated impact of the shock on output gap, inflation, and the sacrifice ratio are reported. In particular, the sacrifice ratio, defined as the number of units of output lost to reduce inflation by one percentage point, is, on impact, about 20 percent lower in the fully heterogeneous Calvo model, although the accumulated impact almost doubles that in the standard Calvo model.

4.1 A standard calibration of heterogenous pricing rules

In the above section, we have presented results from the fully heterogeneous Calvo model, which correctly captures the heterogeneity in price setting observed in price data at the firm level. A simpler approach, followed in Carvalho (2006), is to assume that there is no within-sector heterogeneity in the economy and that each sector follows a Calvo pricing rule with a duration equal to the empirical average duration of the sector. We call this model within-sector homogeneous Calvo [WSHC]. Different macroeconomic impacts from the two models are to be expected to the extent to which they involve different distributions of price durations.

To compare these two alternative ways of accounting for heterogeneity in pricing behavior we calibrate the within-sector homogenous Calvo model using a breakdown of 97 PPI sectors, which correspond to the three-digit NACE classification, and 190 CPI sectors, which corresponds to product codes.[18]

Figure 5 compares the distributions of individual prices implied by the fully heterogenous Calvo and the within-sector homogeneous Calvo models with the empirical ones in terms of aggregate distributions of price durations and hazard rates. It is clearly seen that the WSHC approach implies a severely distorted distribution of price durations in sharp contrast with the fully heterogeneous Calvo model, which closely matches the data. Indeed, the WSHC model considerably underestimates the share of prices with very short durations (up to three months) and clearly overestimates the fraction with intermediate durations (four to 12 months). The WSHC approach also has a disappointing performance in terms of longer price durations, particularly for consumer prices.

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[18] A source of concern relates to the number of sectors used. For confidentiality restrictions, the individual price data sets we use do not allow for a more detailed breakdown. However, Álvarez (2008) provides a similar comparison using 350 sectors for the U.S., finding that, even when there is a very detailed sectoral breakdown, the implied hazard of the within-sector homogeneous Calvo approach fails to capture the empirical distribution.

