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Monetary Policy, Inflation Target and the Great Moderation: An Empirical Investigation

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Keywords

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JEL Classification

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Abstract

This paper estimates a New Keynesian model with trend inflation and contrasts Taylor rules featuring fixed versus time-varying inflation target while allowing for passive monetary policy. The estimation is conducted over the Great Inflation and the Great Moderation periods. Time-varying inflation target empirically fits better and active monetary policy prevails in both periods, thereby ruling out sunspots as an explanation of the Great Inflation episode. Counterfactual simulations suggest that the decline in inflation volatility since the mid-1980s is mainly driven by monetary policy, while the reduction in output growth variability is explained by the reduced volatility of technology shocks.

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1 Introduction

Post-World War II U.S. economy is generally characterized by two particular eras: the Great Inflation and the Great Moderation. There is strong evidence that the former era is represented by highly volatile inflation and output growth while there has been a marked decline in macroeconomic volatility in the latter period (Blanchard and Simon, 2001; McConnell and Perez Quiroz, 2000; and Stock and Watson, 2002). What has led to the transition from the Great Inflation to the Great Moderation era? The two main hypotheses put forth by the empirical literature are either 'good luck' or 'good policy'. The 'good luck' interpretation - a decline in the variance of the exogenous shocks hitting the economy - has been supported by a number of authors including Stock and Watson (2002), Primiceri (2005), Sims and Zha (2006), Smets and Wouters (2007), and Justiniano and Primiceri (2008). Within the 'good policy' framework, the monetary policy literature has offered at least two competing explanations regarding this shift to macroeconomic stability - a stronger policy response to inflation and an enhanced stability of the Federal Reserve's inflation target.

This paper evaluates the competing 'good policy' views on the U.S. economy's shift from the Great Inflation to the Great Moderation by estimating a New Keynesian model with positive trend inflation while allowing for inflation target to be potentially varying over time and policy response to inflation to be either passive or active.[1] In particular, the paper compares the empirical performance of the model featuring a Taylor rule with fixed versus time-varying inflation target, while also allowing for indeterminacy.[2] The estimation is conducted over two different periods covering the Great Inflation and the Great Moderation. First, the paper shows that the rule embedding time variation in inflation target turns out to be empirically superior and as a result determinacy prevails not only in the Great Moderation era as suggested by the literature, but most likely also in the pre-Volcker period. Therefore, unlike the literature's preponderant view, this finding works against self-fulfilling inflation

[1] A policy response to inflation is called *active* if it satisfies the Taylor Principle - an aspect of the Taylor rule that describes how, for each one percent increase in inflation, the central bank should raise the nominal interest rate by more than one percentage point to ensure determinacy. Otherwise, it is labelled as *passive*.

[2] Roughly speaking, *indeterminacy* refers to the multiplicity of rational expectations equilibria while an equilibrium that is locally isolated and uniquely determined by preferences and technologies is called *determinate*. See Farmer (1999) for a formal definition.

expectations, i.e. sunspots, as an explanation of the Great Inflation episode. Second, the paper shows that both features of 'good policy' are jointly required to explain the decline in inflation volatility. Counterfactual exercises suggest that better monetary policy, both in terms of a stronger response to the inflation gap and a better anchored inflation target, has dampened most of the fluctuations in inflation. In contrast, changes in monetary policy alone fail to explain the reduced variability of output growth, which is explained by a reduction in the volatility of technology shocks. Hence, these findings suggest that both 'good policy' and 'good luck' are jointly required to explain the Great Moderation.

The empirical plausibility of a link between monetary policy and macroeconomic instability was established by Clarida, Gali and Gertler (2000) and further advocated by Lubik and Schorfheide (2004). These authors argue that U.S. monetary policy in the 1970s failed to respond sufficiently strongly to inflation thereby generating indeterminacy. Consequently, self-fulfilling inflation expectations are regarded as the driver of the high inflation episode in the 1970s. According to this view, a switch from a passive to an active response to inflation brought about a stable and determinate environment since the early 1980s. In a conceptually related study, Boivin and Giannoni (2006) find that this switch has also been instrumental in reducing observed output and inflation volatility. Moreover, Benati and Surico (2008) show that by responding more strongly to inflation, monetary policy has contributed to the decline in persistence and predictability of inflation relative to a trend component.

While these studies only consider a constant zero inflation target (i.e. a zero inflation steady state), a slightly different picture emerges from studies allowing for positive trend inflation. For instance, Coibion and Gorodnichenko (2011) and Hirose, Kurozumi and Van Zandweghe (2017) argue that a stronger response to inflation is not enough to explain the shift to determinacy after the Great Inflation. Instead, they document that a decline in trend inflation as well as a change in the policy response to the output gap and output growth have played a crucial role. Nonetheless, there is a large literature disputing the view of a fixed inflation target. Amongst them Kozicki and Tinsley (2005, 2009), Ireland (2007), Stock and Watson (2007), Cogley and Sbordone (2008) and Castelnuovo, Greco and Raggi (2014) find evidence in favor of time-varying inflation target. Furthermore, Cogley, Primiceri and Sargent (2010) argue that the decline in the variability of the Federal Reserve's inflation target is the single most important factor behind the reduction in inflation volatility and persistence.

Empirical investigations conducted so far have either looked at the plausibility of a switch from indeterminacy to determinacy through the lens of a model featuring fixed (either zero or positive) target or allowed for time-varying inflation target while restricting the model to determinacy alone. Unfortunately, the assumption of a fixed versus time-varying inflation target is not innocuous for both the determinacy properties and the role of monetary policy in the Great Moderation. For instance, the parameter estimate of the Taylor rule's response to the inflation gap depends on whether the Federal Reserve is responding to deviations from a fixed target or time-varying target. This feature then affects the probability of being in a determinate or indeterminate regime. One exception is Coibion and Gorodnichenko (2011) who use a single-equation approach to estimate a Taylor rule with time-varying coefficients to extract a measure of time-varying trend inflation. A time-series for the probability of determinacy is then constructed by feeding the empirical estimates of the Taylor rule into a prespecified New Keynesian model. This series indicates that the probability of determinacy was essentially zero in the second half of the 1970s. In contrast, this paper treats (in-)determinacy as a property of a rational expectations system that requires a full information estimation approach such that the parameter estimates of the Taylor rule account for the endogeneity of its targeted variables. Moreoever, Coibion and Gorodnichenko (2011) do not estimate the shock processes and so the effect on indeterminacy cannot be quantified as completely as in a fully specified and estimated DSGE model, as they point out. In particular, inflation target shocks have implications for indeterminacy as further discussed below.

Following the methodology proposed by Lubik and Schorfheide (2004), the paper estimates the model under both fixed and time-varying inflation target over the entire stable region of the parameter space - determinacy and indeterminacy.[3] In contrast to the existing literature, the current paper distinguishes between trend inflation and time-varying inflation target. Trend inflation, a term coined by Ascari (2004), stands

[3] Ascari, Bonomolo and Lopes (2019) allow for temporarily unstable paths, while we require all solutions to be stationary, in line with previous contributions in the literature.

for a strictly positive level of steady state inflation around which to approximate firms' first-order conditions in the derivation of the New Keynesian Phillips curve (henceforth NKPC). Allowing for positive trend inflation is important as it affects the determinacy properties of the model. Ascari and Ropele (2007, 2009) show that trend inflation makes price-setting firms more forward-looking which flattens the NKPC and widens the indeterminacy region. On the other hand, following Sargent (1999), Cogley and Sargent (2005), Primiceri (2006), and Sargent, Williams and Zha (2006) time-varying inflation target is interpreted as the short-term goal pursued by the Federal Reserve conditional on economic situation and its knowledge about the inflation-output volatility trade-off. In this line of argument, trend inflation stands for the Federal Reserve's long-run target compatible with its long-run goals such as inflation stability and sustainable economic growth. A fixed inflation target is simply equal to trend inflation in the model. In contrast, time-varying inflation target follows a persistent exogenous autoregressive process as in Cogley, Primiceri and Sargent (2010), but one whose unconditional mean is equal to positive trend inflation.[4]

The paper finds that when considering the model with fixed inflation target, indeterminacy cannot be ruled out before 1979 while determinacy prevails after 1984. Yet, this upshot differs when allowing for time-varying inflation target. This time the posterior density favors determinacy for both the pre-1979 and the post-1984 sub-samples. This result suggests that monetary policy, even during the pre-Volcker period, was likely to be sufficiently active to ensure determinacy. Using posterior odds ratio to compare the two specifications, the paper then reports evidence in favor of time variation in the inflation target process.

The finding that allowing for time-varying inflation target leads to determinacy in the Great Inflation era might be surprising given that the literature has established the pre-Volcker period as characterized by indeterminacy. What's driving this result? First of all, the inflation gap that enters the Taylor rule when the target is drifting over time is less volatile than the inflation gap with a fixed target (at the steady state level). For a given historical path of the nominal interest rate, then the response of the nominal rate to the inflation gap turns out to be higher in the case of time-varying

[4] For models in which inflation target evolves partly or fully endogenously, see Ireland (2007), Zanetti (2014) and Eo and Lie (2017).

target, which leads to determinacy. Secondly, Fujiwara and Hirose (2012) argue that a model under indeterminacy can generate richer persistent inflation dynamics compared to determinacy. However, Cogley, Primiceri and Sargent (2010) document that inflation target shocks induce persistent responses to the inflation gap that capture the permanent component of inflation. According to the posterior estimates, inflation target was loosely anchored during the pre-Volcker period as evident from its higher innovation variance. As such, the model does not require the richer endogenous inflation dynamics that arise under indeterminacy to explain the Great Inflation episode.

Perhaps most closely related to this paper are studies by Castelnuovo (2010), Cogley, Primiceri and Sargent (2010), Castelnuovo, Greco and Raggi (2014), and Hirose, Kurozumi and Van Zandweghe (2017). Both Castelnuovo (2010) and Cogley, Primiceri and Sargent (2010) estimate a New Keynesian model with zero inflation in the steady state while restricting the parameter space to determinacy and perform counterfactual simulations to assess the drivers of the Great Moderation. The current paper, on the other hand, estimates a model with positive trend inflation which alters the NKPC relationship and therefore changes the inflation dynamics and determinacy regions. Moreover, it estimates the model over the entire region of the parameter space while testing for indeterminacy, i.e. simultaneously estimating the model over both determinacy and indeterminacy regions. The paper also compares the fit of fixed versus time-varying target and shows that the latter specification fits better.

