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: (i) is consistent with micro data on price setting frequency; (ii) gives rise to an accelerating Phillips curve that is steeper during expansions and flatter during recessions; (iii) explains shifts in the Phillips curve associated with different historical episodes without relying on implausible high cost-push shocks and nominal rigidities inconsistent with micro data; (iv) largely improves the macroeconomic time series fit of a medium-scale NK model.

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, Vice Chair, Board of Governors, Federal Reserve System)

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, high price indexation and nominal rigidities that are by-and-large inconsistent with observed price setting frequency at the micro level. For instance, Del Negro, Giannoni & Schorfheide (2015) or Guerrieri & Iacoviello (2017) estimate Calvo (1983) parameters as high as $\theta = 0.87$ or 0.9. Yet, this remedy creates an unfortunate tension. On the one hand, large and highly auto-correlated cost-push shocks and high degrees of price stickiness reduce the covariance between inflation and output and improve the model's fit to inflation. On the other hand, the inflation dynam-

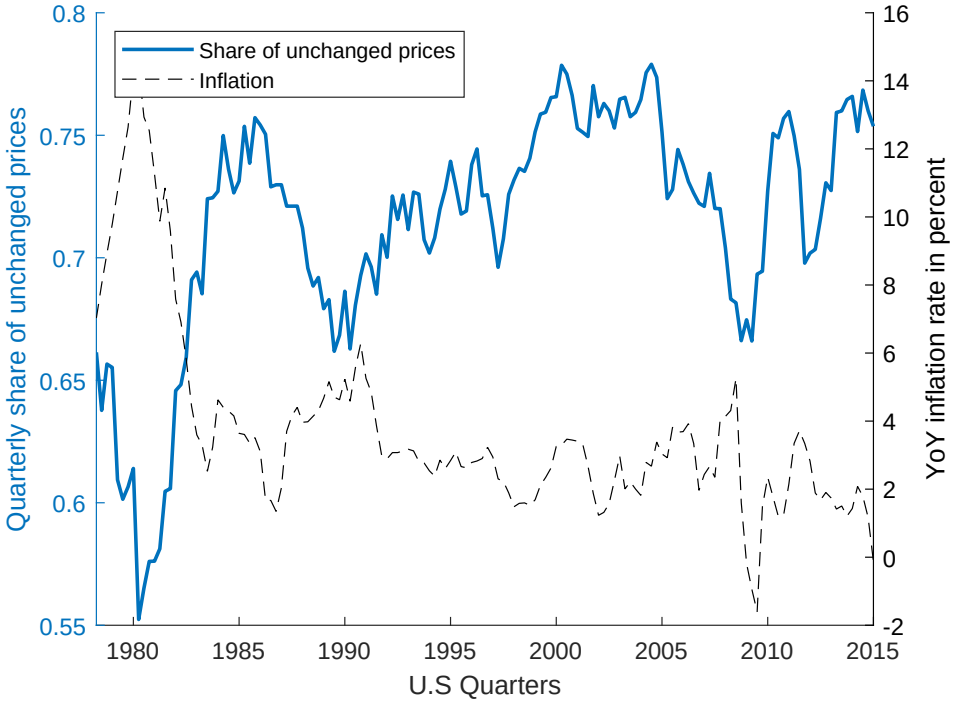
ics are then mostly explained by large cost-push shocks (see, e.g., King & Watson 2012, Fratto & Uhlig 2020). For example, Del Negro et al. (2015, p.169) argue that explaining inflation mainly with cost-push shocks is unfortunate, because these shocks lack a clear economic interpretation and fail to explain a lot of variation in other variables.

Next, explaining inflation mainly through cost-push shocks and high degrees of price rigidities and indexation also seems implausible from the viewpoint of the *Great Recession*. The latter is perceived as a demand-driven downturn that caused the observed inflation and output gap dynamics during and after the crisis. Explaining inflation via high degrees of nominal price rigidities and indexation also seems implausible in light of empirical evidence on the price setting frequency and indexation 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] A model that is consistent with macro data (e.g., flattening of the Philips curve, missing deflation puzzle) may still be subject to observational equivalence with many other models. If this very same model were also consistent with micro data (e.g., price setting frequency), it would clearly outperform these other models along an important dimension (see Christiano, Eichenbaum & Trabandt 2018). For instance, Nakamura, Steinsson, Sun & Villar (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

[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 fail to account for heterogeneity and price dispersion.



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 price 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

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 the price updating frequency varies over time and is negatively correlated with inflation and price indexation. It is then natural to conjecture that a time-varying price setting frequency may be an alternative explanation for the observed flattening and shifts in the Phillips curve.

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

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 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 following 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. This evidence shows that posting a new price is the result of a complex cost-benefit analysis by the firms' managers rather than a random process.[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

[3]For instance see Blinder, Canetti, Lebow & Rudd (1998) and Zbaracki, Ritson, Levy, Dutta & Bergen (2004) for qualitative and quantitative surveys with managers about their prices setting decisions.

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.

Our main theoretical finding is 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 low, but positive inflation during times of slack.

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, while the contribution of cost-push shocks is very limited. These results are consistent with the findings in Del Negro, Lenza, Primiceri & Tambalotti (2020) on the flattening of the price Phillips Curve. Finally, we show that the Calvo law of motion largely improves the macroeconomic time series fit of the

medium-scale NK model developed in (Fernández-Villaverde & Rubio-Ramírez 2006).

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, Lippi & Paciello (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 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

[4]See Chari, Kehoe & McGrattan (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, Khan & Rudolf (2007) and Levin & Yun (2007) for model with endogenous foundation of price setting frequency with respect to its relation to the trend inflation.

evidence. Theoretical implications of individual price dynamics are extensively discussed by Alvarez, Lippi & Passadore (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, Gagnon (2009), 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 and idiosyncratic shocks.[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 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, Plagborg-Møller & Stock (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 contains the quantitative analysis of the small-scale NK model based on micro and macro data. Section 5 provides a horse-race

[5]Another related branch of the literature are the sticky information models (see, e.g., Mankiw & Reis 2002, Mankiw, Reis & Wolfers 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.

between a standard medium-scale DSGE model with and without the Calvo law of motion. 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]

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

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

[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 $w_t N_t = C_t$.

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.

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

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

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

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

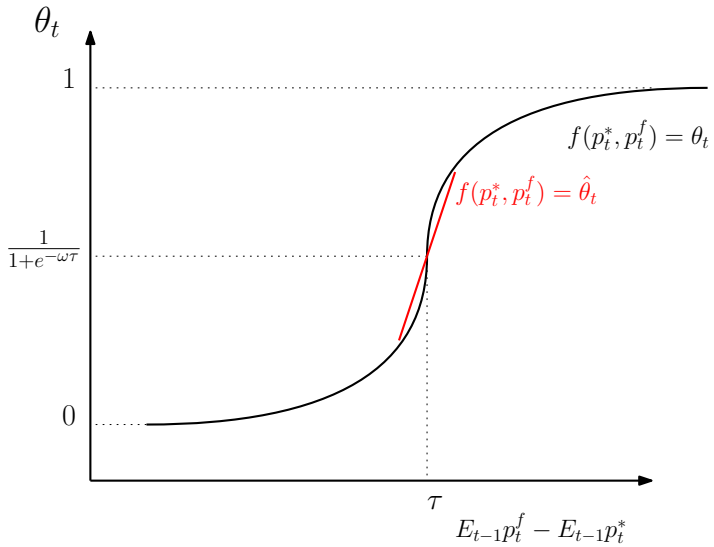
where $0 < \theta_t < 1$, and $(1 - \theta_t)$ denotes the share of updated prices. Parameter $\omega \geq 0$ is denoted the *intensity of choice* and captures the idea that every period some firms update their prices and others do not as long as $\omega < \infty$. Thus, this parameter captures the above 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] Parameter τ denotes an updating cost and ε_t^θ denotes a contract shock, which follows an $AR(1)$ stationary process. The shock captures exogenous variation in the managers' relative cost of updating their price. We set this shock to zero for now, but use it for estimation purposes in later sections.[9]

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

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

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).



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

[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 markups 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] This specification nests the standard Calvo pricing model for $\omega \to 0$.

One can observe several worthwhile features from Figure 2. The function is bounded between zero and one. In steady state, θ is determined by the intensity of choice ω and the updating cost τ, i.e., $\theta = 1/(1 + e^{-\omega\tau})$. 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 for $\omega \to 0$ as in the standard Calvo model.

However, out of steady state, managers' cost-benefit analysis implies state-dependent pricing. In states where the benefit of updating the price outweighs the cost, the share of firms that update their price increases. In states where the cost of updating the price outweighs the benefit, the share of 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 $\tau \to +\infty$, $\hat{U}_t^* \to -\infty$ or $\hat{U}_t^f \to +\infty$. 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

$\omega \to +\infty$, 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 $\omega \to +\infty$ 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 $\varepsilon_t^\theta = 0 \ \forall t$ 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]

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

[10] Brock & Hommes (1997) argue that when $\omega \to +\infty$ 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
ω	Intensity of choice	2
θ	Calvo share steady state	$\frac{1}{1+e^{-\omega\tau}} = 0.75$
σ	Relative risk aversion	1
φ	Frisch elasticity	1
ϵ	Price elasticity of demand	9
ρ	Demand shock, AR(1)	0.8

Table 1: Calibrated parameters (quarterly basis)

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.

