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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 in a given period depends on an analysis of expected cost and benefits modelled by a discrete choice process. A firm decides to update the price when expected benefits outweigh expected cost and then resets the price optimally. As markups are countercyclical, the model predicts that prices are more flexible during expansions and less flexible during recessions. Our quantitative analysis shows that contrary to the standard NK model, the assumed price setting behaviour: is consistent with micro data on price setting frequency; gives rise to an accelerating Phillips curve that is steeper during expansions and flatter during recessions; explains shifts in the Phillips curve associated with different historical episodes without relying on implausible high cost-push shocks and nominal rigidities.

Keywords: Price setting, inflation dynamics, monetary policy, Phillips curve.
JEL Classification: E31, E32, E52.

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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)

The flattening of the Phillips curve and historical shifts in this relationship between the output gap and inflation are well documented in the data. As pointed out by Clarida (2019) and others, these observations pose a challenge to frameworks for monetary policy analysis and the frameworks are now put under scrutiny. This certainly includes frameworks such as 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.

Under standard assumptions the NK model predicts a Phillips curve relationship that is much steeper than in the data. 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 excess inflation-less recovery.

A well-known potential remedy to reconcile the NK model with the data are implausible high cost-push shocks and nominal rigidities that are by-and-large inconsistent with observed price setting frequency at the micro level. For instance, Del Negro et al. (2015) or Guerrieri & Iacoviello (2017) estimate a Calvo (1983) parameter as high as $\theta = 0.87$ or 0.9. Yet, this remedy creates an unfortunate tension. On the one hand, high cost-push shocks and high degrees of price stickiness reduce the covariance between inflation and output and improve the fit with data on inflation and the output gap. On the other hand, the dynamics in inflation and the output gap are then mostly explained by high cost-push shocks and high degrees of price stickiness (see, e.g., King & Watson 2012, Fratto & Uhlig 2020).

This seems implausible from the viewpoint that the *Great Recession* was a demand-driven downturn that caused the observed inflation and output gap dynamics during and after the crisis, and also in light of empirical evidence on the price setting frequency at the micro level.

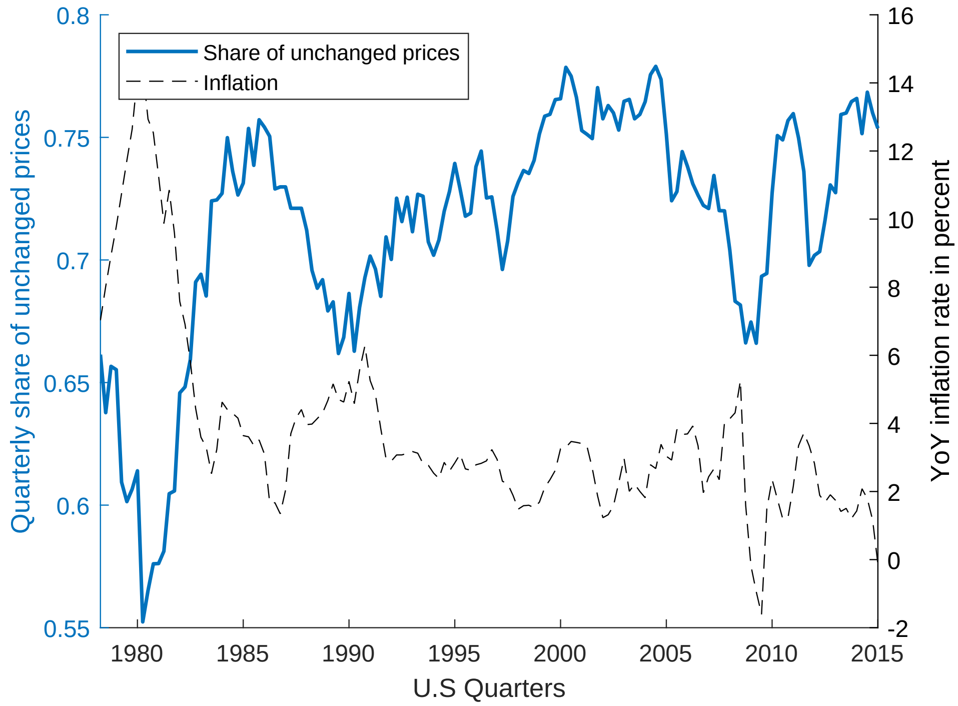
Admittedly, the insight that Calvo (1983) pricing models are notoriously difficult to reconcile with observed price setting at the micro level is not new, but nevertheless important in this context.[1] For instance, Nakamura et al. (2018) use US CPI micro data from the BLS to analyze the evolution, dispersion, heterogeneity and duration of US prices. They conclude that the magnitude and frequency of price changes are heterogeneous and time-varying over time. Figure 1 reconstructs the frequency of price adjustment based on the Nakamura et al. (2018) data and its relation to inflation.

Most strikingly, the share of non-updated prices corresponding to the Calvo (1983) parameter varies from $\theta = 0.55$ to $\theta = 0.78$, which implies a very large variation in the slope of the Phillips curve. Clearly, the negative correlation between the two variables is inconsistent with the Calvo (1983) pricing model that assumes a constant θ.[2] Moreover, Fernández-Villaverde & Rubio-Ramírez (2007) with a different identification technique based on macro-data show that price updating frequency varies over time and is correlated with inflation. It is then natural to conjecture that a time-varying price setting frequency may be an alternative explanation for the observe flattening and shifts in the Phillips curve.

Against this background we propose a simple extension of the Calvo (1983) pricing model to reconcile the NK model with the observed flattening of the Phillips curve

[1] Menu cost models suffer from the same problem. At the macro level, estimates of the quadratic cost have increased a lot. At the micro level, the simple models failed to account for heterogeneity and price dispersion.

[2] The coefficient of correlation between inflation and *the Calvo share* is equal to -0.808 over the Nakamura et al. (2018) sample.



Notes: Values are computed using Nakamura et al. (2018) monthly seasonally adjusted frequency of price changes (defined as the prices' increases and decreases with $\ln(p_{i,t}/p_{i,t-1}) > 1$ within the BLS consumer goods' price tags database) corresponding to the weighted of the medians across goods' baskets (based on households expenditure weights at their value in 2000 by the BLS) from the BLS micro data. Seasonally adjustment is done by averaging those monthly values over the last 12 months. See Figure 15 of Nakamura et al. (2018) for monthly disaggregated figure with prices increases and decreases and for more methodological developments on the question, see Nakamura et al. (2018) and the appendix therein. We use the product of those values to deduce the quarterly share of unchanged prices. Inflation is the seasonally adjusted year to year CPI growth from Fred.

Figure 1: Quarterly historical share of unchanged prices or θ_t the Calvo share based on micro-econometric data and its relation to inflation

and the evidence on time-varying price setting frequency at the micro level. The key novelty is that the aggregate price setting frequency - *discussed in this paper as the 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 followin Brock & Hommes (1997) that we denote the *Calvo law of motion.* The latter can be interpreted as an approximation to the firm's managerial decision of whether or not to update the price. A firm decides to update the price when expected benefits outweigh expected cost and then resets the price optimally.

Our main analysis implements the *Calvo law of motion* in a linearised trend inflation NK model (see, e.g., Ascari & Sbordone 2014). Relative to the Calvo (1983) pricing model, our model has several advantages. First, the aggregate price setting frequency is no longer static, but time-varying. Second, we achieve that by introducing the *Calvo law of motion* which captures the managerial decision process regarding price setting in line with survey evidence. The latter shows that posting a new price is the result of a complex cost-benefit analysis by the firms' managers rather than a random process.[3] The *Calvo law of motion* models this idea by taking into account the observed and expected evolution of markups, average relative prices and aggregate demand. We assume that there exists a trade off between updating and not updating current prices. Updating prices requires firms to gather information, spend resources and renegotiate contracts and so on. In a sense, updating prices is an inherently costly dynamic process where firms face heterogeneous opportunity costs. We assume that firms' managers decide to update their prices when it will increase the firm's expected markup by more than the updating cost. As markups are countercyclical, the model predicts that prices are more flexible during expansions and less flexible 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 a Calvo (1983) pricing model 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 a full information technique. In turn, we can assess the *Calvo share*'s contribution to the flattening of the Phillips curve and its shifts over time.

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

Our main theoretical finding is that the model's prediction of more flexible prices during expansions and less flexible prices during recessions, which can explain the non-linearity in the Phillips curve documented in the data. The price setting frequency accelerates during booms implying an accelerating inflation. In contrast, the model permits a decelerating price setting frequency during recessions and thus allows for mild deflation.

The quantitative main results of our paper are as follows. First, we find that our setup with the *Calvo law of motion* provides a good approximation of the observed aggregate price setting frequency depicted in Figure 1. Second, our model, despite its small scale, also fits the observed dynamics in inflation and output well. Third, the *Calvo law of motion* enables the model to explain the dynamics of inflation data to a large extent by shocks to aggregate demand and the endogenous evolution of the aggregate price setting frequency within a plausible range. The contribution of cost-push shocks to the shifts in the Phillips curve is very limited.

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 modification of the pricing model that gives rise to a time-varying aggregate price setting frequency. This modification is in part motivated by discussions over the stability of the original Calvo parameter as in Fernández-Villaverde & Rubio-Ramírez (2007), Alvarez et al. (2011) or Berger & Vavra (2018) and its consistency with the paradigm of micro-founded models.[4]

The *Calvo law of motion*, our proposed modification to the NK model is essentially a discrete choice model inspired by Brock & Hommes (1997). While modelling the decision of whether to update the price as a discrete choice is a novelty within the NK

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

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 & McGough 2010, Branch & Evans 2011, Hommes & Lustenhouwer 2019, Branch & Gasteiger 2019).

Very closely related to ours, is the proposal of Davig (2016) to model shifts in the Phillips curve. Davig (2016) develops a simple NK model with a representative firm and a quadratic price adjustment cost à la Rotemberg (1982). The key feature is the cost parameter that follows a two states Markov process and gives rise to changes in the slope of the Phillips curve. Davig (2016) uses this model to theoretically analyze optimal monetary policy. In contrast, our proposal is within the realm of the Calvo (1983) pricing model, introduces an explicit cost-benefit analysis of price updating, and our main results are derived within a quantitative analysis.

Our quantitative work also relates to sticky prices models based on micro-econometric evidence. Theoretical implications of individual price dynamics are extensively discussed by Alvarez et al. (2017). In a series of papers, Nakamura & Steinsson (2008), Nakamura & Steinsson (2013) and Nakamura et al. (2018) develop a deep analysis of the implications of *heterogeneous* menu costs models and their fit to micro data constructed using BLS prices tag data. We apply the Nakamura et al. (2018) data to match one dimension of it: the aggregate price setting frequency. In related work, Klenow & Kryvtsov (2008) and Alvarez & 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 price dynamics because of the heterogeneity in price stickiness.[5] The proposed *Calvo law of motion* in this paper captures this heterogeneity in reduced form.

Finally, our model speaks to the rapidly expanding discussion on the explanations

[5]Another related branch of the literature are the sticky information models (see, e.g., Mankiw & 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, forecasts behaviours, cross-sectional dynamics and stickiness. Yet, the updating property 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.

and implications of the flattening of the Phillips curve in the data in general, the missing deflation puzzle (Hall 2011) in particular. For instance, Mavroeidis et al. (2014) discuss dynamics in inflation expectations as an explanation of the observe data. Moreover, Lindé & Trabandt (2019) resolve the missing deflation puzzle with a non-linear model.

The rest of the paper is organized as follows. Section 2 presents a simplified model with endogenous price setting frequency to illustrate the key novelties and to build intuition. Section 3 embeds the proposed Calvo law of motion in a small scale NK model with trend inflation. Section 4 examines the equilibrium dynamics of the model and Section 5 contains the quantitative analysis. Section 6 concludes.

2 A simplified model

We begin with discussing the model in its simplest setting. This model allows us to illustrate the key features of the proposed Calvo law of motion and to build intuition for the results derived in this paper. Two simplifications relative to a standard DSGE model are worth mentioning. In this simple model firms are myopic. They do not take the future into account, when they set their prices. Moreover, aggregate demand is assumed to be an exogenous stationary AR(1) process.

2.1 Model outline

Aggregate demand for consumption Y_t is normalized and follows

$$Y_t = \overline{Y} e^{\varepsilon_t}$$

$$\varepsilon_t = \rho \varepsilon_{t-1} + u_t,$$

where $\overline{Y} = 1$ is the steady state, ε is a preference perturbation that follows an AR(1) stationary process with $0 \leq \rho < 1$ and u_t i.d.d and normally distributed. Labor supply is determined by the following schedule[6]

$$N_t^{\varphi} Y_t^{\sigma} = \frac{W_t}{P_t},$$

where W_t denotes the nominal wage and P_t is the aggregate price level.

The production technology is linear, where labour N_t is the only input

$$Y_t = N_t.$$

This implies that the real marginal cost are $w_t \equiv W_t/P_t$.

We assume that firms operate under monopolistic competition. The aggregate price level evolves according to equation (1) similar to the Calvo (1983) model, where a share of θ_t firms keep their former price and $1-\theta_t$ firms update their price, i.e.,

$$\begin{aligned} P_t &= (\theta_t P_{t-1}^{1-\epsilon} + (1-\theta_t) P_t^{*\,1-\epsilon})^{\frac{1}{1-\epsilon}} \qquad (1) \\ \Leftrightarrow 1 &= (\theta_t \pi_t^{\epsilon-1} + (1-\theta_t) p_t^{*\,1-\epsilon})^{\frac{1}{1-\epsilon}} \\ \Leftrightarrow \pi_t &= \left(\frac{(\theta_t - 1) p_t^* + 1}{\theta_t} \right)^{\frac{1}{1-\epsilon}}, \end{aligned}$$

where ϵ is the price elasticity of demand of goods and, $P_{i,t}^*$ is the optimal re-setting price, $p_{i,t}^* \equiv P_{i,t}^*/P_t$ is the relative optimal price and $\pi_t \equiv P_t/P_{t-1}$ denotes inflation. Firms are myopic and therefore their optimal price is not set in a forward-looking way. Given the firms' market power, it is simply optimal to charge a constant markup over real marginal cost, i.e., $p_t^* = \frac{\epsilon}{\epsilon-1} w_t$.[7] Finally, note that the relative price of non price resetting firms is given by $p_t^f \equiv 1/\pi_t$ and that the relative prices $p_{i,t}^*$ and p_t^f determine the respective firms' share in aggregate demand and their respective labor demand.