Figure 5: Duration and hazard distributions

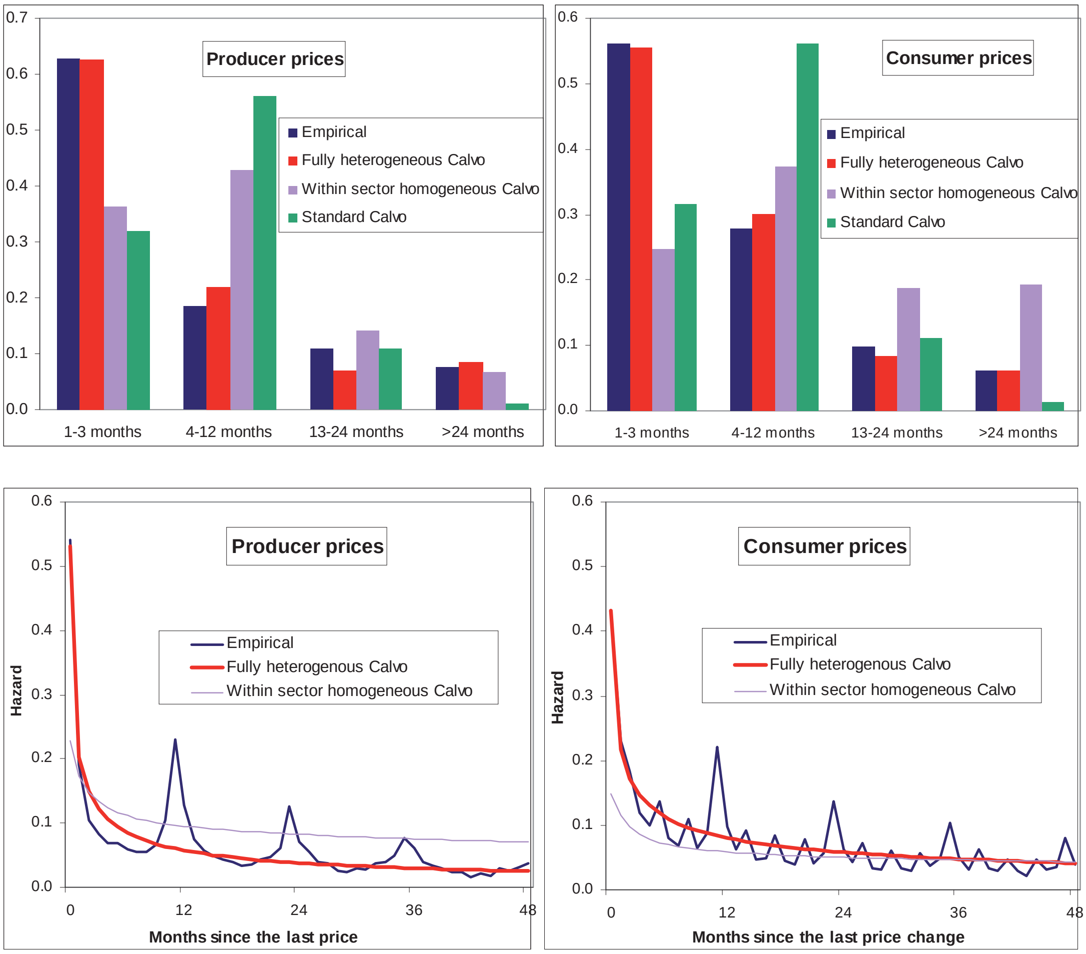
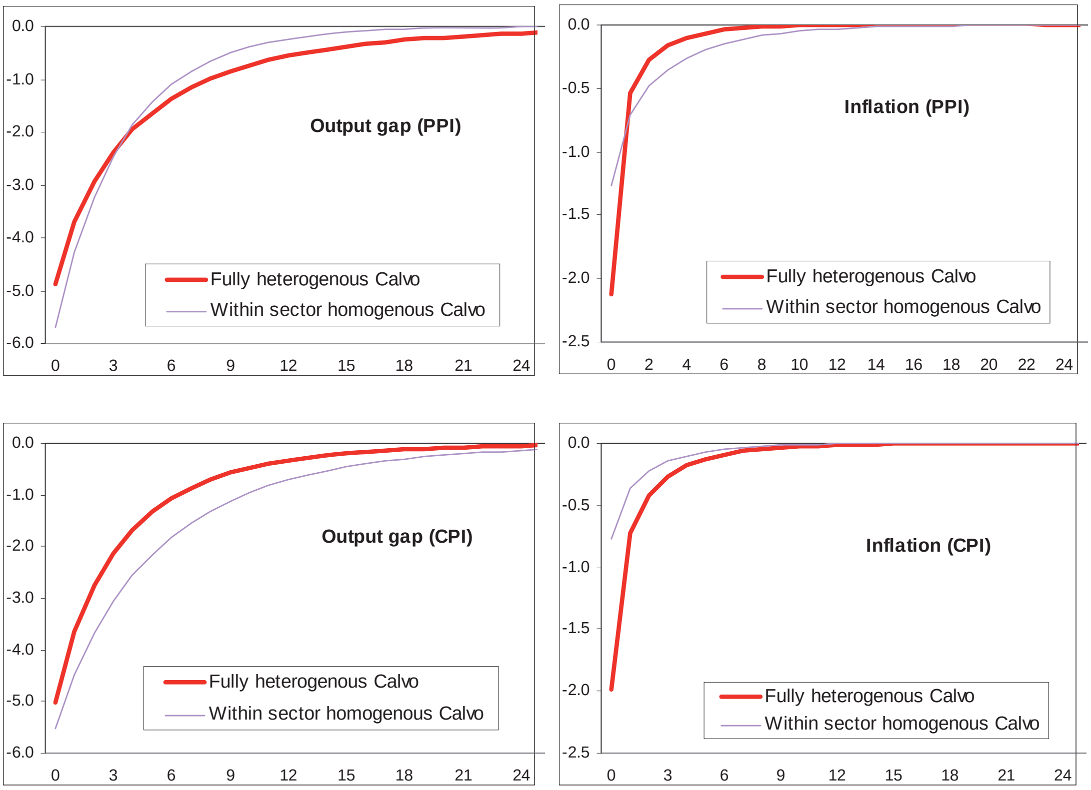


Figure 6: Impulse response functions to a monetary shock



Important distortions are also seen in terms of hazard rates. Measures of quadratic distances between fitted and observed probability mass functions and hazard functions reported in the second row of Table 1 confirm the bad performance of the WSHC model.

To assess the macro implications of failing to replicate the distribution of individual prices, we compare the impulse response functions of the DSGE model developed above under these two alternative calibrations for price setting. Figure 6 compares the impulse responses of the output gap and the inflation rate after a money shock, and Table 4 reports initial and accumulated impacts on the output gap and inflation. There are sizable quantitative differences between the fully heterogeneous Calvo model and the WSHC models in terms of the response of inflation and the output gap. Therefore, the distortions introduced by assuming no firm-level heterogeneity lead to important macroeconomic implications. In particular, the within-sector homogeneous economy is always more rigid on impact, although the accumulated effect might be greater or smaller than in a fully heterogeneous economy, mainly depending on whether this approach overestimates, as with consumer prices, or underestimates, as with producer prices, the share of more rigid firms in the economy. In fact, under the WSHC calibration for consumer prices the sacrifice ratio in the long term is five times larger than under full heterogeneity, although for producer prices it is thirty percent smaller.