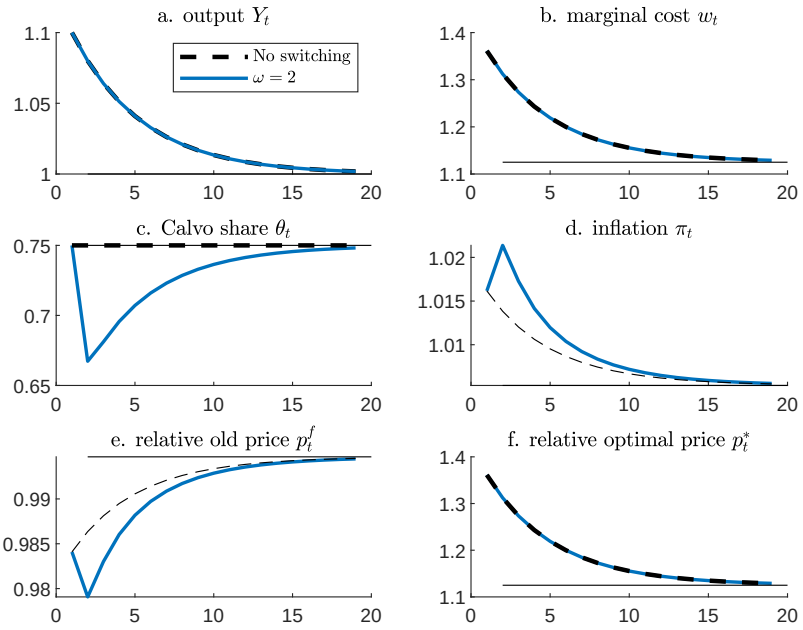
Relative to the benchmark model, a time-varying Calvo share θ_t (blue solid line) has novel and important implications: while the responses of output and marginal cost are identical, the responses of nominal variables are strikingly different after the initial impact of the shock in $t = 1$. The boom 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 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.

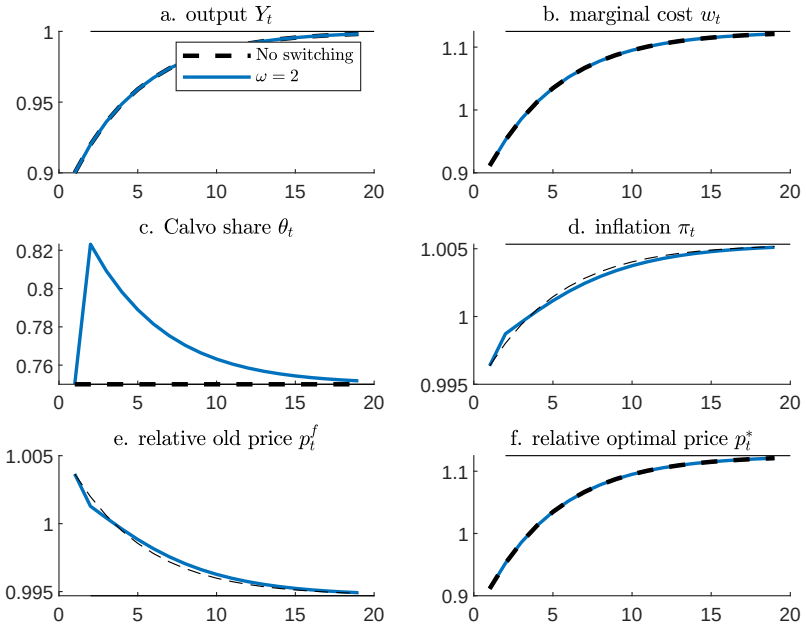
The initial effects are again identical to the benchmark model. In subsequent periods, the performance review of managers leads them to the conclusion that lowering the price net of the cost τ implies a lower markup relative to maintaining the price. Thus, a lower share of managers will set up meetings 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



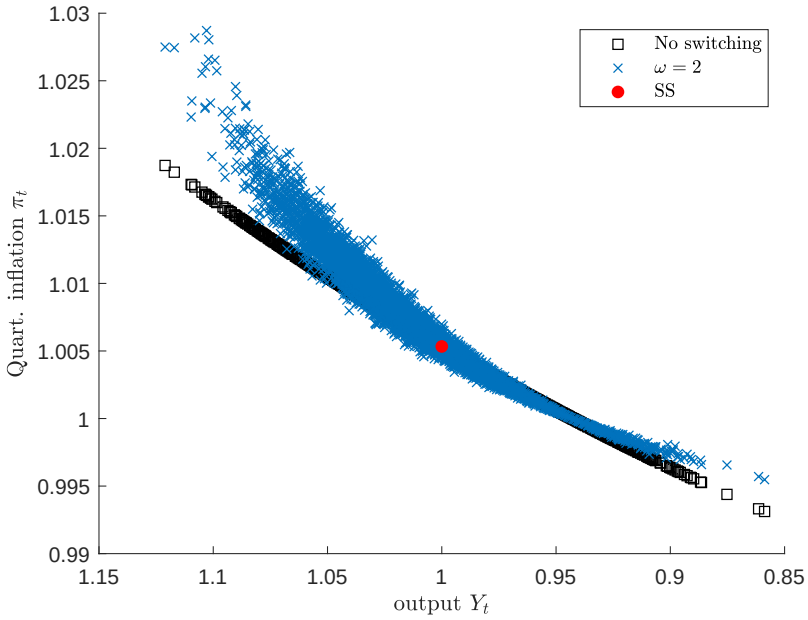
(a) Response to a positive +10% demand shock



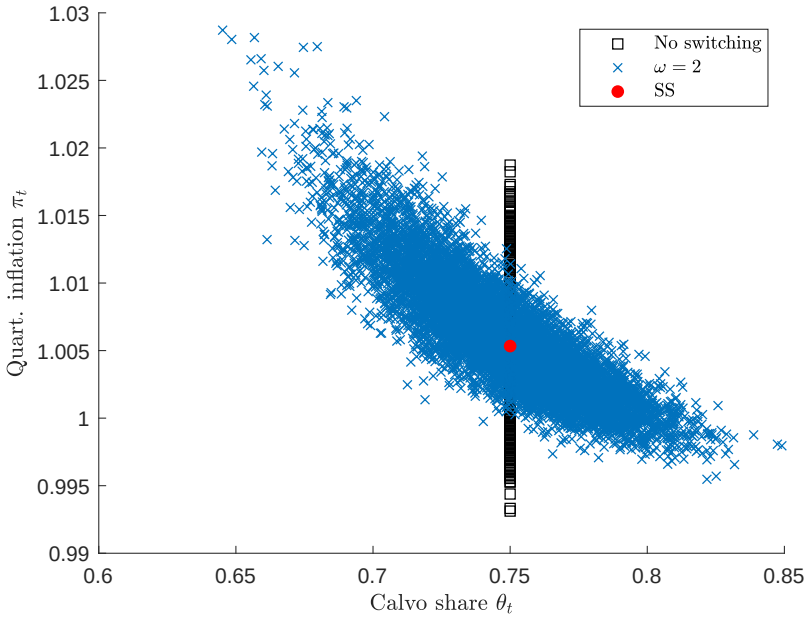
(b) Response to a negative -10% demand shock

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



(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. The demand shock standard deviation is 0.1.)

Figure 4: Global dynamics in the simplified model

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 small-scale NK model

Herein we develop a standard small-scale NK model augmented with the Calvo law of motion (2). This model has similar predictions as the simple model discussed above (see Appendix C for details). In the subsequent section, 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.

3.1 The firm's pricing problem

First we discuss the intermediate firms' price setting 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 $\Gamma'_{t+j} = w_{t+j}$ holds because of the simple linear production function of intermediate goods producers. 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

$$\begin{aligned} p_t^* &= \frac{\epsilon}{\epsilon - 1} \frac{\psi_t}{\phi_t}, \qquad \text{where} \\ \psi_t &= \mathbb{E}_t \sum_{j=0}^{\infty} \theta_{t+j}^j \beta^j \Pi_{t+1,t+j}^{\epsilon} Y_{t+j} w_{t+j}, \\ \phi_t &= \mathbb{E}_t \sum_{j=0}^{\infty} \theta_{t+j}^j \beta^j \Pi_{t+1,t+j}^{\epsilon-1} Y_{t+j}. \end{aligned} \tag{6}$$

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 $\mathbb{E}_{t-1}\hat{p}^f_t$. 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. Accordingly, these complex, time-varying effects on price dispersion can have novel and important effects on inflation dynamics.

3.4 The linearised Phillips curve

In order to understand how the Calvo law of motion affects the model dynamics, we linearise the NK Phillips curve around a trend inflation steady state as in Ascari & Sbordone (2014) (see Appendix A.3). Throughout the linearisation, we assume $0 < \theta < 1$ to avoid the empirically implausible polar cases $\theta = \{0, 1\}$.[12] Thus, the NK Phillips curve can be written as

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

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

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 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.

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.

Finally, 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.

3.5 The complete model

Our model is very similar to a standard NK model with trend inflation, (see, e.g., Ascari & Sbordone 2014) as we only add the Calvo law of motion. The complete non-linear system of model equations is as follows:

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

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

4 Empirical analysis of the small-scale NK model

The augmented NK model confirms the intuitions and predictions discussed in the context of the simple model above (see Appendix C). However, there are quantitative differences relative to the standard NK model and two key predictions distinguish the

augmented from the standard NK model: first, the price setting frequency is time-varying and the relative price dispersion moves in opposite directions (again see Appendix C for more details). 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 by comparing an estimated version of the augmented NK model to the standard NK model.

4.1 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 (GDPC1),[13] inflation (CPI) and the Federal Funds (FEDFUNDS) rate are taken from Fred.

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 data on monthly prices changes 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.[14]

[13]The output gap is the log deviation of the real GDP time series from a linear growth trend computed by the authors in order to keep a zero mean time series

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

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

$$
\begin{aligned}
y_t^{obs} &= \hat{y}_t \\
\pi_t^{obs} &= 100 \times \ln(1 + \gamma_\pi/100 = \overline{\pi}) + \hat{\pi}_t \\
r_t^{obs} &= 100 \times \overline{r} + \hat{i}_t \\
\theta_t^{obs} &= 100 \times \ln(\theta) + \hat{\theta}_t,
\end{aligned}
$$

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

4.2 Parameter estimates

We linearise the model around a trend inflation steady state as in Ascari & Sbordone (2014) (see Appendix A.3 for the detailed derivation of the NK Philips curve) and estimate the model using a linear Kalman filter with Bayesian Priors and Monte-Carlo Markow chain sampling. The linearisation, optimization and sampling are handled by Dynare (Juillard et al. 1996) using the Metropolis Hastings algorithm with a diagonal covariance matrix.