[6]This schedule could be derived from assuming instantaneous utility $U(C_t, N_t) = \frac{C_t^{1-\sigma}-1}{(1-\sigma)} - \frac{N_t^{1+\varphi}}{(1+\varphi)}$, aggregate goods market clearing $Y_t = C_t$, and the budget constraint $w_t N_t = C_t$.

[7]This could be derived from a Dixit & Stiglitz (1977) model of monopolistic competition.

2.2 The Calvo law of motion

This paper proposes to model firms as being run by managers that, in principle, consider to reset the price for their firm's good in each period. Managers base the strategic decision of updating or not updating the price on a cost-benefit analysis. Managers cannot observe the resetting price before updating it, but they have expectations about the relative resetting price $E_{t-1}\hat{p}_t^*$ and the average old price $E_{t-1}\hat{p}_t^f$. Thus, the cost-benefit analysis is based on a measure of expected performance making use of this knowledge.

We assume that the performance measure is based on the firm's profits and due to firms' homogeneity finally based on markups. While maintaining the price has no cost, resetting the price 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, τ may capture information acquisition, contract revisions, negotiations, working time, agency cost, or, simply menu costs (Rotemberg 1982). Thus, only if the expected performance of resetting the price net of the cost τ outperforms the expected performance of maintaining the price, managers will initiate the price resetting process.

Yet, there is an additional subtle but essential point that has to be taken into account when computing the expected performance of maintaining the price. Even in a model with a fixed parameter θ, maintaining the price has fundamentally different implications for each individual firm as long as there is non-zero trend inflation. Each firm has a different old price and thus faces a different opportunity cost between keeping or changing their price. This heterogeneity among firms increases the complexity in quantifying the expected performance of maintaining the price at the cost of model tractability. We propose to sidestep this complex issue for the sake of tractability and to approximate the aggregate Calvo share variation θ_t in reduced form by building on

Brock & Hommes (1997) and assuming the following Calvo law of motion

$$\theta_t = \frac{e^{\omega \mathbb{E}_{t-1} \hat{U}_t^f}}{e^{\omega \mathbb{E}_{t-1} \hat{U}_t^f} + e^{\omega \mathbb{E}_{t-1} \hat{U}_t^* - \tau}}, \tag{2}$$

where $0 < \theta_t < 1$, and $(1 - \theta_t)$ denotes the share of updated prices. Parameter $\omega \geq 0$ is denoted the *intensity of choice* and captures 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. $\mathbb{E}_{t-1}\hat{U}_t^*$ and $\mathbb{E}_{t-1}\hat{U}_t^f$ are the respective expected markup of updating and non updating firms in t considering the available information set in $t-1$.[8] [9]

Once we take into account that firms in the model have an identical cost structure, face identical demand curves and that in equilibrium markets clear, the Calvo law of motion can be equivalently expressed as

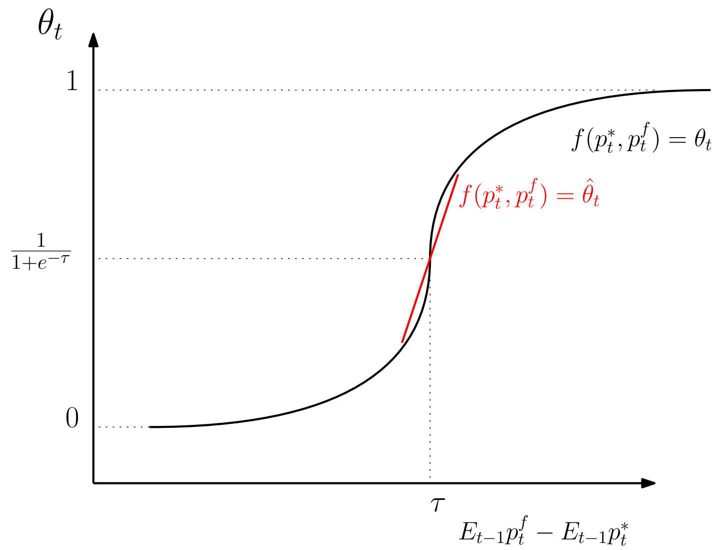
$$\theta_t = \frac{e^{\omega \mathbb{E}_{t-1} \hat{p}_t^f}}{e^{\omega \mathbb{E}_{t-1} \hat{p}_t^f} + e^{\omega \mathbb{E}_{t-1} \hat{p}_t^* - \tau}}. \tag{3}$$

That is, the price setting frequency is driven by the difference between relative prices with $\hat{p}_t^f$ denoting the average relative past price and $\hat{p}_t^*$ denoting the relative optimal price. Figure 2 illustrates the properties of (3).

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 updating cost τ, i.e., $\theta = 1/(1 + e^{-\tau})$. For instance, zero updating cost, $\tau = 0$, imply a share of $\theta = 1/2$. Moreover, in steady state the Calvo law of motion nests pure time-dependent pricing as in the standard Calvo model.

[8] A hat $(\hat{\cdot})$ indicates that a variable is expressed in log-deviation from their steady state. Without any implications for the results in this paper, we directly express profits in log deviation rather than in real deviation in order to harmonise this model in levels and the linearised NK model that will be developed in the following section.

[9] In order to keep our model embedded into the standard sticky prices model, we slightly deviate from the standard set-up of Brock & Hommes (1997). We do not multiply the fix cost by the intensity of choice. This allows the model to nest the standard Calvo pricing when $\omega = 0$, while preserving the fixed cost τ. Note that this modification has no impact on any of our results.



Notes: The y axis is the level of θ and the x axis is the difference between the expected profit of not updating and updating the price. The Calvo law of motion in functional form is in black. The linearised version is in red.

Figure 2: The Calvo law of motion and its linearised form

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 firms that maintain the price increases. From (2) it is clear that managers have a stronger incentive to organize a price resetting meeting when the expected future optimal price is higher than the expected average price, because this suggests that the firm's markup will increase. Yet, when the expected optimal price is lower relative to the expected average price, there is a weaker incentive for managers to set up a meeting as it suggests that the firm's markup will decrease.

While finite ω and τ as well as modest deviations of markups 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, $\theta_t = 0$, emerges if either $\hat{U}_t^* \to +\infty$ or $\hat{U}_t^f \to -\infty$. In these extreme cases the benefit of 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 not evolving and is equal to the steady state value of the marginal cost. This becomes feasible if either $\tau \to +\infty$,

$\hat{U}_t^* \rightarrow -\infty$ or $\hat{U}_t^f \rightarrow +\infty$. These are extreme cases, where the cost of resetting the price will always outweigh the benefit.

Also ω is a crucial parameter in determining price setting behavior in our model. Above we have interpreted it as a measuring how rational and heterogeneous agents are in the strategy selection (Brock & Hommes 1997). If $\omega = 0$, then θ is constant as in Calvo (1983) and pricing is entirely time-dependent. On the other hand, when $\omega \rightarrow +\infty$, all managers consider the whole set of information and do the optimal trade off between both strategies. This leads to the extreme case where $\theta_t = \{0, 1\}$. However, while the true value of ω is an empirical question, we do not consider $\omega \rightarrow +\infty$ to be a likely case even if strategy selection is entirely rational.[10]

2.3 Asymmetric dynamics in the Phillips curve

In the simplified model of this section we assume $\varepsilon_t^U = 0 \ \forall t$ and that agents are not forward-looking. Nevertheless, they observe the past. Therefore, we assume $\mathbb{E}_{t-1}\hat{p}_{i,t}^* = \hat{p}_{i,t-1}^*$ and $\mathbb{E}_{t-1}\hat{p}_t^f = \hat{p}_{t-1}^f$ in (3). Then the model can be solved recursively after defining the size of the shock at every period.

We use simulated impulse responses to illustrate an important feature of this simplified model that will also appear in the NK model that we analyse further below: asymmetric dynamics in the Phillips curve implied by the Calvo law of motion. As this analysis is solely for illustrative purposes, we parametrize the model with values that are frequently used in the literature as can be seen from Table 1. Appendix A.1 reports the steady state for this model and it becomes clear that this calibration implies a steady state gross rate of inflation of $\overline{\pi} = 1.0052$, which corresponds to 2 percent in annualized terms.[11]

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

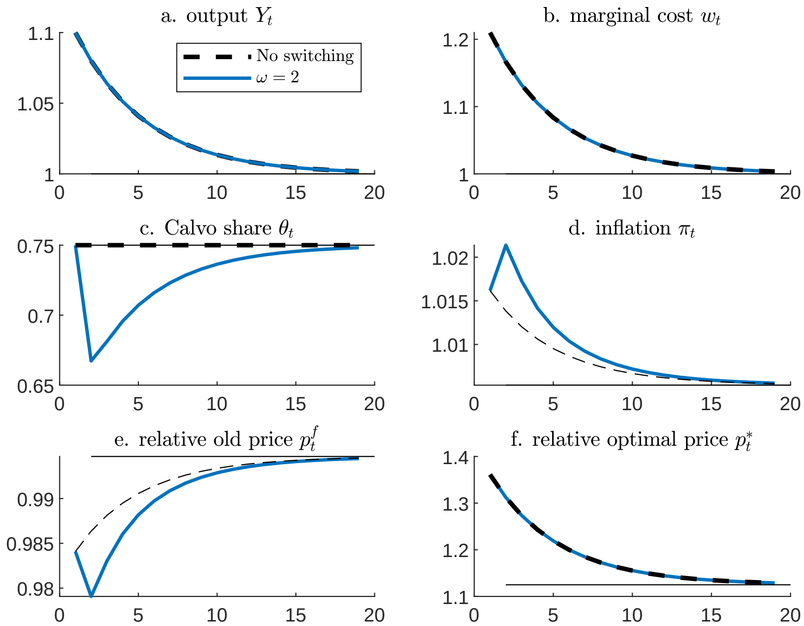
[11] The results are robust to different calibrations. Here, we assume log utility. The intensity of choice is taken from the heuristic switching learning literature. The price elasticity of demand tunes the level of inflation and the optimal relative price.

		Values
ϵ	price elasticity of demand	9
ρ	Persistence of demand shock	0.8
θ	Calvo steady state	$\frac{1}{1+e^{-\tau}} = 0.75$
ω	Intensity of choice	2
σ	risk aversion	1
φ	Frish labor elasticity	1

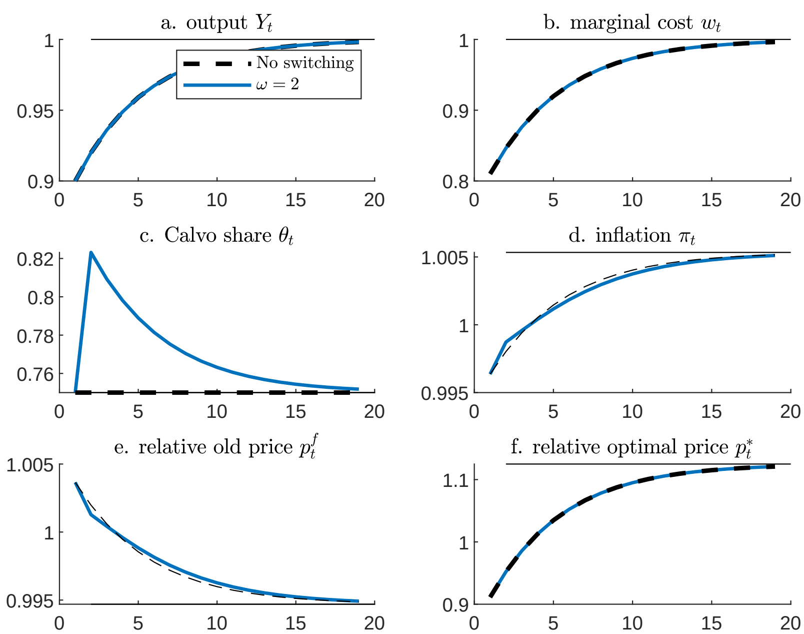
Table 1: Calibrated parameters (quarterly basis)

Figure 3a displays the simulated impulse response functions to a *positive* 10 percent demand shock. We start with the benchmark of time invariant θ (black dashed line). The shock raises output and 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 markup. In consequence, p_t^* and π_t increase and p_t^f must decline on impact. The subsequent periods show a persistent monotonic convergence of endogenous variables toward their steady state levels. This is due to the persistence in the demand shock 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. It is important to note that because of an exogenous aggregate demand side (i.e., the absence of feedback loop between prices and demand), output, marginal cost, and the optimal price decision are the same between the benchmark and the model enriched with θ_t.

Relative to the benchmark model, a time-varying Calvo share θ_t (blue solid line) has novel and important implications: while the responses of output and marginal cost are identical, the responses of nominal variables are strikingly different after the initial impact of the shock in $t = 1$. The boom in demand implies that the performance review of managers modelled by (2) after the impact period leads managers to the conclusion that raising the price net of the cost τ implies a higher markup relative to not raising the price. This implies that managers will setup meetings to reset the price and more firms will actually do so. Therefore θ_t declines, which translates into even higher inflation relative to the impact period and an even larger share of firms that have reset the price



(a) Response to a positive +10% demand shock



(b) Response to a negative -10% demand shock

Notes: IRFs are displayed in levels. The blue line depicts the IRFs for the enriched model with θ_t. The black dashed line depicts the IRFs for the benchmark model with fixed θ. The black solid line depicts the steady state.

Figure 3: Asymmetric impulse responses of the simple model

since the shock occurred. As more and more firms have already reset their price and marginal cost monotonically decline, more managers refrain from organizing meetings as their performance review modelled by (2) suggests that maintaining the price is the better strategy. This implies a hump-shaped response of inflation to a positive demand shock.

Next, we report simulated impulse response functions to a *negative* 10 percent demand shock in Figure 3b. In the benchmark with time invariant θ (black dashed line), the impulse responses and the economic intuition behind them are exactly the opposite of the positive demand shock. However, in the case of time-varying θ_t (blue solid line) the responses in the recession are strikingly different compared to a boom, but more in line with the benchmark model.