Castelnuovo, Greco and Raggi (2014) estimate a regime-switching policy rule and find support in favor of time-varying inflation target as well. The authors employ a partial equilibrium single-equation approach with two monetary regimes - active and passive. They characterize monetary policy during much of the 1970s as passive and identify a switch to an active regime soon after Paul Volcker's appointment as Chairman of the Federal Reserve. While similar in spirit to this paper, their approach to deal with the issue of passive monetary policy does not allow for multiplicity of equilibria and sunspot shocks. Also, the limited information approach can be prone to weak identification as shown by Mavroeidis (2010).

Hirose, Kurozumi and Van Zandweghe (2017) estimate a New Keynesian model with firm-specific labor and fixed inflation target (equal to positive steady state or trend inflation) using similar methodologies as in this paper. They find that the pre-Volcker period is characterized by indeterminacy while better systematic monetary policy as well as changes in the level of trend inflation resulted in a switch to determinacy after 1982.[5] In contrast, the current paper estimates a similar model with homogenous labor while also allowing for time variation in the inflation target process. The paper documents that time-varying inflation target empirically fits better (or at least no worse in the case of firm-specific labor) than constant target and determinacy prevails in both sample periods.

This paper is the first one to test for indeterminacy using a full-information structural approach while allowing for both positive trend inflation and time variation in the Federal Reserve's inflation target. The finding that the pre-Volcker period could possibly be characterized by a unique equilibrium is in line with Orphanides (2004), Bilbiie and Straub (2013) and Haque, Groshenny and Weder (2018). Orphanides (2004) finds an active response to expected inflation in a Taylor-type rule estimated for the pre-1979 period, thereby claiming that self-fulfilling inflation expectations cannot be a source of macroeconomic instability during the Great Inflation. Bilbiie and Straub (2013) show that limited asset market participation results in an inverted IS curve and inverted aggregate demand logic, i.e. interest rate increases becoming expansionary. Accordingly, they document passive monetary policy during the pre-Volcker period being consistent with equilibrium determinacy. Haque, Groshenny and Weder (2018) document that commodity price shocks during the seventies generated a trade-off for the Federal Reserve in stabilizing inflation and the output gap. Faced with this trade-off, they find that the Federal Reserve responded aggresively to inflation (and negligibly to the output gap) in the pre-Volcker period such that its conduct did not lead to indeterminacy. One reason for drifting inflation target during the Great Inflation period could be the central bank's changing beliefs about this inflation-output gap trade-off. As argued by Sargent (1999), Cogley and Sargent (2005), Primiceri (2006) and Sargent, Williams and Zha (2006), the Federal Reserve adjusted its inflation target as it learned about the structure of the economy.

[5] Arias, Ascari, Branzoli and Castelnuovo (2017) corroborate these findings by revisiting the relation between the sytematic component of monetary policy, trend inflation and determinacy within a medium-scale DSGE model. However, due to the complexities arising from the medium-scale nature of their model, they estimate the model over the period 1984:I - 2008:II focusing on determinacy alone.

The next section sketches the model and its solution. Section 3 presents the econometric strategy while Section 4 documents the estimation results. Section 5 assesses the drivers of the Great Moderation and conducts counterfactual simulations. Robustness checks are performed in Section 6. Section 7 concludes.

2 Model

The estimation is based on a version of Ascari and Sbordone's (2014) Generalized New Keynesian (GNK) model.[6] The model economy consists of an inter-temporal Euler equation obtained from the household's optimal choice of consumption and bond holdings, a discrete-time staggered price-setting model of Calvo (1983) that features a positive steady state trend inflation, and a Taylor rule that characterizes monetary policy. As discussed earlier, allowing for positive steady state inflation is important for the following reasons: (i) positive trend inflation makes price-setting firms more forward-looking which flattens the NKPC and makes the inflation rate less sensitive to current economic conditions; (ii) it alters the determinacy properties of the model; and (iii) trend inflation generates richer endogenous persistence of inflation and output even in the determinacy case. Unlike Ascari and Sbordone (2014), the paper assumes stochastic growth modelled as the technology level following a unit root process, replaces their labor supply disturbance by a discount factor shock as a stand-in for demand shock and introduces (external) habit formation in consumption to generate output persistence. In light of the result of Cogley and Sbordone (2008) regarding the lack of empirical support for intrinsic inertia in the GNK Phillips curve (GNKPC), the baseline model is estimated in the absence of rule-of-thumb price-setting. Finally, the Taylor rule involves responses to the inflation gap, the output gap and output growth and also allows for interest rate smoothing.

[6]Following Ascari and Sbordone (2014), we use the term GNK to refer to the New Keynesian model log-linearized around a positive inflation rate in the steady state.

2.1 The log-linearized model

The log-linearized equilibrium conditions are given by the following equations.[7]

$$\begin{aligned}\widehat{y}_t \;=\; & \left(\frac{h}{g+h}\right)[\widehat{y}_{t-1}-\widehat{g}_t]+\left(\frac{g}{g+h}\right)[E_t\widehat{y}_{t+1}+E_t\widehat{g}_{t+1}]-\left(\frac{g-h}{g+h}\right)[\widehat{r}_t-E_t\widehat{\pi}_{t+1}]\\ & +\left(\frac{g-h}{g+h}\right)\left[\widehat{d}_t-E_t\widehat{d}_{t+1}\right], \end{aligned} \tag{1}$$

$$\widehat{\pi}_t=\kappa E_t\widehat{\pi}_{t+1}+\vartheta\left[\varphi\widehat{s}_t+(1+\varphi)\widehat{y}_t\right]+\chi\left(\frac{h}{g-h}\right)[\widehat{y}_t-\widehat{y}_{t-1}+\widehat{g}_t]-\varpi E_t\widehat{\Psi}_{t+1}+\varpi\widehat{d}_t, \tag{2}$$

$$\widehat{\Psi}_t=(1-\xi\beta\pi^{\varepsilon})\left[\varphi\widehat{s}_t+(1+\varphi)\widehat{y}_t+\widehat{d}_t\right]+\xi\beta\pi^{\varepsilon}\left[E_t\widehat{\Psi}_{t+1}+\varepsilon E_t\widehat{\pi}_{t+1}\right], \tag{3}$$

$$\widehat{s}_t=\varepsilon\xi\pi^{\varepsilon-1}\left(\frac{\pi-1}{1-\xi\pi^{\varepsilon-1}}\right)\widehat{\pi}_t+\xi\pi^{\varepsilon}\widehat{s}_{t-1}, \tag{4}$$

$$\widehat{r}_t=\rho_r\widehat{r}_{t-1}+(1-\rho_r)\left\{\psi_\pi\left(\widehat{\pi}_t-\widehat{\pi}^*_t\right)+\psi_x\widehat{x}_t+\psi_{\Delta y}\left(\widehat{y}_t-\widehat{y}_{t-1}+\widehat{g}_t\right)\right\}+\epsilon_{r,t}, \tag{5}$$

$$\widehat{x}_t=\widehat{y}_t-\widehat{y}^n_t, \tag{6}$$

$$\widehat{y}^n_t=\frac{h}{g(1+\varphi)-h\varphi}\left(\widehat{y}^n_{t-1}-\widehat{g}_t\right), \tag{7}$$

where $\kappa\equiv\beta\left[1+\varepsilon(\pi-1)(1-\xi\pi^{\varepsilon-1})\right]$, $\vartheta\equiv(1-\xi\pi^{\varepsilon-1})(1-\xi\beta\pi^{\varepsilon})/\xi\pi^{\varepsilon-1}$, $\chi\equiv(1-\xi\pi^{\varepsilon-1})(1-\xi\beta\pi^{\varepsilon-1})/\xi\pi^{\varepsilon-1}$ and $\varpi\equiv\beta(1-\pi)(1-\xi\pi^{\varepsilon-1})$. Hatted variables denote log-deviations from steady state. Here y_t and y^n_t stand for de-trended output and natural level of output respectively, x_t is the output gap, r_t denotes the nominal interest rate, π_t symbolizes inflation, π^*_t represents the Federal Reserve's time-varying inflation target, Ψ_t is an endogenous auxiliary variable, s_t denotes the resource cost due to relative price dispersion and E_t represents the expectations operator. Eq. (1) is the dynamic IS relation reflecting an Euler equation where $h\in[0,1]$ represents the degree of habit persistence and g stands for the steady state gross rate of technological

[7] A full description of the model is delegated to the Appendix.

progress which is also equal to the steady state balanced growth rate. Eq. (2) and (3) represent the GNK Phillips curve where $\beta \in (0,1)$ is the subjective discount factor, $\xi \in [0,1)$ is the fraction of firms whose prices remain unchanged from previous period, π is the steady state gross inflation rate or trend inflation, $\varepsilon > 1$ is the price elasticity of demand, and φ is the inverse elasticity of labor supply. Eq. (2) boils down to a standard NKPC when trend inflation is zero (i.e. $\pi = 1$) and this assumption also implies that $\Psi_t = 0$. Eq. (4) is a recursive log-linearized expression for the price dispersion measure under Calvo pricing mechanism. Eq. (5) represents monetary policy, i.e. a Taylor-type rule in which $\psi_\pi, \psi_x, \psi_{\Delta y}, \rho_r$ are chosen by the central bank and echo its responsiveness to the inflation gap, the output gap, output growth and the degree of inertia in interest rate setting respectively. The term $\epsilon_{r,t}$ is an exogenous transitory monetary policy shock whose standard deviation is given by σ_r. Eq. (6) is the definition of the output gap while the law of motion for the natural level of output is given by Eq. (7).