For the parameters shared by the augmented and the standard NK model, we define priors according to Table 2. Our choices are broadly in line with the Smets & Wouters (2007) priors.[15] In addition, for the augmented NK model, we choose a prior for ω normally distributed around 10 with a standard deviation of 0.5. 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, Hommes & Massaro 2019, 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 relatively tight prior. Consequently, our choice is motivated by delivering the best fit in the range for ω.

[15] The only deviation from Smets & Wouters (2007) is a reduced standard deviation for ϕ_π and a change in the mean γ_π. The former guarantees plausible estimates of ϕ_π and the latter ensures that the prior matches the historical average.

As is standard in the literature, we calibrate the price elasticity of demand to $\epsilon = 21$, which implies a mark-up of 5% in line with empirical estimates by Basu & Fernald (1997). Finally, we do not 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. This would make it difficult to rationalize the empirical performance of the augmented relative to the standard model exclusively by the Calvo law of motion.

		Prior			*Posterior: Dynamic Calvo*		
Price- and wage-setting		Shape	Mean	STD	Mean	5%	95%
ω	Intensity of choice	$\mathcal{N}$	10	.5	12.8981	12.3587	13.5742
θ	Calvo share	$\mathcal{B}$	.5	.1	0.7174	0.7074	0.7279
Monetary authority							
ϕ_π	MP. stance, π_t	$\mathcal{N}$	1.5	.15	1.5206	1.3851	1.6456
ϕ_y	MP. stance, Y_t	$\mathcal{N}$	.125	.05	0.0052	0.0000	0.0117
ρ	Interest-rate smoothing	$\mathcal{B}$	.75	.1	0.4899	0.3991	0.5764
Preferences and technology							
$100((\overline{\pi}/\beta)-1)$	Natural interest rate	$\mathcal{G}$	.75	.1	0.8481	0.7705	0.9716
σ	Relative risk aversion	$\mathcal{N}$	1.5	.37	0.9072	0.8500	0.9749
φ	Inverse of Frisch elasticity	$\mathcal{N}$	2	.75	2.3461	2.1320	2.5604
$\hbar$	Consumption habit	$\mathcal{B}$	.7	.1	0.6333	0.5561	0.7432
Exogenous processes							
σ_d	Discount factor shock, std.	$\mathcal{IG}$	.1	2	0.0234	0.0174	0.0301
σ_s	Cost-push shock, std.	$\mathcal{IG}$	.1	2	0.0483	0.0414	0.0550
σ_r	MP shock, std.	$\mathcal{IG}$	.1	2	0.0063	0.0057	0.0068
σ_θ	Contract shock, std.	$\mathcal{IG}$	.1	2	0.0151	0.0133	0.0168
ρ_d	Discount factor shock, AR(1)	$\mathcal{B}$	.5	.2	0.7789	0.6802	0.8790
ρ_s	Cost-push shock, AR(1)	$\mathcal{B}$	.5	.2	0.9819	0.9687	0.9950
ρ_r	MP shock, AR(1)	$\mathcal{B}$	.5	.2	0.3958	0.2113	0.5142
ρ_θ	Contract shock, AR(1)	$\mathcal{B}$	.5	.2	0.4879	0.3941	0.5883
γ_π	Quarterly inflation trend	$\mathcal{G}$	.849	.2	0.6975	0.6146	0.7680
Log-likelihood					-996.583602		

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

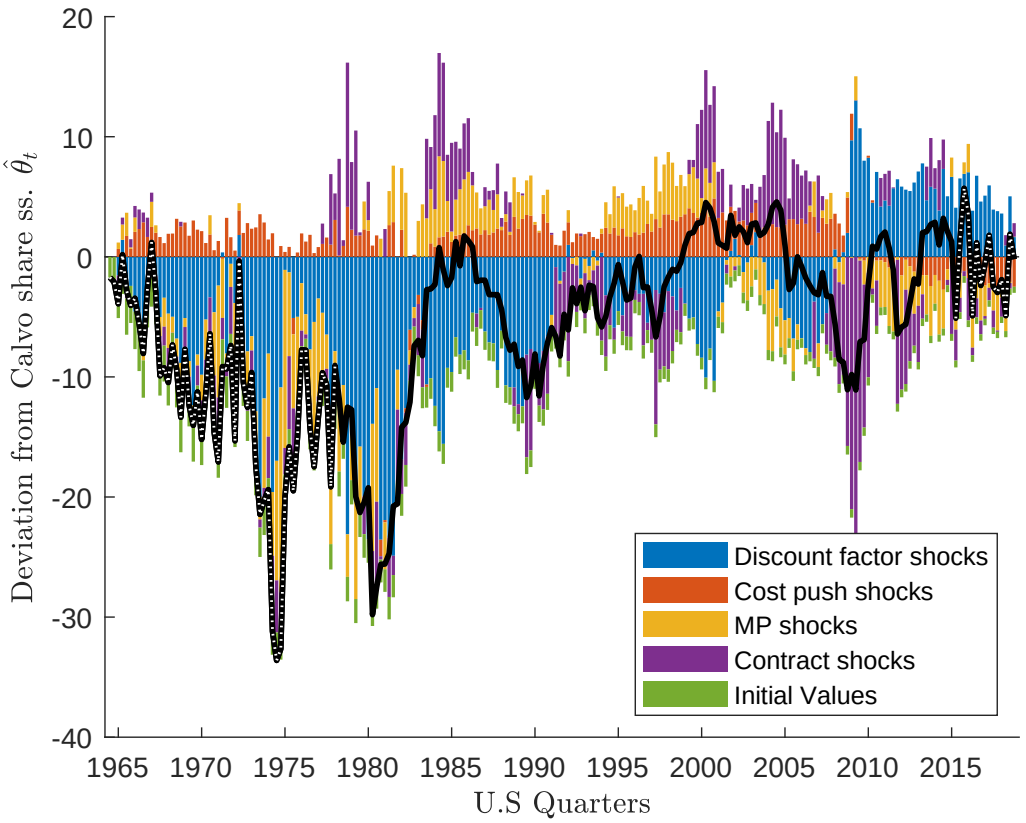
Our estimated parameter values are reported in Table 2. The parameters shared with the standard NK model are all broadly in line with the previous literature. Also the parameter estimates for the Calvo law of motion are plausible. The steady state Calvo share $\theta = 0.7174$ is fairly close to the historical average in various datasets. The

intensity of choice $\omega = 12.8981$ is strictly positive and in line with the evidence on dynamic predictor selection. Our estimates for the standard shock processes are also in line with existing literature, and, most important, these shocks are the main drivers of the variation in the Calvo share. Figure 5 illustrates that monetary policy and discount factor shocks play an important role in explaining the variation of the Calvo share over the sample. This finding demonstrates the consistency of the Calvo law of motion with the US business cycle. Remarkably, contract shocks appear to play a key role mostly right before and at the onset of the Great Recession. We rationalize this finding by the extraordinary events on commodity markets underlying the dynamics in the price setting frequency data (see Nakamura et al. 2018, pp.1968-1969). By construction, our model is too abstract to capture these extraordinary dynamics as this is not our objective in this paper. The contract shock seems to absorb these dynamics.

4.3 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 two exercises. First, we 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. Second, we assess the model's capability to replicate the post-WWII US Phillips curves during four different episodes: pre-Great Moderation, Great Moderation, Great Recession and New Normal.

The relevance of the Calvo law of motion. The estimated model naturally raises the question of whether the augmented NK model is consistent with the Nakamura et al. (2018) data. We provide an answer by comparing the 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 6.

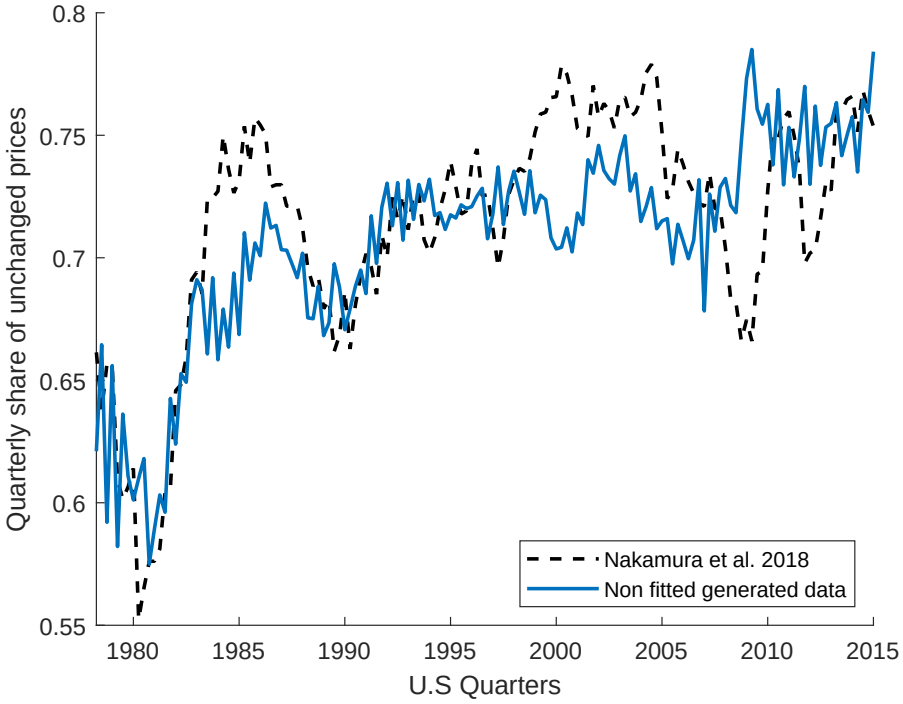


Notes: Values are in log deviation from the steady state. Dotted line is generated/unobserved data

Figure 5: Historical decomposition of the Calvo's dynamic based on US data (1964-2018)

Overall, the predicted path and the data line up fairly good both in qualitative and quantitative terms. The only notable deviation is again the 2008 crisis where our model generates a spike in θ_t (less price updating) while the data displays a drop (more price updating). As above, this finding can be rationalized by extraordinary events (see Nakamura et al. 2018, pp.1968-1969). Therefore, in sum, Figure 6 suggests that the Calvo law of motion is a relevant and reasonable modelling device as it makes the NK model consistent with microeconomic data on price setting frequency.