The initial effects are again identical to the benchmark model. In subsequent periods, the performance review of managers leads them to the conclusion that lowering the price net of the cost τ implies a lower markup relative to maintaining the price. Thus, a lower share of managers will set up meetings to reset the price and less firms will actually do so. Thus, θ_t increases, which translates into lower inflation relative to the impact period and a lower share of firms that have reset the price since the shock occurred. The relative advantage of not resetting the price dies out as marginal cost monotonically increase toward their steady state. It follows that more managers organize meetings and more firms reset their price. Thus, θ_t reverts back to its steady state as well.

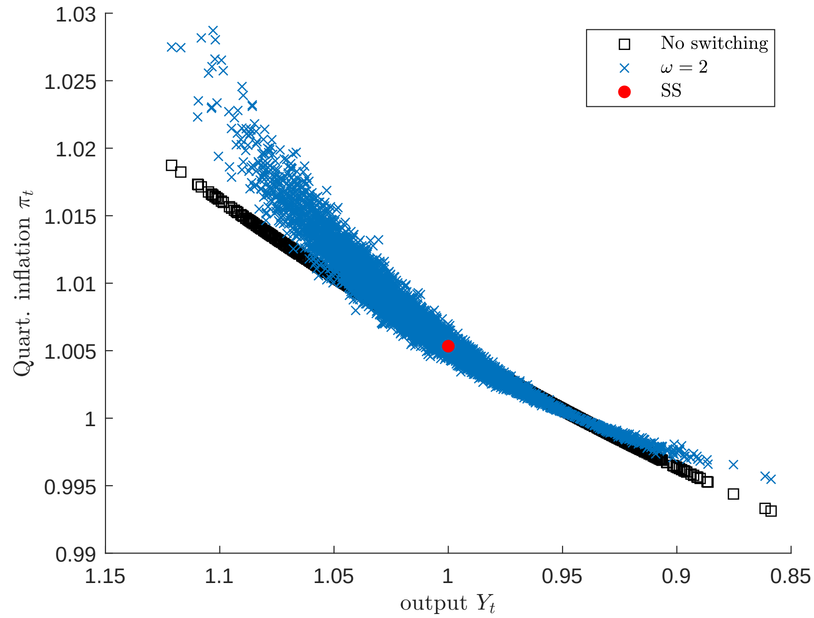
The above exercise makes clear that the Calvo law of motion implies an asymmetry in price setting by firms. The source of this behaviour is rooted in the countercyclical markups. Raising prices in booms raises markups (and therefore profits) relative to keeping the price unchanged. In contrast, lowering prices in recessions lowers markups relative to maintaining the price. As a consequence, the model with time-varying θ_t generates hump-shaped and larger responses of inflation relative to the benchmark case of the invariant θ in booms (see Figure 3a), but responses close to the benchmark model in recessions (see Figure 3b).

This asymmetry in impulse response functions to a demand shock translates into a prediction for the Phillips curve of this simple model, which is illustrated in Figure 4a. The Phillips curve is flat in recessions and steep in booms, which can be rationalized by the adjustment of the Calvo share over time, see Figure 4b. When inflation is high, the markup implied by the past average price level is low and the of price resetting frequency is high. In contrast, when inflation is low, the markup implied by the past average price level is high and the price resetting frequency is low.

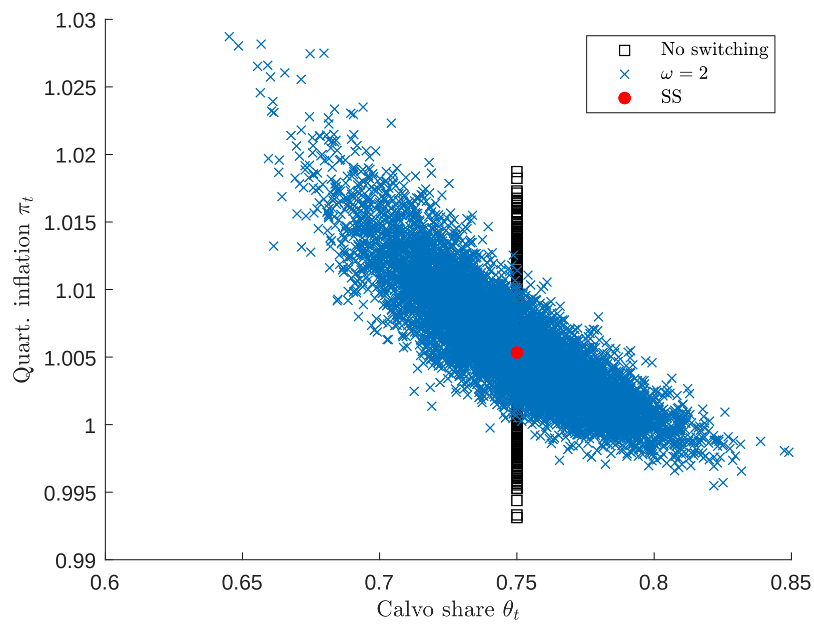
It is remarkable that even without any forward-looking private sector behavior or features such as price indexation, our model displays an asymmetric accelerating Phillips curve where deflation is limited and inflation is self re-enforcing. Therefore our modelling approach has the potential to explain low, but positive inflation during times of persistent slack as observed during the Great Recession, which the literature denotes the *missing deflation puzzle*. Widely used models such as the standard NK model fail to explain these observations (Hall 2011). Thus, the results obtained in our simplified model with exogenous aggregate demand, naturally motivate to examine the implications of the Calvo law of motion within an otherwise standard linearised NK model, where there is endogenous feedback to price setting. Even more important, this exercise equips us with a framework to assess the fit of this augmented NK model to both micro and macro data.

3 An augmented NK model

Herein we develop a standard NK model that we augment with the Calvo law of motion (2). In the subsequent sections, we will use the model to assess the extent to which this model has similar predictions as the simple model discussed above. Thereafter,



(a) Phillips curve



(b) Relation between inflation and the Calvo share

Notes: Blue crosses are the model's responses. Black squares are in the benchmark case with $\omega = 0$ and no active switching. Results are computed over 1,000,000 periods (Results are displayed in levels. Demand shock standard deviation correspond to $u_t = 0.1$)

Figure 4: Global dynamics in the simplified model

we use this model to examine the extent to which the Calvo law of motion (2) helps to make the NK model consistent with both macroeconomic and microeconomic data. The novelty in the model is that the time-varying Calvo share θ_t enters in the forward looking profit maximization problem of intermediate firms. Most parts of the model are identical to Ascari & Sbordone (2014). Therefore we focus on the departures from this model, namely the firms' pricing problem, the Calvo law of motion and the resulting price dispersion. The complete non-linear model is summarized in Appendix A.3.

3.1 The NK firm's pricing problem

First we discuss the intermediate firms' price setting problem profit maximization problem. The novelty is that we consider θ_t as an endogenous variable and not as a parameter. These firms maximize the expected present value of profits over an infinite horizon by applying the stochastic discount factor and the current and expected future frequency of price setting in an inflationary world. The price setting frequency and therefore the optimal reset price depends on the current and expected markup generated by the pricing decision. Those assumptions generate a complex feedback loop between the pricing decision and the resetting decision. Formally the problem is

$$\begin{aligned} \max_{\{P_t^*\}_{t=0}^{\infty}} \quad & \mathbb{E}_t \sum_{j=0}^{\infty} \mathcal{D}_{t,t+j} \theta_{t+j}^{j} \left[\frac{P_t^*}{P_{t+j}} - \frac{\Gamma'_{t+j}}{P_{t+j}} \right] Y_{i,t+j} \\ \text{s.t.} \quad & Y_{i,t+j} = \left(\frac{P_t^*}{P_{t+j}} \right)^{-\epsilon} Y_{t+j}, \end{aligned}$$

where $\mathcal{D}_{t,t+j} \equiv \beta^j \frac{\lambda_{t+j}}{\lambda_o}$ is the stochastic discount factor with λ_{t+j} denoting the $t+j$ marginal utility of consumption. Γ'_t is the marginal cost, P_t is the price level, Y_t is the output level ϵ is the price elasticity of demand and P_t^* is the optimal price for the resetting firm.

The first-order necessary condition for an optimum boils down to the following equation which stands for the optimal price set by the resetting firm

$$P_t^* = \frac{\epsilon}{\epsilon - 1} \frac{\mathbb{E}_t \sum_{j=0}^{\infty} \theta_{t+j}^j \mathcal{D}_{t,t+j} (P_{t+j}^{\epsilon} Y_{t+j} \Gamma'_{t+j})}{\mathbb{E}_t \sum_{j=0}^{\infty} \theta_{t+j}^j \mathcal{D}_{t,t+j} (P_{t+j}^{\epsilon-1} Y_{t+j})}. \tag{4}$$

We note that given the simple linear production function of intermediate goods producers, function $\Gamma'_{t+j} = w_{t+j}$. Moreover, the aggregate price level evolves according to

$$P_t = \left(\theta_t P_{t-1}^{1-\epsilon} + (1 - \theta_t) P_t^{*\,1-\epsilon} \right)^{\frac{1}{1-\epsilon}}. \tag{5}$$

We define $\Pi_{t,t+j-1}$ as the cumulative gross inflation between t and $t + j - 1$

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

Dividing both sides of (4) by P_t we obtain

$$p_t^* = \frac{\epsilon}{\epsilon - 1} \frac{\mathbb{E}_t \sum_{j=0}^{\infty} \theta_{t+j}^j \beta^j \Pi_{t+1,t+j}^{\epsilon} Y_{t+j} w_{t+j}}{\mathbb{E}_t \sum_{j=0}^{\infty} \theta_{t+j}^j \beta^j \Pi_{t+1,t+j}^{\epsilon-1} Y_{t+j}},$$

where $p_t^* \equiv P_{i,t}^*/P_t$ is the relative price level implied by the optimal price decision. Then we apply the definition of one period gross inflation in t, $\pi_t \equiv P_t/P_{t-1}$ and use (5) to obtain

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

It follows that we can rewrite (4) as

$$p_t^* = \frac{\epsilon}{\epsilon - 1}\frac{\psi_t}{\phi_t}, \qquad \text{where} \tag{6}$$

$$\psi_t = \mathbb{E}_t \sum_{j=0}^{\infty} \theta_{t+j}^j \beta^j \Pi_{t+1,t+j}^{\epsilon} Y_{t+j} w_{t+j},$$

$$\phi_t = \mathbb{E}_t \sum_{j=0}^{\infty} \theta_{t+j}^j \beta^j \Pi_{t+1,t+j}^{\epsilon-1} Y_{t+j}.$$

The latter two expressions can be written recursively as

$$\psi_t = w_t + \mathbb{E}_t \beta \theta_{t+1} \pi_{t+1}^{\epsilon} \psi_{t+1} \tag{7}$$

$$\phi_t = 1 + \mathbb{E}_t \beta \theta_{t+1} \pi_{t+1}^{\epsilon-1} \phi_{t+1}. \tag{8}$$

3.2 The Calvo law of motion with forward-looking firms

Similar to the simplified model above, the price setting frequency of intermediate firms in the augmented NK model depends on the managers' decisions on organizing a price setting meeting. However, given that firms are no longer myopic, it is important to note the timing. At the beginning of period t, managers form expectations about the current relative prices given the information set available at the end of period $t-1$. This implies that managers do not know the period t optimal price $p_{i,t}^*$, but have to form rational expectations about this price, i.e., $\mathbb{E}_{t-1}\hat{p}_{i,t}^*$. The same is true for the expected benefit of not updating the price $\mathbb{E}_{t-1}\hat{p}_t^f$. These expected relative prices are equal to the respective expected markup of updating and non updating firms in t considering the available information set in $t-1$. Given the general Calvo law of motion (2) discussed above, these expected markups determine whether a firm organizes a meeting for updating the price in period t. Once a firm has decided to organize a meeting, information available in period t is collected and the optimal price is determined in the meeting. This can be envisioned as a costly updating process similar to the one in

Mankiw & Reis (2002).

3.3 Price dispersion

Given the Calvo law of motion, price dispersion is a more complex process relative to the standard trend inflation NK model. Due to the time-varying θ_t, when relative current optimal prices, inflation or past dispersion are high, price dispersion increases. In order to illustrate this point, consider the definition of relative price dispersion

$$s_t \equiv \int_0^1 \left(\frac{P_{i,t}}{P_t}\right)^{-\epsilon} di. \tag{9}$$

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 complex, time-varying effects on price dispersion. On the one side, when the price setting frequency is low, i.e., θ_t is high, less firms are updating to the new optimal price, which implies an increase in price dispersion. On the other side, when the price setting frequency is high, i.e., θ_t is low, more firms update their price optimally, which implies that more firms choose the optimal price. This decreases price dispersion.

3.4 Linearised equations

In order to solve the model, we linearise it around a trend inflation steady state as in Ascari & Sbordone (2014) (see Appendix A.4). Throughout the linearisation, we assume $0 < \theta < 1$ to avoid the empirically implausible polar cases $\theta = \{0, 1\}$.[12] Thus, the linearized Calvo law of motion is driven by the difference between relative prices, i.e.,

$$\hat{\theta}_t = \theta^{-1}\frac{\omega}{2}\left\{\mathbb{E}_{t-1}\hat{p}_t^f - \mathbb{E}_{t-1}\hat{p}_t^*\right\} + \varepsilon_t^U,$$

where ε_t^U denotes a contract shock, which follows an $AR(1)$ stationary process and captures residual dynamics, for example an exogenous variation in contract duration with retailers. We use this shock for estimation purpose. 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 purposes. With a zero inflation steady state, there is no difference in the steady state price of a price re-setter and a non price re-setter, i.e., $p^f = p_i^*$. Thus, in a first order approximation of the effect of the variations of the resetting and non resetting shares would simply cancel themselves.

Next, the linearised version of the Phillips curve can be written as

$$\hat{\pi}_t = \alpha_1\hat{w}_t + \alpha_2\mathbb{E}_t\hat{\pi}_{t+1} + \alpha_3\mathbb{E}_t\hat{\phi}_{t+1} + \alpha_4\hat{\theta}_t + \alpha_5\mathbb{E}_t\hat{\theta}_{t+1} \tag{10}$$

with $\alpha_1, \alpha_2, \alpha_3 > 0$ and $\alpha_4, \alpha_5 < 0$ being the composite parameters displayed and discussed in Appendix B. The last two terms in (10) emerge because of the Calvo law of motion. In addition, as we discuss below, also $\mathbb{E}_t\hat{\phi}_{t+1}$ is affected by the time-varying price setting frequency.

