Price setting frequency and the Phillips curve*

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Abstract

We develop a New Keynesian (NK) model with endogenous price setting frequency. Whether a firm updates its price is a discrete choice: when expected benefits outweigh expected costs, prices are reset optimally. The model gives rise to a non-linear Phillips curve as prices are more flexible during demand-driven expansions and less so during demand-driven recessions. Monetary policy can have substantial real effects despite the model having a state-dependent pricing component. Our quantitative analysis shows that contrary to the standard NK model, the assumed price setting behaviour: (i) is consistent with micro data on price setting frequency; (ii) generates a direct effect of the time-varying price setting frequency on inflation; (iii) creates time-variation in the Phillips curve slope that explains shifts in the Phillips curve associated with different historical episodes; (iv) explains inflation dynamics without relying on implausible high cost-push shocks and nominal rigidities inconsistent with micro data; (v) reconciles the NK model with observed inflation moments.

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1 Introduction

> *'Another key development in recent decades is that price inflation appears less responsive to resource slack. That is, the short-run price Phillips curve [...] appears to have flattened, implying a change in the dynamic relationship between inflation and employment.'*
>
> (Clarida, 2019, Vice Chair, Board of Governors, Federal Reserve System)

The debate on the flattening of the Phillips curve reminds us of empirically documented historical shifts in the relationship between the output gap and inflation. As pointed out by Clarida (2019) and others, these shifts pose a challenge to frameworks for monetary policy analysis and they are again put under scrutiny. This certainly includes the New Keynesian (NK) model and its theory of the Phillips curve. At the heart of the NK model are assumptions about price setting behavior such as the popular Calvo (1983)-Yun (1996) pricing model that give rise to the Phillips Curve. The Calvo (1983) parameter θ governing the price stickiness, in turn, is the key determinant of the Phillips curve slope.

Plausible parametrizations of θ, consistent with observed price setting frequency at the micro level, make it notoriously difficult to reconcile the standard NK model with macro data. For instance, the model predicts a Phillips curve relationship that is much steeper than in the data observed in recent decades.[1] A well-known remedy are large and highly auto-correlated cost-push shocks and a high degree of nominal rigidities. Yet, this remedy creates unfortunate tension. On the one hand, these features reduce the covariance between inflation and output and improve the model's fit to inflation.

On the other hand, there are at least three concerns. First, inflation dynamics are then mostly explained by exogenous cost-push shocks (see, e.g., King and Watson, 2012; Lindé et al., 2016; Fratto and Uhlig, 2020), which is problematic because cost-push shocks lack a clear economic interpretation and fail to explain variation in other model variables (e.g.,

[1] This has undesirable implications such as the *missing deflation puzzle* (Hall, 2011), i.e., while NK models predict high deflation along with a dramatic downturn such as the *Great Recession*, one can actually observe surprisingly modest declines in inflation and a subsequent inflation-less recovery.

Del Negro et al., 2015). Second, a story for inflation based on cost-push shocks and high degrees of nominal rigidities seems implausible from the viewpoint of past recessions and expansions. For example, the Great Recession is perceived as a demand-driven downturn that caused the observed inflation and output gap dynamics during and after the crisis. A third problem, we believe, is that while high degrees of nominal price rigidities improve the NK model's fit to macro data, they are by-and-large inconsistent with observed price setting frequency at the micro level. For instance, Del Negro et al. (2015) or Guerrieri and Iacoviello (2017) estimate Calvo (1983) parameters as high as $\theta = 0.87$ or 0.9 implying an average price duration of up to 10 quarters.

Admittedly, the insight that Calvo (1983) pricing models are notoriously difficult to reconcile with observed price setting at the micro level is not new, but nevertheless important in this context.[2] A model that is consistent with macro data (e.g., variation in the Philips curve relationship over time) may still be subject to observational equivalence with many other models. If this very same model were also consistent with micro data (e.g., price setting frequency), it would clearly outperform these other models along an important dimension (see Christiano et al., 2018). For instance, Nakamura et al. (2018) use US CPI micro data from the BLS to analyze the evolution, dispersion, heterogeneity and duration of US prices. They conclude that the magnitude and frequency of price changes are heterogeneous and time-varying. Figure 1 reconstructs the weighted median price setting frequency based on the Nakamura et al. (2018) data and its relation to inflation.[3]

Most strikingly, the quarterly share of unchanged prices corresponding to the Calvo (1983) parameter varies from 0.55 to 0.78. This corresponds to an average price duration

[2] Standard menu cost models à la Rotemberg (1982) face a similar issue. At the macro level, recent menu cost estimates are implausibly high. At the micro level, these models fail to account for price dispersion.

[3] Nakamura et al. (2018) define price changes as any entry with $\ln(p_{i,t}/p_{i,t-1}) \neq 0$ within the BLS consumer goods' price tags database. They discard $\ln(p_{i,t}/p_{i,t-1}) > 1$ as inputs errors. Based on the mean frequency of price change in each CPI Entry Level Items of the remaining values, they compute the monthly expenditure-weighted medians across CPI Entry Level Items. Expenditure weights are fixed at their year 2000 value. The series is seasonally-adjusted by averaging monthly values over the previous 12 months. See Nakamura et al. (2018) (also their Figure XV) for further details.

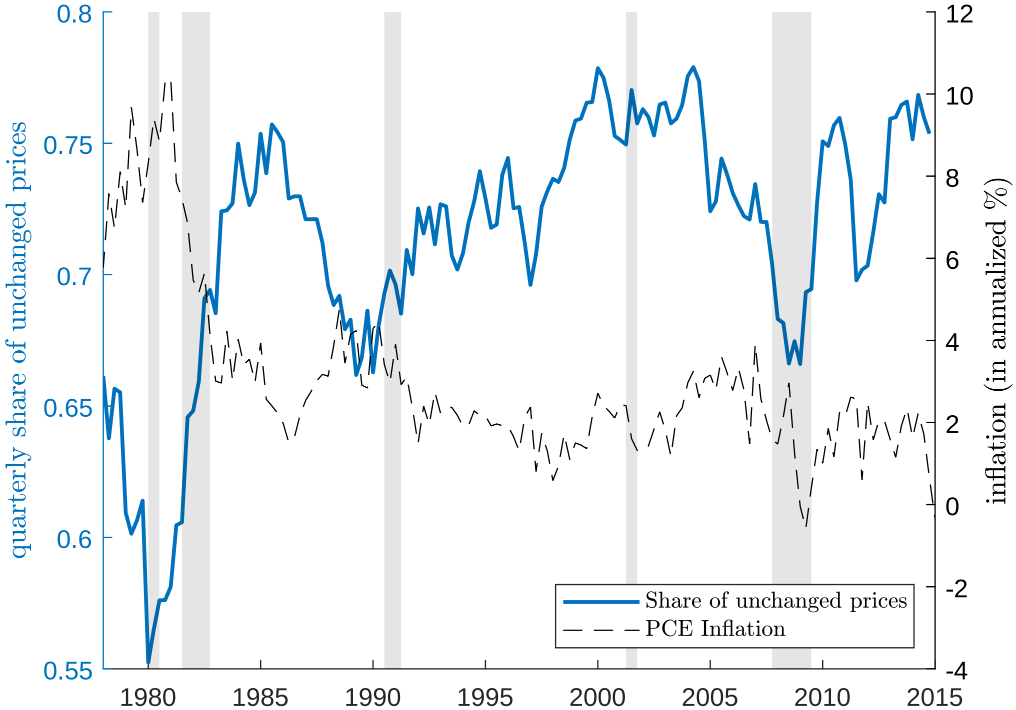


Figure 1: Quarterly share of unchanged prices and inflation, United States, 1978-2014. Inflation is the annualized log PCE growth based on DPCERD3Q086SBEA obtained via FRED. The quarterly share of unchanged prices is computed by multiplying one minus the sum of the monthly seasonally-adjusted frequencies of price in- and decreases of Nakamura et al. (2018) for the respective months.

between 2 and 4.5 quarters and implies a very large variation in the NK Phillips curve slope. Clearly, this variation and the negative correlation with inflation, -0.7893, is inconsistent with the Calvo (1983) pricing model that assumes a constant θ. Moreover, based on macro data, Fernández-Villaverde and Rubio-Ramírez (2007) show that the price setting frequency varies over time and is negatively correlated with inflation and price indexation. The evidence points to time-varying price setting frequency as an alternative explanation for the observed time-variation in the Phillips curve relationship.

Against this background, we propose to augment Calvo's (1983) time-dependent pricing model by a state-dependent component. We argue that this extension can reconcile the NK model with the observed dynamics of the Phillips curve *and* the evidence on time-varying price setting frequency at the micro level. The key novelty relative to the standard NK model is that the price setting frequency (henceforth also called Calvo share) is endogenous and time-varying. Whether a firm updates its price in a given period depends on its assessment of expected cost and benefits modelled by a discrete choice process (Brock and Hommes, 1997; Matějka and McKay, 2015). We denote this the *Calvo law of motion* and interpret it as an approximation to firms' managerial decision of whether to update the price, i.e., the extensive margin. Firms are more likely to update their prices when expected benefits outweigh expected costs and then set the price optimally. This approximation is broadly in line with state-dependent pricing models with random menu costs (e.g., Costain and Nakov, 2011a; Nakamura and Steinsson, 2010) or information constraints (Woodford, 2009). Yet, our approach retains the greater tractability of purely time-dependent pricing models. Thus, it can be applied to medium- and large-scale models, and, importantly, the models remain amenable to business cycle analysis with full information Bayesian methods.

We implement the *Calvo law of motion* in a NK model with trend inflation (Ascari and Sbordone, 2014). Our approach offers several advantages. First, the price setting frequency is no longer constant, but state-dependent and time-varying. Second, the *Calvo law of motion* captures the managerial decision process regarding price setting in line with micro evidence. This evidence shows that posting a new price is the result of a complex cost-benefit analysis by the firms' managers rather than a random process.[4] The *Calvo law of motion* models this idea by taking into account the expected present value of profits. We assume that there exists a trade off between updating and not updating current prices. Updating prices requires firms to spend resources (e.g., gather information, renegotiate contracts). In a sense, updating prices is an inherently costly dynamic process where firms face heterogeneous opportunity costs. We assume that firms decide to update their prices when it will increase the firm's expected present value of profits by more than maintaining price.

[4]For instance see Blinder et al. (1998) and Zbaracki et al. (2004) for qualitative and quantitative surveys with managers about their prices setting decisions.

For plausible parametrizations, profits are countercyclical. Around the steady state, for any given price, profits are relatively higher in a recession and relatively lower in an expansion. However, profits are more sensitive to low relative prices than to high relative prices. Thus, for a positive discount factor shock, the benefit (in present value terms) of raising the price optimally net of updating cost outweighs the cost of maintaining the price by more than for a negative discount factor shock of equal magnitude. In consequence, the model predicts that prices are more flexible during expansions and less so during recessions.

Third, another appealing feature of our approach is that the aggregate equilibrium conditions of the model are isomorphic to the standard NK model with trend inflation, except for the time-varying price setting frequency following the *Calvo law of motion*. On the one side, this implies that the proposed mechanism can be easily embedded into any DSGE model with Calvo (1983) pricing including large-scale models used in policy making institutions. On the other side, this implies that the model can be analyzed and estimated with standard tools. We exploit this fact in our quantitative analysis and estimate the model over the micro time series in Figure 1 and standard macro time series under full information. In turn, we can assess the *Calvo share*'s role in explaining shifts in the Phillips curve.

In sum, our main theoretical findings are two key model predictions. First, prices are more flexible during expansions and less flexible during recessions. The price setting frequency is positively related with inflation. It accelerates during demand-driven booms implying an accelerating inflation. In contrast, the model permits a decelerating price setting frequency during demand-driven recessions and thus allows for low, but stable inflation during times of slack. This prediction can explain variations in the Phillips curve slope documented in the data. Second, monetary policy has substantial real effects. This is a consequence of approximating the pricing decision at the extensive margin, which eliminates selection effects common to state-dependent models à la (Golosov and Lucas, 2007).

The quantitative main results of our paper are as follows. First, the proposed mechanism makes the model consistent with micro data. It provides a good approximation of the observed share of unchanged prices depicted in Figure 1. Second, the model generates a direct effect of the time-varying price setting frequency on inflation. The endogenous correlation between the share of unchanged prices and inflation is -0.6768. Third, our small-scale model also fits the observed inflation and output gap dynamics well by exploiting the theoretical Phillips curve relationship. The time-varying price setting frequency generates time-variation in the Phillips curve gradient helping the model to fit observed macro data. Fourth, the *Calvo law of motion* enables the model to explain observed inflation data to a large extent by discount factor and monetary policy shocks as well as the endogenous evolution of the price setting frequency. Fifth, the role of cost-push shocks is very limited.[5] Finally, the proposed mechanism gives rise to a non-linear Phillips curve implying asymmetrical effects on inflation in line with observed inflation moments.

Related literature. Our paper is related to a large literature relying on the seminal Calvo (1983)-Yun (1996) pricing model to generate a Phillips curve. We contribute to this literature by proposing a modified pricing model that gives rise to a time-varying price setting frequency. This modification is in part motivated by discussions about the stability of the Calvo parameter as in Fernández-Villaverde and Rubio-Ramírez (2007), Alvarez et al. (2011) or Berger and Vavra (2018) and its consistency with the paradigm of micro-founded models.[6] Therefore, also Davig (2016)'s implementation of Phillips curve shifts via a quadratic price adjustment cost following a two state Markov process is closely related to ours.

In contrast, the *Calvo law of motion*, our proposed modification to the NK model is essentially a discrete choice model inspired by Brock and Hommes (1997). Moreover, our proposal is within the realm of the Calvo (1983) pricing model and introduces an explicit

[5]These results are consistent with the findings in Del Negro et al. (2020) on the flattening of the price Phillips Curve.

[6]See Chari et al. (2009), Plosser (2012) and Lubik and Surico (2010) for discussions of sticky price models being subject to the Lucas Critique and see Caplin and Spulber (1987) and Gertler and Leahy (2008) for sticky price models explicitly aimed at addressing the Lucas Critique. Finally, see Bakhshi et al. (2007) and Levin and Yun (2007) for a model with an endogenous foundation of the price setting frequency with respect to its relation to trend inflation.

cost-benefit analysis of price updating. While modelling the decision of whether to update the price as a discrete choice is a novelty within the time-dependent NK model, a well-established literature has used discrete choice processes in NK models for modelling expectations and belief formation (see, e.g., Branch, 2004; Branch and McGough, 2010; Branch and Evans, 2011; Hommes and Lustenhouwer, 2019; Branch and Gasteiger, 2019).[7]

Although the use of the Calvo law of motion is inspired by a different strand of the literature, it is reminiscent of the random menu cost models by Costain and Nakov (2011a,b, 2015, 2019); Costain et al. (2022). In these models, individual firms are subject to control cost and decide optimally about when and how they reset their price. Thereby a firm also takes the effect on its own future probability of adjustment into account. Consequently, the price setting frequency has a micro-foundation. Moreover, next to aggregate shocks, these models use idiosyncratic shocks to account for the cross sectional distribution of price adjustment observed in the data. Despite these advantages, it is not straightforward how one can solve and estimate such models with full information Bayesian methods. As the latter is an essential exercise in our paper, we deliberately approximate these important aspects of price resetting in reduced form.