The remaining fundamental disturbances involve a preference shock d_t, a shock to the growth rate of technology g_t, and an inflation target shock π_t^*. Each of these three shocks follow $AR(1)$ processes:

$$\log d_t = (1 - \rho_d) \log d + \rho_d \log d_{t-1} + \epsilon_{d,t} \qquad 0 < \rho_d < 1,$$

$$g_t = \left(1 - \rho_g\right) g + \rho_g g_{t-1} + \epsilon_{g,t} \qquad 0 < \rho_g < 1, \tag{8}$$

and

$$\log \pi_t^* = (1 - \rho_{\pi^*})\, \pi + \rho_{\pi^*} \log \pi_{t-1}^* + \epsilon_{\pi^*,t} \qquad 0 < \rho_{\pi^*} < 1,$$

where the standard deviations of the innovations $\epsilon_{d,t}$, $\epsilon_{g,t}$ and $\epsilon_{\pi^*,t}$ are denoted by σ_d , σ_g and σ_{π^*} respectively.

Under a fixed inflation target, the paper assumes that the policy rules becomes

$$\widehat{r}_t = \rho_r \widehat{r}_{t-1} + (1 - \rho_r) \left\{ \psi_\pi \widehat{\pi}_t + \psi_x \widehat{x}_t + \psi_{\Delta y} \left(\widehat{y}_t - \widehat{y}_{t-1} + \widehat{g}_t \right) \right\} + \epsilon_{r,t}, \tag{9}$$

where the central bank's target is now equal to steady-state or trend inflation π.

2.2 Rational expectations solution under indeterminacy

To solve the model, the paper applies the method proposed by Lubik and Schorfheide (2003). The linear rational expectations (LRE) system can be compactly written as

$$A_0(\theta)\varrho_t = A_1(\theta)\varrho_{t-1} + B(\theta)\epsilon_t + C(\theta)\eta_t, \tag{10}$$

where ϱ_t, ϵ_t and η_t denote the vector of endogenous variables, fundamental shocks and one-step ahead expectation errors respectively and $A_0(\theta)$, $A_1(\theta)$, $B(\theta)$ and $C(\theta)$ are appropriately defined coefficient matrices. From a methodological perspective, the solution of Lubik and Schorfheide (2003) follows from Sims (2002). However, it has the added advantage of being general and explicit in dealing with expectation errors since it makes the solution suitable for solving and estimating models which feature multiple equilibria. In particular, under indeterminacy, η_t becomes a linear function of the fundamental shocks and purely extrinsic sunspot disturbances, ζ_t. Hence, the full set of solutions to the LRE model entails

$$\varrho_t = \Phi(\theta)\varrho_{t-1} + \Phi_\epsilon(\theta, \widetilde{M})\epsilon_t + \Phi_\zeta(\theta)\zeta_t, \tag{11}$$

where $\Phi(\theta)$, $\Phi_\epsilon(\theta, \widetilde{M})$ and $\Phi_\zeta(\theta)$[8] are the coefficient matrices.[9] The sunspot shock satisfies $\zeta_t \sim i.i.d.\ \mathsf{N}(0, \sigma_\zeta^2)$. Accordingly, indeterminacy can manifest itself in one of two different ways: (i) purely extrinsic non-fundamental disturbances can affect the model dynamics through endogenous expectation errors; and (ii) the propagation of fundamental shocks cannot be uniquely pinned down and the multiplicity of equilibria affecting this propagation mechanism is captured by the arbitrary matrix $\widetilde{M}$.

Following the methodology proposed by Lubik and Schorfheide (2004), $\widetilde{M}$ is replaced with $M^*(\theta) + M$ and the prior mean for M is set equal to zero. The particular solution employed selects $M^*(\theta)$ by using a least squares criterion to minimize the distance between the impact response of the endogenous variables to fundamental shocks, $\partial\varrho_t/\partial\epsilon_t'$, at the boundary between the determinacy and the indeterminacy region.[10] Finding an analytical solution to the boundary in this model is infeasible

[8] Lubik and Schorfheide (2003) express this term as $\Phi_\zeta(\theta, M_\zeta)$, where M_ζ is an arbitrary matrix. For identification purpose, the paper imposes their normalization such that $M_\zeta = I$.

[9] Under determinacy, the solution boils down to $\varrho_t = \Phi^D(\theta)\varrho_{t-1} + \Phi_\epsilon^D(\theta)\epsilon_t$.

[10] This methodology has been used in previous studies, such as Benati and Surico (2009), Doko Tchatoka et al (2017) and Hirose (2007, 2008, 2013, 2014).

and hence, following Justiniano and Primiceri (2008) and Hirose (2014), the paper resorts to a numerical procedure to find the boundary by perturbing the parameter ψ_π in the monetary policy rule.

2.3 Equilibrium determinacy and trend inflation

Before moving onto the empirical investigation, this subsection revisits how allowing for trend inflation affects the determinacy properties of the model. Ascari and Ropele (2009) and Ascari and Sbordone (2014) show that trend inflation makes price-setting firms more forward-looking thereby flattening the NKPC and widening the indeterminacy region. Figure 1 documents how trend inflation affects the determinacy region. Since analytical solution is infeasible unless one assumes indivisible labor, the determinacy results shown here are numerical.[11]

The determinacy region shrinks with trend inflation as documented by Ascari and Ropele (2009) and Ascari and Sbordone (2014).[12] In other words, a stronger response to the inflation gap together with a weaker response to the output gap is required to generate determinacy at higher levels of trend inflation. Therefore, monetary policy should respond more to the inflation gap and less to the output gap in order to stabilize inflation expectations. Moreover, in the case of positive trend inflation, Coibion and Gorodnichenko (2011) show that interest rate smoothing and stronger response to output growth, instead of the output gap, are stabilizing and widen the determinacy region.

3 Econometric strategy

3.1 Bayesian estimation with Sequential Monte Carlo

The paper uses Bayesian techniques for estimating the parameters of the model and tests for indeterminacy using posterior model probabilities. It employs the Sequential

[11] The parameter values and the policy rule used in the numerical computation are similar to Ascari and Sbordone (2014). In particular, $\beta = 0.99$, $\varepsilon = 11$, $\xi = 0.75$, $h = 0$ implying no habit formation in consumption, and $g = 1.005$ such that the steady state growth rate of real per capita GDP is 2 per cent per year. The policy rule is a simple Taylor rule of the form $r_t = \psi_\pi \pi_t + \psi_x x_t$.

[12] The figure is the same as Figure 4 in Ascari and Ropele (2009) and Figure 11 in Ascari and Sbordone (2014).

Monte Carlo (SMC) algorithm proposed by Herbst and Schorfheide (2014, 2015) which is particularly suitable for irregular and non-elliptical posterior distributions.[13]

First, priors are described by a density function of the form

$$p(\theta_S|S), \tag{12}$$

where $S \in \{D, I\}$, D and I stand for determinacy and indeterminacy respectively, θ_S represents the parameters of the model S and $p(.)$ stands for the probability density function. Next, the likelihood function, $p(X_T|\theta_S, S)$, describes the density of the observed data where X_T are the observations through to period T. Following Bayes theorem, the posterior density is constructed as a combination of the prior density and the likelihood function:

$$p(\theta_S|X_T, S) = \frac{p(X_T|\theta_S, S)p(\theta_S|S)}{p(X_T|S)}, \tag{13}$$

where $p(X_T|S)$ is the marginal data density conditional on the model which is given by

$$p(X_T|S) = \int_{\theta_S} p(X_T|\theta_S, S)p(\theta_S|S)d\theta_S. \tag{14}$$

A difficulty in the methodology of Lubik and Schorfheide (2003) is that the likelihood function of the model is possibly discontinuous at the boundary between the determinacy and indeterminacy region. As noted before, Lubik and Schorfheide (2004) propose to select $M^*(\theta)$ such that the impulse responses of the endogenous variables to fundamental shocks are continuous at the boundary. To test for indeterminacy, they then estimate the model twice, first under determinacy and then under indeterminacy and compare the fit of the model under these alternative specifications. However, an importance sampling algorithm like SMC can use a single chain to explore the entire parameter space. Hence, to take full advantage of the algorithm, the paper estimates the model simultaneously over both determinate and indeterminate parameter space.[14] The likelihood function is then given by

[13] See Hirose, Kurozumi and Van Zandweghe (2017) who were the first to apply Bayesian estimation using the SMC algorithm to test for indeterminacy following Lubik and Schorfheide's (2003, 2004) methodology.

[14] Hirose, Kurozumi and Van Zandweghe (2017) also use SMC to estimate their model over the

$$p(X_T|\theta_S,S) = 1\{\theta_S \in \Theta^D\}p^D(X_T|\theta_D,D) + 1\{\theta_S \in \Theta^I\}p^I(X_T|\theta_I,I), \qquad (15)$$

where Θ^D, Θ^I are the determinacy and indeterminacy regions of the parameter space, $1\{\theta_S \in \Theta^S\}$ is the indicator function that equals 1 if $\theta_S \in \Theta^S$ and zero otherwise, and $p^D(X_T|\theta_D,D)$, $p^I(X_T|\theta_I,I)$ are the likelihood functions under determinacy and indeterminacy respectively. Following Herbst and Schorfheide (2014, 2015), the paper builds a particle approximation of the posterior distribution through tempering the likelihood. A sequence of tempered posteriors is defined as

$$\Pi_n(\theta_S) = \frac{[p(X_T|\theta_S,S)]^{\phi_n} p(\theta_S|S)}{\int_{\theta_S}[p(X_T|\theta_S,S)]^{\phi_n} p(\theta_S|S)d\theta_S}, \qquad (16)$$

where ϕ_n is the tempering schedule that slowly increases from zero to one.

The algorithm generates weighted draws from the sequence of posteriors $\{\Pi_n(\theta_S)\}_{n=1}^{N_\phi}$, where N_ϕ is the number of stages. At any stage, the posterior distribution is represented by a swarm of particles $\left\{\theta_n^i, W_n^i\right\}_{i=1}^N$, where W_n^i is the weight associated with θ_n^i and N denotes the number of particles. The algorithm has three main steps. First, in the *correction* step, the particles are re-weighted to reflect the density in iteration n. Next, in the *selection* step, any particle degeneracy is eliminated by resampling the particles. Finally, in the *mutation* step, the particles are propagated forward using a Markov transition kernel to adapt to the current bridge density.