As in a standard trend inflation model, inflation $\hat{\pi}_t$ is positively linked to expected

[12] Based on Figure 1 this seems to be a reasonable assumption.

inflation $\mathbb{E}_t\hat{\pi}_{t+1}$, marginal cost $\hat{w}_t$ and the additional term $\hat{\phi}_t$. Moreover, we can disentangle the relation between $\hat{\theta}_t$, $\mathbb{E}_t\hat{\theta}_{t+1}$ and $\hat{\pi}_t$. First of all, there is a negative relation between $\hat{\theta}_t$ and $\hat{\pi}_t$. Consistent with our discussion of the effect of θ_t on price dispersion s_t in (9), the higher $\hat{\theta}_t$, the less frequent price changes are and thus the less inflation we observe. The relation is also negative between $\mathbb{E}_t\hat{\theta}_{t+1}$ and $\hat{\pi}_t$. Thus, if the economy is expected to be less flexible in the next period, inflation will also be lower.

Moreover, the Calvo law of motion and a positive trend inflation steady state together have an additional effect on inflation in (10) via

$$\hat{\phi}_t = \beta\theta\overline{\pi}^{\epsilon-1}(\mathbb{E}_t\hat{\theta}_{t+1} + (\epsilon - 1)\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t\hat{\phi}_{t+1}).$$

Indeed, the higher expected values of $\hat{\theta}_t$ are, the higher current inflation is. This is generated by the same effect as a "fear of missing out" on price adjustment. If a firm expects less flexibility of the economy in the future in an inflationary environment, it may increase the price now.

Next, linearized price dispersion is given by

$$\hat{s}_t = \psi_1\hat{\pi}_t + \psi_2\hat{s}_{t-1} + \psi_3\hat{\theta}_t, \tag{11}$$

where $\psi_1 \equiv \epsilon\frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}(\overline{\pi} - 1) > 0$, $\psi_2 \equiv \theta\overline{\pi}^{\epsilon} > 0$ and $\psi_3 \equiv \overline{\pi}^{\epsilon}\theta - p^{*\,-\epsilon}\theta > 0$. Consistent with our discussion from above, the higher $\hat{\theta}_t$, the lower is the price setting frequency and the higher is relative price dispersion.

Finally, via (11), the price setting frequency also affects marginal cost given by

$$\hat{w}_t = (\sigma + \varphi)\hat{y}_t + \varphi\hat{s}_t + \alpha_1^{-1}\varepsilon_t^s.$$

We can see that a lower price setting frequency, i.e., a higher $\hat{\theta}_t$, increases price dispersion and therefore also marginal cost and consequently inflation.

The remaining model parts are taken from Ascari & Sbordone (2014) and given by

$$
\begin{aligned}
\textbf{Euler equation:} \quad & \hat{y}_t = \mathbb{E}_t \hat{y}_{t+1} - \sigma^{-1}(\hat{i}_t - \mathbb{E}_t \hat{\pi}_{t+1}) + \varepsilon_t^d \\
\textbf{Monetary Policy:} \quad & \hat{i}_t = \phi^\pi \hat{\pi}_t + \phi^y \hat{y}_t + \varepsilon_t^r \\
\textbf{Resetting rel. price:} \quad & \hat{p}_t^* = \frac{\theta \overline{\pi}^{\epsilon-1}}{1-\theta \overline{\pi}^{\epsilon-1}} \hat{\pi}_t - \frac{\overline{\pi}^{1-\epsilon} - p^*}{(1-\epsilon)(1-\theta \overline{\pi}^{\epsilon-1})} \theta \hat{\theta}_t \\
\textbf{Non-Resetting rel. price:} \quad & \hat{p}_t^f = -\overline{\pi} \hat{\pi}_t \\
\textbf{Shocks:} \quad & \varepsilon_t^j = \rho^j \varepsilon_{t-1}^j + u_{\varepsilon^j, t} \qquad \text{where} \qquad j \in \{d, s, r, U\}.
\end{aligned} \tag{12}
$$

4 Equilibrium dynamics

We now demonstrate that the linearised augmented NK model generates similar predictions in response to a demand shock as the simplified model with the Calvo law of motion as discussed above.[13]

4.1 Calibration

In order to elaborate the difference between our augmented and the benchmark model, we use a standard calibration, see Table 2, together with an intensity of choice $\omega = 2$.[14] We choose τ in such a way that it implies a steady state value of $\theta = 0.75$, which is standard in the NK literature. Most parameters are taken from Galí (2015). The parametrization of shocks is solely for illustrative purposes, but in line with findings in the literature.

[13]We have carried out similar exercises for the contract shock, cost-push and monetary policy shocks. However, we do not report them in this paper to keep the exposition concise. Impulse responses plots are available in the Appendix C

[14]Sensitivity analysis for the values of ω are available in Appendix C

		Values	Sources
β	discount factor	0.99	Galí (2015)
σ	risk aversion	1	Galí (2015)
φ	Frish labor elasticity	1	Galí (2015)
ϕ^{π}	policy stance on inflation	1.5	Galí (2015)
ϕ^{y}	policy stance on output	0.125	Galí (2015)
$\overline{\pi}$	inflation target	1.005	Fed official target
ϵ	price elasticity of demand	6	Galí (2015)
θ	Calvo steady state	$\frac{1}{1+e^{-\tau}} = 0.75$	Galí (2015)
ω	Intensity of choice	2	illustrative purpose
ρ^{D}	Persistence of demand shock	0.8	illustrative purpose

Table 2: Calibrated parameters for dynamic simulations (quarterly basis)

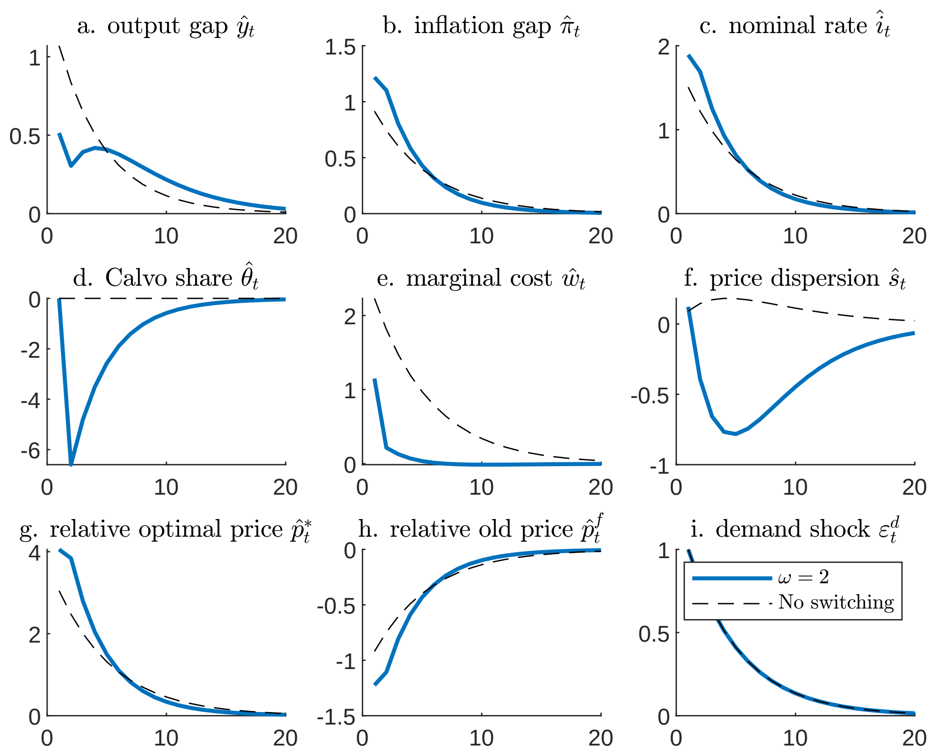
4.2 Impulse response functions

The impulse response functions to a demand shock in the linearised augmented NK model are depicted in Figure 5.

One can observe that the impulse responses are to a large extent in line with the ones in Figure 3a.[15] Consistent with an exogenous increase in demand, the output gap and real marginal costs increase independent of whether the price setting frequency is time-varying or time-invariant. In response, firms that reset their price, increase their price to stabilize their markup, which creates higher inflation than in the long-run and lowers the relative old price. In case of the augmented model, the price setting frequency increases, i.e. $\hat{\theta}_t$ declines, as more manages organize meetings to reset the price. Moreover, our calibration implies an increase in the nominal interest rate in line with the Taylor principle that ensures convergence to the steady state.

However, there are also important differences between the standard and the augmented model. With a time-varying price setting frequency, the impact responses of the output gap and real marginal costs are muted and the impact responses of nominal variables are amplified. This result can be traced back to the higher flexibility of prices

[15]The disappearance of the hump-shaped response of inflation as found in the simplified model is explained by the differing assumption on firm behavior. In the augmented NK model we assume forward-looking firms, whereas in the simplified model we assume myopic firms.



Notes: Results are in percentage point of the log deviation from the steady state.

Figure 5: demand shock

in the augmented model. The higher price flexibility implies a diametrically opposing prediction for price dispersion in the two models. In the standard NK model, relative price dispersion increases, whereas it decreases in the augmented NK model.

The mechanism behind the decline in relative price dispersion can be examined in more detail by the help of Figures 6a and 6b.[16] Figure 6a shows that relative to the steady state distribution ($t = 0$) both the price setting frequency and the magnitude of the optimal reset price are higher until the shock decays. Figure 6b shows that relative to the steady state distribution ($t = 0$), consistent with the higher price setting frequency, the age of the optimal reset price is lower until the shock dies out. In contrast, in the standard NK model, neither the frequency, nor the magnitude or the age of the

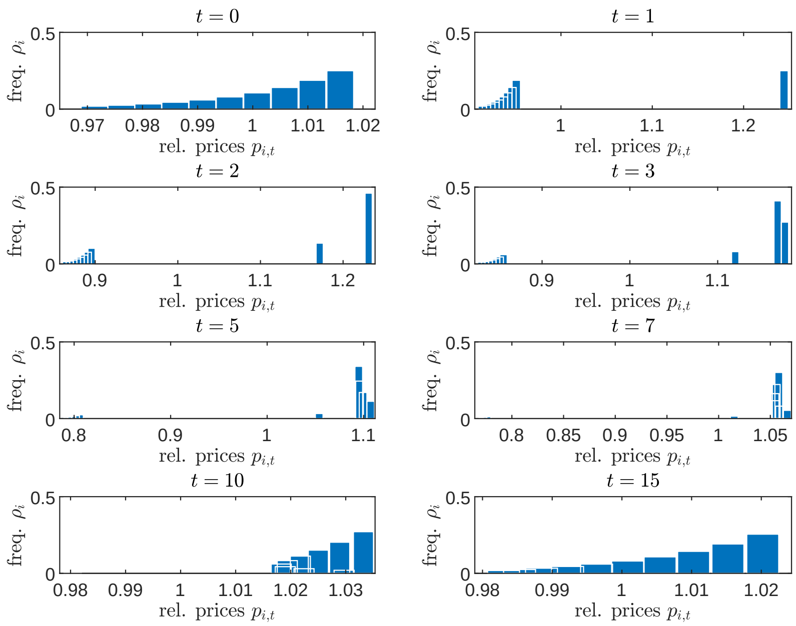
[16] Note that in these figures we increased the standard deviation for the shock for illustrative purposes.

optimal reset price would be time-varying.

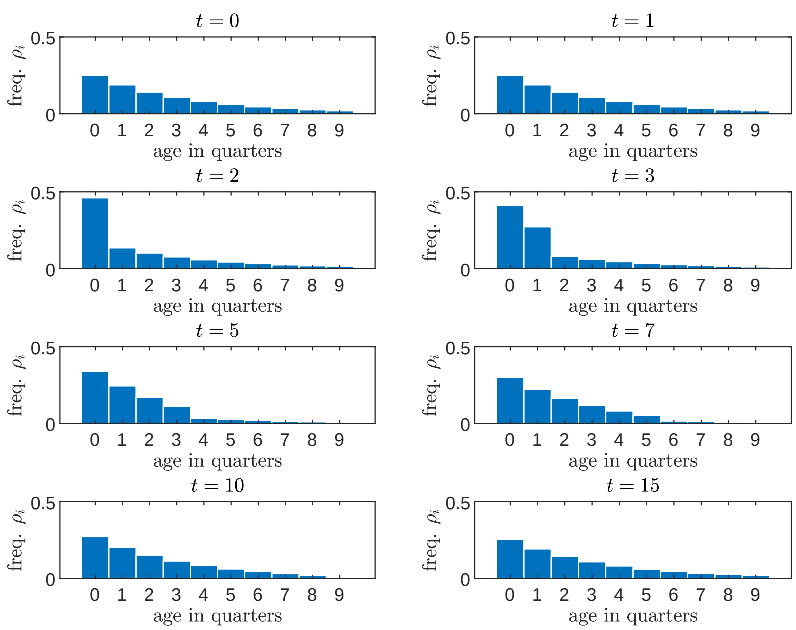
The higher price resetting frequency and the resulting lower age of optimal reset prices are a direct consequence of the managers' cost-benefit analysis approximated by the Calvo law of motion. Relative to the standard NK model more firms reset their price earlier after impact of the shock. This means that the relative price dispersion declines. Also households foresee this. While a demand shock tends to raise the output gap, the price increases by firms work in the opposite direction. Thus, once most of the aggregate price adjustment is done, i.e., the price setting frequency starts reverting and convergence of the relative optimal price accelerates, the negative effect of price increases gets weaker. This generates a persistent hump-shaped output gap response.

Next, the higher magnitude of optimal reset prices is due to the fact that firms take into account the higher price setting frequency in subsequent periods. Therefore firms set a higher optimal price relative to the standard NK model. The combination of higher price setting frequency and higher relative optimal prices explains why marginal costs increase by less on impact and converge faster. The firms that reset their price face a lower demand for their product and therefore have lower marginal costs.

In sum, the augmented NK model confirms the predictions discussed in the simplified model above. Moreover, despite the fact that the predictions for most variables are qualitatively in line with the standard NK model, there are quantitative differences for all variables and two key predictions to distinguish the augmented NK model from the standard NK model: first, the price setting frequency is time-varying and the relative price dispersion moves in the opposite direction. Thus, a natural question presents itself: which model is more consistent with the data? The remainder of the paper provides an answer to this question.