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



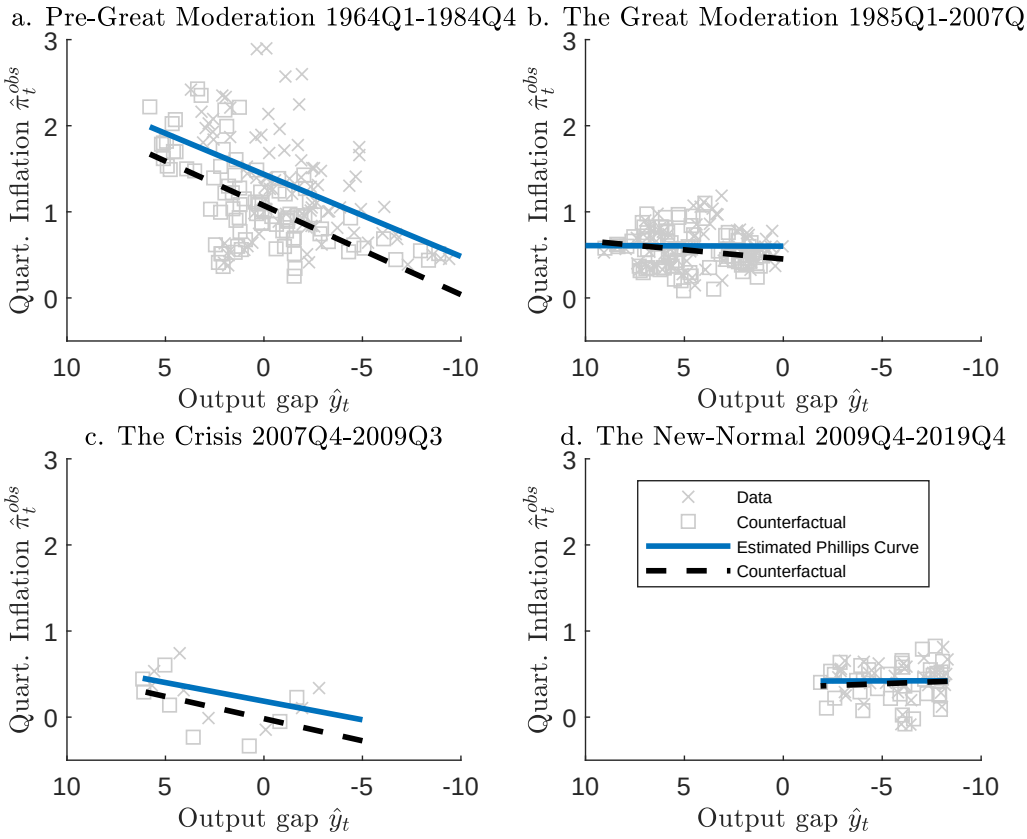
Notes: Nakamura et al. 2018 data are computed by the authors as in Figure 2. Non fitted generated data are the latent state variable generated by the model when estimated to fit only inflation, Fed Fund Rate and output gap. In order to avoid identification issue on θ we define a normally distributed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

Figure 6: Generated Calvo share as latent state variable vs. micro data

sense that it enables the NK model to better explain the post-WWII US Phillips curves during four different historical episodes: pre-Great Moderation, Great Moderation, Great Recession and New Normal.

In order to do so, we compare the observed data for inflation and the output gap, π_t^{obs} and y_t^{obs}, to counter-factual predictions derived from an exercise in which the Calvo parameter is equal to the mean estimate of the steady state $\theta_t = \theta$. We then apply the same sequences of aggregate shocks, same initial values and the same estimated parameter values.

Figure 7 contrasts the observed data and the data generated by the counter-factual exercise. During the pre-Great Moderation sample in Panel (a.), the counter-factual scenario with a static Calvo share exhibits systematically lower inflation than the data. Consistent with this observation, Table 3 reports that the average of quarterly observed



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

inflation was 1.3% during that period, whereas the counter-factual predicts 1.02%. Table 3 also contains estimated Phillips Curve slope coefficients, b, from regressing inflation on the output gap. While the slope in the data and the counter-factual is comparable during the pre-Great Moderation sample, the counter-factual slope does not flatten to a similar extent during the Great Moderation period (see also Panel (b.)). In contrast, the augmented model can capture this observed flatting to a better extent. The explanation is the dynamic Calvo share, which allows the model to better fit the data despite comparable average inflation and mean estimates for the Calvo share. These findings already demonstrate that the standard NK model with a fixed Calvo share fails to predict important patterns in macroeconomic data and that the

dynamic Calvo share improves the fit to the data.

We now turn to the Great Recession period. In the data, the slope of the Phillips Curve is less flat relative to the Great Moderation, but flatter relative to the counter-factual. The key insight is that in the counter-factual scenario of a static Calvo share, the model predicts deflation, whereas this *missing deflation puzzle* is resolved by the dynamic Calvo share. This insight is based on two observations: first, the counter-factual again predicts systematically lower inflation; second, the regression intercept, a, which can be interpreted as the zero output gap inflation prediction, is negative, whereas it is positive in the data.

Finally, during the New Normal, the slope is slightly negative, but essentially zero in the data and the counter-factual. It is tempting to interpret this finding as an indication that both models predict an inversion of the Phillips curve and a slope that could resolve the *missing inflation puzzle* during the New Normal. Indeed, average inflation is predicted to be slightly below the period of the Great Moderation in both cases. However, one has to be cautious. The result could be driven by the fact that we compute the output gap with a linear trend. It is well known that under the assumption of a linear trend, the output gap has been far from closing throughout the New Normal. In turn, this could affect the sequences of estimated shocks during this period (identified under the assumption of a dynamic Calvo share). As the counter-factual is based on these shocks, the counter-factual results for the New Normal could be driven by these shocks rather than the fixed Calvo share.

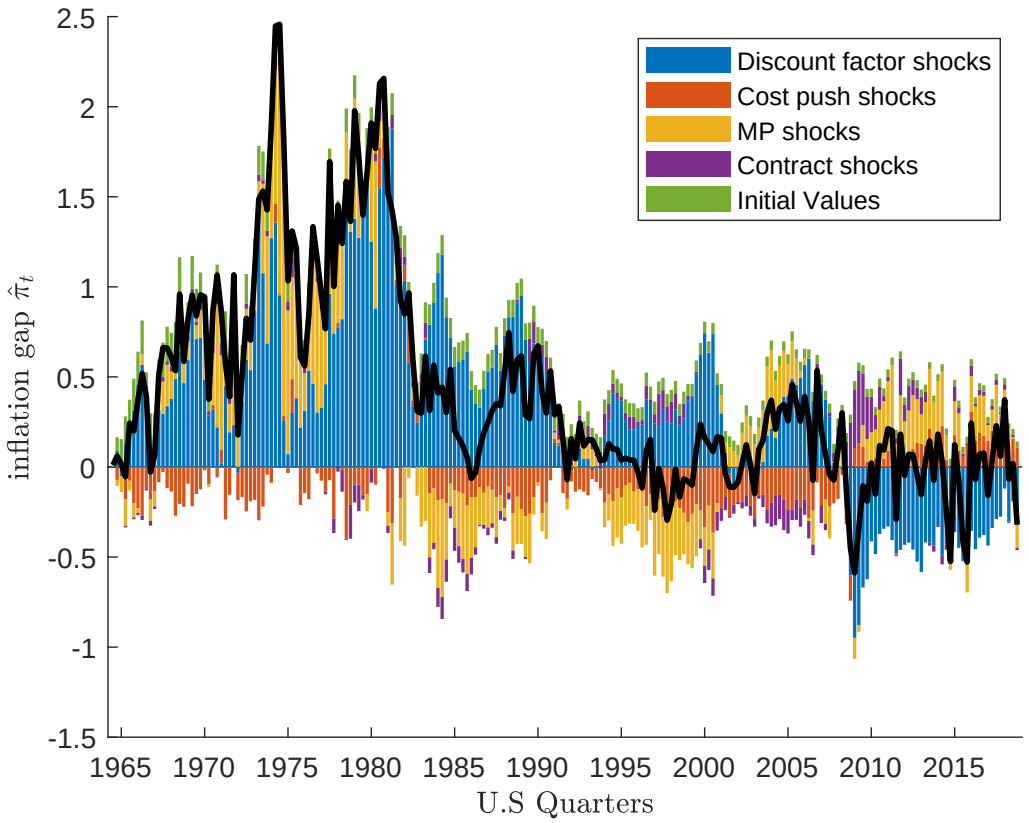
In sum, both the figure and table document the flattening of the Phillips curve during the Great Moderation that prevails throughout the Great Recession and New Normal in the data. The augmented NK model fits these patterns better than the standard NK model. This is no surprise as it is known that for 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

	Dynamic Calvo Data	*Static Calvo* Counter-factual
Pre-Great Moderation 1964Q1-1984Q4:		
a - estimated inflation at zero output gap	1.4353	0.9440
b - estimated linear relation $\hat{y}_t/\hat{\pi}_t^{obs}$	0.0953	0.1033
$av(\hat{\pi}_t^{obs})$ - average inflation (%)	1.3006	1.0235
$av(\theta_t)$ - average Calvo Share	0.6644	0.7174
Great Moderation 1985Q1-2007Q3:		
a - estimated inflation at zero output gap	0.6013	0.4400
b - estimated linear relation $\hat{y}_t/\hat{\pi}_t^{obs}$	0	0.0170
$av(\hat{\pi}_t^{obs})$ - average inflation (%)	0.6013	0.5375
$av(\theta_t)$ - average Calvo Share	0.7279	0.7174
Great Recession 2007Q4-2009Q3:		
a - estimated inflation at zero output gap	0.1854	0.0086
b - estimated linear relation $\hat{y}_t/\hat{\pi}_t^{obs}$	0.0432	0.0455
$av(\hat{\pi}_t^{obs})$ - average inflation (%)	0.1805	0.0086
$av(\theta_t)$ - average Calvo Share	0.6859	0.7174
New Normal 2009Q4-2019Q4:		
a - estimated inflation at zero output gap	0.4051	0.1795
b - estimated linear relation $\hat{y}_t/\hat{\pi}_t^{obs}$	-0.0024	-0.0143
$av(\hat{\pi}_t^{obs})$ - average inflation (%)	0.4212	0.3787
$av(\theta_t)$ - average Calvo Share	0.7452	0.7174

Table 3: Results for the Phillips curve statistics and additional counterfactual simulations. 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.

price setting frequency tend to exhibit Calvo parameter estimates that are inconsistent with microeconomic data on price setting frequency and large cost-push shocks that are negatively correlated with the output gap.