In the first stage, i.e. when $n = 1$, ϕ_1 is zero. Hence, the prior density serves as an efficient proposal density for $\Pi_1(\theta_S)$. That is, the algorithm is initialized by drawing the initial particles from the prior. Likewise, the idea is that the density of $\Pi_n(\theta_S)$ may be a good proposal density for $\Pi_{n+1}(\theta_S)$.

Number of particles, Number of stages, Tempering schedule The tempering schedule is a sequence that slowly increases from zero to one and is determined by $\phi_n = \left(\frac{n-1}{N_\phi - 1}\right)^\tau$ where τ controls the shape of the schedule. The tuning parameters N, N_ϕ and τ are fixed ex ante. The estimation uses $N = 10000$ particles and $N_\phi = 200$ stages. The parameter that controls the tempering schedule, τ, is set at 2 following

entire parameter space. For an alternative approach that allows estimation over the entire parameter space while using standard packages like Dynare and standard estimation algorithms see Bianchi and Nicolò (2017).

Herbst and Schorfheide (2015).

Resampling Resampling is necessary to avoid particle degeneracy. A rule-of-thumb measure of this degeneracy, proposed by Liu and Chen (1998), is given by the reciprocal of the uncentered variance of the particles and is called the effective sample size (ESS). The estimation employs systematic resampling whenever $ESS_n < \frac{N}{2}$.

Mutation Finally, one step of a single-block Random-Walk Metropolis Hastings (RWMH) algorithm is used to propagate the particles forward.

The SMC algorithm has several practical advantages as discussed below. First, it allows estimation over the entire parameter space. Lubik and Schorfheide (2004) show that the shape of the likelihood function may be different under indeterminacy. This then makes MCMC-based inference complicated because it is less suited to approximating the posterior when the latter is not well shaped or has multiple modes. In order to deal with this issue, Lubik and Schorfheide (2004) estimate the model over determinacy and indeterminacy separately. However, SMC methods are more appropriate when the posterior distribution displays irregular patterns as also pointed out by Ascari, Bonomolo and Lopes (2019) in a similar context.

Second, the algorithm does not require one to find the mode of the posterior distribution.[15] Computing the posterior mode when allowing for indeterminacy can be computationally cumbersome in practice because of the irregular shape of the likelihood function. The SMC algorithm is an "importance sampling algorithm", i.e. instead of attempting to sample directly from the posterior, the algorithm draws from a different tractable distribution, commonly referred to as an importance distribution. The re-weighting of a particle from the importance distribution gives the particle the status of an actual draw from the posterior distribution. Here, the initial particles are drawn from the prior, i.e. the prior serves as the initial proposal density for this tractable distribution. In subsequent steps, the density in the current stage of the algorithm, i.e. $\Pi_n(\theta_S)$, serves as a proposal density for the next stage.

[15] Standard methods like Metropolis-Hastings algorithm constructs a Gaussian approximation around the posterior mode and uses a scaled version of the asymptotic covariance matrix (taken to be the inverse of the Hessian computed at the mode) as the covariance matrix for the proposal distribution.

Finally, an additional advantage on the computational front is parallelization. The particle mutation phase is ideally suited for parallelization because the propagation steps are independent across particles and do not require any communication across processors. For models allowing for indeterminacy, the evaluation of the likelihood function is computationally very costly because it requires to run a model solution procedure that bridges the gap between the impact response of the variables to fundamental shocks at the boundary between determinacy and indetermiancy by picking $M^*(\theta)$. Whenever analytical solution to the boundary is not available, this requires numerically tracing the boundary for every draws at every stage. Thus, gains from parallelization can be quite large.

3.2 Data

The paper employs three U.S. quarterly time series: per capita real GDP growth rate $100\Delta \log Y_t$, quarterly growth rate of the GDP deflator $100\Delta \log P_t$, and the Federal Funds rate $100 \log R_t$. The model is estimated over two sample periods. The first sample, 1966:I - 1979:II, corresponds to the Great Inflation period. The second one, 1984:I - 2008:II, corresponds to the Great Moderation period that is characterized by dramatically milder macroeconomic volatilities. The measurement equations relating the relevant elements of ϱ_t to the three observables are given by

$$\begin{bmatrix} 100\Delta \log Y_t \\ 100\Delta \log P_t \\ 100 \log R_t \end{bmatrix} = \begin{bmatrix} 100(g-1) \\ 100(\pi-1) \\ 100(r-1) \end{bmatrix} + \begin{bmatrix} \widehat{y}_t - \widehat{y}_{t-1} + \widehat{g}_t \\ \widehat{\pi}_t \\ \widehat{r}_t \end{bmatrix}. \tag{17}$$

3.3 Calibrations and prior distributions

The discount factor β is set to 0.99, the steady-state markup to ten percent (i.e. $\varepsilon = 11$), and the inverse of the labor-supply elasticity to one. The remaining parameters are estimated. Table 1 summarizes the specification of the prior distributions. The prior for the inflation coefficient ψ_π follows a gamma distribution centered at 1.10 with a standard deviation of 0.50 while the response coefficient to the output gap and output growth are centered at 0.125 with standard deviation 0.10. The paper uses Beta distributions with mean 0.50 for the smoothing coefficient ρ_r, the Calvo probability ξ, and habit persistence in consumption h, and 0.70 for the persistence of the discount factor shock. The autoregressive parameter of the TFP shock follows a Beta distribution centered at 0.40 since this process already includes a unit-root while that of the inflation target shock is assumed to be highly persistent and is centered at 0.95.[16] The priors for the quarterly steady state rates of output growth, inflation and interest rate, denoted by g^*, π^* and r^*, respectively are distributed around their averages over the period 1966:I-2008:II.

For the shocks, the prior distributions for all but one follow an inverse-gamma distribution with mean 0.60 and standard deviation 0.20. The exception is the standard deviation of the innovation to the inflation target shock which is an important parameter in the analysis. Following Cogley, Primiceri and Sargent (2010), the paper adopts a weakly informative uniform prior on $(0, 0.15)$ for this parameter.

Finally, in line with Lubik and Schorfheide (2004), the coefficients M follow standard normal distributions. Hence, the prior is centered around the baseline solution of Lubik and Schorfheide (2004). Importantly, the choice of the priors leads to a prior predictive probability of determinacy of 0.498, which is quite even and suggests no prior bias toward either determinacy or indeterminacy.

4 Estimation results

4.1 Model comparison

Table 2 collects the results for the empirical performance of the model with fixed versus time-varying inflation target. To assess the quality of the model's fit to the data, log marginal data densities and posterior model probabilities are reported. The posterior probability of determinacy is calculated as the fraction of the draws in the final stage of the SMC algorithm that generate determinate equilibrium. The SMC algorithm delivers a numerical appoximation of the marginal data density as a by-product in the *correction* step which is given by

[16] The paper also estimates the model when the persistence of the inflation target shock is calibrated instead as in Cogley, Primiceri and Sargent (2010). The results reported below remain robust as shown in Section 6.

$$p^{SMC}(X_T|S) = \prod_{n=1}^{N_\phi} \left(\frac{1}{N} \sum_{i=1}^{N} \widetilde{w}_n^i W_{n-1}^i \right),$$

where $\widetilde{w}_n^i$ is the incremental weight defined by

$$\widetilde{w}_n^i = [p(X|\theta_{n-1}^i, S)]^{\phi_n - \phi_{n-1}}.$$

and W_n^i are the normalized weights. Herbst and Schorfheide (2014,2015) show that the particle weights converge under suitable regularity conditions as follows:

$$\begin{aligned} \frac{1}{N} \sum_{i=1}^{N} \widetilde{w}_n^i W_{n-1}^i \quad &\Longrightarrow \quad \int [p(X|\theta_s, S]^{\phi_n - \phi_{n-1}} \frac{[p(X|\theta_s, S]^{\phi_{n-1}} p(\theta_S|S)}{\int [p(X|\theta_s, S]^{\phi_{n-1}} p(\theta_S|S) d\theta_S} d\theta_S \\ &= \quad \frac{\int [p(X|\theta_s, S]^{\phi_n} p(\theta_S|S) d\theta_S}{\int [p(X|\theta_s, S]^{\phi_{n-1}} p(\theta_S|S) d\theta_S}. \end{aligned}$$

Table 2 shows that in case of fixed inflation target, the evidence for indeterminacy for the pre-Volcker period is weak while determinacy unambiguously prevails after 1984. The fact that determinacy cannot be ruled out in the pre-Volcker period even when inflation target is fixed is *a priori* unexpected given the empirical findings of Lubik and Schorfheide (2004) and Hirose, Kurozumi and Van Zandweghe (2017) who show that the pre-Volcker period is characterized by indeterminacy. In fact, upon further investigation, the paper finds that when using CPI to measure inflation instead of GDP deflator (as in Lubik and Schorfheide) or assuming firm-specific labor instead of homogenous labor (as in Hirose, Kurozumi and Van Zandweghe), strong evidence for indeterminacy re-emerges and results are documented in Section 6 of the paper.