(a) Frequency of relative prices



(b) Prices' ages distribution

Notes: Blue bars are the frequency ($\rho_{i,t}$) of pricing decision ($p_{i,t}$) or of the age of the price (only the 10 most used pricing decision a display. We increase the size of the shock to enhance the change in frequency level.)

Figure 6: Prices dynamic after a demand shock of +5%

5 Empirical analysis

In order to empirically validate the augmented NK model and especially the proposed Calvo law of motion, we estimate versions of the model by using Bayesian techniques.

5.1 Data and measurement equations

We use four quarterly time series in log-levels: the output gap, inflation, the Federal Funds rate and the share of unchanged prices depicted in Figure 1. The sample ranges from 1964 to 2018. The output gap, inflation and the Federal Funds rate are taken from the Fred website.[17]

The main innovation of our estimation is that we use the share of unchanged prices in the estimation in order to assess the consistency of our model with microeconomic next to macroeconomic data. To construct this time series we use the monthly prices increases and decreases data from Nakamura et al. (2018) between 1978 to 2015 (see the note in Figure 1 for methodological details). Conceptually this share of unchanged prices corresponds to the Calvo share θ_t, which accounts for the share of prices that are not updated per quarter. Note that θ_t is not available for the periods 1964 to 1978 and 2015 to 2018. Thus, for these periods we treat θ_t as a latent state variable and exclude it from the likelihood optimization problem.[18]

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

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

[17]The output gap is the log deviation from a linear growth trend computed by the authors in order to keep a zero mean time series. Result are robust to the Fred output gap time series.

[18]An alternative is to estimate the model solely for the sample 1978 to 2015. However, such short samples raise many general identification problems.

where $\overline{r} = \frac{\overline{\pi}}{\beta} - 1$ is the quarterly risk free rate.

5.2 Calibration and priors

We estimate our model using a linear Kalman filter with Bayesian Priors and Monte-Carlo Markow chain sampling. The optimization is handled by Dynare (Juillard et al. 1996) using the Metropolis Hastings algorithm with a diagonal covariance matrix. We define priors according to Table 3, mostly in line with Smets & Wouters (2007).

DSGE			*Prior Distributions*			*Posterior Results*				
Estimated Parameters			Shape	Mode	STD	Mode	STD	Mean	5%	95%
std. $u_{\varepsilon^d,t}$	-	Demand shock std	Invgamma	.1	2	0.0389	0.0171	0.0516	0.0290	0.0736
std. $u_{\varepsilon^s,t}$	-	Cost shock std	Invgamma	.1	2	0.3040	0.02762	0.2974	0.2484	0.3434
std. $u_{\varepsilon^r,t}$	-	MP shock std	Invgamma	.1	2	0.2762	0.0203	0.2854	0.2548	0.3154
std. $u_{\varepsilon^\theta,t}$	-	Contract shock std	Invgamma	.1	2	2.9903	0.2015	2.9870	2.6671	3.2956
ρ^d	-	Demand shock auto.	Beta	.5	.2	0.9474	0.0170	0.9401	0.9144	0.9663
ρ^s	-	Cost shock auto.	Beta	.5	.15	0.9947	0.0041	0.9918	0.9875	0.9960
ρ^r	-	Rate shock auto.	Beta	.5	.2	0.2388	0.0492	0.2433	0.1605	0.3244
ρ^θ	-	Contract shock auto.	Beta	.5	.1	0.7267	0.0376	0.7360	0.6758	0.7969
$\overline{\pi}$	-	Quarterly inflation trend	Calibrated	1.005	-	-	-	-	-	-
$\overline{r} = 100 \times (\frac{\overline{\pi}}{\beta} - 1)$	-	Natural interest rate	Normal	1	.3	0.6901	0.0928	0.6606	0.5019	0.8256
$\theta = \frac{1}{1+e^{-\tau}}$	-	Quarterly share of non upd. p.	Beta	.5	.2	0.7213	0.0071	0.7188	0.7078	0.7309
ω	-	Intensity of choice	Normal	5	0.2	4.0613	0.1582	4.0656	3.7705	4.3291
σ^C	-	Consumption risk	Gamma	1.4	.4	2.7196	0.3864	2.5178	1.7901	3.2042
σ^L	-	Frish labor elasticity	Gamma	2	.25	2.3557	0.2539	2.3870	2.0004	2.7611
$\hbar$	-	Consumption habit	Beta	0.7	.1	0.2825	0.0476	0.2889	0.2170	0.3591
ϕ^π	-	MP. stance on inf.	Normal	1.5	.37	2.0747	0.2119	2.2393	1.9154	2.5607
ϕ^y	-	MP. stance on out.	Normal	.125	.05	-0.00075	0.0137	-0.0058	-0.0284	0.0163
ρ	-	Lag in MP. stance	Beta	.5	.2	0.6959	0.0311	0.7062	0.6577	0.7562
ϵ	-	Elasticity of substitution of goods	Normal	4	1.5	8.7948	0.8485	9.5747	7.0552	10.0608
						Log-likelihood		-783.14668		

Table 3: Estimated parameters using Monte Carlo Markow Chain Bayesian estimation technique (US: 1964-2019)

Due to under-identification issues we calibrated the inflation trend at $\overline{\pi} = 1.005$ which stands for 2% yearly inflation. In order stabilize the estimation we choose a prior for ω normally distributed around 5 with a standard deviation of 0.2. This choice is in line with empirical and experimental evidence of $\omega \in [0, 10]$ using the heuristic switching model, see, e.g., Hommes (2011), Cornea-Madeira et al. (2019) and Hommes (2020). Results are robust for a prior range of $0 < \omega < 10$, but the identification is fairly challenging and we need to use a tight prior. Consequently, our choice is motivated by delivering the best fit in the range for ω.

In order to facilitate convergence of the estimation, we introduce a consumption habit parameter h that stabilizes the consumption response to variations in the real interest rate and interest-rate smoothing with a parameter ρ.[19]

Finally, we do not want to use price indexation in order to facilitate convergence by the implied additional lags in the Phillips curve and the Calvo law of motion. Thus, price indexation would have an interaction with the mechanism introduced by the Calvo law of motion and this would make it difficult to rationalize the empirical performance of the model relative to exclusively by the Calvo law of motion. Therefore, in order to avoid a unit root, we reduce the standard deviations for the autocorrelation parameters of the supply and the contract shock from 0.2 to 0.15 and 0.1 respectively.

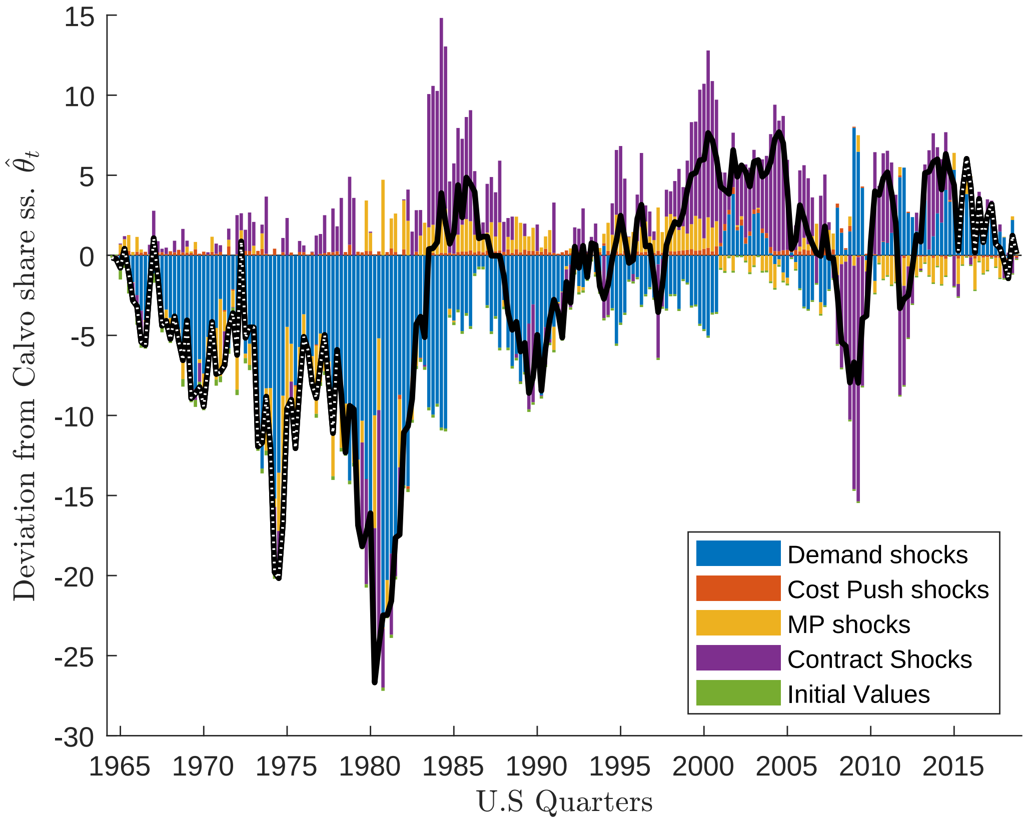
5.3 Parameter estimates

Our estimated parameter values are displayed in Table 3 and broadly in line with the previous literature. The steady state Calvo share $\theta = 0.7188$ is fairly close to the historical average in various datasets. The intensity of choice $\omega = 4.0613$ is strictly positive and in line with the evidence on dynamic predictor selection. The value is also close to the one that we used in our simulated impulse response analysis above. The estimated standard deviation of the contract shock is large and can be explained by the large historical variation of the observed Calvo share (see Figure 7). Yet despite the large contract shocks, the Calvo share is still mostly driven by demand shock, see Figure 7. The latter indicates the consistency of the Calvo law of motion with the US business cycle.

5.4 Consistency with the data

We next demonstrate that the Calvo law of motion improves the consistency of the NK model with macroeconomic and microeconomic data by four exercises. First, we

[19]Thus, monetary policy follows the rule $\hat{i}_t = \rho\hat{i}_{t-1} + (1-\rho)(\phi^\pi\hat{\pi}_t + \phi^y\hat{y}_t)$ and the Euler equation is given by$\hat{y}_t = \frac{h}{1+h}\hat{y}_{t-1} + \frac{1}{1+h}\mathbb{E}_t\hat{y}_{t+1} - \frac{\sigma^{-1}}{1+h}(\hat{i}_t - \mathbb{E}_t\hat{\pi}_{t+1}) + \varepsilon^d_t$.



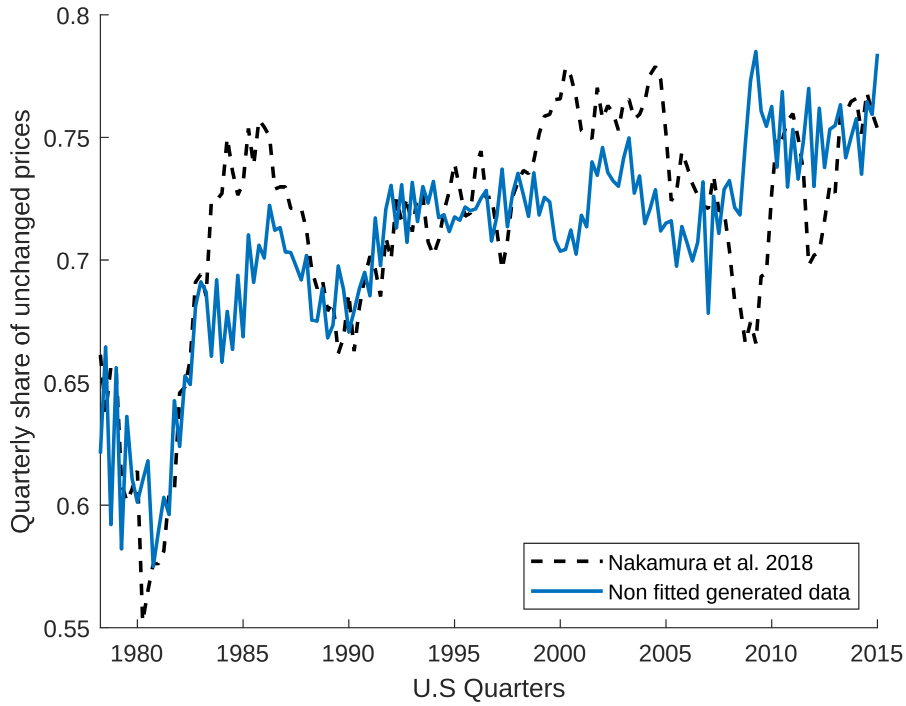
Notes: Values are in log deviation from the steady state. Dotted line is generated/unobserved data

Figure 7: Historical decomposition of the Calvo's dynamic based on US data (1964-2018)

re-estimate the augmented NK model while treating θ_t as a latent state variable. We then compare the predicted path for the latent state variable θ_t to the series from Nakamura et al. (2018) depicted in Figure 1. Then, we assess the model's capability to replicate the post-WWII US Phillips curves during three different episodes: pre-Great Moderation, Great Moderation and New Normal.

5.4.1 The relevance of the Calvo law of motion

The estimated of the 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 predicted path for the latent state variable θ_t from the estimation of the augmented NK model with three observables to the Nakamura et al. (2018) data in Figure 8.



Notes: Nakamura et al. 2018 data are computed by the authors as in Figure 2. Non fitted generated data are the latent state variable generated by the model when estimated to fit only inflation, Fed Fund Rate and output gap. In order to avoid identification issue on θ we define a normally distributed prior with a mean of 0.75 and standard deviation of 0.05.