Our quantitative work also relates to state or time-dependent sticky price models based on micro-econometric evidence.[8] In a series of papers, Nakamura and Steinsson (2008), Nakamura and Steinsson (2013) and Nakamura et al. (2018) develop a thorough analysis of the implications of *heterogeneous* menu costs models and their fit to micro data constructed using BLS price tag data. We apply the Nakamura et al. (2018) data to match one dimension of it: the price setting frequency. In related work, Gagnon (2009), Klenow and Kryvtsov (2008) and Alvarez and Burriel (2010) obtain similar conclusions about the inconsistency of the Calvo (1983) pricing model with pricing data at the micro level as, for instance, Nakamura et al. (2018). The models proposed in that literature fit better the cross-sectional

[7]Woodford (2009) generalizes a state-dependent pricing model with a discrete choice approach. Therein the frequency of price adjustment is determined optimally at the firm level under rational inattention.

[8]Theoretical and empirical implications of those models are extensively discussed in Alvarez et al. (2017).

price dynamics because of the heterogeneity in price stickiness and idiosyncratic shocks.[9] The proposed *Calvo law of motion* in this paper captures this heterogeneity in reduced form.

Our paper is also related to multisector menu cost models such as Nakamura and Steinsson (2010)'s *CalvoPlus* model or more recently Gautier and Le Bihan (2022). Therein firms reset their price at a zero or low menu cost with a certain probability. With the converse probability firms face a potentially high idiosyncratic menu cost. This combination of state- and time-dependent pricing matches the observed distribution of frequency and size of price changes in the cross-section. Moreover, it generates a plausible degree of money non-neutrality, mostly because of the time-dependent component. We use a combination of state- and time-dependent pricing to reconcile the NK model with the observed shifts of the Phillips curve and the evidence on time-varying price setting frequency at the micro level.

Finally, our non-linear analysis complements the rapidly expanding discussion on the explanations and implications of the empirically documented nonlinearity and flattening of the Phillips curve. For instance, Mavroeidis et al. (2014) discuss inflation expectations as an explanation of the observed data. Aruoba et al. (2017) and Forbes et al. (2021) point toward the non-linearity in price and nominal wages adjustment costs. Moreover, Harding et al. (2022) resolve the missing deflation puzzle with the use of the Kimball aggregator.

The rest of the paper is organized as follows. Section 2 embeds the endogenous price setting frequency in a standard NK model with trend inflation. Section 3 illustrates the model predictions. Section 4 contains the quantitative analysis based on micro and macro data. Section 5 concludes.

[9]Another related branch of the literature are the sticky information models (see, e.g., Mankiw and Reis, 2002; Mankiw et al., 2003). These papers introduce sticky price models based on the frequency of forecast updating by firms. Firms have a probability to update their forecasts and thus their prices. Those models generate meaningful price dispersion, forecast behaviour, cross-sectional dynamics and stickiness. Yet, the updating probability is fixed as in the Calvo-Yun model because observing the world is costly. Thus, the concerns regarding the Calvo-Yun model also apply to this branch of the literature.

2 The augmented NK model

We begin with developing a textbook NK model augmented with the Calvo law of motion. The novelty in the model is that the time-varying share of maintained prices θ_t enters the forward-looking profit maximization problem of intermediate firms. Most other parts of the model are identical to Ascari and Sbordone (2014). Therefore we focus on the departures from this model, namely the intermediate firms' price setting problem and the Calvo law of motion proposed in this paper.

2.1 The firm's price setting problem

First, we discuss the intermediate firms' price setting problem. Intermediate firms maximize the expected present value of profits over an infinite horizon by applying the stochastic discount factor. In addition, similar to the standard NK model, they apply the same current and expected future share of unchanged prices θ_t. It is important to stress the latter. If all firms face the same independent probability θ_t of not being able to adjust their prices in period t, there are no selection effects, which typically emerge in state-dependent pricing models (Golosov and Lucas, 2007). Moreover, when prices are changed, the share of unchanged prices θ_t is taken as given by all firms. Consequently, firms do not consider the effect of their decision on future θ_t.

Formally, the problem is

$$\max_{P_t^*} \ \mathbb{E}_t \sum_{j=0}^{\infty} \mathcal{D}_{t,t+j} \left(\prod_{k=0}^{j} \theta_{t+k} \right) \theta_t^{-1} \left[\frac{P_t^*}{P_{t+j}} - w_{t+j} \right] Y_{i,t+j} \tag{1}$$

$$\text{s.t. } Y_{i,t+j} = \left(\frac{P_t^*}{P_{t+j}} \right)^{-\epsilon} Y_{t+j},$$

where $\mathcal{D}_{t,t+j} \equiv \beta^j \frac{\lambda_{t+j}}{\lambda_t}$ is the stochastic discount factor with λ_{t+j} denoting the $t+j$ marginal utility of consumption and the discount factor $\beta \in (0,1)$.[10] Because we assume a linear production function for intermediate goods producers, real marginal cost equal the real wage w_t. P_t is the aggregate price level, Y_t is the aggregate output level, $Y_{i,t}$ is demand for the good of firm i and $\epsilon > 1$ is the price elasticity of demand. The optimal price for the resetting firm, P_t^*, has to satisfy the first-order necessary condition for an optimum

$$P_t^* = \frac{\epsilon}{\epsilon - 1} \frac{\mathbb{E}_t \sum_{j=0}^{\infty} \left(\prod_{k=0}^{j} \theta_{t+k} \right) \theta_t^{-1} \mathcal{D}_{t,t+j} (P_{t+j}^{\epsilon} Y_{t+j} w_{t+j})}{\mathbb{E}_t \sum_{j=0}^{\infty} \left(\prod_{k=0}^{j} \theta_{t+k} \right) \theta_t^{-1} \mathcal{D}_{t,t+j} (P_{t+j}^{\epsilon-1} Y_{t+j})}. \tag{2}$$

Moreover, the aggregate price level evolves according to

$$P_t = \left(\theta_t P_{t-1}^{1-\epsilon} + (1-\theta_t) P_t^{*\,1-\epsilon} \right)^{\frac{1}{1-\epsilon}}. \tag{3}$$

We define $\Pi_{t,t+j}$ as the cumulative gross inflation between t and $t+j$

$$\Pi_{t,t+j} \equiv \begin{cases} \frac{P_{t+1}}{P_t} \times \cdots \times \frac{P_{t+j}}{P_{t+j-1}} & \text{for } j = 1, 2, ... \\ 1 & \text{for } j = 0. \end{cases}$$

Dividing both sides of (2) by P_t, we obtain

$$p_t^* = \frac{\epsilon}{\epsilon - 1} \frac{\mathbb{E}_t \sum_{j=0}^{\infty} \left(\prod_{k=0}^{j} \theta_{t+k} \right) \theta_t^{-1} \mathcal{D}_{t,t+j} \Pi_{t,t+j}^{\epsilon} Y_{t+j} w_{t+j}}{\mathbb{E}_t \sum_{j=0}^{\infty} \left(\prod_{k=0}^{j} \theta_{t+k} \right) \theta_t^{-1} \mathcal{D}_{t,t+j} \Pi_{t,t+j}^{\epsilon-1} Y_{t+j}}, \tag{4}$$

where $p_t^* \equiv P_t^*/P_t$ is the optimal relative price. By applying the definition of gross inflation,

[10] Following Ascari and Sbordone (2014), we assume a period utility function $U(C_t, N_t; \epsilon_t^d, \epsilon_t^s) = \begin{cases} \left(\frac{C_t^{1-\sigma}}{1-\sigma} - \chi \exp(\epsilon_t^s) \frac{N_t^{1+\varphi}}{1+\varphi} \right) \exp(\epsilon_t^d) & \text{for } \sigma \neq 1 \\ \left(\log(C_t) - \chi \exp(\epsilon_t^s) \frac{N_t^{1+\varphi}}{1+\varphi} \right) \exp(\epsilon_t^d) & \text{for } \sigma = 1 \end{cases}$, where $\sigma, \varphi, \chi \geq 0$. C_t and N_t denote consumption and labor. ϵ_t^d and ϵ_t^s are a discount factor and a labor supply shock. We interpret the latter as a cost-push shock.

$\pi_t \equiv P_t/P_{t-1}$, and by using (3), we can express the aggregate price level dynamics by

$$1 = (\theta_t \pi_t^{\epsilon-1} + (1-\theta_t) p_t^{*\,1-\epsilon})^{\frac{1}{1-\epsilon}}.$$

It also follows that we can rewrite (4) recursively as

$$p_t^* = \frac{\epsilon}{\epsilon - 1}\frac{\psi_t}{\phi_t}, \qquad \text{where} \tag{5}$$

$$\psi_t = Y_t^{1-\sigma} w_t + \mathbb{E}_t \beta \theta_{t+1} \pi_{t+1}^{\epsilon} \psi_{t+1}, \tag{6}$$

$$\phi_t = Y_t^{1-\sigma} + \mathbb{E}_t \beta \theta_{t+1} \pi_{t+1}^{\epsilon-1} \phi_{t+1}. \tag{7}$$

As we discuss next, θ_t and therefore the optimal reset price p_t^* in (5) depend on the current and expected future profit generated by this price. These assumptions generate a complex feedback loop between the pricing and the resetting decision.

2.2 The Calvo law of motion

This paper proposes a model where firms are run by managers who, in principle, consider resetting the price for their firm's goods in each period. Managers base the strategic decision of updating or not updating the price optimally on a cost-benefit analysis.

The benefit of optimally updating the price is quantified based on the expected present value of the firm's profits when setting p_t^*, which we denote U_t^*. Computing the latter requires coordination within the firm that comes at a cost τ that has to be taken into account, say, a meeting to establish what is the optimal price in period t. More generally, in line with Zbaracki et al. (2004), τ may capture information acquisition, contract revisions, negotiations, working time, agency cost, or, simply menu costs (Rotemberg, 1982). Thus, only if the expected present value of the firm's profits implied by p_t^* net of the cost outperforms the expected benefit of maintaining the price, managers will reset the price.

Yet, there is an additional subtle but essential point that has to be taken into account when computing the benefit of maintaining the price. Even in a model with a fixed parameter θ, maintaining the price has fundamentally different implications for each individual firm. Each firm i has a different old price and thus faces a different opportunity cost of changing the price $U_{i,t}^f$. This heterogeneity among firms increases the complexity in quantifying the benefit of maintaining the price at the cost of model tractability.

We sidestep this complex issue for the sake of tractability and quantify the benefit of maintaining the price as the expected present value of the firm's profits when choosing the average relative old price level in the economy $p_t^f \equiv P_t^f / P_t$ at no cost. We denote this benefit $U_{i,t}^f = U_t^f \; \forall i$, which we interpret as the average benefit of maintaining the price.[11] We also abstract from idiosyncratic shocks and assume that the cost τ is common to all firms. These assumptions set the model apart from state-dependent pricing models in the tradition of Golosov and Lucas (2007) as they eliminate the selection effect. Yet, they allow us to approximate the variation in θ_t in reduced form by building on Brock and Hommes (1997) and assuming the following *Calvo law of motion* for the share of unchanged prices

$$\theta_t = \frac{\exp\left(\omega U_t^f\right)}{\exp\left(\omega U_t^f\right) + \exp\left(\omega\left(U_t^* - \tau + \epsilon_t^\theta\right)\right)}, \tag{8}$$

where $\theta_t \in [0,1]$ and $(1-\theta_t)$ denotes the share of updated prices. Parameter $\omega \geq 0$ is denoted the *intensity of choice* and formalizes the idea that every period some firms update their prices and others do not as long as $\omega < \infty$. Thus, this parameter captures the above discussed heterogeneity of firms in reduced form. ϵ_t^θ follows a stationary exogenous process. The shock captures exogenous variation in the managers' cost of updating their price. We only use this shock for estimation purposes in Section 4 below. The shock is neither essential for generating results nor do we interpret it as structural. We call it resetting shock.

[11] An alternative would be to compute U_t^f as the average of profits over the distribution of existing prices. However, this would imply a substantial loss of tractability.

The present value of expected profits implied by the pricing decision $x \in \{*, f\}$ is obtained by evaluating the firm's objective function (1) at relative price p_t^x. Recursively this is

$$U_t^x = \left(p_t^{x^{1-\epsilon}} \phi_t - p_t^{x^{-\epsilon}} \psi_t\right) Y_t^{\sigma}, \tag{9}$$

where ψ_t and ϕ_t are given by (6) and (7).[12,13] Figure 2 illustrates the properties of (8).

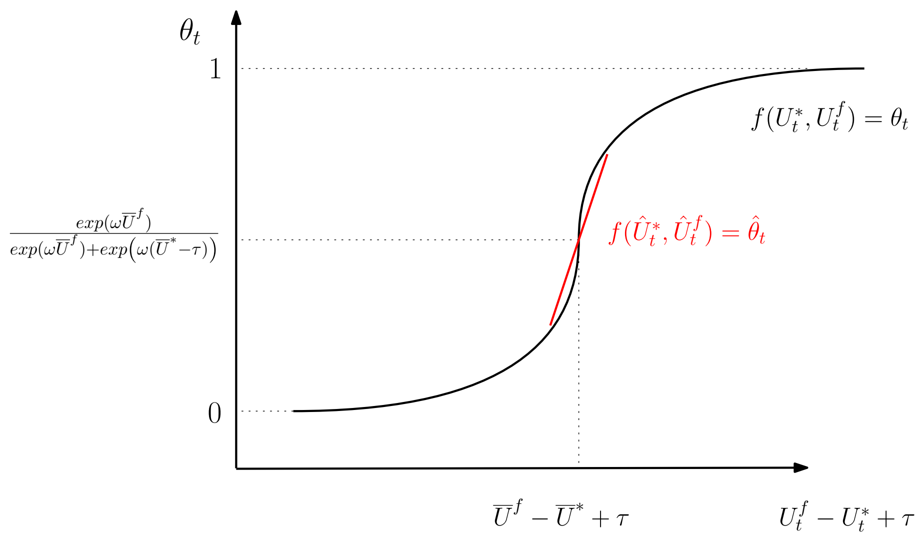


Figure 2: The Calvo law of motion (black) and its linearised form (red).