5 Conclusions

In recent years, there has been a burst of papers analyzing price-setting strategies using individual consumer and producer price data. A stylized fact found in this literature is that pricing behavior, as measured by the frequency of price adjustment, is highly heterogeneous at the firm level. Major differences in the frequency of price adjustment are found not only across different goods but also for the same good sold in different cities or even within the same city if different types of outlets are analyzed. Further, differences in the frequency of price change are found to be related to a number of factors, including cost structure or market competition.

In contrast, the Calvo model, which is a central element in DSGE models, assumes that the frequency of price adjustments is the same for all price setters. In this paper, we find that the standard Calvo model clearly fails to account for the empirical distribution of price durations, a fact that is not surprising given the heterogeneity in the frequency of price adjustments. This paper proposes a novel way to capture the observed distribution of price durations found with micro data. More specifically, we develop a fully heterogenous Calvo model in which there is an infinite number of agents, each of them setting prices following a Calvo mechanism.

The distribution across the population of the Calvo price adjustment parameter is characterized by a density with only three parameters and can be easily estimated using standard maximum likelihood techniques. Our estimates using CPI and PPI Spanish data show that this model is able to accurately match the distribution of price durations.

This fully heterogenous Calvo model is then used to calibrate an otherwise standard DSGE model. We find that explicitly considering heterogeneity in price setting improves the understanding of economic fluctuations and inflation dynamics. Indeed, we find that ignoring pricing heterogeneity severely underestimates the impact of nominal shocks on real variables. We also compare our fully heterogenous model with a specification that does not allow for within-sector heterogeneity in the frequency of price adjustments. We find that this assumption is clearly at odds with the observed distribution of price durations, a fact that has important macroeconomic implications in terms of the quantitative impact of nominal shocks.

A natural area of further research is to estimate this fully heterogeneous Calvo model for other countries and develop an estimation procedure that combines aggregate and individual data. The optimal response of monetary policy and the impact of targeting core instead of headline inflation in the fully heterogenous Calvo framework are also worth investigating. Another area that deserves further attention is the development of state-dependent models that fully account for firm-level heterogeneity in terms of the frequency and size of price changes.

Appendix: Heterogeneity and decreasing population hazard rates

In this appendix, we present the relationship between the change in the hazard rate of a population of pricing agents and the change in individual hazard rates. We use a discrete time approach because this is the one most frequently used for price-setting models. The expression found is the discrete time analog of a well-known result in the failure time literature (see Proschan 1963). Interestingly, the aggregation bias in the discrete time case need not be negative in contrast to the continuos time case.

The hazard rate of price changes is defined as the probability that a price will change in period k provided that it has remained constant during the previous $k-1$ periods. We denote this by $h(k)$ and $S(k)$, the population hazard and survival rates, respectively. For simplicity, we consider an economy composed of two groups of agents with sizes s_1 and s_2 with different hazard $h^i(k)$ and survivals functions $S^i(k)$.

It is straightforward to show that the change in $h(k)$ for a given change in k is equal to

$$\frac{\Delta h(k)}{\Delta k} = \frac{\Delta h^1(k)}{\Delta k}\beta(k) + \frac{\Delta h^2(k)}{\Delta k}\left[1-\beta(k)\right] + H(k),$$

where

$$\begin{aligned} H(k) &= -\beta(k)\left[1-\beta(k)\right]\left[h^1(k)-h^2(k)\right]^2 \varepsilon(k) \\ \beta(k) &= \lambda\left(\frac{S^1(k)}{S(k)}\right) \\ \varepsilon(k) &= \left\{\frac{1+\left[h^1(k)-h^2(k)\right]^{-1}\left[\frac{\Delta h^1(k)}{\Delta k}-\frac{\Delta h^2(k)}{\Delta k}\right]\Delta k}{1-h(k)\Delta k}\right\}. \end{aligned}$$

This expression shows that the change in the population hazard rate is a convex linear combination of the change in the individual hazard rates plus a heterogeneity effect. This expression is the discrete time version of the well-known result in the failure literature (see Proschan 1963).[19] In fact, $\varepsilon(k)$ converges to one as Δk tends to zero, and the expression of $H(k)$ converges to the continuous time one. Notice, however, that in the discrete time case, in contrast with the continuous time one, the heterogeneity effect will be positive if $\varepsilon(k) < 0$.

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[19] In the duration analysis literature, it is also well known that not controlling for unobserved heterogeneity biases estimated hazard functions towards negative duration dependence.

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Alcalá, 522; 28027 Madrid
Teléfono +34 91 338 6363. Fax +34 91 338 6488
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