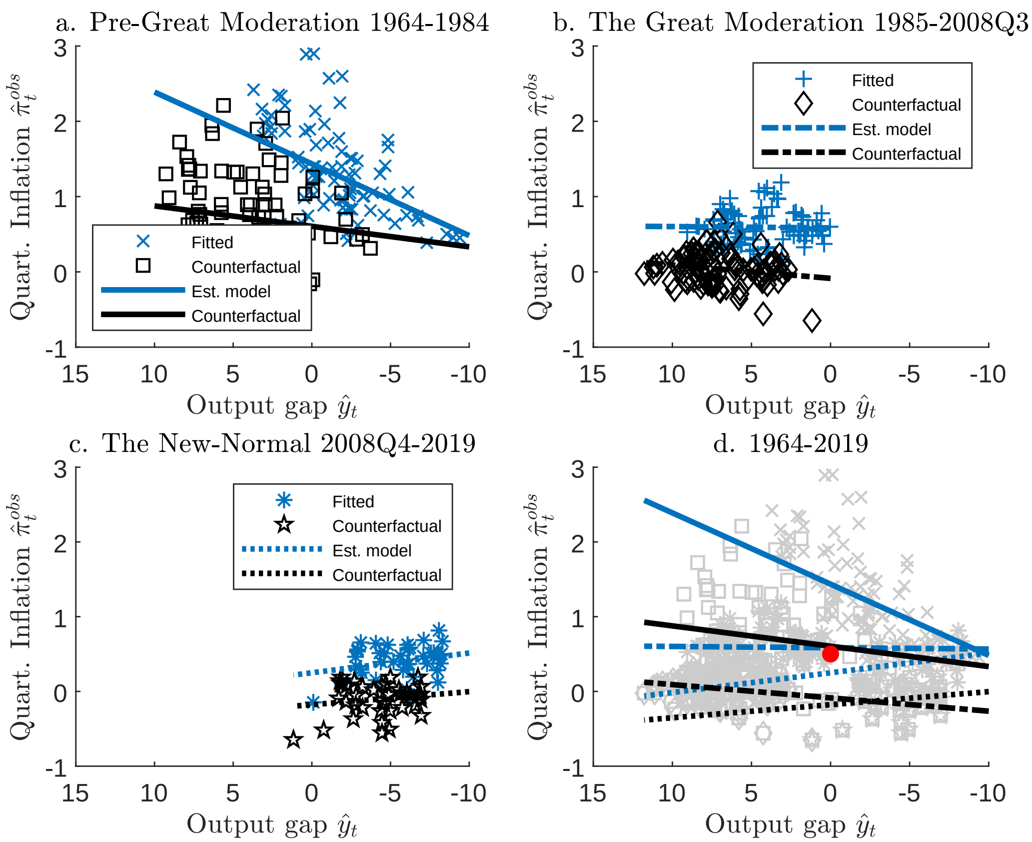
Figure 8: Generated Calvo share as latent state variable vs. micro data

Overall, the predicted path and the data line up fairly good both in qualitative and quantitative terms. The only notable deviation is the 2008 crisis where our model generates a spike in θ_t (less price updating) while the data displays a drop (more price updating). Nevertheless, Figure 8 suggests that the Calvo law of motion is reasonable modelling device and makes the NK model consistent with microeconomic data on price setting frequency.

5.4.2 Fitting the post-WWII US Phillips curves

We now show that the Calvo law of motion also improves the consistency of NK model with macroeconomic data in the sense that it enables the NK model to explain the post-WWII US Phillips curves during three different historical episodes: pre-Great Moderation, Great Moderation and New Normal.

In order to do so, we compare the model fitted data from the augmented NK model to generated data from a counter-factual exercise. In the counter-factual exercise we switch off the Calvo law of motion by setting $\omega = 0$ and $u_{\varepsilon^U,t} = 0$. We then apply the same sequences of the remaining shocks, same initial values and the same parameter values. This helps us to illustrate the relative improvements due to the Calvo law of motion. Figure 9 contrasts the model fitted data and the data generated by the counter-factual exercise in which the Calvo parameter is equal to the steady state $\theta_t = \theta$.



Notes: The counter-factual scenario is computed with neither active $\omega = 0$ switching nor contract shocks $u_{\varepsilon^U,t} = 0$. Thus $\hat{\theta}_t = 0$ and no switching occurs. Shocks, initial values and parameter values are strictly the same.

Figure 9: Phillips curve dynamics in the NK models and its counter-factual

Interestingly, the counter-factual scenario displays systematic lower inflation (see

Figure 9 and the first two columns in bold of Table 4). It seems to be rather intuitive considering how low the observed values of the Calvo share are before the Great Moderation. The low inflation after the Volcker disinflation is due to the lower overall output. The lower output is generated by the relative higher marginal cost associated with outside steady-state inflation. Indeed, in the benchmark model, high inflation generates high price dispersion, high marginal cost and consequently lower output. On the other hand, the time-varying price setting frequency tends to decrease price dispersion when inflation is high due to more firms updating to the optimal price. Thus, inflation has a lower cost in terms of output in the augmented NK model. For this reason inflation is very much correlated with output gap level in the standard NK model. Thus, the counter-factual scenario generates too little inflation before the Great Moderation and too much deflation during the Great Moderation and especially during the New Normal.

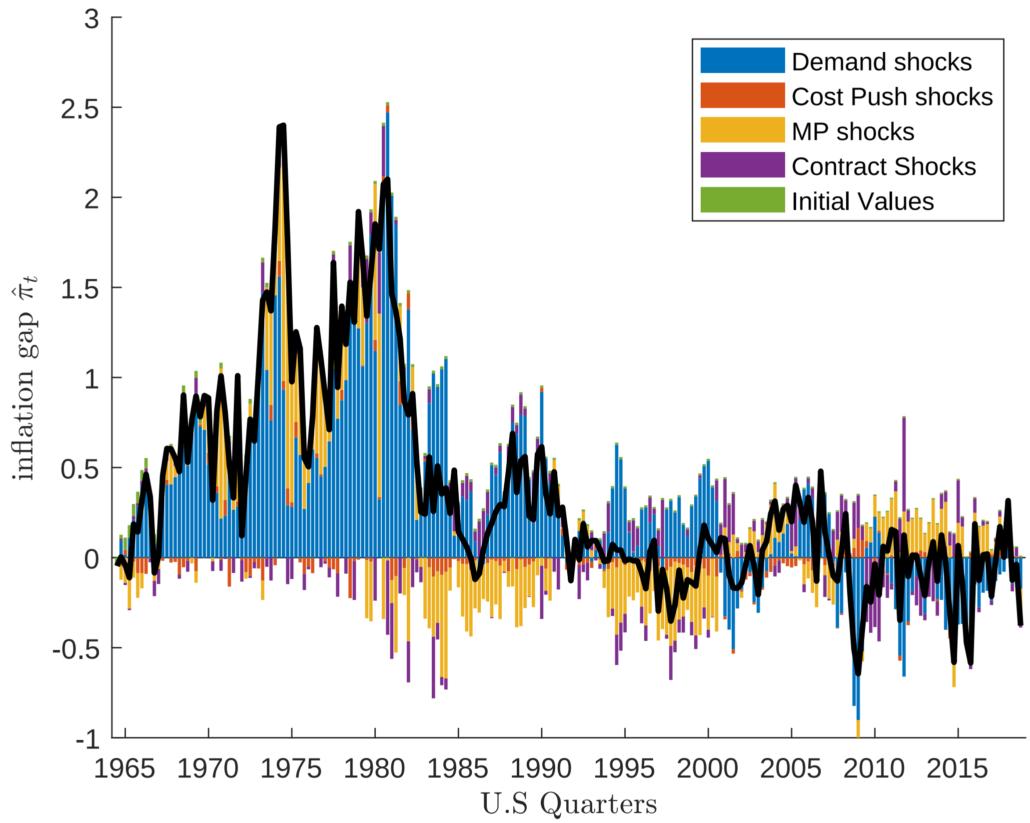
Further insights can be gained by analysing the three different historical episodes separately, see Figure 9 and Table 4.

Model: *Phillips curve estimates*	***Dynamic Calvo*** **Fitted to data**	***Static Calvo*** **Counterfactual**	*No contract shocks and switching* Counterfactual	*Contract shocks and no switching* Counterfactual
Pre-Great Moderation 1964-1984:				
a - estimated inflation at zero output gap	**1.435**	**0.568**	0.356	0.42
b - estimated linear relation $\hat{y}_t/\hat{\pi}_t^{obs}$	**0.095**	**0.032**	0.067	0.061
$av(\hat{\pi}_t^{obs})$ - average inflation	**1.3%**	**0.735%**	0.734%	0.732%
$av(\hat{y}_t)$ - average output gap	**−1.413%**	**5.169%**	5.7%	5.137%
$av(\theta_t)$ - average Calvo Share	**0.670**	**0.719**	0.673	0.726
The Great Moderation 1985-2008Q3:				
a - estimated inflation at zero output gap	**0.584**	**−0.084**	−0.153	−0.05
b - estimated linear relation $\hat{y}_t/\hat{\pi}_t^{obs}$	**0.002**	**0.013**	0.021	0.013
$av(\hat{\pi}_t^{obs})$ - average inflation	**0.592%**	**0.026%**	0.026%	0.055%
$av(\hat{y}_t)$ - average output gap	**4.269%**	**8.41%**	8.488%	8.068%
$av(\theta_t)$ - average Calvo Share	**0.725**	**0.719**	0.714	0.726
The New-Normal 2008Q4-2019:				
a - estimated inflation at zero output gap	**0.25**	**−0.141**	−0.176	−0.179
b - estimated linear relation $\hat{y}_t/\hat{\pi}_t^{obs}$	**−0.026**	**−0.012**	−0.024	−0.019
$av(\hat{\pi}_t^{obs})$ - average inflation	**0.397%**	**−0.105%**	−0.105%	−0.124%
$av(\hat{y}_t)$ - average output gap	**−5.574%**	**−2.901%**	−2.906%	−2.845%
$av(\theta_t)$ - average Calvo Share	**0.732**	**0.719**	0.734	0.738

Notes: Philips curves are computed as a linear approximation of the relation between $\hat{y}_t$ and $\hat{\pi}_t^{obs}$ such as $\hat{\pi}_t^{obs} = a + b\hat{y}_t + \epsilon_t$ that satisfies the least square error term. The *'no contract shocks and switching'* counterfactual scenario displays the statistics for the Phillips Curve estimates when there is no contract shock *i.e* std. $u_{\varepsilon^\theta,t} = 0$ and $\omega = 4.0656$. The *'contract shocks and no switching'* counterfactual scenario displays the statistics for the Phillips Curve estimates when there is the estimated contract shock time series with a std. $u_{\varepsilon^\theta,t} = 2.9870$ but no switching $\omega = 0$.

Table 4: Results for the Phillips curve statistics and additional counterfactuals simulations

Both the figure and table illustrate the flattening of the Phillips curve in the Great Moderation and an inversion of the relation after the 2008 crisis for the model fitted data. The estimates of the counter-factual Phillips curve have very similar slope coefficients in all three historical periods. Thus, the standard NK model fails to show the pattern found in the data. This is no surprise as it is known that for the standard NK model with fixed θ, the only way to change the slope of the Phillips curve is through implausible high cost-push shocks. This is why standard estimates with time-invariant price setting frequency tend to exhibit Calvo parameter estimates that inconsistent with microeconomic data on price setting frequency and large cost-push shocks that are negatively correlated with the output gap.



Notes: Values are in log deviation from the steady state. Dotted line is generated/unobserved data

Figure 10: Historical decomposition of the inflation dynamic based on US data (1964-2019)

In contrast, in the augmented NK model, 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 and monetary policy shocks. Figure 10 displays the shocks driving the variation in inflation. Another interesting observation in this figure is that the cost-push shock and the contract shock do not play a large role during the pre-Great Moderation and the New Normal period. This suggests that during these periods, inflation is driven by the time-varying price setting frequency, which depends on demand shocks and by changes in the monetary policy stance. Thus, in the augmented NK model, inflation can be explained directly by the dynamics of the output gap driving price dispersion and the price setting frequency. In order to replicate the flattening of the Phillips curve during the Great Moderation and the reversal during the New Normal, the augmented NK model does not require implausible large residual shocks on inflation and an implausible high constant Calvo parameter that reduces the co-movement between inflation and output. Therefore we conclude that the Calvo law of motion also helps to make the NK model more consistent with macroeconomic data.

An obvious remaining question is then, which component of the Calvo law of motion is the main driver behind this result? Inspection of (3) makes clear that the time variation in the Calvo share is the product of an endogenous and exogenous component. The endogenous component is the discrete choice function for the price updating decision that approximates the cost-benefit analysis in firms. The exogenous component are the contract shocks. In order to disentangle the effect of the endogenous and exogenous component on generating our results, we also compute the Phillips Curve estimates for a counterfactual scenario with contract shocks but no endogenous variation ($\omega = 0$) and a scenario with endogenous variation ($\omega = 4.0656$) but no contract shocks. It is crucial to understand that even though both components change the value of the Calvo share, they generate very different effects on the expectations of future state variables, especially inflation. On the one side, the contract shock generates rational micro-founded best responses from the model's agents to an exogenous process. On the other side, the discrete choice function creates endogenous responses to the expected variations of the Calvo share in response to every variation of every other state variables. The results are displayed in the last two columns of Table 4 above.

First we can observe that both scenarios exhibit shifts in the Phillips curves' slopes and intercepts across the post WW2 US business cycle. Second, nonetheless, the endogenous component - i.e., the switching - tends to be the main driver of the change in the Phillips Curve slope during the pre-Great Moderation and post-2008 Crisis periods (compare the Phillips Curves' coefficients 'b' of the first column to the third and fourth columns of Table 4). Third, only the interaction between the endogenous and exogenous component seems to explain the flattening during the Great Moderation, i.e., the observed changes in inflation and output. We can observe the importance of the contract shock during the beginning of the Great Moderation in Figure 7. This is a reasonable interpretation in light of the insight that the contract shocks have fairly different effect on output when $\omega > 0$, i.e., the cost-benefit analysis of resetting the price is activated (see Figure C.1 in Appendix C for an illustration). Overall, this counterfactual exercise demonstrates that the main driver behind the augmented NK model's consistency with macroeconomic data is the endogenous component of the Calvo law of motion, i.e., the cost-benefit analysis of resetting the price.

6 Conclusion

We developed a New Keynesian model with endogenous price setting frequency that is consistent with the data both at the macro and micro level. In this way the NK model can potentially be reconciled with phenomena such as the flattening of the Phillips curve and the missing deflation puzzle.

In our model, expected markups and costly updating drive heterogeneity and stickiness in price setting. A firm decides to update the price when expected benefits outweigh expected cost and then resets the price optimally. We model the updating decision with a discrete choice process that we denote the Calvo law of motion. The process approximates well the individual trade offs that firms face when deciding about price updating.

As markups are countercyclical, the model predicts that prices are more flexible during expansions and less flexible during recessions. This in turn gives rise to a nonlinear Phillips curve. The price setting frequency accelerates during booms implying an accelerating inflation. In contrast, the model permits a decelerating price setting frequency during recessions and thus allows for mild deflation. This mechanism remains effective in a linearised version of model that we take to the data.