One can observe several worthwhile features from Figure 2. The function is bounded between zero and one. In steady state, θ is determined by the intensity of choice ω, the updating cost τ and the present values of profits $\overline{U}^*$ and $\overline{U}^f$.[14] For instance, a zero inflation

[12] This specification nests the standard Calvo pricing model for $\omega \to 0$. Moreover, note that (8) implies $(1 - \theta_t) = 1/\left[\exp\left(-\omega\left(U_t^* - U_t^f - \tau + \epsilon_t^{\theta}\right)\right) + 1\right]$. This functional form corresponds to the one assumed or derived for the individual firm price resetting probability in random menu cost models such as Costain and Nakov (2011a,b), or, more recently Costain and Nakov (2019) and Costain et al. (2022). In particular, it resembles a random menu cost model with a logistic distribution of menu costs with standard deviation $\pi/(\omega\sqrt{3})$, where one can interpret τ as the mean, $1/\omega$ as the scale parameter. However, in our reduced form approach, we do not endogenize θ_t at the individual firm level. Therefore, in contrast to random menu cost models, in our model firms do not consider the effect of the price setting decision on future θ_{t+j}. The quantitative importance of the latter channel is an open empirical question beyond the scope of our paper.

[13] Woodford (2009) shows that the functional form in (8) for a binary choice (adjust or not) can also be derived from a model where the frequency of price adjustment is determined optimally under rational inattention. The finding that rational inattention to discrete choices gives rise to a logit model has been generalized in Matějka and McKay (2015) and Matějka (2016).

[14] Note that trend inflation has a direct effect on the steady state price setting frequency. The higher trend inflation, $\overline{\pi} > 1$, the higher the difference between relative prices, $\overline{p}^* > \overline{p}^f$, and the larger the difference

steady state implies $\overline{p}^* = \overline{p}^f$ and therefore $\overline{U}^* = \overline{U}^f$. With zero updating cost, $\tau = 0$, this in turn implies a share of $\theta = 1/2$. Moreover, in steady state the Calvo law of motion nests pure time-dependent pricing for $\omega \to 0$ as in the standard Calvo model.

However, out of steady state, managers' cost-benefit analysis implies state-dependent pricing. In states where the benefit of updating the price outweighs the cost, the share of firms that update their price increases. In states where the cost of updating the price outweighs the benefit, the share of unchanged prices increases. As we show below, for standard parametrizations, the incentive to optimally update the price is stronger in expansions and weaker in recessions. In the NK model, profits are countercyclical and their price sensitivity varies between high and low relative prices: in the neighborhood of the steady state, for any given price, profits and therefore their present value are relatively higher in a recession and relatively lower in an expansion. Via (9) this leads to the prediction that in recessions U_t^f exceeds $U_t^* - \tau$ and the opposite is true in expansions.

While finite ω and τ as well as modest variations of profits imply that θ_t varies between zero and one, the two polar cases $\theta_t = 0$ and $\theta_t = 1$ are feasible. Fully flexible prices, $\theta_t = 0$, emerge if either $U_t^* \to +\infty$ or $U_t^f \to -\infty$. In these extreme cases the benefit of optimally resetting the price will always outweigh the cost and the economy behaves similar to a flexible price economy. In the case of fixed prices, $\theta_t = 1$, the optimal price is constant. Firms charge the desired markup over steady state marginal cost. This becomes feasible if either $\tau \to +\infty$, $U_t^* \to -\infty$ or $U_t^f \to +\infty$. These are extreme cases, where the cost of optimally resetting the price will always outweigh the benefit.

Also ω is a crucial parameter in determining price setting behavior in our model. Above we interpret it as measuring how rational and heterogeneous agents are in the strategy selection (Brock and Hommes, 1997). If $\omega \to 0$, then θ is constant as in Calvo (1983) and pricing is entirely time-dependent. On the other hand, when $\omega \to +\infty$, all managers consider

in implied steady state present values of profits, $\overline{U}^* > \overline{U}^f$. Thus, the higher trend inflation, the higher the price setting frequency, the lower $\overline{\theta}$. This is an interesting implication in line with the ones by Levin and Yun (2007) and Bakhshi et al. (2007), where higher trend inflation also leads to higher price resetting frequency.

the whole information set and do the optimal trade off between both strategies. This leads to the extreme case where $\theta_t \in \{0, 1\}$. However, while the true ω is an empirical question, we do not consider $\omega \to +\infty$ to be a likely case even if strategy selection is entirely rational.[15]

2.3 The complete model

Our model is very similar to a standard NK model with trend inflation, (see, e.g., Ascari and Sbordone, 2014) as we only add the Calvo law of motion. The complete non-linear system of model equations is as follows. Solving the household optimization problem gives the two first-order conditions in equilibrium

$$\textbf{Aggregate demand:} \quad Y_t^{-\sigma} \exp(\epsilon_t^d) = \beta \mathbb{E}_t \left\{ \frac{(1+i_t)}{\pi_{t+1}} Y_{t+1}^{-\sigma} \exp(\epsilon_{t+1}^d) \right\}$$

$$\textbf{Labor supply:} \quad w_t = \exp(\epsilon_t^s) \chi N_t^{\varphi} Y_t^{\sigma},$$

where i_t is the nominal interest rate. The assumed price setting mechanism gives rise to the following aggregate supply equations

$$\textbf{Price setting frequency:} \quad \theta_t = \frac{\exp\left(\omega U_t^f\right)}{\exp\left(\omega U_t^f\right) + \exp\left(\omega\left(U_t^* - \tau + \epsilon_t^\theta\right)\right)},$$

$$\textbf{Value of firm:} \quad U_t^x = \left(p_t^{x\,1-\epsilon} \phi_t - p_t^{x\,-\epsilon} \psi_t\right) Y_t^{\sigma} \quad \text{for} \quad x \in \{*, f\}$$

$$\textbf{Optimal relative reset price:} \quad p_t^* = \frac{\epsilon}{\epsilon - 1} \frac{\psi_t}{\phi_t}$$

$$\psi_t = w_t Y_t^{1-\sigma} + \mathbb{E}_t \beta \theta_{t+1} \pi_{t+1}^{\epsilon} \psi_{t+1}$$

$$\phi_t = Y_t^{1-\sigma} + \mathbb{E}_t \beta \theta_{t+1} \pi_{t+1}^{\epsilon-1} \phi_{t+1}$$

$$\textbf{Average relative old price:} \quad p_t^f = 1/\pi_t$$

$$\textbf{Inflation:} \quad 1 = \left(\theta_t \pi_t^{\epsilon-1} + (1-\theta_t) p_t^{*\,1-\epsilon}\right)^{\frac{1}{1-\epsilon}}$$

[15] Brock and Hommes (1997) argue that when $\omega \to +\infty$ the Calvo law of motion reaches the *neoclassical limit* where $\theta_t \in \{0, 1\}$ is *rational* because it is always optimal.

$$\textbf{Price dispersion:} \quad s_t = (1-\theta_t) p_t^{*\,-\epsilon} + \theta_t \pi_t^{\epsilon} s_{t-1}$$

$$\textbf{Aggregate output:} \quad Y_t = N_t / s_t.$$

The nominal interest rate follows a standard Taylor rule

$$\textbf{Monetary policy:} \quad \left(\frac{1+i_t}{1+\bar{\imath}}\right) = \left(\frac{1+i_{t-1}}{1+\bar{\imath}}\right)^{\rho} \left(\left(\frac{\pi_t}{\overline{\pi}}\right)^{\phi_\pi} \left(\frac{Y_t}{\overline{Y}}\right)^{\phi_y}\right)^{(1-\rho)} \exp(\epsilon_t^r),$$

where ϵ_t^r is a monetary policy shock and we assume that $\phi_\pi, \phi_y \geq 0$ and $\rho \in [0,1]$. Regarding the evolution of exogenous shock processes, we assume

$$\textbf{Cost-push shock:} \quad \epsilon_t^s = \rho_s \epsilon_{t-1}^s - \mu_s u_{\epsilon^s, t-1} + u_{\epsilon^s, t}$$

$$\textbf{Other shocks:} \quad \epsilon_t^j = \rho_j \epsilon_{t-1}^j + u_{\epsilon^j, t}, \qquad \text{where} \qquad j \in \{d, r, \theta\},$$

with $0 \leq \rho_j, \rho_s < 1$, $0 \leq \mu_s < 1$ and $u_{\epsilon^j,t}, u_{\epsilon^s,t} \sim \text{iid } \mathcal{N}(0, \sigma_j^2)$.

Following the literature (see, e.g., Smets and Wouters, 2007), we model the cost-push shock as an ARMA(1,1) process. This allows the model to better capture the high-frequency movements in inflation and gives more potential to the model to explain inflation simply by cost-push shocks and without relying on the Calvo law of motion.

Two remarks are worthwhile. First, as one can see from the equation for price dispersion s_t above, the time-varying price setting frequency can amplify or mute the non-monotonic behavior of price dispersion (see Appendix A.1 for more details). Second, non-zero trend inflation, $\overline{\pi} \neq 1$, is *not* essential to the non-linear model. However, it is to the log-linear approximation of the model. In the latter, it is essential in the sense that the time-varying price setting frequency would be ineffective in the special case of zero trend inflation, $\overline{\pi} = 1$ (see Appendix A.3). This is not a concern for our analysis. We do resort to log-linear approximation in parts of the quantitative analysis in Section 4 below. However, there we find that the special case $\overline{\pi} = 1$ is not supported by the data.

3 Asymmetric model dynamics

In this section, we use Fair and Taylor's (1983) method to simulate non-linear impulse responses in order to illustrate two important features of the augmented NK model: (i) asymmetric dynamics in the Phillips curve and (ii) substantial real effects of monetary policy, despite the model having a state-dependent pricing component.

3.1 Calibration

We use a standard calibration mostly based on Galí (2015), see Table 1. The results are robust to different calibrations. The intensity of choice, $\omega = 10$, is taken from the range common in the literature on heuristic switching models. We choose τ in such a way that it implies a steady state value of $\overline{\theta} = 0.75$. This is a standard value in the NK literature implying an average price duration of four quarters. The quarterly inflation trend corresponds to the average log growth rate of the US personal consumption expenditures (PCE) implicit price deflator index between 1964 and 2019. We follow Ascari and Ropele (2009) and set the Frisch elasticity φ to zero. In this way, we shut down the effect of price dispersion on labor supply. As a result marginal cost do not depend on price dispersion and we obtain a clear illustration of the proposed mechanism. The parametrization of shocks is solely for illustrative purposes, but in line with findings in the literature.

3.2 Demand-side shocks and the Phillips curve

Figure 3 displays the simulated impulse response functions to a *positive* and *negative* 2.5 percent discount factor shock, $u_{\epsilon^d,0}$.[16] We start with the benchmark of time-invariant $\overline{\theta}$ (black

[16] This choice implies a change in the real interest rate of $(1 - \rho_d)u_{\epsilon^d,0} = \pm 0.5$ percent on impact. The persistence of the shock, $\rho_d = 0.8$ corresponds to a half-life of about 3 quarters and an unconditional standard deviation of 4.2 percent. Thus, the discount factor shocks considered here are quite substantial. For instance, in the standard NK model, the negative shock implies an accumulated decline of real GDP of approximately 4 percent over 7 quarters, which is in line with experience of the Great Recession.

Price setting		Value	Source
ω	Intensity of choice	10	-
$\overline{\theta}$	Calvo share	0.75	Galí (2015)
Monetary authority			
ϕ_π	MP. stance, π_t	1.5	Galí (2015)
ϕ_y	MP. stance, Y_t	0.125	Galí (2015)
ρ	Interest-rate smoothing	0	-
$\overline{\pi}$	Gross inflation trend	1.008387	Average log growth of PCE implicit price deflator, 1964-2019
Preferences and technology			
β	Discount factor	0.99	Galí (2015)
σ	Relative risk aversion	1	Galí (2015)
φ	Inverse of Frisch elasticity	0	Ascari and Ropele (2009)
ϵ	Price elasticity of demand	9	Galí (2015)
Exogenous processes			
ρ_d	Discount factor shock, AR(1)	0.8	illustrative purpose
ρ_r	MP shock, AR(1)	0.8	illustrative purpose

Table 1: Calibrated parameters for dynamic simulations (quarterly basis).

dashed line). A *positive* discount factor shock raises output and real marginal cost, equal to w_t, on impact above their steady state level. Firms that can reset the price raise their price to stabilize their markups and thus profits. In consequence, on impact, p_t^* and π_t increase, p_t^f must decline and price dispersion increases. Due to our calibration of the monetary policy rule, the nominal interest rate increases in response to rising inflation and output. The subsequent periods show a persistent monotonic convergence of endogenous variables (except for s_t) toward their steady state levels. This is due to the shock persistence, which implies that a fixed share of firms will revise their price upward each period until marginal cost have returned to their steady state value.

Relative to the standard model, a time-varying θ_t (blue dashed line) has novel and important implications: while the responses of output and real marginal cost are muted on impact, the responses of nominal variables are amplified on impact. The boom in demand implies that the cost-benefit analysis modelled by (8) leads more managers to the conclusion

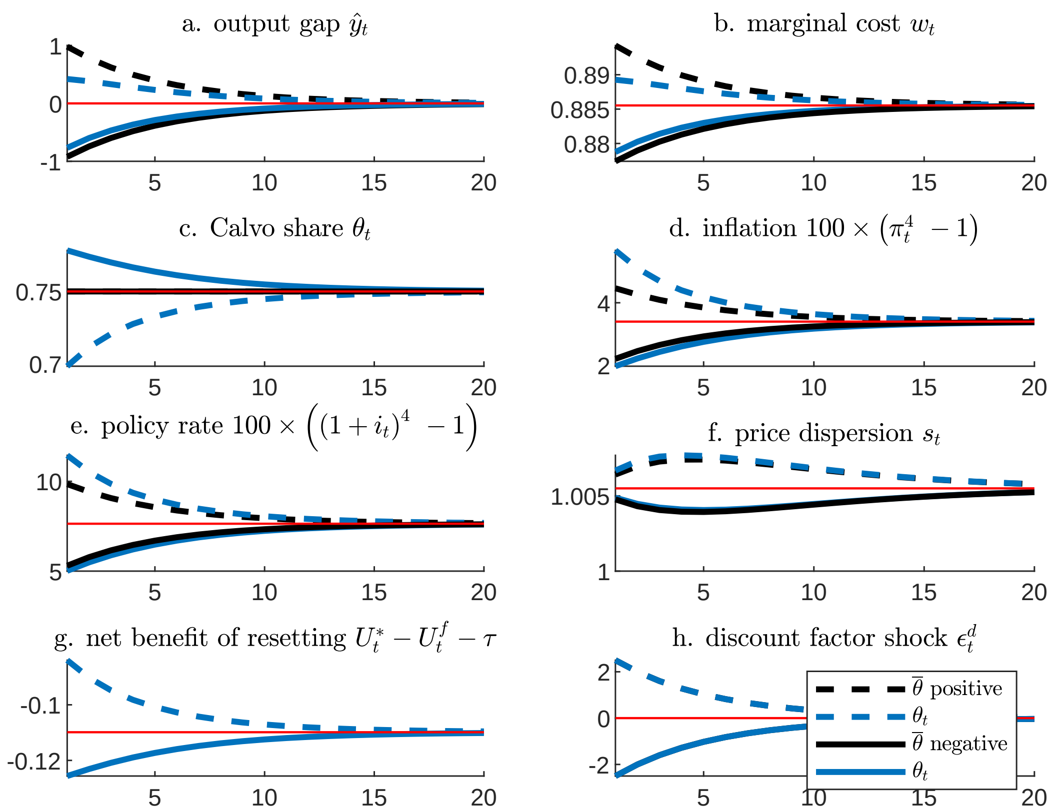


Figure 3: Asymmetric impulse responses to a positive or negative ($\pm 2.5\%$) discount factor shock in the NK model.

that raising the price, net of the cost τ, implies a higher benefit relative to not raising the price. This can be seen from the term $U_t^* - U_t^f - \tau$ in Panel g. Therefore θ_t declines and firms that optimally raise their price anticipate that more prices will be increased during the expansion. This translates into higher inflation and price dispersion on impact. The latter rationalizes both the more aggressive response of monetary policy and the muted response of output and real marginal cost on impact. Subsequent periods are characterized by a similar convergence pattern as in the standard model.