In contrast, in the augmented NK model, inflation is not predominantly driven by cost-push shocks (which is in the end the unexplained inflation residual of the model), but to a large extent driven by discount factor and monetary policy shocks. Figure 8 displays the shocks driving the variation in inflation. Another interesting observation in this figure is that the cost-push shocks and the contract shock do not play a large role



Notes: Values are in log deviation from the steady state.

Figure 8: Historical decomposition of the inflation dynamic based on US data (1964-2019)

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 discount factor and monetary policy shocks.[16] 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 starting in the Great Moderation, the augmented NK model does not require implausible large (residual) cost-push shocks on inflation. It also does not require a Calvo parameter inconsistent with micro

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

data 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.

Overall, our results suggest that the Calvo law of motion also offers great potential to improve the NK model's macroeconomic time series fit. This could be highly relevant for estimated medium-scale NK models. An in-depth assessment of this potential can be done by comparing the marginal likelihood for the augmented and the standard NK model. We pursue this comparison right below.

5 Empirical analysis of a medium-scale NK model

The analysis of the augmented small-scale NK model above suggests that the Calvo law of motion improves the NK model's fit to both macro and micro data. However, the result that cost-push shocks do not play a major role in accounting for inflation contrasts the findings of estimated medium-scale DSGE models in the tradition of Smets & Wouters (2007). We explain this discrepancy in findings with the Calvo law of motion's success in approximating actual price setting behavior of firms. Alternatively, one may rather attribute the discrepancy to the unrealistic nature of the small-scale model than to the Calvo law of motion. In particular, the small-scale model restricts the number of exogenous shock processes relative to more realistic medium-scale DSGE models. Moreover, the small-scale model lacks many potentially important realistic features (e.g., investment, sticky wages), as well as popular mechanical sources of persistence (e.g., habit formation, price indexation) that have been shown to be important in accounting for observed inflation dynamics.

In order to investigate this issue, we estimate a standard and an augmented version of a popular medium-scale NK model with many of the aforementioned features. The augmented version has again an endogenous price setting frequency due to the Calvo

law of motion. However, we now refrain from relating this variable to the observed price setting frequency via a measurement equation. This has the additional advantage that both models can be compared based on the same number of shocks. We then compare the empirical fit of the two estimated versions based on the marginal likelihood.

As a standard medium-scale DSGE model, we take the model developed in Fernández-Villaverde & Rubio-Ramírez (2006) and estimated numerous times (see, e.g., Fernández-Villaverde & Rubio-Ramírez 2007, Fernández-Villaverde 2010, Fernández-Villaverde, Guerron-Quintana & Rubio-Ramírez 2010) off the shelf.[17] Fernández-Villaverde (2010) provides a detailed model description and we stick to this notation. We emphasize that the model assumes sticky prices and wages due to the Calvo (1983) pricing model. In the augmented version, we use the Calvo law of motion to endogenize the price setting frequency for goods prices, θ_p, but not for wages in order to remain consistent with our analysis in the previous sections. This model also contains five exogenous shocks: discount factor shock, labour supply shock, investment-specific technological shock, neutral technology shock and a monetary policy shock.

We estimate the model based on five time series observed for the US over the period 1959Q1 to 2019Q4: real output growth, CPI growth, Fed fund rate, hourly real compensation growth and real investment growth since 1959 in the US.[18] We also estimate both models for the period 1959Q1 to 2007Q3 to guarantee that our conclusions are not altered by changing the sample to the pre-Great Recession period. This also facilitates comparison with the posterior estimates in Fernández-Villaverde (2010). The Bayesian estimation procedure and robustness to different prior settings for the intensity of choice are detailed in the Appendix E. We mostly stick to the Fernández-Villaverde

[17] We choose this model because, contrary to Smets & Wouters (2007), there exists a non-linear version of it. The implementation of our dynamic Calvo share is therefore straightforward and we can avoid cumbersome linearisation. The initial code has been provided by the Macroeconomic Model Data Base (see Wieland, Afanasyeva, Kuete & Yoo 2016).

[18] Fernández-Villaverde & Rubio-Ramírez (2007), Fernández-Villaverde (2010) use the relative price of investment with respect to the price of consumption. Instead we follow the majority of papers in the literature and use investment.

(2010) protocol based on Smets & Wouters (2007) priors. Tables 4 and 5 present information on the parameter prior and posterior distributions.

The most striking result is that the Calvo law of motion improves the model fit to the data regardless of the sample length. While this improvement is rather modest for the subsample 1959Q1 to 2007Q3 in relative terms, it is five times larger for the entire sample including the Great Recession and the New Normal. We now discuss the parameter estimates in greater detail.

Price- and wage-setting. For the augmented model, the estimate of the posterior mean of the Calvo share θ_p is arguably close to the average of 0.7142 found in the Nakamura et al. (2018) data plotted in Figure 1.[19] Price indexation is estimated to be rather unimportant in this model and it is remarkable that both the Calvo share θ_p and the price indexation parameter χ remain rather unaffected by the sample length. This finding stands in sharp contrast to the standard model.

Both the Calvo share and price indexation vary dramatically with the sample length in the standard model. In particular, for the standard model to match the dynamics of inflation over the entire sample, a high price indexation parameter in combination with a rather low static Calvo share is required. This seems implausible for at least two reasons: first, the estimated Calvo share is inconsistent with the average in the Nakamura et al. (2018) data. Second, such a high degree of price indexation seems inconsistent with previous findings (see, e.g., Smets & Wouters 2007, Del Negro et al. 2015).

This exercise also allows us to shed light on how a dynamic price setting frequency interacts with the labor market. In the augmented model, the Calvo probability for

[19]We follow Fernández-Villaverde & Rubio-Ramírez (2007) who interpret the estimated θ_p as a measure of price setting frequency. However, this interpretation is imprecise as the model features price indexation and therefore all prices are changed each period. But at least for the low degrees of price indexation that we estimate for the augmented NK model, this should be a negligible issue. An alternative would be to estimate the model without price indexation.

		Prior			*Posterior: Dynamic Calvo*			*Posterior: Static Calvo*		
Price- and wage-setting		Shape	Mean	STD	Mean	5%	95%	Mean	5%	95%
ω	Intensity of choice	$\mathcal{B}$	5	1	3.5799	2.0638	5.2788			
θ_p	Calvo share, prices	$\mathcal{B}$	.5	.1	0.7258	0.7036	0.7499	0.6895	0.6629	0.7195
χ	Indexation, prices	$\mathcal{B}$	.5	.15	0.0994	0.0341	0.1638	0.1336	0.0640	0.2022
θ_w	Calvo share, wages	$\mathcal{B}$	.5	.1	0.6877	0.6692	0.6692	0.7012	0.6890	0.7135
χ_w	Indexation, wages	$\mathcal{B}$	.5	.1	0.1502	0.1502	0.2082	0.1717	0.1209	0.2139
Monetary authority										
γ_R	Interest-rate smoothing	$\mathcal{B}$	.75	.1	0.3516	0.2653	0.4414	0.4691	0.4168	0.5386
γ_y	MP. stance, output gap	$\mathcal{N}$	.125	.05	0.2866	0.2426	0.3321	0.2766	0.2263	0.3243
γ_π	MP. stance, inflation	$\mathcal{N}$	1.5	.125	1.0146	1.0089	1.0196	1.0129	1.0088	1.0168
$100(\Pi - 1)$	Quarterly inflation trend	$\mathcal{G}$	.95	.1	0.9158	0.7795	1.0511	0.9810	0.9314	1.0523
Preferences and technology										
$100(\beta^{-1} - 1)$	Time preference	$\mathcal{N}$	.25	.1	0.2888	0.1125	0.4664	0.2185	0.1231	0.3367
$\hbar$	Consumption habit	$\mathcal{B}$	.7	.025	0.7349	0.7074	0.7653	0.7596	0.7399	0.7741
ψ	Scaling for labour supply	$\mathcal{N}$	9	3	9.1902	4.4795	13.9383	7.5778	5.0248	10.8963
ϑ	Inverse of Frisch elasticity	$\mathcal{N}$	1	.1	1.1433	1.0185	1.2947	1.1162	1.0284	1.2042
κ	Capital adjustment cost	$\mathcal{N}$	4	1.5	0.2675	0.2007	0.3342	0.3729	0.2933	0.4512
α	Capital share	$\mathcal{N}$	.3	.025	0.1324	0.1171	0.1472	0.1121	0.0990	0.1267
$100\Lambda_\mu$	Investment growth trend	$\mathcal{N}$	.34	.1	0.15	0.04	0.25	0.22	0.13	0.30
$100\Lambda_A$	Technology growth trend	$\mathcal{N}$	.178	.075	0.31	0.23	0.4	0.24	0.19	0.28
Exogenous processes										
σ_d	Discount factor shock, std.	$\mathcal{IG}$	.1	2	0.0217	0.0185	0.0245	0.0230	0.0203	0.0255
σ_φ	Labour supply shock, std.	$\mathcal{IG}$	.1	2	0.2824	0.27	0.3533	0.2566	0.2302	0.2742
σ_μ	Investment techno. shock, std.	$\mathcal{IG}$	.1	2	0.0088	0.0079	0.0096	0.0088	0.0079	0.0096
σ_A	Neutral techno. shock, std.	$\mathcal{IG}$	.1	2	0.0215	0.0183	0.0246	0.0259	0.0224	0.0304
σ_e	MP shock, std.	$\mathcal{IG}$	.1	2	0.0096	0.0086	0.0106	0.0096	0.0086	0.0107
ρ_d	Discount factor shock, AR(1)	$\mathcal{B}$	.5	.1	0.7880	0.7221	0.8537	0.8193	0.8012	0.8423
ρ_φ	Labour supply shock, AR(1)	$\mathcal{B}$	.5	.1	0.9112	0.8974	0.9278	0.8961	0.8831	0.9105
Log-likelihood						-1501.41			-1512.36	