We find that our setup with the Calvo law of motion provides a good approximation of the observed aggregate price setting frequency based on micro data. Second, our model, besides its small scale, also fits the observed dynamics in inflation and output well. Third, the Calvo law of motion enables the model to explain the dynamics in inflation data to a large extent by shocks to aggregate demand and the endogenous evolution of the aggregate price setting frequency, while the contribution of cost-push shocks to the shifts in the Phillips curve is very limited.

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A Model details

A.1 The steady state of the simplified model

The simplified model has the following steady states

$$\begin{aligned}
Y &= 1 \\
N &= Y \\
w &= N^{\varphi} Y^{\sigma} \\
p^* &= \frac{\epsilon}{\epsilon - 1} w \\
\overline{\pi} &= (\frac{(\theta - 1)p_i^* + 1}{\theta})^{\frac{1}{1-\epsilon}} \\
p^f &= \frac{1}{\overline{\pi}} \\
\theta &= \frac{1}{1 + e^{-\tau}} = \frac{1}{1 + (\theta^{-1} - 1)}.
\end{aligned}$$

A.2 The steady state of the NK model

The steady state of the model variables can be determined with the following equations.

$$\begin{aligned}
p^* &= \frac{\epsilon}{\epsilon - 1} \frac{\psi}{\phi} \Leftrightarrow p_i^* = (\frac{1 - \theta \overline{\pi}^{\epsilon - 1}}{1 - \theta})^{\frac{1}{1-\epsilon}} \\
\psi &= \frac{w}{1 - \theta \beta \overline{\pi}^{\epsilon}} \\
\phi &= \frac{1}{1 - \theta \beta \overline{\pi}^{\epsilon - 1}} \\
1 &= (\theta \overline{\pi}^{\epsilon - 1} + (1 - \theta) p_i^{*\,1-\epsilon})^{\frac{1}{1-\epsilon}} \\
\theta &= \frac{1}{1 + e^{-\tau}} = \frac{1}{1 + (\theta^{-1} - 1)} \\
w &= \chi N^{\varphi} Y^{\sigma} \\
\overline{\pi} &= \beta(1 + i) \\
N &= 1/3 \\
Y &= \frac{N}{s} \\
s &= \frac{(1 - \theta) p^{*\ -\epsilon}}{(1 - \theta \overline{\pi}^{\epsilon})} \\
p^f &= \frac{1}{\overline{\pi}}
\end{aligned}$$

A.3 The complete non-linear model

The complete non linear system is very similar to a standard NK model with trend inflation, (see, e.g., Ascari & Sbordone 2014). We only add the Calvo law of motion. We can now sum up our model with the following system of equations:

$$
\begin{aligned}
\textbf{Euler equation:} \quad & (\frac{Y_t}{Y_{t+1}})^{-\sigma} = \frac{\beta}{e^{\varrho\varepsilon_t^d}}\mathbb{E}_t\frac{1+i_t}{\pi_{t+1}} \\
\textbf{Marginal cost:} \quad & w_t = \chi e^{\alpha_1^{-1}\varepsilon_t^s} N_t^{\varphi} Y_t^{\sigma} \\
\textbf{Labour supply:} \quad & Y_t = \frac{N_t}{s_t} \\
\textbf{Relative prices:} \quad & \frac{P_{i,t}^x}{P_t} = p_{i,t}^x \quad \text{for} \quad x \in \{*, f\} \\
\textbf{Calvo law of motion:} \quad & \theta_t = \frac{e^{\omega\mathbb{E}_{t-1}\hat{p}_t^f}}{e^{\omega\mathbb{E}_{t-1}\hat{p}_t^f} + e^{\omega\mathbb{E}_{t-1}\hat{p}_{i,t}^* - \tau}} e^{\varepsilon_t^U} \\
\textbf{Aggregate price dynamics:} \quad & 1 = (\theta_t\pi_t^{\epsilon-1} + (1-\theta_t)p_t^{*\,1-\epsilon})^{\frac{1}{1-\epsilon}} \\
\textbf{Optimal price setting:} \quad & p_{i,t}^* = \frac{\epsilon}{\epsilon-1}\frac{\psi_t}{\phi_t} \\
& \psi_t = w_t + \mathbb{E}_t\beta\theta_{t+1}\pi_{t+1}^{\epsilon}\psi_{t+1} \\
& \phi_t = 1 + \mathbb{E}_t\beta\theta_{t+1}\pi_{t+1}^{\epsilon-1}\phi_{t+1} \\
\textbf{Price law of motion:} \quad & p_t^f = \frac{1}{\pi_t} \\
\textbf{Price dispersion:} \quad & s_t = (1-\theta_t)p_t^{*\,-\epsilon} + \theta_t\pi_t^{\epsilon}s_{t-1} \\
\textbf{Monetary policy:} \quad & \frac{1+i_t}{1+\bar{i}} = (\frac{\pi_t}{\overline{\pi}})^{\phi_\pi}(\frac{Y_t}{\overline{Y}})^{\phi_y} e^{\varepsilon^r} \\
\textbf{Shocks:} \quad & e^{\varepsilon_t^d} = e^{\rho^d\varepsilon_{t-1}^d + u_{\varepsilon^d,t}} \\
& e^{\varepsilon_t^s} = e^{\rho^s\varepsilon_{t-1}^s + u_{\varepsilon^s,t}} \\
& e^{\varepsilon_t^r} = e^{\rho^r\varepsilon_{t-1}^r + u_{\varepsilon^r,t}} \\
& e^{\varepsilon_t^U} = e^{\rho^U\varepsilon_{t-1}^U + u_{\varepsilon^U,t}}
\end{aligned}
$$

with $0 \leq \rho^r, \rho^s, \rho^d < 1$ and $\upsilon^r, \upsilon^d, \upsilon^s$ i.d.d and normally distributed.

A.4 Linearisation

A.4.1 The Phillips curve

Now we log linearize (6)

$$\hat{p}_{i,t}^* = \hat{\psi}_t - \hat{\phi}_t \tag{A.1}$$

then we linearize (7) :

$$\hat{\psi}_t = (1-\theta\beta\overline{\pi}^{\epsilon})\hat{w}_t + \beta\theta\overline{\pi}^{\epsilon}(\mathbb{E}_t\hat{\theta}_{t+1} + \epsilon\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t\hat{\psi}_{t+1})$$

then we linearize (8) :

$$\hat{\phi}_t = \beta\theta\overline{\pi}^{\epsilon-1}(\mathbb{E}_t\hat{\theta}_{t+1} + (\epsilon-1)\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t\hat{\phi}_{t+1})$$

then we linearize (5) :

$$\begin{aligned}0 &= \theta(\epsilon-1)\overline{\pi}^{\epsilon-1}\hat{\pi}_t + [(1-\theta)(1-\epsilon)p_i^{*\,1-\epsilon}]\hat{p}^*_{i,t} + \overline{\pi}^{1-\epsilon}\theta\hat{\theta}_t - p^*\theta\hat{\theta}_t \\ 0 &= \theta(\epsilon-1)\overline{\pi}^{\epsilon-1}\hat{\pi}_t + [(1-\theta)(1-\epsilon)p_i^{*\,1-\epsilon}]\hat{p}^*_{i,t} + (\overline{\pi}^{1-\epsilon} - p^*)\theta\hat{\theta}_t \\ 0 &= \theta(\epsilon-1)\overline{\pi}^{\epsilon-1}\hat{\pi}_t + [(1-\theta)(1-\epsilon)(\frac{1-\theta\overline{\pi}^{\epsilon-1}}{1-\theta})]\hat{p}^*_{i,t} + (\overline{\pi}^{1-\epsilon} - p_i^*)\theta\hat{\theta}_t\end{aligned}$$

$$\hat{p}^*_t = \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_t - \frac{\overline{\pi}^{1-\epsilon} - p^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_t$$

then we substitute (12) into (A.1)

$$\hat{\psi}_t = \hat{\phi}_t + \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_t - \frac{\overline{\pi}^{1-\epsilon} - p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_t \tag{A.2}$$

Now we plug(A.2) into (7)

$$\begin{aligned}\hat{\phi}_t + \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_t - \frac{\overline{\pi}^{1-\epsilon} - p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_t = &(1-\theta\beta\overline{\pi}^{\epsilon})\hat{w}_t... \\ &... + \beta\theta\overline{\pi}^{\epsilon}(... \\ &...\mathbb{E}_t\hat{\theta}_{t+1} + \epsilon\mathbb{E}_t\hat{\pi}_{t+1} + ... \\ &...\mathbb{E}_t[\hat{\phi}_{t+1} + \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_{t+1} - \frac{\overline{\pi}^{1-\epsilon} - p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_{t+1}]... \\ &...)\end{aligned}$$

$$\begin{aligned}\hat{\phi}_t = &(1-\theta\beta\overline{\pi}^{\epsilon})\hat{w}_t - \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_t + \frac{\overline{\pi}^{1-\epsilon} - p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_t... \\ &... + \beta\theta\overline{\pi}^{\epsilon}(\mathbb{E}_t\hat{\theta}_{t+1} + \epsilon\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t[\hat{\phi}_{t+1} + \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_{t+1} - \frac{\overline{\pi}^{1-\epsilon} - p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_{t+1}])\end{aligned}$$

and then we substitute (8)

$$\beta\theta\overline{\pi}^{\epsilon-1}(\mathbb{E}_t\hat{\theta}_{t+1}+(\epsilon-1)\mathbb{E}_t\hat{\pi}_{t+1}+\mathbb{E}_t\hat{\phi}_{t+1}) = (1-\theta\beta\overline{\pi}^{\epsilon})\hat{w}_t - \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_t + \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_t ...$$

$$... + \beta\theta\overline{\pi}^{\epsilon}(...$$

$$...\mathbb{E}_t\hat{\theta}_{t+1} + \epsilon\mathbb{E}_t\hat{\pi}_{t+1} + ...$$

$$...\mathbb{E}_t[\hat{\phi}_{t+1} + \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_{t+1} - \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_{t+1}]...$$

$$...)$$

$$\frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_t = (1-\theta\beta\overline{\pi}^{\epsilon})\hat{w}_t + \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_t - \beta\theta\overline{\pi}^{\epsilon-1}(\mathbb{E}_t\hat{\theta}_{t+1}+(\epsilon-1)\mathbb{E}_t\hat{\pi}_{t+1}+\mathbb{E}_t\hat{\phi}_{t+1})...$$

$$... + \beta\theta\overline{\pi}^{\epsilon}(\mathbb{E}_t\hat{\theta}_{t+1} + \epsilon\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t[\hat{\phi}_{t+1} + \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_{t+1} - \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_{t+1}])$$

$$\hat{\pi}_t = \frac{1-\theta\overline{\pi}^{\epsilon-1}}{\theta\overline{\pi}^{\epsilon-1}}\{...$$

$$(1-\theta\beta\overline{\pi}^{\epsilon})\hat{w}_t + \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_t - \beta\theta\overline{\pi}^{\epsilon-1}(\mathbb{E}_t\hat{\theta}_{t+1}+(\epsilon-1)\mathbb{E}_t\hat{\pi}_{t+1}+\mathbb{E}_t\hat{\phi}_{t+1})...$$

$$... + \beta\theta\overline{\pi}^{\epsilon}(\mathbb{E}_t\hat{\theta}_{t+1} + \epsilon\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t[\hat{\phi}_{t+1} + \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_{t+1} - \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_{t+1}])...$$

$$...\}$$

$$\hat{\pi}_t = \frac{(1-\theta\overline{\pi}^{\epsilon-1})(1-\theta\beta\overline{\pi}^{\epsilon})}{\theta\overline{\pi}^{\epsilon-1}}\hat{w}_t - \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{(1-\epsilon)\pi^{\epsilon-1})}\beta\theta\overline{\pi}^{\epsilon}\mathbb{E}_t\hat{\theta}_{t+1} + \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{\overline{\pi}^{\epsilon-1}}\hat{\theta}_t ...$$

$$... + \beta\overline{\pi}\mathbb{E}_t\hat{\pi}_{t+1} + \beta(\overline{\pi}-1)(1-\theta\overline{\pi}^{\epsilon-1})[(\epsilon-1)\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t\hat{\phi}_{t+1} + \mathbb{E}_t\hat{\theta}_{t+1}]$$

simplifying :

$$\hat{\pi}_t = \kappa\hat{w}_t + \beta\overline{\pi}\mathbb{E}_t\hat{\pi}_{t+1} + \eta[(\epsilon-1)\mathbb{E}_t\hat{\pi}_{t+1} + \mathbb{E}_t\hat{\phi}_{t+1} + \mathbb{E}_t\hat{\theta}_{t+1}] - \iota\frac{\beta\theta\overline{\pi}^{\epsilon}}{1-\epsilon}\mathbb{E}_t\hat{\theta}_{t+1} + \iota\hat{\theta}_t$$

with $\kappa = \frac{(1-\theta\overline{\pi}^{\epsilon-1})(1-\theta\beta\overline{\pi}^{\epsilon})}{\theta\overline{\pi}^{\epsilon-1}}$, $\eta = \beta(\overline{\pi}-1)(1-\theta\overline{\pi}^{\epsilon-1})$ and $\iota = \frac{\overline{\pi}^{1-\epsilon}-p_i^*}{\overline{\pi}^{\epsilon-1}}$.

A.4.2 Price dispersion

linearizing the equation yields to :

$$\hat{s}_t = \xi\hat{\pi}_t + \theta\overline{\pi}^{\epsilon}\hat{s}_{t-1} + (\overline{\pi}^{\epsilon}\theta - p^{*\,-\epsilon}\theta)\hat{\theta}_t$$

with $\xi = \epsilon\frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}(\overline{\pi}-1)$

A.4.3 Calvo law of motion

Linearising the equation around its steady state leads to :

$$\begin{aligned} ln\theta_t = ln(e^{\omega\mathbb{E}_{t-1}\hat{p}_t^f}) - ln(e^{\omega\mathbb{E}_{t-1}\hat{p}_t^f} + e^{\omega(\mathbb{E}_{t-1}\hat{p}_t^*)-\tau}) \\ \frac{ln\theta_t}{\theta} = \frac{1}{\theta}\{\omega\mathbb{E}_{t-1}\hat{p}_t^f - \frac{1}{2}(\omega\mathbb{E}_{t-1}\hat{p}_t^f + \omega(\mathbb{E}_{t-1}\hat{p}_t^*) - \tau)\} \\ \hat{\theta}_t = \frac{1}{2}\theta^{-1}\omega\{\mathbb{E}_{t-1}\hat{p}_t^f - \mathbb{E}_{t-1}\hat{p}_t^*\} \end{aligned}$$

A.4.4 Firms' profits

Linearising the non price resetting equation

$$\hat{p}_t^f = -\overline{\pi}\hat{\pi}_t$$

B Sensitivity of the augmented NK Phillips Curve to the parameter

When the trend inflation $\overline{\pi}$ increases the values of $|\alpha_4|$ and $|\alpha_5|$ increase and thus inflation reacts more to change in θ_t. Indeed, the optimal price is higher relative to the existing prices and thus by construction a change in the share of non-updater generates more change in inflation.