Next, we turn to the impulse response functions to a *negative* 2.5 percent discount factor shock in Figure 3. In the benchmark case with time-invariant $\overline{\theta}$ (black solid line), the impulse responses and the economic intuition behind them are exactly the opposite of the positive discount factor shock. This involves lower inflation as firms that can update the price, are lowering it optimally. However, in the case of time-varying θ_t (blue solid line), the responses in a recession reveal a striking asymmetry compared to an expansion.

In striking contrast to the effects of a positive discount factor shock, the impulse response functions behave rather similarly to the standard model. In particular, the cost-benefit analysis of managers leads them to the conclusion that lowering the price net of the cost implies a lower benefit relative to maintaining the price, see $U_t^* - U_t^f - \tau$ in Panel g. Thus, a lower share of managers intends to reset the price, and fewer firms actually do so. Firms that keep their price experience lower demand for their good. Contrary, firms that optimally lower their price stabilize their markups at relatively higher demand for their good. Note that inflation declines by more than in the standard model. Firms that optimally lower the price take into account that fewer prices will be lowered initially, but prices become increasingly flexible afterward. The relative advantage of not resetting the price dies out as real marginal costs monotonically increase toward their steady state. Thus, θ_t reverts back to its steady state as well.

Overall, in a recession θ_t is less responsive than in an expansion caused by a shock of equal magnitude. Therefore the amplification of the responses of nominal variables is relatively weaker and the responses of real variables is relatively larger.

Building intuition. It is obvious from above that the behavior of the price setting frequency θ_t drives in the asymmetric responses to the discount factor shock. Thus, one may wonder why there is no increase in the price setting frequency in a recession?

The reason is that θ_t depends on the expected present value of real profits via (8). In the NK model, profits are countercyclical and the sensitivity of profits to prices varies between high and low relative prices. If a firm optimally resets the price in a recession, this implies to choose a lower relative price. However, if there is a subsequent recovery, the firm with a lower relative price, sells a sub-optimal *high* volume at a low, eventually negative profit. Contrary, a firm optimally chooses a high relative price in an expansion. If there is a subsequent slowdown, such a firm sells a sub-optimal *low* volume, but at a positive profit.

Firms consider all possible future states of the world, when computing the optimal price based on (9). Moreover, they take into account that they may get stuck at this price, at least for some periods. Thus, U_t^* may be lower in a recession relative to an expansion of equal magnitude. In order to clarify this point, recall (9). Based on the calibration in Table 1, Figure 4 depicts the present value in steady state, $U^*(\overline{p}^*)$, and the same quantity as a function of arbitrary relative prices, $U^i(p_i)$ (red), when holding all variables at their steady state. The blue line is computed similarly, but considers a lower output level. The blue dashed line considers a higher output level.

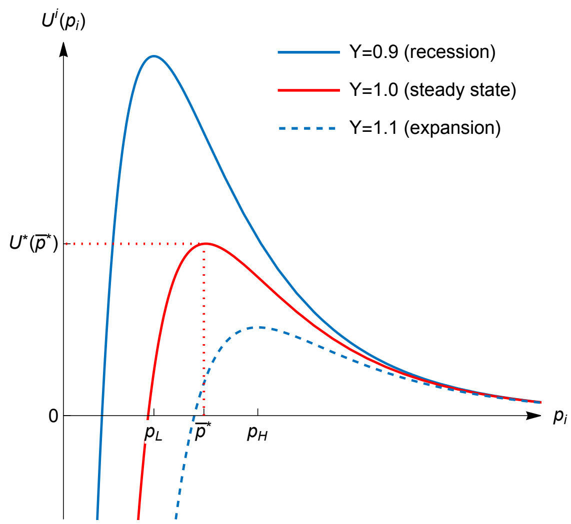


Figure 4: Comparative statics: present value of real profits as function of relative price at different levels of output.

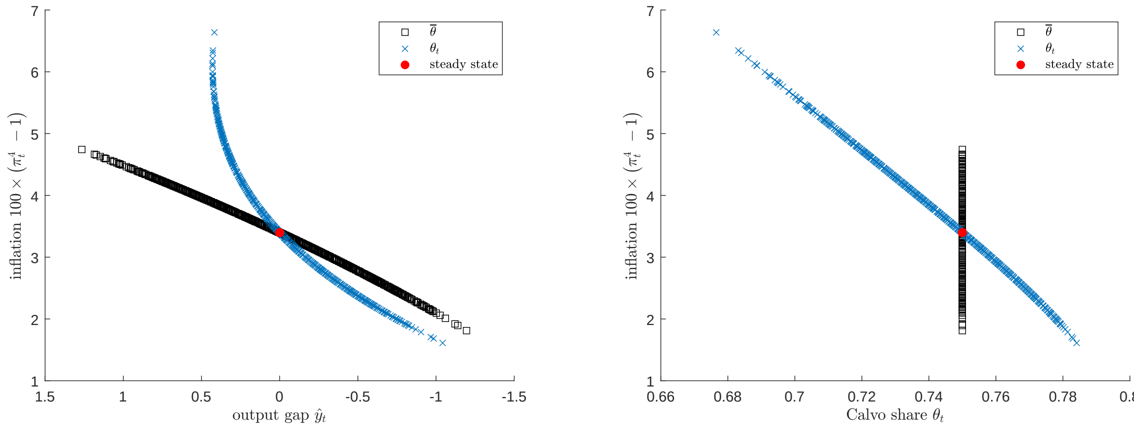
In steady state with positive trend inflation, it holds that $Y = 1$ and $\overline{p}^* \approx 1.03$. All else equal, in an expansion, $Y = 1.1$, a higher relative price, say p_H, implies a positive $U^i(p_H)$ in the expansion, steady state and recession. Contrary, in a recession, $Y = 0.9$, a lower relative price, say p_L, implies a relatively large positive $U^i(p_L)$. However, in steady state p_L implies $U^i(p_L)$ close to zero and in expansion it results in a large negative $U^i(p_L)$. Finally, maintaining the steady state price, $\overline{p}^*$ implies a positive $U^*(\overline{p}^*)$ in all three cases.

Assume equal probability of $Y \in \{0.9, 1, 1.1\}$. The figure then suggests that the expected present value of real profits (recall (9)) implied by optimally lowering the price today may still be positive even when the risk of non-resetting in the future is taken into account. However, net of adjustment costs, the expected present value may not exceed the expected present value of maintaining the relative price at the steady state. For this to be true, the recession must be relatively large or very long. Consistent with this intuition, in recessions as illustrated in Figure 3, lowering the price implies lower expected profits (net of cost) than keeping the price (see Panel g.).[17]

Phillips curve. The above exercise makes clear that the Calvo law of motion implies an asymmetry in price setting by firms. The source of this behaviour is rooted in the countercyclical behavior of firm profits and the sensitivity of profits to prices varying between high and low relative prices. Raising prices in booms raises firm profits relative to keeping the price unchanged. In contrast, whether lowering prices in recessions is more beneficial relative to maintaining the price depends on the size of recession. As a consequence, the model with time-varying θ_t generates larger responses of inflation relative to the benchmark case of the invariant θ in booms, but similar responses in recessions.

This asymmetry in impulse response functions to a discount factor shock translates into a prediction for the Phillips curve, which is illustrated in Figure 5. To produce this figure, we simulate the model for $10,000$ periods under discount factor shocks only. The Phillips curve in Panel 5a is flatter in recessions and steeper in booms. This prediction can be rationalized by the evolution of the price setting frequency θ_t, see Panel 5b. When inflation is high, the average benefit of maintaining the price is low and the price resetting frequency is high. In contrast, when inflation is low, the average benefit of maintaining the price is high and the

[17]Figure B.1 in Appendix B compares the negative 2.5 percent discount factor shock to a seven times larger shock. In the latter case, lowering the price generates a higher benefit, which shows that in our model the price setting frequency increases for extraordinary large recessions.



(a) Phillips curve (b) Relation between θ_t and π_t

Figure 5: Dynamics in the standard (black) and augmented (blue) NK model in levels in response to a discount factor shock with standard deviation of 0.005.

price resetting frequency is low. The correlation between the share of unchanged prices and inflation in this exercise is -0.9996.

3.3 Monetary non-neutrality

One important observation from above is that the monetary policy response is asymmetric. During a recession, monetary policy accommodation and the generated responses of output and inflation are comparable to the fully time-dependent standard model. However, during an expansion, the monetary policy response is larger, contracts output by more, but inflation by less. This observation provokes an important question. What are the implications for monetary non-neutrality of adding a state-dependent component to a time-dependent pricing model via the Calvo law of motion?

It is well known that it is challenging to reconcile textbook state-dependent pricing models with the evidence of the real effects of monetary policy due to the selection effect. Contrary, textbook time-dependent pricing models such as the standard NK model feature a high degree of monetary non-neutrality. Against this background, Nakamura and Steinsson

(2010) show that extending a state-dependent model with a time-dependent component (i.e., the CalvoPlus model) only generates a high degree of monetary non-neutrality for a high share of time-dependent price changes.

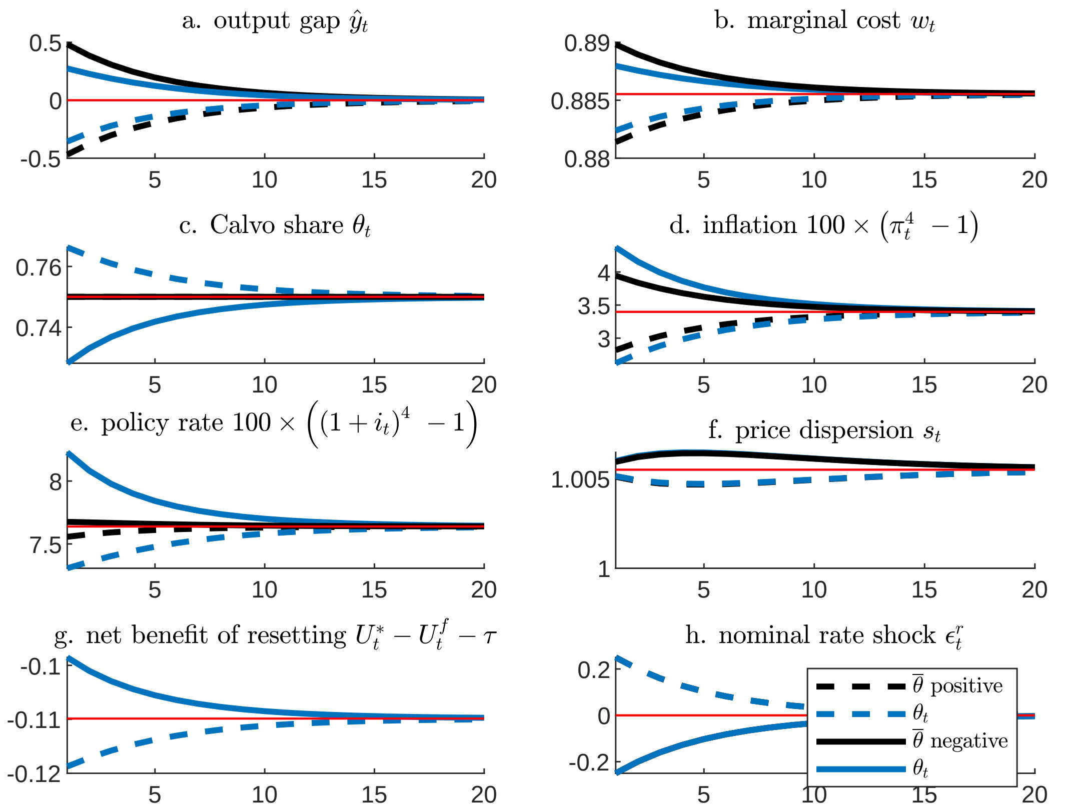


Figure 6: Asymmetric impulse responses to a positive or negative (±0.25%) monetary policy shock in the NK model.

Figure 6 shows the responses to an initial change in the policy rate by 25 basis points. Our model predicts substantial real effects of monetary policy because the state-dependence only holds at the aggregate level, which excludes selection effects. The asymmetry of effects is in line with recent evidence (Barnichon and Matthes, 2018; Stenner, 2022). Contractionary shocks have a larger effect on real economic activity, but less so on inflation. In contrast, expansionary shocks have a smaller effect on real economic activity, but more so on inflation.

4 Empirical analysis

Our augmented NK model has two key predictions that distinguish it from the standard NK model: asymmetric responses to aggregate shocks and a time-varying price setting frequency. Thus, a natural question presents itself: to what extent does the proposed mechanism help to make the NK model more consistent with both macro and micro data? The remainder of the paper provides an answer to this question by turning to a quantitative comparison of estimated versions of the augmented NK model to the standard NK model.

4.1 Data and measurement equations

Our set of observables comprises three quarterly macro time series and the share of unchanged prices depicted in Figure 1. Our sample ranges from 1964Q1 to 2019Q4. We measure the output gap as the log deviation of real GDP (GDPC1, from the FRED database) from the HP filtered trend. Inflation is the log growth rate of the personal consumption expenditures implicit price deflator index (DPCERD3Q086SBEA). The nominal interest rate is measured by the quarterly Federal Funds (FEDFUNDS) rate.