Table 4: Estimated parameters of the Fernández-Villaverde (2010) model (US: 1959-2008Q3). $\mathcal{B}$, $\mathcal{G}$, $\mathcal{IG}$, $\mathcal{N}$ denote beta, gamma, inverse gamma and normal distributions, respectively.

		Prior			*Posterior: Dynamic Calvo*			*Posterior: Static Calvo*		
Price- and wage-setting		Shape	Mean	STD	Mean	5%	95%	Mean	5%	95%
ω	Intensity of choice	$\mathcal{B}$	5	1	4.3112	2.8628	5.5554			
θ_p	Calvo share, prices	$\mathcal{B}$	.5	.1	0.6543	0.6139	0.6911	0.4265	0.3403	0.5164
χ	Indexation, prices	$\mathcal{B}$	.5	.15	0.0994	0.0341	0.1638	0.4384	0.2574	0.6202
θ_w	Calvo share, wages	$\mathcal{B}$	.5	.1	0.3723	0.3273	0.4175	0.2996	0.2309	0.3647
χ_w	Indexation, wages	$\mathcal{B}$	.5	.1	0.4800	0.3246	0.6122	0.6316	0.5058	0.7531
Monetary authority										
γ_R	Interest-rate smoothing	$\mathcal{B}$	.75	.1	0.3905	0.3192	0.4600	0.7663	0.7164	0.8197
γ_y	MP. stance, output gap	$\mathcal{N}$	.125	.05	0.2424	0.2129	0.2717	0.0228	0	0.0499
γ_π	MP. stance, inflation	$\mathcal{N}$	1.5	.125	1.0225	1.0189	1.0258	1.6140	1.4264	1.7806
$100(\overline{\Pi}-1)$	Quarterly inflation trend	$\mathcal{G}$	.95	.1	0.9877	0.8578	1.1164	0.9637	0.8153	1.1263
Preferences and technology										
$100(\beta^{-1}-1)$	Time preference	$\mathcal{N}$	.25	.1	0.1622	0.0645	0.2545	0.2592	0.0938	0.4284
$\hbar$	Consumption habit	$\mathcal{B}$	.7	.025	0.7755	0.7542	0.7982	0.7817	0.7543	0.8113
ψ	Scaling for labour supply	$\mathcal{N}$	9	3	6.7774	2.8349	10.6425	9.1205	4.5937	13.6441
ϑ	Inverse of Frisch elasticity	$\mathcal{N}$	1	.1	0.7461	0.6029	0.9077	0.8575	0.6622	1.0468
κ	Capital adjustment cost	$\mathcal{N}$	4	1.5	0.3076	0.2461	0.3696	2.2009	1.4749	2.9322
α	Capital share	$\mathcal{N}$	.3	.025	0.1984	0.1848	0.2116	0.1380	0.1187	0.1562
$100\Lambda_\mu$	Investment growth trend	$\mathcal{N}$	.34	.1	0.12	0.02	0.21	0.18	0.02	0.32
$100\Lambda_A$	Technology growth trend	$\mathcal{N}$	.178	.075	0.12	0.02	0.20	0.18	0.09	0.27
Exogenous processes										
σ_d	Discount factor shock, std.	$\mathcal{IG}$	.1	2	0.0260	0.0228	0.0294	0.0865	0.0561	0.1144
σ_φ	Labour supply shock, std.	$\mathcal{IG}$	.1	2	0.0431	0.0379	0.0482	0.0543	0.0438	0.064
σ_μ	Investment techno. shock, std.	$\mathcal{IG}$	.1	2	0.0077	0.0071	0.0083	0.0102	0.0092	0.0113
σ_A	Neutral techno. shock, std.	$\mathcal{IG}$	.1	2	0.0196	0.0168	0.0225	0.0122	0.0105	0.0140
σ_e	MP shock, std.	$\mathcal{IG}$	.1	2	0.0085	0.0077	0.0092	0.0095	0.0085	0.0105
ρ_d	Discount factor shock, AR(1)	$\mathcal{B}$	.5	.1	0.8726	0.8395	0.9044	0.9913	0.9875	0.9949
ρ_φ	Labour supply shock, AR(1)	$\mathcal{B}$	.5	.1	0.9947	0.9943	0.9950	0.9653	0.9558	0.9746
Log-likelihood						-1974.58			-2029.85	

Table 5: Estimated parameters of the Fernández-Villaverde (2010) model (US: 1959-2019Q4). $\mathcal{B}$, $\mathcal{G}$, $\mathcal{IG}$, $\mathcal{N}$ denote beta, gamma, inverse gamma and normal distributions, respectively.

wages, θ_w, is 0.68 for the subsample and 0.37 over the entire sample. For the standard model, it is 0.70 for the subsample and 0.29 for the entire sample. Contrary, to fit the data over the entire sample, wage indexation has to be dramatically larger compared to the subsample estimate in both model versions.

To sum up, the subsample estimate regarding wage-setting parameters for both the augmented and standard model are in line with the literature on estimated NK models. This literature assigns an important role to nominal wage rigidities. However, to fit the data over the entire sample, the standard model relies heavily on a dramatic decline in the wage-setting frequency and a dramatic increase in exogenous wage indexation. Contrary, the augmented model's estimates for wage-setting behavior, θ_w and χ_w, are less affected by the change in the sample length. Thus, the Calvo law of motions is a mechanism that mutes labor market parameter instability.

Is the latter desirable? We believe that in light of the evidence provided in Del Negro et al. (2020) the answer is yes. For example, Del Negro et al. (2020) provide evidence from an SVAR and an estimated NK model that does not support the hypothesis that there has been structural change on the labor market in recent years. Therefore the labor market parameter estimates in our models should be unaffected by the sample length.

Notice that our findings are also consistent with the results in Fernández-Villaverde & Rubio-Ramírez (2007) who find that there is an inverse relationship between θ_p and χ and between θ_w and χ_w, once one allows these parameters to vary over time. Fernández-Villaverde & Rubio-Ramírez (2007) conclude that a high exogenous price and wage indexation reflect important price and wage dynamics not captured in the model. We find that the Calvo law of motion improves price- and wage setting parameter stability over different sample lengths. This suggests that the Calvo law of motion can capture these dynamics to some extent.[20]

[20]Consequently, one possible extension of our paper could be a reassessment of our findings in a version where also θ_w is endogenized with the Calvo law of motion.

Another important question is, whether the augmented NK model relies on implausible estimates of the intensity of choice, ω, to fit the data? The answer is clearly no. Independent of the sample length, the parameter is arguably stable and in the range of existing estimates (e.g., Cornea-Madeira et al. 2019). In Appendix E.2 we show that the full sample estimate for ω is robust to different priors.

Monetary authority. Does the augmented NK model yield plausible estimates for the monetary authority parameters? We estimate coefficients for the output gap and interest-rate smoothing that are frequently reported to in the literature. The coefficient on inflation is close to, but above unity. This value is arguably at the lower end of the typical range of estimates found in the literature. However, our sample covers subsamples where this coefficient is typically clearly below unity or clearly above unity (e.g., Lubik & Schorfheide 2004). Therefore, our estimates are arguably within the plausible range. Another plausible explanation is that the coefficients are affected by the zero lower bound period in the data that we do not incorporate in the model.

Preferences and technology. The preference parameters are all in a reasonable range. This holds for both model versions and independent of the sample length. The technology parameters imply estimated average annual growth rates of real GDP per quarter, $400(\Lambda_A + \alpha\Lambda_\mu)/(1-\alpha)$. For the subsample we obtain 1.52% for the augmented and 1.19% for the standard NK model. The corresponding rates for the full sample are 0.70% and 0.95%. Fernández-Villaverde (2010) estimates 1.7% over the sample 1959Q1 to 2007Q1 and uses different data for investment. Thus, while the sample length differs, our subsample estimates are of comparable size. However, our estimates for the full sample clearly lower. This may be rationalized by the fact that our full sample covers the Great Recession and its aftermath.

All told, we conclude that the augmented NK model improves the model fit to the

data. Moreover, while not the primary objective of this exercise, the augmented NK model also makes the model less prone to parameter instability and at the same time it yields estimated parameters for the monetary authority, preferences, technology, and, also for exogenous processes that are within a plausible range.

6 Conclusion

We develop 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 non-linear 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. Fourth, the Calvo law of motion largely improves the macroeconomic time series fit of a medium-scale NK model. This is especially true for samples that include the Great Recession and its aftermath.