In contrast, when allowing for time variation in the inflation target pursued by the Federal Reserve in the pre-Volcker period, the mass of the posterior distribution falls in the determinacy region of the parameter space and this finding remains robust to various perturbations of the baseline model.[17] Phrased alternatively, it suggests that

[17] In fact, when calibrating the persistence of the inflation target process as in Cogley, Primiceri and Sargent (2010), the posterior probability of determinacy turns out to be 0.99 (see Section 6).

monetary policy was unlikely to be de-stabilizing during the Great Inflation period since the possibility that the Federal Reserve responded aggresively to inflation cannot be empirically ruled out.[18]

In terms of posterior odds ratio, the marginal likelihood points toward the empirical superiority of the specification featuring time variation in the inflation target. The Bayes factor involving fixed versus time-varying target reads about 36 and 44 for the pre-Volcker and post-1984 sample periods respectively. Hence, this result points toward a "strong" evidence in favor of the model where the Federal Reserve follows a time-varying inflation target.[19]

4.2 Parameter estimates

Table 1 reports the posterior means and the 90% highest posterior density intervals based on 10000 particles from the final stage in the SMC algorithm under time-varying inflation target.[20] As seen in the table, the Taylor rule's response to the inflation gap is strongly active in the pre-1979 period. In fact, the point estimate is close to two which justifies why the posterior favors determinacy under time-varying target. Moving across the sample, the policy responses to the inflation gap and output growth more than doubled while trend inflation fell considerably by almost a half, which are in line with the findings of Coibion and Gorodnichenko (2011) and Hirose, Kurozumi and Van Zandweghe (2017). Moreover, like Cogley, Primiceri and Sargent (2010), the innovation variance of the two shocks, $\epsilon_{\pi^*,t}$ and $\epsilon_{r,t}$, declined as well. According to the posterior mean estimates, the innovation variance fell from 0.08 to 0.04 for the inflation target shock, and from 0.38 to 0.21 for the policy-rate shock. However, unlike Cogley, Primiceri and Sargent (2010) who find a moderate increase in the responsiveness to the inflation gap, this paper finds quite a substantial increase across the two periods. This suggests that both the systematic response to the inflation gap and better anchoring of the inflation target have played a key role in the decline in inflation volatility, as shown later.

[18] The post-1984 period remain explicitly characterized by determinacy.

[19] According to Kass and Raftery (1995), a Bayes factor between 1 and 3 is "not worth more than a bare mention", between 3 and 20 suggests a "positive" evidence in favor of one of the two models, between 20 and 150 suggests a "strong" evidence against it, and larger than 150 "very strong" evidence.

[20] The appendix reports parameter estimates under fixed target.

Among the non-policy shocks, there is an increase in the persistence and volatility of the discount factor shock, a finding shared with Hirose, Kurozumi and Van Zandweghe (2017). Finally, there is a decline in the volatility of technology shocks, which is in line with Lubik and Schorfheide (2004), Leduc and Sill (2007) and Smets and Wouters (2007).

4.3 Federal Reserve's inflation target

Before moving on to study the drivers of the Great Moderation, this section looks at the model-implied evolution of the Federal Reserve's inflation target. Here, the paper employs the Kalman smoother to obtain ex-post estimates of π_t^* based on the observations that are included in the construction of the likelihood function. Figure 2 plots the smoothed estimates of the latent inflation target process (computed at the posterior mean) on top of actual annualized quarterly inflation of the GDP implicit price deflator. As seen in the figure, inflation target began rising in the mid-1960s and jumped above 6% in the aftermath of the 1973 oil crisis. Subsequently, it dropped significantly during the Volcker-disinflation period and somewhat settled around 2.5% since the mid-1980s.

How does the implicit inflation target compare with the evidence in the literature? Figure 3 compares the estimate with a selection of other proposed measures: Kozicki and Tinsley (2005), Ireland (2007), Leigh (2008), Cogley, Primiceri and Sargent (2010), Aruoba and Schorfheide (2011), and Castelnuovo, Greco and Raggi (2014).[21] Each panel plots GDP deflator inflation rate as well.

Several findings arise. First of all, there is a notable difference between the estimated target and that of Kozicki and Tinsley (2005). The authors estimate a VAR model allowing for shifts in the inflation target and imperfect policy credibility, defined by differences between the perceived and the actual inflation target. The disparity may be due to their imperfect credibility and learning mechanism whereby the private sector cannot perfectly distinguish between permanent target shocks and transitory policy shocks.

As regards the estimates of Cogley, Primiceri and Sargent (2010), the co-movement

[21] Sources: Kozicki and Tinsley (2005), Ireland (2007), Leigh (2008), Cogley, Primiceri and Sargent (2010) and Castelnuovo, Greco and Raggi (2014) - original files provided by the authors; Aruoba and Schorfheide (2011) - *American Economic Review* (website).

between the two series is very similar: with a correlation of 0.97 and 0.83 for the pre-Volcker and the post-1984 sub-sample respectively.[22] However, the fourth panel in Figure 3 documents clear evidence of a gap between the two inflation target series and points to the essence of trend inflation. While Cogley, Primiceri and Sargent (2010) leave the first moment of observed inflation unmodelled, the current paper overcomes this by explicitly modelling inflation's long-run value (by log-linearizing around a positive steady state) on top of its dynamics.

The implicit inflation target is also close to that of Ireland (2007)[23], Aruoba and Schorfheide (2011) and Castelnuovo, Greco and Raggi (2014), particularly for the pre-Volcker period for which the correlation reads 0.99, 0.98 and 0.97 respectively. However, the estimated target turns out to be smoother and somewhat different than theirs in the second sub-sample. In particular, since the early 2000s, there is a clear divergence. During this period, the estimate turns out to be higher than the alternative measures as well as actual inflation itself. This finding is intuitive as it captures the fear of deflation among policymakers at that time which led to extra easy monetary policy and a lowering of the Federal Funds rate.[24] As noted by Eggertsson and Woodford (2003), keeping interest rates low for an extended period of time is equivalent to a rise in the inflation target.

The estimated target is very similar to that of Leigh (2008) who uses a time-varying parameter Taylor rule and the Kalman filter focusing on the post-1980 sample period alone.[25] As in Leigh (2008, p. 2022-23), the time-varying implicit inflation target for the post-1984 sub-sample can be divided into separate chunks: (i) 'the opportunistic approach to disinflation' - a period covering from mid-1980s to mid-1990s - during which, according to Orphanides and Wilcox (2002), the Fed did not take deliberate anti-inflation action but rather waited for external circumstances to

[22]The numbers are conditional on overlapping periods, i.e. 1966:I - 1979:II for the first sub-sample and 1984:I - 2006:IV for the second sub-sample.

[23]Ireland (2007) studies different inflation target processes, including some which allow for a systematic reaction to structural shocks hitting the economy. The second panel in Figure 3 plots the one labelled as "Federal Reserve's Target as Implied by the Constrained Model with an Exogenous Inflation Target" (see Figure 5, page 1869 in the published paper).

[24]See Bernanke (2002, 2010) and Bernanke and Reinhart (2004).

[25]Leigh (2008) focuses on estimating the implicit target based on both core PCE inflation and GDP/GNP implicit deflator inflation. The third panel in Figure 3 plots the one labelled as "Estimate of GDP/GNP deflator target (real-time forecasts)" (see Figure 5, page 2028 in the published paper).

deliver the desired reduction in inflation; (ii) 'the low-inflation equilibrium' in the late 1990s; and (iii) 'the deflation scare' in the early 2000s during which the inflation target rose above actual inflation.[26]

The comparison above with respect to other inflation target estimates in the literature suggests that the paper's estimated target is empirically plausible. However, as a note of caution, the differences could also be due to differences in investigated samples, data transformation, structure imposed on the data and vintage of the data.

5 What explains the Great Moderation in the U.S.?

What are the reasons behind the decline in macroeconomic volatility? To answer this question, the paper conducts counterfactual exercises following Castelnuovo (2010) and Cogley, Primiceri and Sargent (2010). The objective here is to disentangle the role played by good policy and good luck.

First, Table 3 summarizes the model's implications for the volatility of inflation and output growth calculated at the posterior mean of the model parameters. First and foremost, the estimated model is able to capture both the level and the observed drop in macroeconomic volatility quite well. The paper finds a fall of inflation and output growth volatility of 61% and 44% respectively. The data used in estimation implies a fall of the standard deviation of output growth of about 48% and that of inflation of about 57%. The magnitudes of the drop in volatility are comparable to those reported in the literature. For instance, Justiniano and Primiceri (2008) report a fall of output growth variability of about 25% and a drop of inflation variability of about 75%. The numbers in Smets and Wouters (2007) read 35% and 58% respectively.

5.1 Counterfactuals

Next, the paper conducts counterfactual exercises designed to disentangle the role played by 'good policy' and 'good luck' in explaining the Great Moderation. The exercices closely follow the counterfactual scenarios studied in Castelnuovo (2010) and Cogley, Primiceri and Sargent (2010). Following these authors, the paper divides the

[26] For alternative interpretation of monetary policy during the 2000s, see Groshenny (2013), Belongia and Ireland (2016) and Doko Tchatoka et al (2017).

experiments into two broad categories. First, it combines the parameters pertaining to the Taylor rule, i.e. ψ_π, ψ_x, $\psi_{\Delta y}$, ρ_r, ρ_{π^*}, π^*, σ_r, σ_{π^*}, of the post-1984 sub-sample with the private sector parameters of the pre-1979 period which is called 'Policy 2, Private 1'. This exercise is designed to capture the role of better monetary policy in reducing the volatility of inflation and output growth. In the second category, it combines private sector parameters of the second sub-sample with the policy parameters of the first. This scenario, labelled 'Policy 1, Private 2', is designed to study the contribution of non-policy factors. The other scenarios 'plant' in the first subsample only selected parts of the second subsample.

Table 4 reports the counterfactuals. The results reported are percentage deviations with respect to the pre-Volcker scenario. First of all, the decline in inflation volatility is driven by changes in monetary policy (Policy 2, Private 1). However, monetary policy alone cannot explain the decline in output growth variability, a finding shared with Leduc and Sill (2007) and Castelnuovo (2010). As in Leduc and Sill (2007), the decline in output growth variability is mainly explained by the reduction in the volatility of technology shocks. Hence, both 'good policy' and 'good luck' are jointly required to explain the reduction in inflation and output growth volatility.

Digging further, the paper finds that both stronger response to the inflation gap (ψ_π) and better anchored inflation objective, i.e. a reduction in the volatility of inflation target shocks (σ_{π^*}), are key ingredients in the reduction of inflation volatility. This outcome stands in contrast to Castelnuovo (2010) and Cogley, Primiceri and Sargent (2010) who find that a stronger response to the inflation gap during the Great Moderation period only plays a minor role. Interestingly, the decline in the Federal Reserve's long-run inflation target (π^*) plays a negligible role.

6 Sensitivity analysis

Lastly, the paper conducts several robustness checks along the following dimensions: (i) alternative measure of inflation as observable in the estimation, (ii) alternative calibration for the degree of price stickiness and the persistence of the inflation target process, (iii) firm-specific labor, (iv) estimating the NK model of Lubik and Schorfheide (2004) while allowing for time-varying inflation target. Table 5 summarizes the log-data densities and posterior model probabilities.[27] The top half of the table shows results for the Great Inflation period while the bottom half shows results for the Great Moderation period.