The main innovation in our estimation is that we bring to bear the quarterly share of unchanged prices in order to assess the consistency of our model with micro next to macro data. To construct this time series, we use the data on monthly prices changes from Nakamura et al. (2018) between 1978 to 2014 (see the note in Figure 1 for details). Conceptually this share of unchanged prices corresponds to the Calvo share θ_t.

The observables are related to the model variables by the measurement equations

$$
\begin{aligned}
y_t^{obs} &= \hat{y}_t \\
\pi_t^{obs} &= 100 \times \ln(\overline{\pi}) + \hat{\pi}_t \\
r_t^{obs} &= 100 \times \overline{r} + \hat{i}_t
\end{aligned}
$$

$$\theta_t^{obs} = \theta_t,$$

where $\overline{\pi} = 1 + \gamma_\pi/100$ and $\overline{r} = (\overline{\pi}/\beta) - 1$ is the quarterly risk free rate. Note that θ_t^{obs} is not available for the periods 1964 to 1977 and 2015 to 2019. Thus, for these periods we treat θ_t as a latent state variable and exclude it from the likelihood optimization problem.[18]

4.2 Estimation

We estimate a linearised version of the model using a linear Kalman filter with Bayesian Priors and Monte-Carlo Markov chain sampling. The linearisation, optimization and sampling are handled by Dynare (Juillard, 1996) using the Metropolis Hastings algorithm.

Priors. For the parameters shared by the augmented and the standard NK model, we define priors according to Table 2. Our choices are broadly in line with the Smets and Wouters (2007) priors.[19] In addition, we choose a prior for ω normally distributed around 10 with a standard deviation of 0.5. This choice is at the upper end of the empirical and experimental evidence of $\omega \in (0, 10]$ using the heuristic switching model (see, e.g., Hommes, 2011; Cornea-Madeira et al., 2019; Hommes, 2021). Choosing the highest degree of rationality estimated so far is motivated by the view that state-dependent pricing is important quantitatively. Results are robust for a prior range of $5 < \omega < 15$. The priors for γ_π and the natural interest rate correspond to their sample average. As is standard in the literature, we calibrate the price elasticity of demand to $\epsilon = 9$ (Galí, 2015). This implies a steady state mark-up of 12.5% in line with empirical estimates by Basu and Fernald (1997).

[18] An alternative is to estimate the model solely for the sample 1978 to 2014. However, such short samples raise many general identification problems.

[19] Relative to Smets and Wouters (2007), we reduced some standard deviations in order to guarantee plausible parameter estimates and to avoid unit root processes in the shocks.

		Prior			Posterior		
Price setting		Shape	Mean	STD	Mean	5%	95%
ω	Intensity of choice	$\mathcal{N}$	10	.5	8.3664	7.5543	9.1891
$\overline{\theta}$	Calvo share	$\mathcal{B}$	.5	.1	0.7105	0.6984	0.7231
Monetary authority							
ϕ_π	MP. stance, π_t	$\mathcal{N}$	1.5	.15	2.4311	2.2542	2.6162
ϕ_y	MP. stance, Y_t	$\mathcal{N}$	.12	.05	0.2499	0.1886	0.3101
ρ	Interest-rate smoothing	$\mathcal{B}$	.75	.1	0.1585	0.1006	0.2151
γ_π	Quarterly inflation trend	$\mathcal{G}$	.839	.1	0.7486	0.6610	0.8351
Preferences and technology							
$100((\overline{\pi}/\beta)-1)$	Natural interest rate	$\mathcal{G}$	1.292	.1	1.1861	1.0507	1.3224
σ	Relative risk aversion	$\mathcal{N}$	1.5	.25	1.6180	1.2940	1.9398
φ	Inverse of Frisch elasticity	$\mathcal{N}$	2	.37	1.9044	1.3785	2.4297
Exogenous processes							
σ_d	Discount factor shock, std.	$\mathcal{IG}$	.1	2	0.0255	0.0183	0.0320
σ_s	Cost-push shock, std.	$\mathcal{IG}$	.1	2	0.0322	0.0272	0.0371
σ_r	MP shock, std.	$\mathcal{IG}$	.1	2	0.0079	0.0072	0.0086
σ_θ	Resetting shock, std.	$\mathcal{IG}$	.1	2	0.0139	0.0121	0.0155
ρ_d	Discount factor shock, AR(1)	$\mathcal{B}$	.5	.1	0.9362	0.9173	0.9552
ρ_s	Cost-push shock, AR(1)	$\mathcal{B}$	.5	.1	0.9779	0.9676	0.9889
μ_s	Cost-push shock, MA(1)	$\mathcal{B}$	.5	.1	0.1732	0.1195	0.2265
ρ_r	MP shock, AR(1)	$\mathcal{B}$	.5	.1	0.5271	0.4789	0.5770
ρ_θ	Resetting shock, AR(1)	$\mathcal{B}$	.5	.1	0.7749	0.7071	0.8427
Log-likelihood						-74.6242	

Table 2: Estimated parameters of the augmented NK model, United States, 1964-2019. $\mathcal{B}$, $\mathcal{G}$, $\mathcal{IG}$, $\mathcal{N}$ denote beta, gamma, inverse gamma and normal distributions, respectively.

Parameter estimates. Our estimated parameter values are reported in Table 2. The parameters shared with the standard NK model are all broadly in line with the existing literature. Also the parameter estimates for the Calvo law of motion are plausible. The posterior mean of the Calvo share $\overline{\theta} = 0.7105$ is fairly close to the historical average in various datasets and also in line with estimates of the corresponding parameter in random menu cost models.[20] The intensity of choice $\omega = 8.3664$ is strictly positive and in line with the evidence on dynamic predictor selection. Our estimates for the standard shock processes are also broadly in line with existing literature.

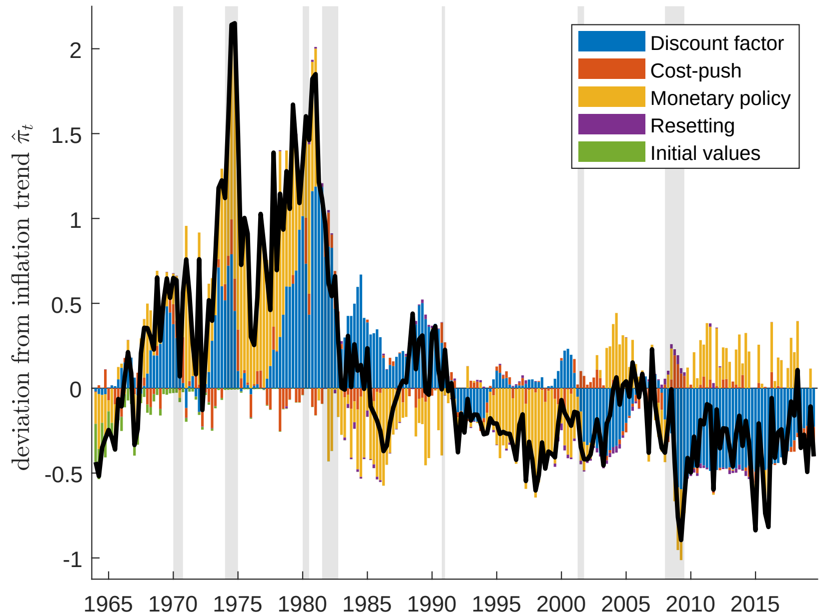
[20]For instance, Costain et al. (2022) estimate a rate of decision making of 0.2707, which corresponds to our posterior mean of the frequency of price change $(1-\overline{\theta}) = 0.2895$.

Historical decomposition. One of our main findings is depicted in Figure 7 below. An inspection of Figure 7a reveals that in the augmented NK model, inflation is not predominantly driven by cost-push shocks (which is in the end the unexplained inflation residual of the model). It is to a large extent driven by discount factor and monetary policy shocks, i.e., shocks that are also important in explaining the variation in the output gap. This finding stands in contrast to the standard NK model with fixed θ, where there is bigger need for volatile cost-push shocks in order to explain inflation.

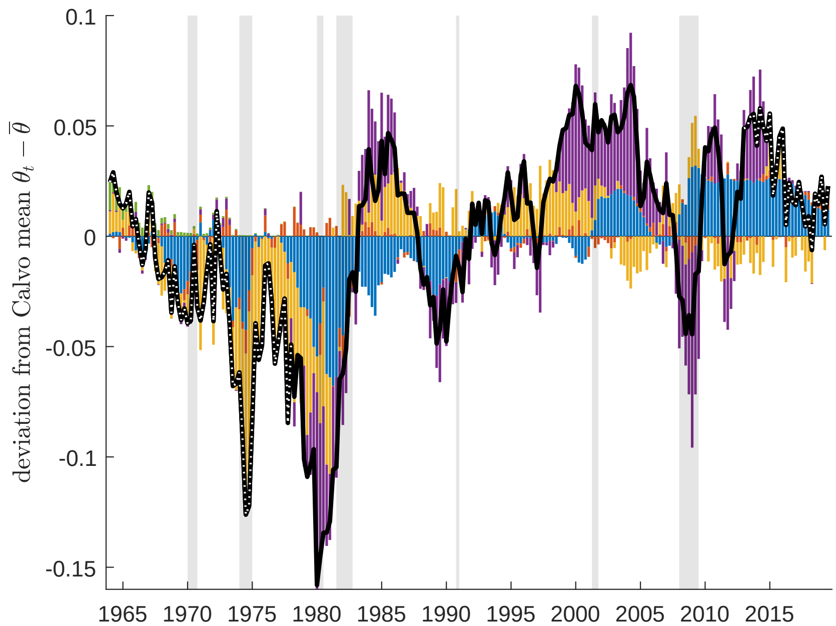
Importantly, discount factor and monetary policy shocks are also the main drivers of the variation in the Calvo share, see Figure 7b. Thus, shocks that play an important role in explaining the variation in real economic activity also explain the variation in price setting frequency and therefore in inflation. This finding demonstrates the consistency of the Calvo law of motion with the US business cycle. Another finding pointing to the model's empirical relevance is the endogenous correlation between the share of unchanged prices and inflation is -0.6768 at the posterior mean, which is in line with the stylized fact in Figure 1.

Remarkably, resetting shocks appear to play a key role mostly during the Volcker disinflation, the later part of the Great Moderation and the Great Recession. We rationalize this finding by the fact that the Calvo law of motion approximates the price setting behavior at the extensive margin. At times, the approximation error may be large and that is captured by the resetting shocks. For example, the Volcker disinflation and the Great Recession are arguably extraordinary events. During the Volcker disinflation the resetting shocks push the frequency downward. Thus, they help to match the extraordinary sharp decline in the frequency of price increases during this period (see Nakamura et al., 2018, Figure XV). The Great Recession features extraordinary events on commodity markets underlying the dynamics in the price setting frequency data (see Nakamura et al., 2018, pp.1968-1969). By construction, our model is too abstract to capture these extraordinary dynamics as this is not our objective in this paper. The resetting shock appears to absorb these dynamics.[21]

[21] Recall that we estimate the linearized model. An obvious question is whether the non-linear model



(a) π_t, log-deviation from the posterior mean of quarterly trend inflation.



(b) θ_t, deviation from the posterior mean

Figure 7: Historical shock decomposition, United States, 1964-2019. Dotted line indicates generated/unobserved data.

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allows for a sharp decline in θ_t as observed in the Nakamura et al. (2018) data during the Great Recession without relying on resetting shocks. We investigate this issue in greater detail below.

Taken together, the historical decomposition in Figure 7 suggests that during most of the sample period, inflation is to a large extent driven by the time-varying price setting frequency, which depends on discount factor and monetary policy shocks.[22] The estimation of the linearized augmented model shows that the mechanism proposed in this paper generates a time-varying relationship between inflation and the output gap. However, the linearized model eliminates the asymmetries that the mechanism generates in the underlying non-linear model. Therefore, the remainder of the paper is dedicated to assessing the consistency of the proposed mechanism with the data by using the non-linear model.

4.3 Consistency with the data

We next use counter-factual analysis to demonstrate that the Calvo law of motion improves the consistency of the NK model with macro *and* micro data. In a preliminary step, we follow the methodology of Harding et al. (2022) to obtain the exogenous shocks of the non-linear model. First, we parameterize the model at the posterior mean obtained from the linear estimation above. Second, we use the inversion filter to solve for the sequence of exogenous shocks given the observed data and an initial condition.[23] Hence, the paths of $\hat{y}_t$, π_t and θ_t predicted by the non-linear model based on the posterior mean and all filtered shocks (henceforth filtered model) equal the observed data by construction.

We then construct two counter-factuals. In one exercise we construct an economy without resetting shocks, $\epsilon_t^\theta = 0 \ \forall t$. In a second exercise, we compute counter-factual paths for $\hat{y}_t$, π_t and θ_t, where the price setting frequency is held fixed at he posterior mean, $\theta_t = \overline{\theta} \ \forall t$.

Comparing the two counter-factuals to the filtered model establishes that the Calvo law of motion is a relevant and reasonable modelling device. It can approximately explain the

[22] This is consistent with the empirical findings in Del Negro et al. (2020). They explain the change in the relation between inflation and unemployment by a flattening of the price Phillips curve.

[23] The set of observables and the sample period are the same as in Subsection 4.2 above. Also note that in order to avoid stochastic singularity, i.e., more shocks than observables, we require the latent state variable generated by the linear estimation to be fitted whenever the Nakamura et al. (2018) series is not available.

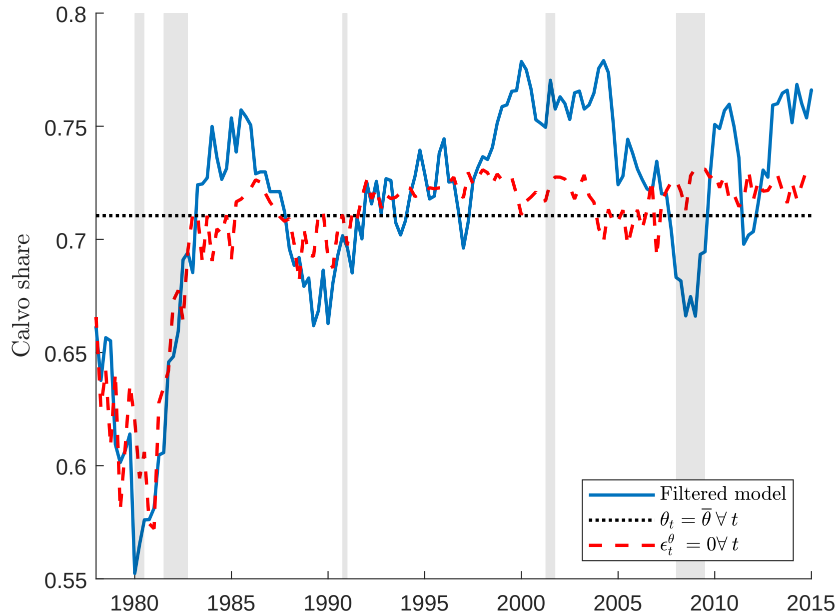
evolution the Nakamura et al. (2018) series depicted in Figure 1. Moreover, the counter-factuals enable us to examine the extent to which the proposed mechanism improves the NK model's ability to explain the joint dynamics of inflation and output gap, i.e., the post-WWII US Phillips curve. Next, the simulations in Section 3 suggest that part of the potential improvement may be due to the asymmetry generated by the Calvo law of motion. Therefore, we use the counter-factuals to quantify how much we can get from this asymmetry in terms of observed inflation skewness and related statistics. Finally, we use additional counter-factuals to assess the importance of structural shocks in explaining inflation.