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A Model details

A.1 The steady state of the simplified model

The simplified model has the following steady states: $Y = 1$, $N = Y$, $w = N^{\varphi}Y^{\sigma}$, as well as

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

A.2 The steady state of the NK model

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

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

A.3 Linearisation

A.3.1 The Phillips curve

We 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) :

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

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

then we substitute (A.2) into (A.1)

$$\hat{\psi}_t = \hat{\phi}_t + \frac{\theta\overline{\pi}^{\epsilon-1}}{1-\theta\overline{\pi}^{\epsilon-1}}\hat{\pi}_t - \frac{\overline{\pi}^{1-\epsilon} - p_i^*}{(1-\epsilon)(1-\theta\overline{\pi}^{\epsilon-1})}\theta\hat{\theta}_t \tag{A.3}$$

Now we plug(A.3) 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 $\iota=\frac{\overline{\pi}^{1-\epsilon}-p_i^*}{\overline{\pi}^{\epsilon-1}}$.

B Detailed in the linearised augmented NK Phillips Curve

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 6: NKPC parameters and their relations to other structural parameters

C Equilibrium dynamics of the calibrated NK model

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.[21]

[21] 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 D

C.1 Calibration

In order to elaborate the difference between our augmented and the benchmark model, we use a standard calibration, see Table 7, together with an intensity of choice $\omega = 2$.[22] 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.

		Values	Sources
β	Discount factor	0.99	Galí (2015)
σ	Relative risk aversion	1	Galí (2015)
φ	Frisch 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 share steady state	$\frac{1}{1+e^{-\omega\tau}} = 0.75$	Galí (2015)
ω	Intensity of choice	2	illustrative purpose
ρ	Discount factor shock, AR(1)	0.8	illustrative purpose

Table 7: Calibrated parameters for dynamic simulations (quarterly basis)

C.2 Impulse response functions

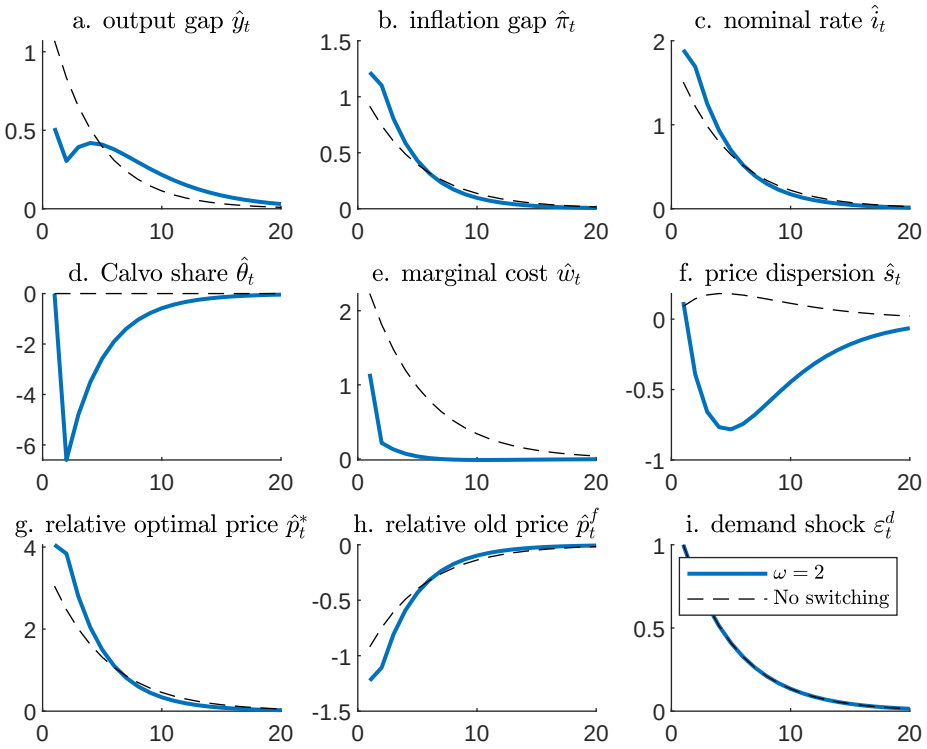
The impulse response functions to a demand shock in the linearised augmented NK model are depicted in Figure C.1.

One can observe that the impulse responses are to a large extent in line with the ones in Figure 3a.[23] 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

[22] Sensitivity analysis for the values of ω are available in Appendix D

[23] 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.

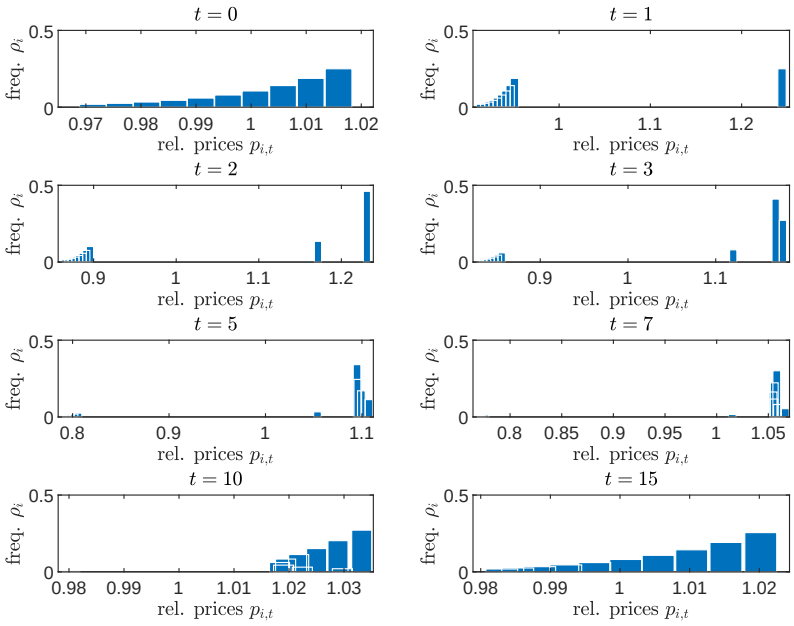
Figure C.1: demand shock

variables are amplified. This result can be traced back to the higher flexibility of prices 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.

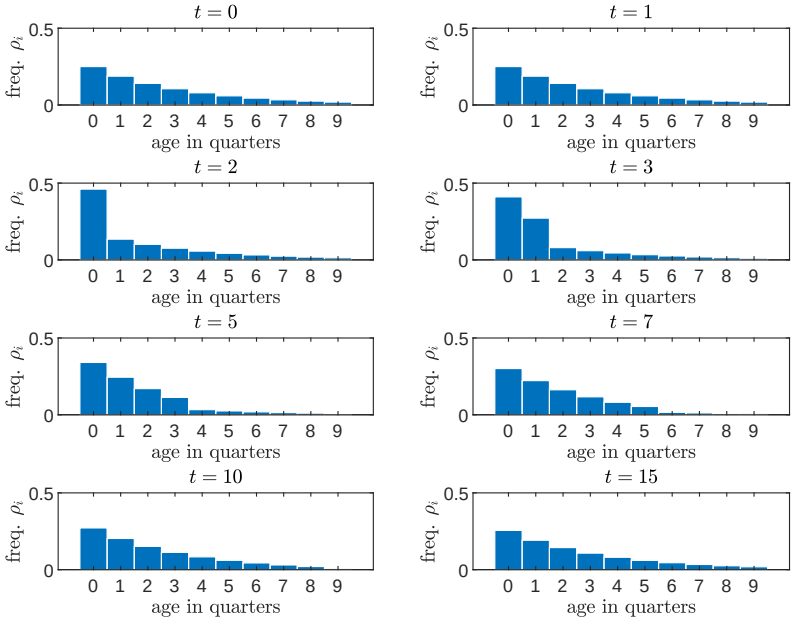
The mechanism behind the decline in relative price dispersion can be examined in more detail by the help of Figures C.2a and C.2b.[24] Figure C.2a shows that relative to the steady state distribution ($t = 0$) both the price setting frequency and the magnitude of the optimal reset price are higher until the shock decays. Figure C.2b 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 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

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



(a) Frequency of relative prices



(b) Prices' ages distribution

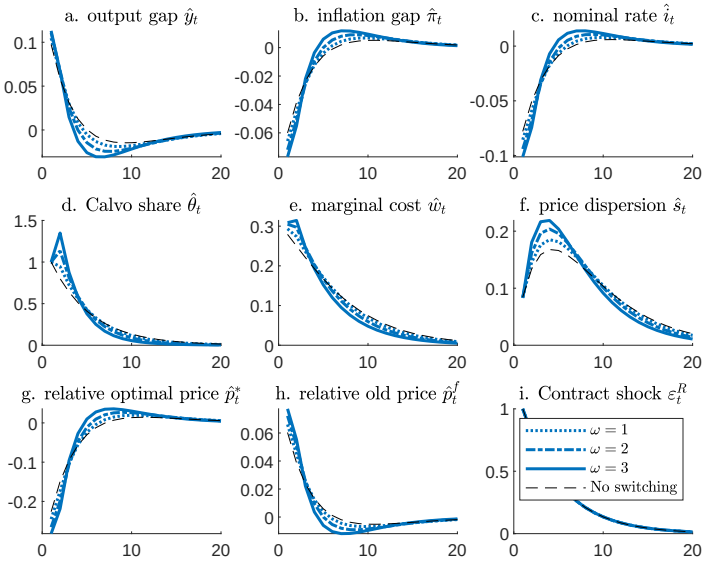
Notes: Blue bars are the frequency ($\rho_{i,t}$) of pricing decision ($p_{i,t}$) or of the age of the price (only the 10 most used pricing decision a display. We increase the size of the shock to enhance the change in frequency level.)

Figure C.2: Prices dynamic after a demand shock of +5%

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.