6.1 Alternative measure of inflation

The baseline models are estimated using GDP deflator as a measure of inflation. Time-varying inflation target fits better and the posterior mass is concentrated in the determinacy region. However, one unexpected finding, given the results of Lubik and Schorfheide (2004), is that one cannot rule out determinacy in the pre-Volcker period even when inflation target is fixed. It turns out that this is an artefact of the model with homogenous labor when using GDP deflator to measure inflation. Instead, when using CPI to measure inflation as in Lubik and Schorfheide (2004), a significant portion of the posterior distribution (three-fourth of the posterior draws from the final stage of SMC) lies in the indeterminacy region when inflation target is fixed. Nevertheless, time-varying inflation target continues to fit better in the pre-Volcker period and as a result determinacy prevails as before. One difference with respect to the baseline results is that the model with fixed target fits better in the post-1984 period, implying a larger role played by the decline in the variability of inflation target in driving the reduction in inflation volatility.

6.2 Alternative calibration

Looking at the posterior distributions of the degree of price stickiness ξ and the persistence of the inflation target process ρ_{π^*} in Table 1, the posteriors look similar to the priors. Hence, it seems the data might not be sufficiently informative to pin down those parameters. To address this issue, the paper calibrates both ξ and ρ_{π^*} while estimating the remaining parameters in the model. First, the degree of price stickiness is set to 0.75, which is the typical value used in calibration studies and the value used in Ascari and Sbordone (2014).[28] A higher degree of price rigidity makes

[27] The Appendix reports the parameter estimates.

[28] The empirical literature reports different degree of price stickiness. For instance, Bils and Klenow (2004) find that firms update prices every four to five months corresponding to $\xi = 0.40$, while Nakamura and Steinsson (2008) find longer duration ranging between 8 and 11 months on average which corresponds to $\xi = 0.70$.

it increasingly difficult to eliminate indeterminacy. This is because when firms reset prices in the Calvo model, the weight placed on future profits depends on how likely it is for a firm not to alter its price by that period. Hence, greater price stickiness will increase the sensitivity of reset prices to expectations of future macroeconomic variables. As a result, a higher degree of price stickiness will widen the indeterminacy region for a given level of trend inflation. In fact, setting ξ to 0.75 implies a prior predictive probability of determinacy of 0.27 such that *a priori* it is more likely for indeterminacy to prevail.[29] Second, following Cogley, Primiceri and Sargent (2010), ρ_{π^*} is set to 0.995. Alternatively, one may follow Ireland (2007) by assuming that the inflation target process has a unit-root. Instead, the paper follows Cogley, Primiceri and Sargent's (2010) calibration as they show that a unit-root inflation target process counterfactually implies low inflation-gap predictability, which is at odds with the VAR evidence in their paper. In the pre-Volcker period, the estimation finds that time-varying target continues to fit better and determinacy prevails despite the estimation being biased toward indeterminacy. However, in the post-1984 period, the model with fixed target fits better, again suggesting a larger role played by better anchored inflation target during the Great Moderation.

6.3 Firm-specific labor

The analysis so far has relied on a GNK model with homogenous labor following Ascari and Ropele (2009) and Ascari and Sbordone (2014). However, Kurozumi and Van Zandweghe (2017) show that a similar model with firm-specific labor leads to a distinct representation of inflation dynamics which makes it more susceptible to indeterminacy induced by higher trend inflation. First, firm-specific labor introduces strategic complementarity in price setting and as a result the GNKPC contains a flatter slope than in the model with homogenous labor. Therefore, inflation is less sensitive to output and so monetary policy is less capable of stabilizing inflation in the model with firm-specific labor. Second, the long-run inflation elasticity of output implied by the GNKPC is highly sensitive to trend inflation in the model with firm-specific labor.[30] Higher trend inflation lowers this elasticity and makes the long-run

[29] Recall that the prior predictive probability of determinacy in the benchmark analysis is 0.50, so that following the literature on testing for indeterminacy, the estimation is *a priori* unbiased.

[30] See Figure 2 of Kurozumi and Van Zandweghe (2017).

version of the Taylor principle more restrictive for the Taylor rule's coefficients on inflation and output. Therefore, a model with firm-specific labor in the presence of trend inflation is meant to work against the results documented in this paper. The paper conducts further investigation along this dimension and estimates a GNK model with positive trend inflation and firm-specific labor along the lines of Hirose, Kurozumi and Van Zandweghe (2017). In order to establish a valid comparison, it uses the exact same set of priors, observables and sample periods as they do.[31] However, to achieve identification between the inflation target process and the policy-rate shock, this paper assumes that the latter follows a transitory i.i.d. process while the former is a highly persistent AR(1) process following the literature.

In line with Hirose, Kurozumi and Van Zandweghe (2017), the pre-Volcker period is unambiguously characterized by indeterminacy while the post-1982 period is characterized by determinacy under the assumption of a fixed inflation target equal to trend inflation. However, when allowing for time-varying inflation target, determinacy prevails as before. In terms of the empirical fit of fixed versus time-varying target, it is comparable for the pre-Volcker period.[32] Given that the model with firm-specific labor is *a priori* expected to work against the baseline results, this set of findings somewhat mitigates, yet does not overturn, the key result. Despite the model being more prone to indeterminacy, the hypothesis that the inflation target has been drifting and as a consequence determinacy might have prevailed even in the pre-Volcker period is a possibility that cannot be empirically ruled out. In fact, Kurozumi (2016) shows that when the degree of price stickiness is endogenously determined in a Calvo model, indeterminacy caused by higher trend inflation is less likely. As mentioned above, a key factor for indeterminacy is the long-run inflation elasticity of output implied by the GNKPC. This elasticity declines substantially with higher trend inflation in the case of exogenously given price stickiness in a model with firm-specific labor and therefore widens the indeterminacy region. In contrast, with endogenous price stickiness this decline in the elasticity is muted because higher trend

[31] The pre-1979 period in Hirose, Kurozumi and Van Zandweghe (2017) is the same as in the current paper, i.e. 1966:I - 1979:II, while for the second sub-sample they use a slightly different period ranging from 1982:IV - 2008:IV. The choice of the second sub-sample is innocuous for the findings.

[32] In the post-1984 period, the model with fixed target fits better. Nonetheless, Table 2 shows that a model with homogenous labor and time-varying target fits much better.

inflation leads to a higher probability of price adjustment.

6.4 Lubik and Schorfheide (2004)

To bridge the gap with key studies in the literature, the paper also estimates a NK model with zero inflation in the steady state.[33] To be transparent, the paper estimates the specification of the NK model as in Lubik and Schorfheide (2004) using the exact same set of priors, observables and sample period as they do. In particular, the observables used in the estimation are HP-filtered output, annualized percentage change of CPI and the average Federal Funds Rate.[34] In line with Lubik and Schorfheide (2004), the paper considers the following sample periods: a pre-Volcker sample from 1960:I to 1979:II and a post-1982 sample from 1982:IV to 1997:IV that excludes the Volcker disinflation period. The findings read as follows.

First, in case of fixed (zero) inflation target, the pre-Volcker period is explicitly characterized by indeterminacy while determinacy prevails after 1982, basically replicating the findings of Lubik and Schorfheide (2004). The log data densities are very similar to those reported in Lubik and Schorfheide (2004)[35], though this paper uses a different algorithm to estimate the DSGE framework over the entire region of the parameter space (Lubik and Schorfheide do not use SMC and they split the estimation separately over determinacy and indeterminacy). Second, when allowing for a drifting inflation target, determinacy prevails in the pre-Volcker period in line with the benchmark results. Moreover, the model with time-varying inflation target under determinacy fits better than the one with fixed target under indeterminacy. Again, these results raise the possibility that the Federal Reserve pursued a time-varying inflation target and possibly did not violate the Taylor Principle and therefore did not generate indeterminacy in the pre-Volcker period.

[33] Hirose, Kurozumi and Van Zandweghe (2017) find that replacing the standard NKPC with a GNKPC alters the estimated cofficient values in the Taylor rule, in particular for the policy response to inflation.

[34] HP-filtered output displays a higher degree of persistence than output growth. Therefore, a model with passive monetary policy could be favoured due to the higher degree of endogenous persistence that arises under indeterminacy.

[35] See Table 2 in page 205 of their paper.

6.5 Further investigation

The paper conducts one further check. Recall that in the analysis so far trend inflation (or steady state inflation) and time-varying inflation target are distinct features (even though they are equal in the long-run). There are two counteracting effects at work here. On one hand, time-varying inflation target captures some of the low frequency movements so that there is less of a need for the richer dynamics characterized by the reduced form under indeterminacy. On the other hand, the presence of positive trend inflation widens the indeterminacy region of the parameter space. The paper finds that inflation target drifts higher during the Great Inflation period, making indeterminacy less likely, but trend inflation remains constant, so that indeterminacy region remains unaffected. However, this is not the case in Coibion and Gorodnichenko (2011), for example, where trend inflation increases during the Great Inflation period and expands the indeterminacy region. Ideally, one would estimate a model with time-varying steady state or trend inflation to address this issue, but then the estimation needs to take into account time-varying parameters (arising from a NKPC with drifting coefficients that depend on trend inflation). To partially address this issue without complicating the inference, the paper estimates the GNK model with firm-specific labor in the pre-Volcker period while calibrating steady state inflation to a higher level and allowing for time-varying inflation target.[36] In particular, trend inflation is set to 8 percent, which corresponds to the highest point estimate of Coibion and Gorodnichenko's (2011) time-varying trend inflation measure in the pre-Volcker period. The estimation continues to favor determinacy with a posterior probability of determinacy of 80 percent, while Coibion and Gorodnichenko (2011) find this probability to be zero with such a high level of trend inflation (see Figure 4 in their paper).