Relevance of the Calvo law of motion. The estimated model naturally raises the question of whether the augmented NK model is consistent with the Nakamura et al. (2018) data. We provide an answer by comparing the model implied paths for θ_t from the filtered model (coinciding with the data) to the counter-factual economies in Figure 8a.

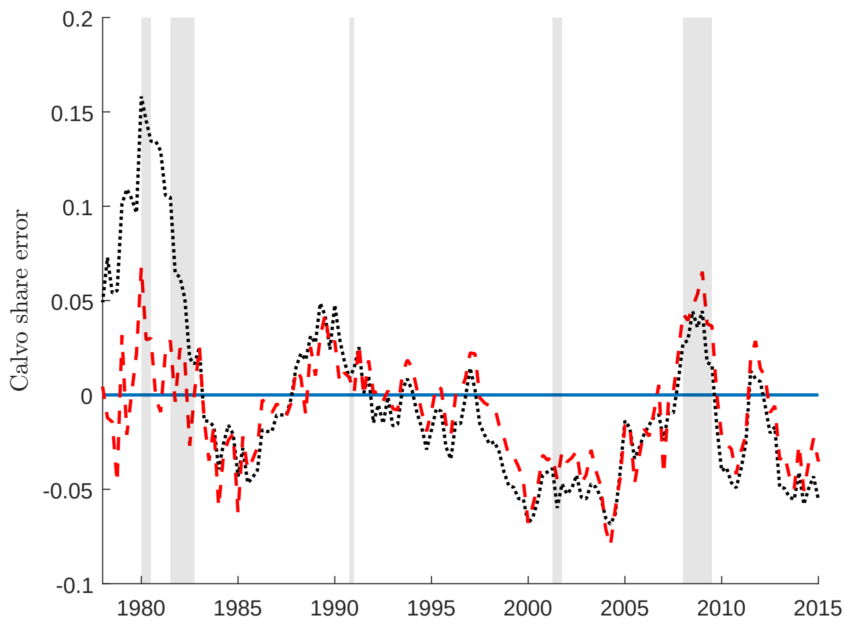
Overall, the counter-factual without resetting shocks (red dashed) appears to be closer to the data/filtered model (blue) than the counter-factual with constant price setting frequency (black dotted). Figure 8b depicts the difference between counter-factuals and the filtered model. Clearly, for most of the sample the counter-factual without resetting shocks is closer to the filtered model than the counter-factual with fixed price setting frequency. The augmented NK model matches the observed micro data fairly well even without resetting shocks. Below we show that this holds not only in qualitative but also in quantitative terms.[24]

Taking the rather small range of the vertical axis in Figure 8a into account, the notable deviations between the data and the counter-factual without resetting shocks are again episodes around the Volcker Disinflation, the later part of the Great Moderation and the Great Recession.

[24] In a previous version (Gasteiger and Grimaud, 2020) we compare the predicted path for the latent state variable θ_t from the re-estimation of the linearized augmented NK model to the Nakamura et al. (2018) data. The re-estimation does not rely on resetting shocks, but treats differences between the data and the model variable as an observation error. We find that the predicted path and the micro data line up fairly good both in qualitative and quantitative terms even in the linearised model.



(a)



(b)

Figure 8: Observed and counter-factual share of unchanged prices θ_t, United States, 1978-2014. Counter-factual errors are the difference between counter-factual and filtered model.

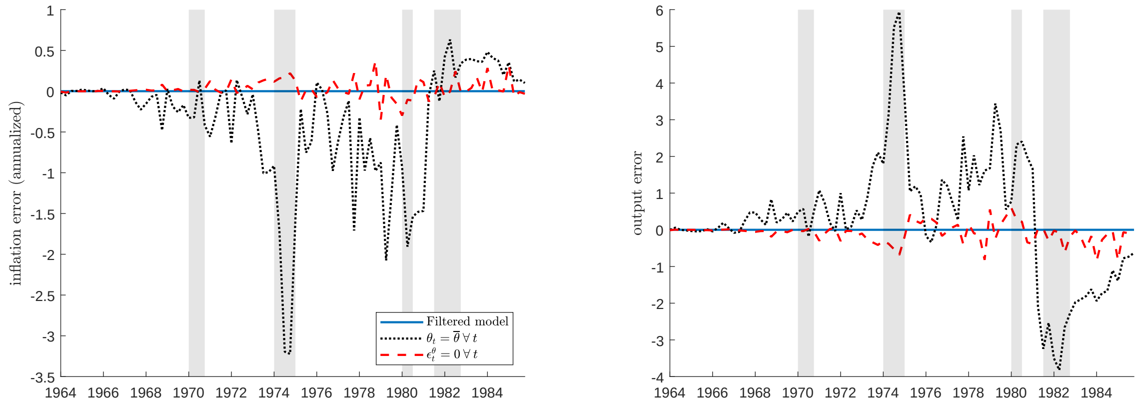
For instance, in the latter case the counter-factual without resetting shocks cannot replicate the sharp ups (less price updating) and downs (more price updating) of the share of unchanged prices in a rather short amount of time. As above, the discrepancy during the Volcker Disinflation and the Great Recession can be rationalized by extraordinary events (see Nakamura et al., 2018). Therefore, in sum, Figure 8 suggests that the Calvo law of motion is a relevant and reasonable modelling device as it makes the NK model consistent with micro data on price setting frequency. Whether this device also improves the model's endogenous propagation mechanism is examined in the remainder of the paper.

Explaining the post-WWII US Phillips curve. We now show that the Calvo law of motion also improves the consistency of the NK model with macro data. It enhances the model's ability to explain post-WWII US inflation and output gap, i.e., the Phillips curve.

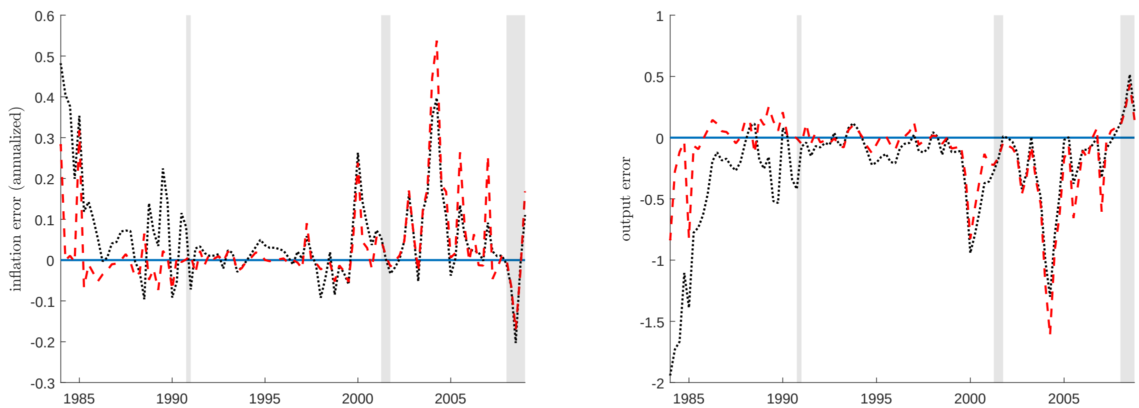
Figure 9 contrasts the filtered model (blue) and the same counter-factual scenarios as above by means of counter-factual errors. The left-hand side panels show the errors for annualized inflation, right-hand side panels for output. Figure 9a reports on the Great Inflation and Volcker Disinflation from 1969 to 1985. In the counter-factual economy with fixed price setting frequency (black dotted) inflation is too low during the Great Inflation and early Volcker Disinflation, whereas it is too high during the late Volcker Disinflation.

Regarding the output gap, the counter-factual with fixed price setting frequency predicts a substantially less recessionary Great Inflation and early Volcker Disinflation in combination with an overly recessionary late Volcker Disinflation. Strikingly, the counter-factual without resetting shocks (red dashed) is closer to the data for both inflation and output. Thus, Figure 9a establishes that the augmented NK model is more consistent with the joint dynamics of observed inflation and output gap during the Great Inflation and Volcker Disinflation.

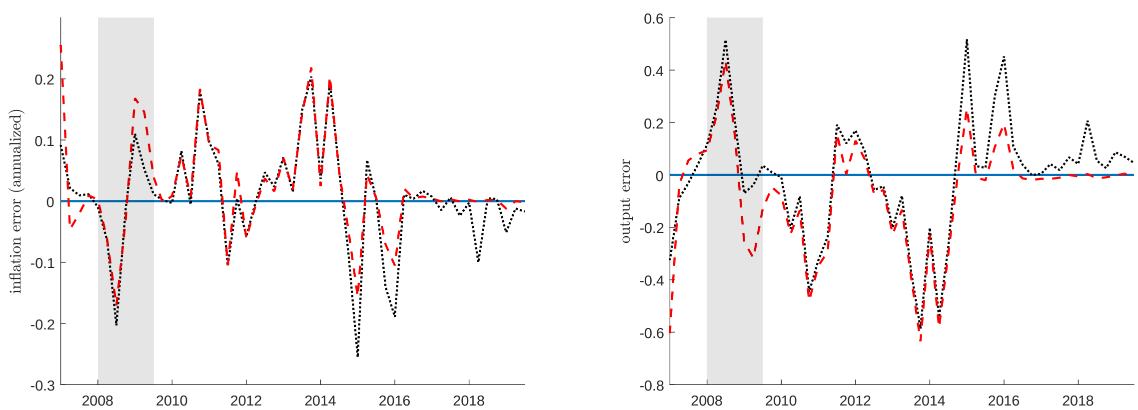
Figure 9b covers the Great Moderation from 1985 to 2008. The augmented NK model is again more consistent with the joint dynamics of observed inflation and output gap even without resetting shocks until after the early 2000s recession, approximately till 2003.



(a) Great Inflation and Volcker Disinflation, 1964-1985



(b) Great Moderation, 1985-2008



(c) Great Recession and New Normal, 2008-2019

Figure 9: Counter-factual errors, computed as the difference between counter-factual and observed data, United States, 1964-2019.

Contrary, the counter-factual scenario with fixed price setting frequency generates too much inflation and too little output. However, toward the end of this period, from 2004 to 2008, the augmented NK model relies on resetting shocks to be more consistent with the data than the counter-factual with fixed price setting frequency. At times, when output falls, the counter-factual without resetting shocks can even be less consistent with the data. It amplifies both the widening of the negative output gap and overshoots inflation.

Figure 9c depicts the Great Recession and the New Normal from 2008 to 2019. From 2008 to 2014 the augmented NK model relies again on resetting shocks to be more consistent with the data. Yet, from 2015 onward, we find that the augmented NK model is again more consistent with the data. It predicts more inflation and less output in line with the data even in the absence of resetting shocks.

The finding that the augmented NK model relies on resetting shocks to explain the data better than the standard NK model during 2004 to 2014 deserves further discussion. Section 3 clarified that the proposed mechanism generates a *negative* correlation between inflation and the share of unchanged prices for shocks with immediate effect on aggregate demand. Adverse shocks would have to be extraordinary large to generate a positive correlation. $\text{corr}(\pi_t, \theta_t) < 0$ implies asymmetric dynamics of output on inflation. The mechanism accelerates inflation increases in expansions and decelerates inflation decreases in recessions of similar magnitude. In other words, the predicted positive correlation $\text{corr}(\pi_t, \hat{y}_t) > 0$ is higher in expansions and lower in recessions. Thus, it is obvious that the augmented model may have difficulties to fit the data in episodes characterized by $\text{corr}(\pi_t, \theta_t) > 0$ *and* $\text{corr}(\pi_t, \hat{y}_t) > 0$. We will investigate this in greater detail right below.

Moreover, we believe, the finding reminds us that the proposed mechanism only approximates the extensive margin of price adjustment that may be inaccurate at times. A more elaborate pricing model of the extensive and intensive margin such as in the state-dependent pricing literature since Golosov and Lucas (2007) may yield further improvement.

In sum, our findings demonstrate that the augmented NK model fits important patterns in the joint inflation and output gap dynamics, i.e., the Phillips curve, during the post-WWII period better than the standard NK model with fixed price setting frequency. This is no surprise as it is known that for the standard NK model with fixed $\overline{\theta}$, the only way to allow for changes in the inflation-output gap relationship over time is through implausible high (residual) cost-push shocks. This is why standard estimates with time-invariant price setting frequency tend to exhibit Calvo parameter estimates that are inconsistent with micro data on price setting frequency (to reduce the co-movement between inflation and output) and large cost-push shocks that are negatively correlated with the output gap.

In contrast, the augmented NK model has an enhanced endogenous propagation mechanism. Structural shocks create variation in the price setting frequency, output gap and inflation consistent with the data. Moreover, Figure 7a suggests that inflation is not driven by cost-push shocks (which is in the end the unexplained inflation residual of the model), but to a large extent by demand-side shocks (discount factor and monetary policy).[25] In what follows, we further assess our model's ability to explain inflation and the role of shocks.

Asymmetry and inflation skewness. The proposed mechanism predicts an asymmetry in response to shocks of equal magnitude that is approximately consistent with micro data and offers an improved explanation of the post-WWII US Phillips curve. This begs the question of whether part of this improvement is due to the fact that the asymmetry helps the model to match the observed inflation skewness. We compare the observed and counter-factual inflation skewness and related statistics to provide a quantitative answer.

Panel (a) in Table 3 reports on the mean, median, variance, and skewness of inflation as well as on the correlation between inflation and the share of unchanged prices and the output gap respectively over the full sample.[26] Comparing the data to the counter-factuals

[25]This is consistent with the empirical findings in Del Negro et al. (2020). They explain the change in the relation between inflation and unemployment by a flattening of the price Phillips curve.