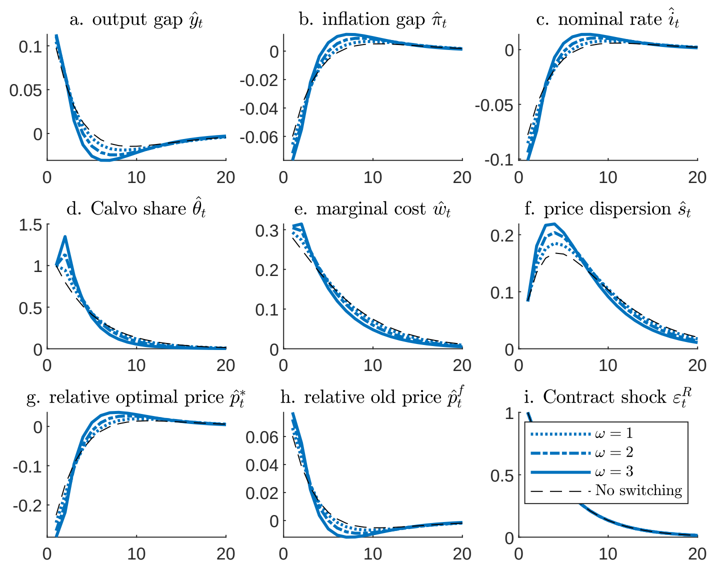
An increase of the steady state share of non updating firms θ generates larger $|\alpha_4|$ and $|\alpha_5|$ and thus, the response of inflation is higher. There is a proportional effect: a 1% deviation of a larger number is larger in absolute value. There is also an effect on the optimal relative price p_i^* that tends to be farther from the other price if the resetting probability is lower.

An increase in the value of the price elasticity of goods ϵ generates a lower steady state markup and thus increase the response from change in marginal cost deviation of the optimal pricing decision from the distribution of relative prices. This increases $|\alpha_4|$ and increases the response the of inflation to the change in the Calvo share. On the other side, it decreases the value of $|\alpha_5|$ and thus decreases the response of inflation toward expected Calvo share. This is explain by the lower markups generated by the change in ϵ and smaller expected deviations implies by the new optimal pricing decision.

Phillips curve parameters			*Value of the parameter*	*Sign*	*Relative to parameter* $\overline{\pi}$	θ	ϵ	β
α_1	-	Relation to marginal cost	$\frac{(1-\theta\overline{\pi}^{\epsilon-1})(1-\theta\beta\overline{\pi}^{\epsilon})}{\theta\overline{\pi}^{\epsilon-1}}$	$\alpha_1 > 0$	$-$	$-$	$-$	$-$
α_2	-	Relation to expected inflation	$\beta\overline{\pi} + \beta(\overline{\pi}-1)(1-\theta\overline{\pi}^{\epsilon-1})(\epsilon-1)$	$\alpha_2 > 0$	$+$	$+$	$+$	$+$
α_3	-	Relation to trend inflation variable	$\beta(\overline{\pi}-1)(1-\theta\overline{\pi}^{\epsilon-1})$	$\alpha_3 > 0$	$+$	$-$	$-$	$+$
α_4	-	Relation to value of the Calvo	$\frac{\overline{\pi}^{1-\epsilon}-p_i^*}{\overline{\pi}^{\epsilon-1}}$	$\alpha_4 < 0$	$-$	$-$	$-$	$=$
α_5	-	Relation to the expected value of the Calvo	$\frac{\overline{\pi}^{1-\epsilon}-p_i^*}{\overline{\pi}^{\epsilon-1}}\frac{\beta\theta\overline{\pi}^{\epsilon}}{1-\epsilon} + \beta(\overline{\pi}-1)(1-\theta\overline{\pi}^{\epsilon-1})$	$\alpha_5 < 0$	$-$	$-$	$+$	$-$

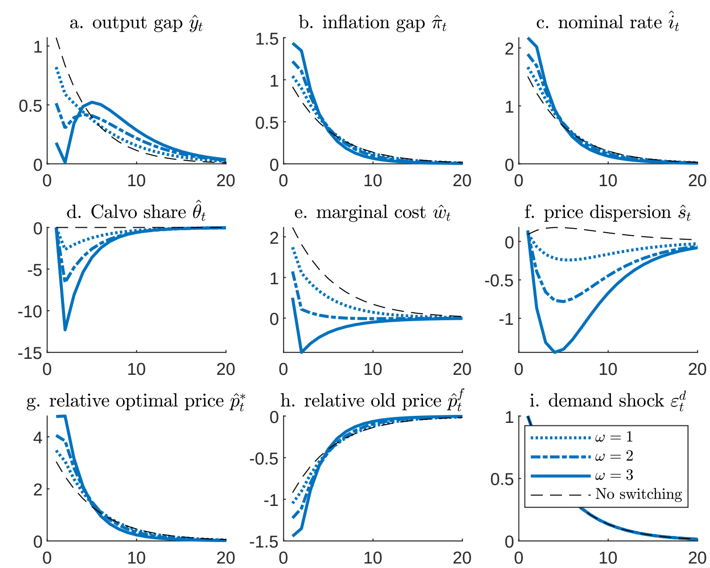
Table 5: NKPC parameters and their relations to other structural parameters

C Sensitivity to the intensity of choice parameter



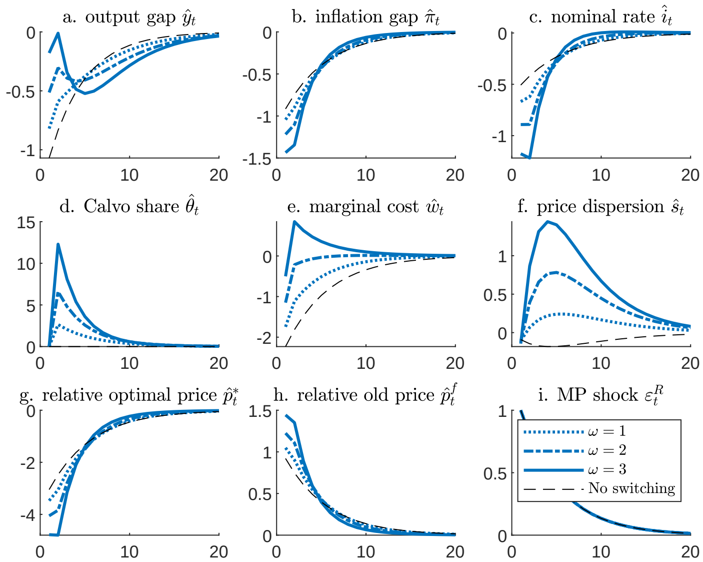
Notes: Results are in percentage point of the log deviation from the steady state.

Figure C.1: Contract shock



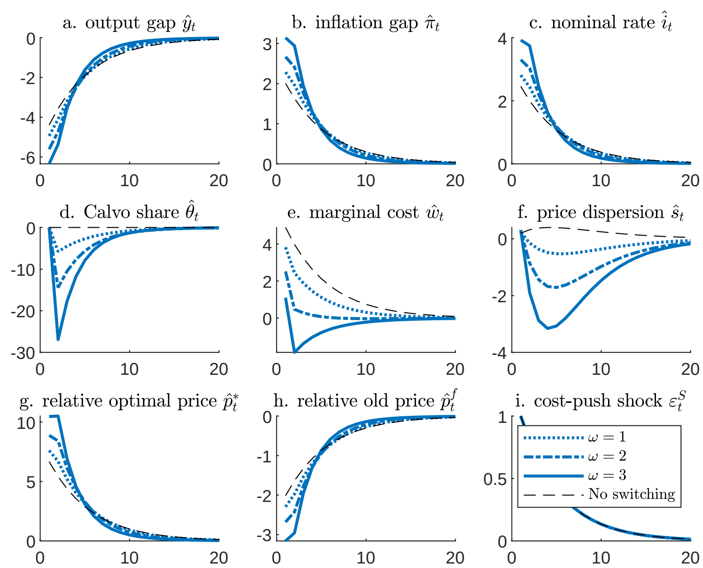
Notes: Results are in percentage point of the log deviation from the steady state.

Figure C.2: Demand shock



Notes: Results are in percentage point of the log deviation from the steady state.

Figure C.3: Monetary policy shock

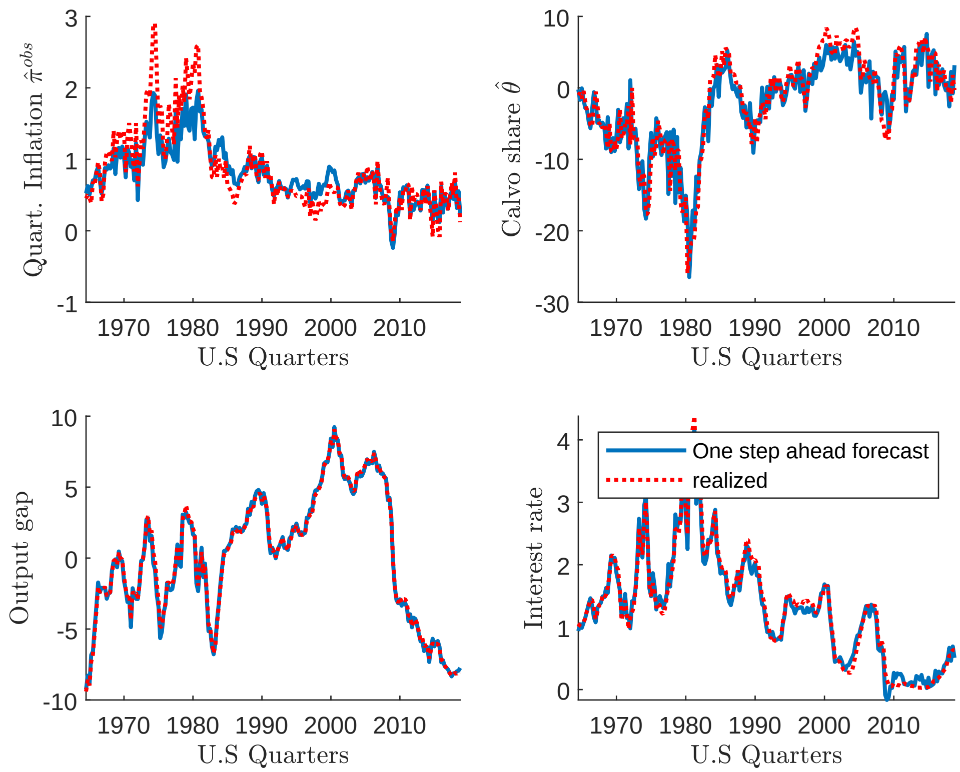


Notes: Results are in percentage point of the log deviation from the steady state.

Figure C.4: Markup shock

D In-sample forecast performance

The in-sample forecast performance of the model is displayed in Figure D.1.



Notes: see figure 1 for methodological point on the time series.

Figure D.1: In sample one step ahead forecast and observed data

The model's performance with regard to the Calvo share, the output gap and the nominal interest rate appears satisfactory. Nonetheless, due to the absence of price indexation, the model struggles to match the high inflation periods from the 1970s. Indeed, the asymmetric accelerating Phillips curve in the augmented model fails to generate persistent enough inflation when price changes are very frequent. So the model can generate high inflation for short periods of time, but falls short of doing so for longer periods. Nevertheless, we conclude that overall the model has reasonable in-sample forecasting performance.

E Comparison of log-likelihoods

One way of assessing the consistency of our estimated model with the data is to compute the log-likelihood as a measure of fit and to compare it to the log-likelihood of other models. For this purpose we also estimate the augmented NK model, with three observables only (output gap, inflation, and nominal interest rate), the standard NK model without the Calvo law of motion, and BVAR models with up to four lags. For the BVAR models we use Minnesota priors.

One issue that emerges is that BVAR models cannot account for the missing observations in the Calvo time series. Therefore, we use the predicted data for θ_t of the augmented NK model when observations for θ_t are unavailable. The log-likelihoods for the various models are listed in Table 6 below.

Model	Priors	Type	*4 Observables*	*3 Observables*
BVAR(1)	Minnesota	Unconstrained Coef.	-816.8810	-299.1786
BVAR(2)	Minnesota	Unconstrained Coef.	-781.8089	-282.0678
BVAR(3)	Minnesota	Unconstrained Coef.	-775.6193	-264.3715
BVAR(4)	Minnesota	Unconstrained Coef.	-787.5819	-265.4516
DSGE	Table 3	Augmented	-783.14668	-373.0930
DSGE	Table 3	Standard	-	-324.8771

Notes: Missing Calvo observations are replaced by the DSGE model generated Calvo data. For the 3 equations DSGE case we use the same prior as in Table 3 except for θ where for identification issue we use a prior mean of 0.75 and a standard deviation of 0.1.

Table 6: Relative fitting performance for 4 observables (output gap, inflation, nominal interest rate, and frequency of price adjustment) and only 3 observables (no fitting of frequency of price adjustment and static Calvo) (US: 1964-2019)

From the column for models with four observables, one can see that all BVAR models exhibit a close log-likelihood to the augmented NK model. Yet, the BVAR(3) and BVAR(2) have a slightly better performance. Next, the column for models with three observables on first sight suggests that the augmented is outperformed by the standard NK model. However, the estimated mode of the fixed Calvo share is $\theta = 0.9267$ in the latter case and this is clearly in-consistent with the Nakamura et al. (2018) data. Thus, we conclude that the augmented NK model does relatively better at fitting the data.