7 Conclusion

This paper estimates a New Keynesian model with positive trend inflation while allowing for indeterminacy and possible time variation in the inflation target pursued by the Federal Reserve. The paper finds that inflation target has been drifting over

[36] Firm-specific labor is assumed to maintain continuity with Coibion and Gorodnichenko (2011).

time and as a result determinacy cannot be ruled out in the pre-Volcker period. The intuition for this result can be understood as follows. First, the inflation gap that enters the Taylor rule when the inflation target is time-varying is less volatile than the inflation gap that keeps the target fixed. For a given historical path of the nominal interest rate, therefore, the response of the nominal rate to the inflation gap must be higher in the case of a time-varying target, which is more likely to lead to determinacy. Second, inflation target shocks induce persistent inflation dynamics that capture the low frequency component of inflation and as such the model does not need to resort to the richer endogenous dynamics that arise under indeterminacy to explain the Great Inflation episode. One implication of this finding is that self-fulfilling inflation expectations aka sunspots are not required to explain the high inflation out-turns during this episode.

The paper also looks at the drivers of the joint decline in inflation and output growth volatility. Counterfactual simulations suggest that both ‘good policy’ and ‘good luck’ are jointly required to explain the Great Moderation phenomenon. In particular, the decline in inflation volatility is driven by better monetary policy, both in terms of a more aggressive response to the inflation gap and a better anchored inflation target. In contrast, the reduction in output growth variability is mainly explained by the reduced volatility of technology shocks.

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Table 1: Prior and Posterior Distributions

Name	Density	Prior Mean (std. dev.)	$1966:I-1979:II$ Posterior Mean [90% interval]	$1984:I-2008:II$ Posterior Mean [90% interval]
ψ_π	Gamma	1.10 [0.50]	1.82 [1.08,2.49]	3.92 [2.97,4.72]
ψ_x	Gamma	0.125 [0.10]	0.19 [0.00,0.46]	0.15 [0.00,0.31]
$\psi_{\Delta y}$	Gamma	0.125 [0.10]	0.15 [0.01,0.27]	0.38 [0.06,0.60]
ρ_r	Beta	0.50 [0.20]	0.48 [0.26,0.80]	0.71 [0.58,0.80]
π^*	Normal	0.976 [0.50]	1.32 [1.02,1.66]	0.70 [0.52,0.87]
r^*	Gamma	1.612 [0.25]	1.59 [1.28,1.88]	1.47 [1.22,1.72]
g^*	Normal	0.50 [0.10]	0.52 [0.38,0.66]	0.51 [0.40,0.62]
h	Beta	0.50 [0.10]	0.43 [0.32,0.54]	0.40 [0.30,0.51]
ξ	Beta	0.50 [0.10]	0.50 [0.32,0.78]	0.49 [0.35,0.62]
ρ_d	Beta	0.70 [0.10]	0.72 [0.55,0.86]	0.92 [0.87,0.95]
ρ_g	Beta	0.40 [0.10]	0.24 [0.12,0.44]	0.17 [0.11,0.25]
ρ_{π^*}	Beta	0.95 [0.025]	0.95 [0.91,0.98]	0.95 [0.91,0.99]
σ_r	Inv-Gamma	0.60 [0.20]	0.38 [0.22,0.51]	0.21 [0.17,0.28]
σ_d	Inv-Gamma	0.60 [0.20]	1.03 [0.39,2.21]	1.67 [1.11,2.10]
σ_g	Inv-Gamma	0.60 [0.20]	1.19 [0.32,1.64]	0.71 [0.59,0.84]
σ_{π^*}	Uniform	0.075 [0.0433]	0.08 [0.03,0.13]	0.04 [0.03,0.06]
σ_ζ	Inv-Gamma	0.60 [0.20]	0.53 [0.25,0.85]	0.53 [0.24,0.82]
$M_{r,\zeta}$	Normal	0.00 [1.00]	0.09 [−1.52,1.61]	−0.02 [−1.68,1.63]
$M_{d,\zeta}$	Normal	0.00 [1.00]	−0.19 [−1.88,1.52]	0.01 [−1.67,1.62]
$M_{g,\zeta}$	Normal	0.00 [1.00]	0.09 [−1.56,1.55]	−0.03 [−1.67,1.61]
$M_{\pi^*,\zeta}$	Normal	0.00 [1.00]	0.01 [−1.48,1.57]	−0.01 [−1.66,1.69]

Note: The prior probability of determinacy is 0.498.

Table 2: Determinacy versus Indeterminacy

Sample	Inflation target	Log-data density	Probability of determinacy
1966:I-1979:II	Fixed	-124.87	0.60
	Time-varying	-121.29	0.81
1984:I-2008:II	Fixed	-32.31	1.0
	Time-varying	-28.52	1.0

Table 3: The Great Moderation

	1966:I-1979:II		1984:I-2008:II		Percent Change	
	Data	Model	Data	Model	Data	Model
Inflation	0.54	0.66	0.23	0.26	-57%	-61%
Output Growth	1.01	1.01	0.53	0.57	-48%	-44%

Table 4: Counterfactual standard deviations

Scenarios	Inflation		Output growth	
	St. Dev	% Change	St. Dev	% Change
Policy 2, Private 1	0.29	-56	0.99	-2
ψ_π, ψ_x, $\psi_{\Delta y}$, ρ_r	0.43	-35	1.00	-1
ψ_π	0.37	-44	1.01	0
π^*	0.64	-3	1.01	0
σ_{π^*}	0.47	-29	1.01	0
Policy 1, Private 2	0.70	+6	0.60	-41
σ_g	0.66	0	0.63	-38

Table 5: Determinacy versus Indeterminacy (Robustness Checks)

	Constant Target	Time-varying Target
	Log-data density (Probability of determinacy)	Log-data density (Probability of determinacy)
CPI	-122.00 (0.24)	-118.19 (0.81)
Alternative Calibration	-128.17 (0.12)	-120.82 (0.99)
Firm-specific Labor	-120.23 (0)	-119.67 (0.80)
Lubik and Schorfheide (2004)	-359.59 (0)	-357.92 (0.97)
CPI	-89.28 (1.0)	-92.46 (1.0)
Alternative Calibration	-30.24 (0.99)	-32.21 (1.0)
Firm-specific Labor	-48.42 (1.0)	-50.89 (1.0)
Lubik and Schorfheide (2004)	-238.63 (0.97)	-237.38 (0.99)