[26]Table 3 reports the corr(π_t, θ_t) from 1964 to 2019. In the computation, we use the available observations from 1978 to 2014 for θ_t and its values as latent state variable (see Subsection 4.1) otherwise. This explains, why the correlation for the full sample differs from the -0.7893 reported for Figure 1.

yields a striking insight. The augmented NK model provides a large improvement relative to the standard NK model. Furthermore, when comparing the counter-factuals to the observed moments, it is evident that this striking improvement is not driven by resetting shocks, but by and large by the Calvo law of motion.

However, one may argue that the counter-factual errors in Figure 9 suggests that the striking improvement may be due to certain episodes in the data. For instance, the magnitude of counter-factual errors in Figures 9b and 9c are small in comparison to Figure 9a. Moreover, recall that the augmented NK model relies on resetting shocks in order to improve the fit to the joint dynamics of inflation and the output gap over the period 2004 to 2014. Therefore, we also compare the observed and counter-factual moments for sub-samples.

Panel (b) in Table 3 shows the moments for the Great Inflation and Volcker Disinflation period. The augmented NK model generates an asymmetry consistent with the data even without resetting shocks. A similar conclusion can be drawn from Panels (c) and (e). The exception is Panel (d), which reports on the period 2004 to 2014. This period is characterized by $\text{corr}(\pi_t, \theta_t) > 0$ *and* $\text{corr}(\pi_t, \hat{y}_t) > 0$. The comparison of the observed and counter-factual moments makes clear that unsurprisingly the augmented NK model relies on resetting shocks to re-produce the observed moments. As discussed above, the augmented NK model has difficulties to generate this feature.

In sum, consistent with our previous findings, Table 3 suggests that the striking improvement in explaining the post-WWII US Phillips curve, including inflation skewness is present over most of the full sample. The Calvo law of motion enhances the NK model's endogenous propagation mechanism.

(a) 1964-2019 (full sample)		Filtered model	$\theta_t = \overline{\theta}\ \forall t$	$\epsilon_t^\theta = 0\ \forall t$
π_t	mean	3.3665	3.2370	3.3926
	median	2.6056	2.6782	2.6595
	variance	5.3527	3.8370	5.4351
	skewness	1.3271	0.8472	1.3343
$\text{corr}(\pi_t, \theta_t)$		-0.8443	0	-0.9844
$\text{corr}(\pi_t, \hat{y}_t)$		0.0839	0.1442	0.0734
(b) 1964-1984				
π_t	mean	5.3995	5.0033	5.4256
	median	5.1631	4.9164	5.1602
	variance	6.0894	3.5740	6.2343
	skewness	0.4630	-0.0172	0.4876
$\text{corr}(\pi_t, \theta_t)$		-0.9327	0	-0.9951
$\text{corr}(\pi_t, \hat{y}_t)$		0.0905	0.1564	0.0802
(c) 1985-2003				
π_t	mean	2.3207	2.3583	2.3314
	median	2.2032	2.2698	2.2279
	variance	0.7802	0.8181	0.7958
	skewness	0.7364	0.5821	0.7155
$\text{corr}(\pi_t, \theta_t)$		-0.6005	0	-0.9820
$\text{corr}(\pi_t, \hat{y}_t)$		0.3484	0.3553	0.3390
(d) 2004-2014				
π_t	mean	2.0393	2.0902	2.1094
	median	2.0967	2.0852	2.0811
	variance	0.9520	1.0121	1.0373
	skewness	-0.4800	-0.3945	-0.2448
$\text{corr}(\pi_t, \theta_t)$		0.2980	0	-0.9530
$\text{corr}(\pi_t, \hat{y}_t)$		0.5540	0.4783	0.4577
(e) 2015-2019				
π_t	mean	1.6207	1.5995	1.6196
	median	1.7169	1.7668	1.7643
	variance	0.9075	1.0221	0.9890
	skewness	-0.5074	-0.7083	-0.6060
$\text{corr}(\pi_t, \theta_t)$		-0.7487	0	-0.9096
$\text{corr}(\pi_t, \hat{y}_t)$		0.1297	0.0697	0.0907

Table 3: Inflation moments and related statistics, filtered model and counter-factuals.

The role of shocks. A historical shock decomposition similar to Figure 7 above is not feasible within the non-linear model. Nevertheless, we can use the observed and counter-factual inflation moments and related correlations to gauge the importance of structural shocks in explaining inflation. To this end, we construct additional counter-factual economies, where we leave out one structural shock per counter-factual. Moreover, we build a counter-factual with only demand-side shocks (discount factor and monetary policy), $\epsilon_t^s = \epsilon_t^\theta = 0 \ \forall t$, and, only supply-side shocks (resetting and cost-push), $\epsilon_t^d = \epsilon_t^r = 0 \ \forall t$.

Table 4 reports on the same statistics as Table 3 above. Panel (a) confirms the findings from the historical decomposition in Figure 7 above. Comparing the observed mean, median, variance, and skewness of inflation to the counter-factual economies without resetting shock, cost-push shock, or neither of the two shocks makes clear that supply-side shocks play no essential role in explaining inflation. The moments are not substantially changing in these counter-factual scenarios. However, the resetting shock matters for fitting the observed correlation between price setting frequency and inflation and the cost-push shock matters for the correlation between inflation and the output gap.

Contrary, comparing the data to the counter-factual economies without discount factor shock, monetary policy shock, or neither of the two shocks demonstrates that demand-side shocks are essential for explaining inflation. This applies to all reported moments of inflation. Moreover, the fact that it also applies to the reported correlations of inflation with the Calvo share and the output gap suggests that the augmented model's endogenous propagation mechanism interacts with these shocks. Panels (b) to (e) demonstrate that these findings are by and large robust to considering different episodes in the data.

Finally, Figure 7 suggests that not only discount factor, but also monetary policy shocks become very important for explaining inflation in the linearized model. While this result is not in line with most of the literature (e.g., Smets and Wouters, 2007), it stands to reason that this is no major concern for our finding that inflation is mainly driven by demand-side shocks. First, the counter-factual scenarios reported in Panels (b) to (e) of Table 4

(a) 1964-2019 (full sample)		Filtered model	$\epsilon_t^\theta = 0\ \forall t$	$\epsilon_t^s = 0\ \forall t$	$\epsilon_t^s = \epsilon_t^\theta = 0\ \forall t$	$\epsilon_t^d = 0\ \forall t$	$\epsilon_t^r = 0\ \forall t$	$\epsilon_t^d = \epsilon_t^r = 0\ \forall t$
π_t	mean	3.3665	3.3926	3.3725	3.4013	3.3195	3.0151	2.9678
	median	2.6056	2.6595	2.7075	2.7123	2.9865	2.9039	2.9555
	variance	5.3527	5.4351	5.2963	5.3741	3.1133	1.9792	0.1025
	skewness	1.3271	1.3343	1.2980	1.3160	1.6055	0.8554	0.5939
$\text{corr}(\pi_t, \theta_t)$		-0.8443	-0.9844	-0.8359	-0.9836	-0.7522	-0.7249	-0.4065
$\text{corr}(\pi_t, \hat{y}_t)$		0.0839	0.0734	-0.0296	-0.0380	-0.0994	0.1762	-0.5882
(b) 1964-1984								
π_t	mean	5.3995	5.4256	5.3968	5.4270	4.4178	3.9173	2.9924
	median	5.1631	5.1602	4.9738	4.9894	4.0428	3.4877	2.9997
	variance	6.0894	6.2343	5.8975	6.0505	4.7642	2.0190	0.1814
	skewness	0.4630	0.4876	0.4977	0.5253	0.9690	1.0406	0.3136
$\text{corr}(\pi_t, \theta_t)$		-0.9327	-0.9951	-0.9288	-0.9953	-0.8757	-0.8319	-0.4095
$\text{corr}(\pi_t, \hat{y}_t)$		0.0905	0.0802	-0.0136	-0.0486	-0.0741	0.0891	-0.5886
(c) 1985-2003								
π_t	mean	2.3207	2.3314	2.3316	2.3405	2.1526	3.1477	2.9542
	median	2.2032	2.2279	2.1992	2.1889	2.0992	3.0875	2.9703
	variance	0.7802	0.7958	0.8222	0.8333	0.5783	0.7724	0.0441
	skewness	0.7364	0.7155	0.8576	0.8082	0.1354	-0.0328	0.0495
$\text{corr}(\pi_t, \theta_t)$		-0.6005	-0.9820	-0.6236	-0.9848	-0.2971	-0.7056	-0.2960
$\text{corr}(\pi_t, \hat{y}_t)$		0.3484	0.3390	0.1707	0.2207	-0.4339	0.5908	-0.6399
(d) 2004-2014								
π_t	mean	2.0393	2.1094	2.0240	2.1017	3.3201	1.7428	2.9709
	median	2.0967	2.0811	2.0509	2.1373	3.4543	1.4219	2.9350
	variance	0.9520	1.0373	1.1295	1.1798	0.7157	0.5455	0.0802
	skewness	-0.4800	-0.2448	-0.7384	-0.5228	-0.5588	0.6189	1.3824
$\text{corr}(\pi_t, \theta_t)$		0.2980	-0.9530	0.3193	-0.9351	0.1237	-0.2042	-0.5880
$\text{corr}(\pi_t, \hat{y}_t)$		0.5540	0.4577	0.4975	0.5322	-0.2105	0.7310	-0.5130
(e) 2015-2019								
π_t	mean	1.6207	1.6196	1.6882	1.6916	3.1784	1.3842	2.9028
	median	1.7169	1.7643	1.8971	1.9032	3.4464	1.3859	2.9042
	variance	0.9074	0.9890	0.8298	0.8996	0.7946	0.1362	0.0446
	skewness	-0.5074	-0.6060	-0.5028	-0.5992	-0.1402	-0.0915	0.6438
$\text{corr}(\pi_t, \theta_t)$		-0.7487	-0.9096	-0.7578	-0.9210	-0.8215	-0.7935	-0.4349
$\text{corr}(\pi_t, \hat{y}_t)$		0.1297	0.0907	0.8588	0.8924	-0.2886	0.3788	-0.6304

Table 4: Inflation moments and related statistics, filtered model and more counter-factuals.

clarify that in the non-linear model at times the discount factor and monetary policy shock amplify or mute each other's effect on inflation moments. Therefore, the relative importance of monetary policy shocks for inflation in Figure 7 could be an artifact of estimating the shocks by using a linear approximation of the model, which ignores the interaction of shocks. Second, the demand side in our model coincides with the standard NK model. Medium-scale DSGE models (e.g. Smets and Wouters, 2007) have a much more elaborate demand side that allows for way more potent endogenous propagation mechanism and more demand-side shocks (e.g., investment-specific shocks) besides a monetary policy specification similar to our model. This, in turn, can lead to a less important role for monetary policy shocks even in a linear context. We leave the examination of this issue to future research.

All told, the counter-factuals in Table 4 confirm that our augmented NK model explains inflation to a large extent by the time-varying price setting frequency and demand-side shocks. This suggests that the Calvo law of motion offers great potential to improve the NK model's macro time series fit, which is highly relevant for estimated medium-scale NK models. An in-depth assessment of this potential can be done by a likelihood-based comparison.[27]

5 Conclusion

We develop a New Keynesian model with endogenous price setting frequency by augmenting the time-dependent price setting mechanism with a state-dependent component. The augmented NK model is consistent with macro *and* micro data. In this way the NK framework can be reconciled with phenomena such as shifts in the Phillips curve associated with different historical episodes.

In our model, the expected present value of firm profits and costly price updating drive heterogeneity and price setting stickiness. A firm updates the price optimally when expected benefits outweigh expected cost. The updating decision follows a discrete choice process that we denote the Calvo law of motion. The process approximates well the idiosyncratic trade offs that firms face when deciding about price updating.

Profits are countercyclical and their price sensitivity varies between high and low relative prices, the model predicts more flexible prices in expansions and less flexible prices in recessions. This gives rise to a non-linear Phillips curve. The price setting frequency accelerates during booms implying accelerating inflation. Contrary, the model permits a decelerating

[27] We pursue this comparison in an earlier version of this paper (Gasteiger and Grimaud, 2020). Therein we show that the proposed mechanism largely improves the macro time series fit of the medium-scale NK model developed in Fernández-Villaverde and Rubio-Ramírez (2006).

price setting frequency during recessions and thus allows for low, but stable inflation.

We find that our setup with the Calvo law of motion provides a good approximation of the observed price setting frequency based on micro data. Second, it generates a direct effect of the time-varying price setting frequency on inflation. Third, our model creates time-variation in the Phillips curve slope. Therefore, besides its small scale, it is able to explain shifts in the Phillips curve associated with different historical episodes. Fourth, the Calvo law of motion enables the model to explain the dynamics in inflation data to a large extent by discount factor and monetary policy shocks as well as the endogenous evolution of the price setting frequency. The model does not rely on implausible high cost-push shocks and nominal rigidities inconsistent with micro data. Fifth, the proposed mechanism reconciles the NK model with observed inflation moments.

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Appendix

Price setting frequency and the Phillips curve

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A Model details

A.1 Price dispersion

Given the Calvo law of motion, price dispersion is a more complex process relative to the standard trend inflation NK model. The time-varying θ_t, can amplify or mute the non-monotonic behavior of price dispersion. In order to illustrate this point, consider the definition of relative price dispersion

$$s_t \equiv \int_0^1 \left(\frac{P_{i,t}}{P_t} \right)^{-\epsilon} di.$$

Under the Calvo pricing this can be expressed as

$$s_t = \frac{1}{P_t^{-\epsilon}} \left(\sum_{k=0}^{\infty} \theta_{t|t-k} (1-\theta_{t-k}) (P^*_{i,t-k})^{-\epsilon} \right), \quad \text{where } \theta_{t|t-k} = \begin{cases} \Pi_{s=0}^{k-1} \theta_{t-s}, & \text{if} \quad k \geq 1, \\ 1, & \text{if} \quad k = 0, \end{cases}$$

or, recursively as

$$s_t = (1-\theta_t)(p_t^*)^{-\epsilon} + \theta_t \pi_t^{\epsilon} s_{t-1}.$$

From the above expression for s_t one can see that the time-varying Calvo share θ_t implies time-varying effects on price dispersion that can amplify or mute the non-monotonic effects of p_t^* and π_t on s_t. Suppose that a shock creates an incentive for firms to lower p_t^* and consequently leads to a decline in π_t. First, a lower p_t^* tends to raise s_t. Second, a lower π_t

tends to decrease s_t. A higher θ_t implies that less firms update to the new optimal price and therefore mutes the first effect and amplifies the second. The reverse is true for a lower θ_t. A similar reasoning applies to a shock that creates an incentive for firms to increase p^*_t.