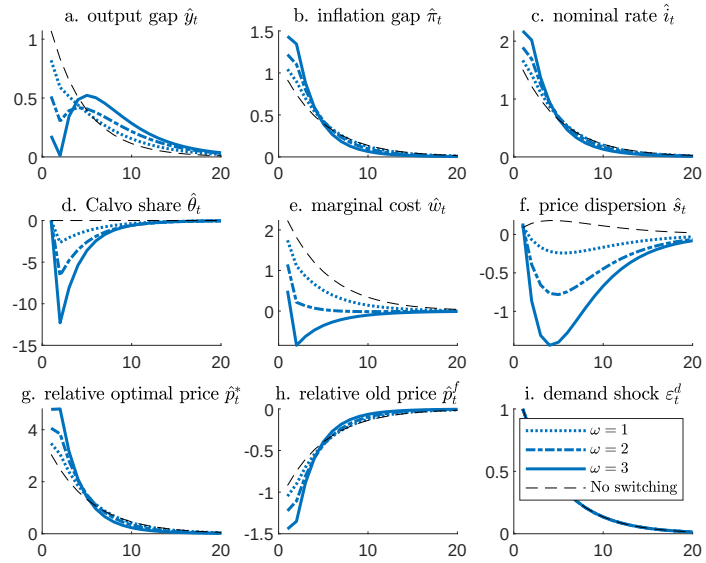
Next, the higher magnitude of optimal reset prices is due to the fact that firms take into account the higher price setting frequency in subsequent periods. Therefore firms set a higher optimal price relative to the standard NK model. The combination of higher price setting frequency and higher relative 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.

D Sensitivity to the intensity of choice parameter



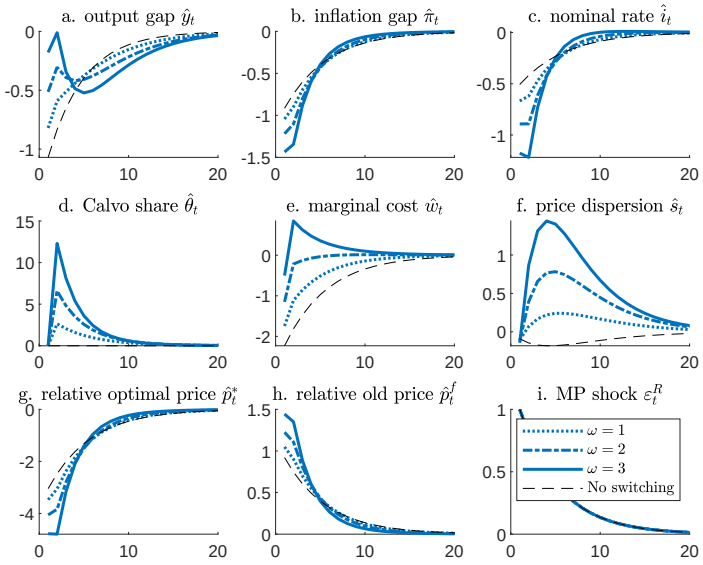
Notes: Results are in percentage point of the log deviation from the steady state.

Figure D.1: Contract shock



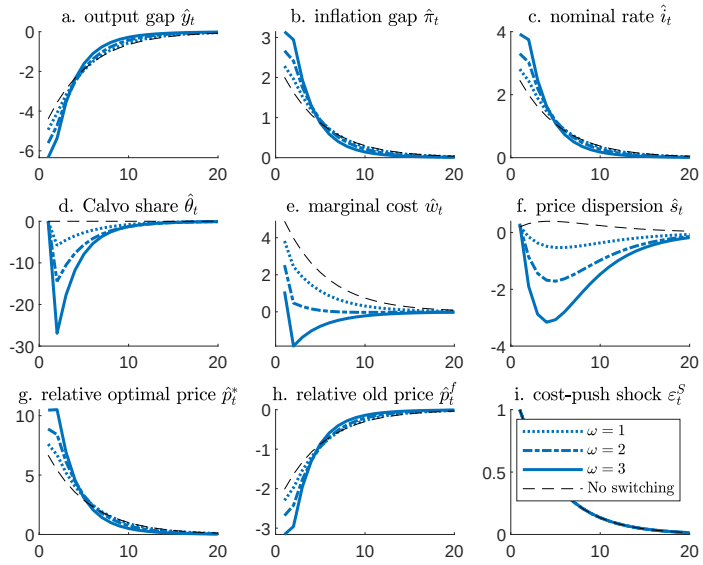
Notes: Results are in percentage point of the log deviation from the steady state.

Figure D.2: Demand shock



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

Figure D.3: Monetary policy shock



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

Figure D.4: Markup shock

E Estimation strategy and detailed results of the medium-scaled estimations

E.1 Priors and calibration

As in Fernández-Villaverde (2010), we calibrate capital depreciation $\delta = 0.025$, the price elasticity of demand $\epsilon = 10$, fixed cost $\Phi = 0$ and the elasticity of demand between labours at $\eta = 10$. Due to difficulty for the model in both case and periods to not generate unit-root dynamic within discount factor and labour disutility shocks, we reduce the standard deviation of the autocorrelation coefficients priors from 0.2 to 0.1. In the same way, we reduce the standard deviation of the consumption habit coefficient from 0.1 to 0.025. It appears to be a characteristic of this model. Indeed in the initial estimation of Fernández-Villaverde (2010) $\hbar = 0.97$, which is very much in the upper bound of the literature. Without the need to fit micro data, we keep the mean of the prior of $\omega = 5$ but widen its standard deviation to 1 in order to avoid over identification. Robustness to this prior is presented later in this section.

E.2 Robustness of the estimation to priors for the intensity of choice

In this subsection, as a robustness check we report the results of the estimation with a prior for the intensity of choice at $\omega = 3$ and $\omega = 7$ in Table 8.

		Prior			*Posterior: Dynamic Calvo* *Prior mean* $\omega = 3$			*Posterior: Dynamic Calvo* *Prior mean* $\omega = 7$		
Price- and wage-setting		Shape	Mean	STD	Mean	5%	95%	Mean	5%	95%
ω	Intensity of choice	$\mathcal{B}$	3 or 7	1	2.1413	0.7744	3.3249	5.5117	3.7134	7.2778
θ_p	Calvo share, prices	$\mathcal{B}$	.5	.1	0.6625	0.6276	0.7037	0.6895	0.6629	0.7195
χ	Indexation, prices	$\mathcal{B}$	.5	.15	0.1440	0.0625	0.2215	0.0994	0.0341	0.1638
θ_w	Calvo share, wages	$\mathcal{B}$	.5	.1	0.3741	0.3274	0.4176	0.3705	0.3171	0.4251
χ_w	Indexation, wages	$\mathcal{B}$	.5	.1	0.4048	0.2838	0.5183	0.4018	0.2732	0.5178
Monetary authority										
γ_R	Interest-rate smoothing	$\mathcal{B}$	.75	.1	0.3853	0.3160	0.4673	0.3516	0.2653	0.4414
γ_y	MP. stance, output gap	$\mathcal{N}$	.125	.05	0.2316	0.2055	0.2603	0.2866	0.2426	0.3321
γ_π	MP. stance, inflation	$\mathcal{N}$	1.5	.125	1.0233	1.0198	1.0266	1.0146	1.0089	1.0196
$100(\Pi - 1)$	Quarterly inflation trend	$\mathcal{G}$	.95	.1	0.9200	0.7864	1.0343	0.9158	0.7795	1.0511
Preferences and technology										
$100(\beta^{-1} - 1)$	Time preference	$\mathcal{N}$	.25	.1	0.3225	0.0950	0.5459	0.2888	0.1125	0.4664
$\hbar$	Consumption habit	$\mathcal{B}$	.7	.025	0.7737	0.7488	0.7996	0.7349	0.7074	0.7653
ψ	Scaling for labour supply	$\mathcal{N}$	9	3	6.5509	6.5509	9.6674	6.0861	3.0208	9.4932
ϑ	Inverse of Frisch elasticity	$\mathcal{N}$	1	.1	0.7953	0.5956	0.9609	0.7661	0.5586	0.9443
κ	Capital adjustment cost	$\mathcal{N}$	4	1.5	0.2980	0.2367	0.3612	0.2675	0.2007	0.3342
α	Capital share	$\mathcal{N}$	.3	.025	0.1938	0.1797	0.2069	0.1963	0.1819	0.2101
$100\Lambda_\mu$	Investment growth trend	$\mathcal{N}$	.34	.1	0.09	0.00	0.17	0.14	0.04	0.23
$100\Lambda_A$	Technology growth trend	$\mathcal{N}$	.178	.075	0.20	0.12	0.30	0.20	0.14	0.40
Exogenous processes										
σ_d	Discount factor shock, std.	$\mathcal{IG}$	.1	2	0.0255	0.0224	0.0287	0.0258	0.0258	0.0293
σ_φ	Labour supply shock, std.	$\mathcal{IG}$	.1	2	0.0436	0.0380	0.0495	0.0432	0.0369	0.0491
σ_μ	Investment techno. shock, std.	$\mathcal{IG}$	.1	2	0.0078	0.0071	0.0084	0.0077	0.0071	0.0083
σ_A	Neutral techno. shock, std.	$\mathcal{IG}$	.1	2	0.0203	0.0175	0.0234	0.0083	0.0165	0.0225
σ_e	MP shock, std.	$\mathcal{IG}$	.1	2	0.0085	0.0077	0.0093	0.0084	0.0076	0.0092
ρ_d	Discount factor shock, AR(1)	$\mathcal{B}$	.5	.1	0.8732	0.8391	0.9054	0.7880	0.7221	0.8537
ρ_φ	Labour supply shock, AR(1)	$\mathcal{B}$	.5	.1	0.9947	0.9943	0.9950	0.9112	0.8974	0.9278
Log-likelihood					-1973.29			-1975.19		

Table 8: Estimated parameters of the Fernández-Villaverde (2010) model (US: 1959-2019Q4). $\mathcal{B}$, $\mathcal{G}$, $\mathcal{IG}$, $\mathcal{N}$ denote beta, gamma, inverse gamma and normal distributions, respectively.