A.2 Steady state

For $Y = 1$ and $\theta_t = \overline{\theta}$, the steady state of the model variables is determined by

$$\begin{aligned}
(1+i) &= \overline{\pi}/\beta \\
w &= -\frac{\overline{\pi}\,(\epsilon-1)\left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}-1\right)}{\epsilon\left(\overline{\pi}-\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\right)\left(\frac{\overline{\pi}^{\epsilon-1}\,\overline{\theta}-1}{\overline{\theta}-1}\right)^{\frac{1}{\epsilon-1}}} \\
p^* &= \frac{\epsilon}{\epsilon-1}\frac{\psi}{\phi} \\
\psi &= \frac{wY^{1-\sigma}}{1-\overline{\theta}\beta\overline{\pi}^{\epsilon}} \\
\phi &= \frac{Y^{1-\sigma}}{1-\overline{\theta}\beta\overline{\pi}^{\epsilon-1}} \\
p^f &= 1/\overline{\pi} \\
1 &= (\overline{\theta}\overline{\pi}^{\epsilon-1} + (1-\overline{\theta})p^{*\,1-\epsilon})^{\frac{1}{1-\epsilon}} \\
s &= \frac{(1-\overline{\theta})p^{*\,-\epsilon}}{(1-\overline{\theta}\overline{\pi}^{\epsilon})} \\
N &= Ys.
\end{aligned}$$

A.3 The linearised New-Keynesian Phillips Curve

In order to understand how the Calvo law of motion affects the model dynamics in the linearised case, we linearise the NK Phillips curve around a trend inflation steady state as in Ascari and Sbordone (2014).[i] Throughout the linearisation, we assume $0 < \overline{\theta} < 1$ to avoid

[i] A hat $(\hat{\cdot})$ indicates that a variable is expressed in log-deviation from their steady state.

the empirically implausible polar cases $\overline{\theta} = \{0, 1\}$.

We start by linearising (5)

$$\hat{p}_t^* = \hat{\psi}_t - \hat{\phi}_t, \qquad \text{where} \tag{A.3.1}$$

$$\hat{\psi}_t = \hat{y}_t \left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta} - 1\right)(\sigma - 1) - \hat{w}_t \left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta} - 1\right) + \beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\,\mathbb{E}_t\hat{\psi}_{t+1} + \beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\,\mathbb{E}_t\hat{\theta}_{t+1} + \beta\,\epsilon\,\overline{\pi}^{\epsilon}\,\overline{\theta}\,\mathbb{E}_t\hat{\pi}_{t+1} \tag{A.3.2}$$

$$\hat{\phi}_t = \hat{y}_t \left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta} - 1\right)(\sigma - 1) + \beta\,\overline{\pi}^{\epsilon-1}\,\overline{\theta}\,\mathbb{E}_t\hat{\phi}_{t+1} + \beta\,\overline{\pi}^{\epsilon-1}\,\overline{\theta}\,\mathbb{E}_t\hat{\theta}_{t+1} + \beta\,\overline{\pi}^{\epsilon-1}\,\overline{\theta}\,\mathbb{E}_t\hat{\pi}_{t+1}\,(\epsilon - 1). \tag{A.3.3}$$

Linearising (3) yields

$$\hat{p}_t^* = \frac{\overline{\theta}\,\hat{\theta}_t\,(\overline{\pi} - \overline{\pi}^{\epsilon}) + \overline{\pi}^{\epsilon}\,\overline{\theta}\,\hat{\pi}_t\,(\epsilon - 1)\left(\overline{\theta} - 1\right)}{(\epsilon - 1)\left(\overline{\theta} - 1\right)\left(\overline{\pi} - \overline{\pi}^{\epsilon}\,\overline{\theta}\right)}. \tag{A.3.4}$$

Then we substitute (A.3.4) into (A.3.1)

$$\hat{\psi}_t = \hat{\phi}_t + \frac{\overline{\theta}\,\hat{\theta}_t\,(\overline{\pi} - \overline{\pi}^{\epsilon}) + \overline{\pi}^{\epsilon}\,\overline{\theta}\,\hat{\pi}_t\,(\epsilon - 1)\left(\overline{\theta} - 1\right)}{(\epsilon - 1)\left(\overline{\theta} - 1\right)\left(\overline{\pi} - \overline{\pi}^{\epsilon}\,\overline{\theta}\right)}. \tag{A.3.5}$$

Next, equalize (A.3.5) and (A.3.2)

$$\begin{aligned}
&\hat{\phi}_t + \frac{\overline{\theta}\,\hat{\theta}_t\,(\overline{\pi} - \overline{\pi}^{\epsilon}) + \overline{\pi}^{\epsilon}\,\overline{\theta}\,\hat{\pi}_t\,(\epsilon - 1)\left(\overline{\theta} - 1\right)}{(\epsilon - 1)\left(\overline{\theta} - 1\right)\left(\overline{\pi} - \overline{\pi}^{\epsilon}\,\overline{\theta}\right)} \\
&\quad = \hat{y}_t \left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta} - 1\right)(\sigma - 1) - \hat{w}_t \left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta} - 1\right) + \beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\,\mathbb{E}_t\hat{\theta}_{t+1} \\
&\qquad + \beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\left(\mathbb{E}_t\hat{\phi}_{t+1} + \frac{\overline{\theta}\,\mathbb{E}_t\hat{\theta}_{t+1}\,(\overline{\pi} - \overline{\pi}^{\epsilon}) + \overline{\pi}^{\epsilon}\,\overline{\theta}\,\hat{\pi}_{t+1}\,(\epsilon - 1)\left(\overline{\theta} - 1\right)}{(\epsilon - 1)\left(\overline{\theta} - 1\right)\left(\overline{\pi} - \overline{\pi}^{\epsilon}\,\overline{\theta}\right)}\right) + \beta\,\epsilon\,\overline{\pi}^{\epsilon}\,\overline{\theta}\,\hat{\pi}_{t+1}.
\end{aligned} \tag{A.3.6}$$

Finally, we use (A.3.3) to eliminate $\hat{\phi}_t$

$$\hat{y}_t\left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}-1\right)(\sigma-1)+\beta\,\overline{\pi}^{\epsilon-1}\,\overline{\theta}\,\mathbb{E}_t\hat{\phi}_{t+1}+\beta\,\overline{\pi}^{\epsilon-1}\,\overline{\theta}\,\mathbb{E}_t\hat{\theta}_{t+1} + \frac{\overline{\theta}\,\hat{\theta}_t\,(\overline{\pi}-\overline{\pi}^{\epsilon})+\overline{\pi}^{\epsilon}\,\overline{\theta}\,\hat{\pi}_t\,(\epsilon-1)\left(\overline{\theta}-1\right)}{(\epsilon-1)\left(\overline{\theta}-1\right)\left(\overline{\pi}-\overline{\pi}^{\epsilon}\,\overline{\theta}\right)} + \beta\,\overline{\pi}^{\epsilon-1}\,\overline{\theta}\,\hat{\pi}_{t+1}\,(\epsilon-1) = \hat{y}_t\left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}-1\right)(\sigma-1)-\hat{w}_t\left(\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}-1\right)+\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\,\mathbb{E}_t\hat{\theta}_{t+1} + \beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\left(\mathbb{E}_t\hat{\phi}_{t+1}+\frac{\overline{\theta}\,\mathbb{E}_t\hat{\theta}_{t+1}\,(\overline{\pi}-\overline{\pi}^{\epsilon})+\overline{\pi}^{\epsilon}\,\overline{\theta}\,\hat{\pi}_{t+1}\,(\epsilon-1)\left(\overline{\theta}-1\right)}{(\epsilon-1)\left(\overline{\theta}-1\right)\left(\overline{\pi}-\overline{\pi}^{\epsilon}\,\overline{\theta}\right)}\right)+\beta\,\epsilon\,\overline{\pi}^{\epsilon}\,\overline{\theta}\,\hat{\pi}_{t+1}. \tag{A.3.7}$$

Rearranging and collecting terms yields

$$\hat{\pi}_t=\alpha_1\hat{w}_t+\alpha_2\mathbb{E}_t\hat{\pi}_{t+1}+\alpha_3\mathbb{E}_t\hat{\phi}_{t+1}+\alpha_4\hat{\theta}_t+\alpha_5\mathbb{E}_t\hat{\theta}_{t+1},$$

where $\alpha_1=\frac{\left(1-\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\right)\left(\overline{\pi}^{1-\epsilon}-\overline{\theta}\right)}{\overline{\theta}}$, $\alpha_2=\beta\left(\overline{\pi}^{\epsilon}\,\overline{\theta}-\epsilon+\epsilon\,\overline{\pi}-\epsilon\,\overline{\pi}^{\epsilon}\,\overline{\theta}+1\right)+\frac{\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}\,(\epsilon-1)}{\overline{\pi}}$, $\alpha_3=-\frac{\overline{\pi}^{1-\epsilon}-1}{(\epsilon-1)\left(\overline{\theta}-1\right)}$, $\alpha_4=\beta\,\overline{\pi}-\beta-\frac{\beta\,\overline{\pi}^{\epsilon}}{\epsilon-1}+\frac{\beta\,\overline{\pi}}{\epsilon-1}-\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}+\frac{\beta\,\overline{\pi}^{\epsilon}\,\overline{\theta}}{\overline{\pi}}-\frac{\beta\,\overline{\pi}^{\epsilon}}{(\epsilon-1)\left(\overline{\theta}-1\right)}+\frac{\beta\,\overline{\pi}}{(\epsilon-1)\left(\overline{\theta}-1\right)}$, and , $\alpha_5=-\beta\left(\overline{\pi}^{\epsilon-1}\,\overline{\theta}-1\right)$ $(\overline{\pi}-1)$. We can distinguish two cases.

$\overline{\pi}=1$. The special case of zero trend inflation implies $\alpha_3=\alpha_4=\alpha_5=0$. Thus, we obtain the textbook NK Phillips curve with $\alpha_1=\frac{(1-\beta\overline{\theta})(1-\overline{\theta})}{\overline{\theta}}$ and $\alpha_2=\beta$.

As in the standard NK model, inflation $\hat{\pi}_t$ is positively linked to expected inflation $\mathbb{E}_t\hat{\pi}_{t+1}$ and marginal cost $\hat{w}_t$. Thus, in a first-order approximation, the effect of the time-varying price setting frequency simply cancels. Nonetheless, it is important to mention that, while considering a non-zero trend inflation steady state appears generally plausible in light of the positive inflation targets proclaimed by many central banks, it is essential for our linear estimation. Also note that there is no difference in the steady state price of a price re-setter and a non price re-setter, i.e., $\overline{p}^f=\overline{p}^*$.

$\overline{\pi}>1$. The general case considers positive trend inflation. Our assumptions imply that $\alpha_1,\alpha_2,\alpha_3>0$, i.e., as in a standard trend inflation model, inflation $\hat{\pi}_t$ is positively linked to expected inflation $\mathbb{E}_t\hat{\pi}_{t+1}$, marginal cost $\hat{w}_t$ and $\mathbb{E}_t\hat{\phi}_{t+1}$. The last two terms with current and expected Calvo share $\hat{\theta}_t$ emerge because of the Calvo law of motion. In addition, also $\mathbb{E}_t\hat{\phi}_{t+1}$ is potentially affected by the time-varying price setting frequency via (A.3.3). Note that $\alpha_5 > 0 > \alpha_4$ with $|\alpha_4| > |\alpha_5|$. Moreover, $|\alpha_4|$ and $|\alpha_5|$ are increasing in $\overline{\pi}$ as well as $\overline{\theta}$, i.e., the higher trend inflation or the lower the steady state price setting frequency, the stronger does inflation react to the changes in the actual and expected share of unchanged prices $\hat{\theta}_t$.

B The Calvo share in a large recession

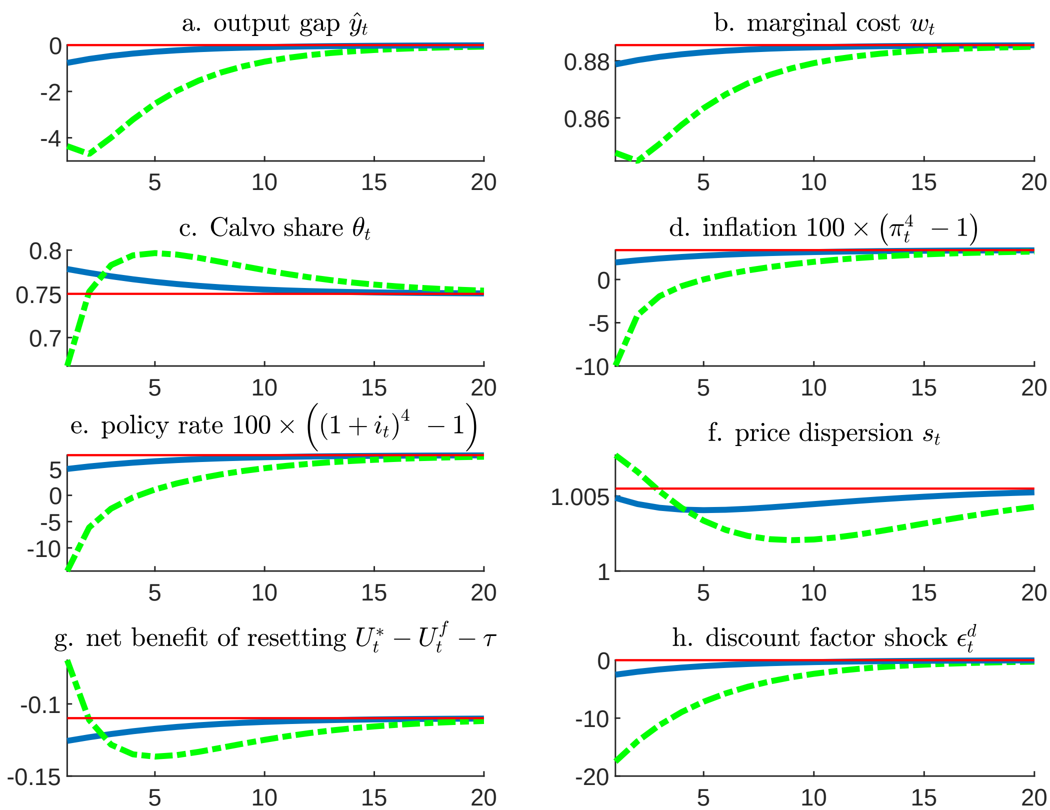

Figure B.1: Asymmetric impulse responses to a negative 2.5% (blue) and 17.5% (green) discount factor shock in the NK model. This choice implies a decline in the real interest rate of 0.5 (3.5 for the large shock) percent on impact. The persistence of the shock, $\rho_d = 0.8$ corresponds to a half-life of about 3 quarters in both cases. The unconditional standard deviation is 4.2 (29.2) percent. The negative shock implies an accumulated decline of real GDP of approximately 3 (22) percent over 7 quarters.