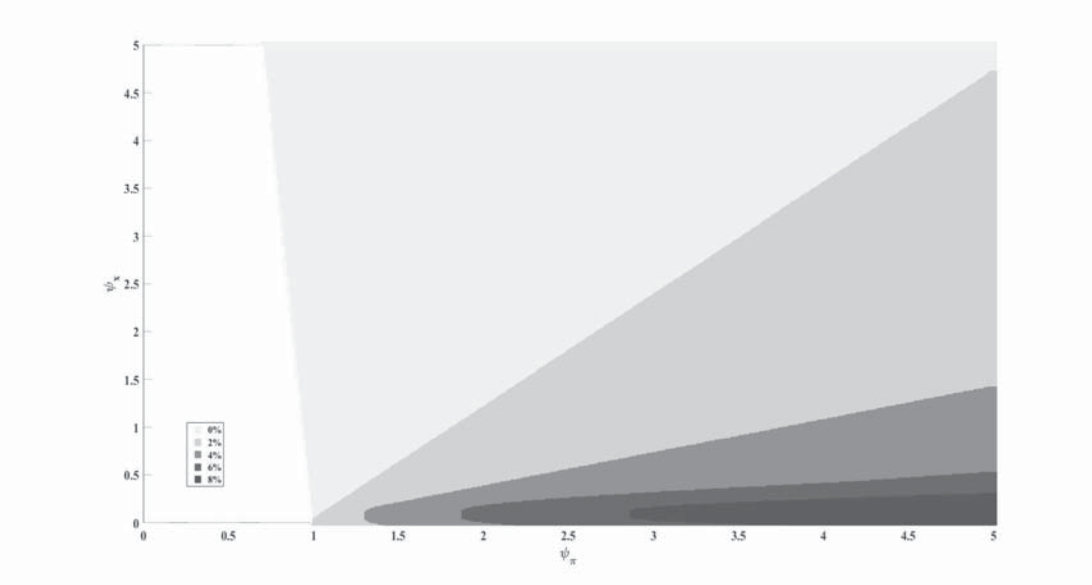

Figure 1: Determinacy region and trend inflation

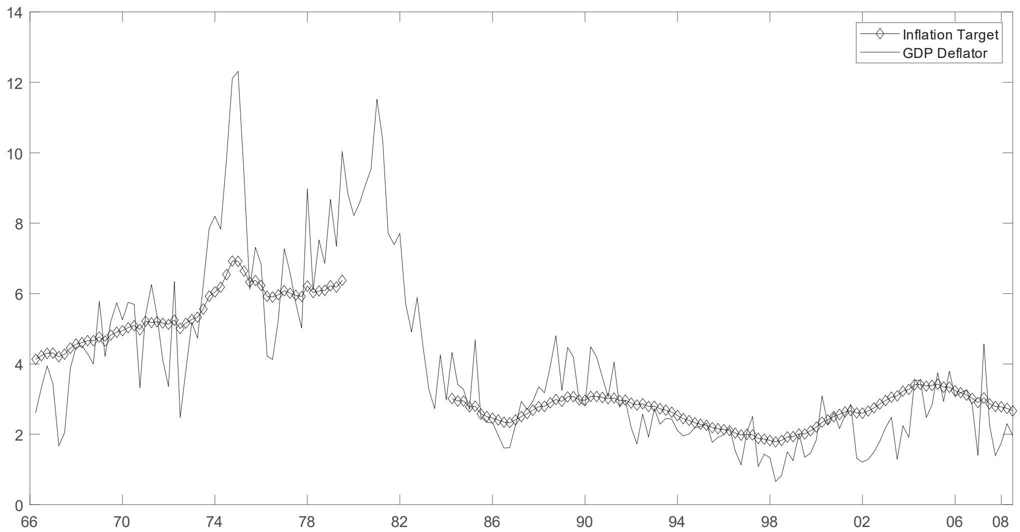

Figure 2: Federal Reserve's inflation target

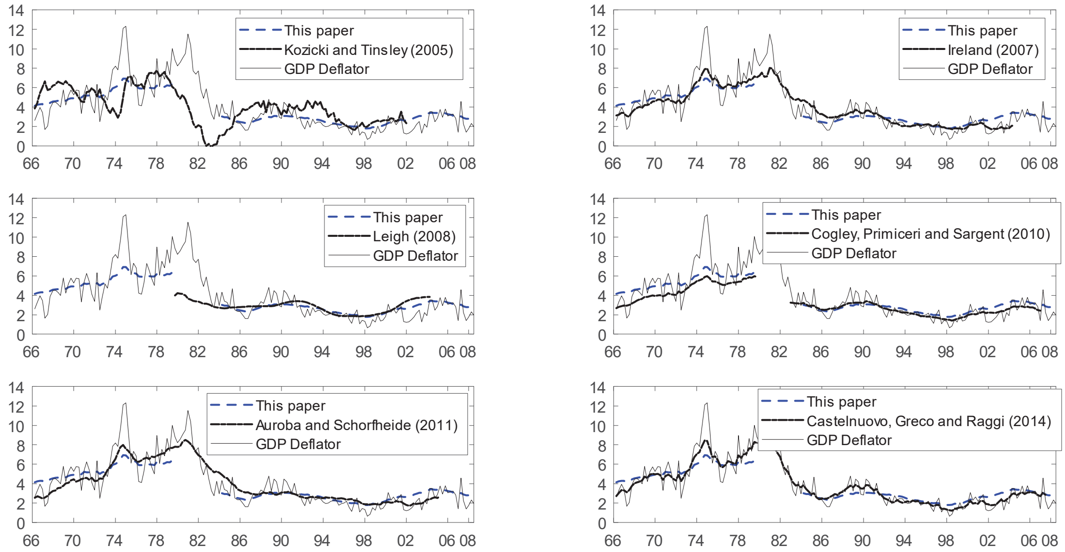

Figure 3: A comparison of inflation target estimates

Appendix for "Monetary Policy, Inflation Target and the Great Moderation: An Empirical Investigation" *

Qazi Haque†

June 18, 2019

1 Model

The artificial economy is a variant of the Generalized New Keynesian (GNK) model of Ascari and Sbordone (2014) and so the description of the model below draws heavily from their exposition. The model consists of a representative household, a representative final-good firm, a continuum of intermediate-good firms, and a central bank. The behavior of these agents are described as follows.

1.1 Households

The representative agent's preferences depend on consumption of final goods, C_t, and labor, N_t, and they are represented by the expected utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t d_t u(C_t, N_t) \qquad 0 < \beta < 1,$$

which the agent acts to maximize. Here, E_0 represents the expectations operator. The term d_t stands for a shock to the discount factor, β, which follows the stationary autoregressive process

$$\log d_t = (1 - \rho_d) \log d + \rho_d \log d_{t-1} + \epsilon_{d,t},$$

where $\epsilon_{d,t}$ is a zero-mean, serially uncorrelated innovation that is normally distributed with standard deviation σ_d. The period utility is additively separable in consumption and labor and it takes on the functional form

$$u(C_t, N_t) = \ln\left(C_t - h\widetilde{C}_{t-1}\right) - d_n \frac{N_t^{1+\varphi}}{1+\varphi} \qquad d_n > 0,\ \varphi \geq 0,\ 0 \leq h \leq 1.$$

* *JEL codes* **C11**; **C52; C62; E31**; **E32**; **E52.** *Keywords*: Taylor rules; Inflation target; Indeterminacy; Great Inflation; Great Moderation; Sequential Monte Carlo.

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Logarithmic utility is the only additive-separable form consistent with balanced growth. The term φ is the inverse of the Frisch labor supply elasticity, d_n governs the steady state disutility of work, and h is the degree of habit persistence in consumption. Habit formation is 'external' implying that the consumer is concerned with the level of her current consumption C_t relative to the aggregate consumption in the previous period $\widetilde{C}_{t-1}$ such that the consumer wants to "keep up with the Joneses". The period by period budget constraint is given by

$$P_t C_t + R_t^{-1} B_t = W_t N_t - T_t + D_t + B_{t-1},$$

where P_t is the price level, R_t is the gross nominal interest rate on bonds, B_t is one-period bond holdings, W_t is the nominal wage rate, T_t is lump sum taxes, and D_t is the profit income. The representative consumer's problem is to maximize the expected discount intertemporal utility subject to the budget constraint. The first-order conditions with respect to consumption, labor supply and bond holdings yield

$$\lambda_t = \frac{d_t}{C_t - hC_{t-1}},$$

$$\frac{W_t}{P_t} = \frac{d_n d_t N_t^{\varphi}}{\lambda_t},$$

$$1 = E_t \frac{\beta \lambda_{t+1}}{\lambda_t} \frac{R_t}{\pi_{t+1}},$$

where Ξ_t is the marginal utility of consumption, and $\pi_t = \frac{P_t}{P_{t-1}}$ is the gross inflation rate.

1.2 Firms

Firms come in two forms. Final-good firms produce output that can be consumed. This output is made from the range of differentiated goods that are supplied by intermediate-good firms who have market power.

1.2.1 Final-good firm

In each period t, a final good, Y_t, is produced by a perfectly competitive representative final-good firm, by combining a continuum of intermediate inputs, $Y_{i,t}$, $i \in [0,1]$, via the technology

$$Y_t = \left[\int_0^1 Y_{i,t}^{\frac{\varepsilon-1}{\varepsilon}} di \right]^{\frac{\varepsilon}{\varepsilon-1}},$$

where $\varepsilon > 1$ is the elasticity of substitution among intermediate inputs. The first-order condition for profit maximization yields the final-good firm's demand for intermediate good i

$$Y_{i,t} = \left(\frac{P_{i,t}}{P_t}\right)^{-\varepsilon} Y_t.$$

The final-good market clearing condition is given by

$$Y_t = C_t.$$

1.2.2 Intermediate-good firms

Each intermediate-good firm i produces a differentiated good $Y_{i,t}$ under monopolistic competition using the production function

$$Y_{i,t} = A_t N_{i,t}.$$

Here A_t denotes the level of aggregate technology that is non-stationary and its growth rate ($g_t \equiv \Delta \ln A_t$) follows an AR(1) process

$$g_t = \left(1 - \rho_g\right) g + \rho_g g_{t-1} + \epsilon_{g,t},$$

where g is the steady-state gross rate of technological progress which is also equal to the steady-state balanced growth rate, $\epsilon_{g,t}$ is a zero-mean, serially uncorrelated innovation that is normally distributed with standard deviation σ_g.

Unlike, Ascari and Sbordone (2014) I assume stochastic growth modelled as the technology level following a unit root process. The labor demand and the real marginal cost of firm i is therefore given by

$$N_{i,t}^d = \frac{Y_{i,t}}{A_t},$$

and

$$MC_{i,t} = \frac{W_t/P_t}{A_t}.$$

Due to the assumption of constant returns to scale and perfectly competitive labor markets, the real marginal cost of firm i, $MC_{i,t}$, depends only only aggregate variables and thus are the same across firms, i.e. $MC_{i,t} = MC_t$.

1.2.3 Firms' price-setting

The intermediate goods producers face a constant probability, $0 < \xi < 1$, of being able to adjust prices to a new optimal one, $P_{q,t}^*(i)$, in order to maximize expected discounted profits

$$E_t \sum_{j=0}^{\infty} \xi^j \beta^j \frac{\lambda_{t+j}}{\lambda_0} \left[\frac{P_{i,t}^* \left(\pi^{\omega j}\right)^{1-\mu} \left(\pi_{t-1|t+j-1}^{\omega}\right)^{\mu}}{P_{q,t+j}} Y_{i,t+j} - \frac{W_{t+j}}{P_{t+j}} \frac{Y_{i,t+j}}{A_{t+j}} \right],$$

subject to the constraint

$$Y_{i,t+j} = \left[\frac{P_{i,t}^{*} \left(\pi^{\omega j}\right)^{1-\mu} \left(\pi_{t-1|t+j-1}^{\omega}\right)^{\mu}}{P_{t+j}} \right]^{-\varepsilon} Y_{t+j},$$

and

$$\begin{aligned} \pi_{t|t+j} &= \frac{P_{t+1}}{P_t} \times \frac{P_{t+2}}{P_{t+1}} \times ... \times \frac{P_{t+j}}{P_{t+j-1}} \qquad \text{for } j \geqslant 1 \\ &= 1 \qquad\qquad\qquad\qquad\qquad\qquad \text{for } j = 0, \end{aligned}$$

where π denotes the central bank's long-run inflation target and is equal to the level of trend inflation, $\Lambda_{t,t+j} = \beta^j \frac{\lambda_{t+j}}{\lambda_0}$ is the stochastic discount factor. This formulation is general as $\omega \in [0,1]$ allows for any degree of price indexation and $\mu \in [0,1]$ allows for any degree of geometric combination of the two types of indexation usually employed in the literature: to steady state inflation and to past inflation rates.

The first order condition for the optimized relative price $p_{i,t}^{*}(=\frac{P_{i,t}^{*}}{P_t})$ is given by

$$p_{i,t}^{*} = \frac{\varepsilon}{(\varepsilon-1)} \frac{E_t \sum_{j=0}^{\infty} (\xi\beta)^j \lambda_{t+j} \frac{W_{t+j}}{P_{+j}} \left[\frac{Y_{t+j}}{A_{t+j}}\right] \left[\frac{\left(\pi^{\omega j}\right)^{1-\mu} \left(\pi_{t-1|t+j-1}^{\omega}\right)^{\mu}}{\pi_{t|t+j}} \right]^{-\varepsilon}}{E_t \sum_{j=0}^{\infty} (\xi\beta)^j \lambda_{t+j} \left[\frac{\left(\pi^{\omega j}\right)^{1-\mu} \left(\pi_{t-1|t+j-1}^{\omega}\right)^{\mu}}{\pi_{t|t+j}} \right]^{1-\varepsilon} Y_{t+j}}.$$

Moreover, the aggregate price level evolves according to:

$$\begin{aligned} P_t &= \left[\int_0^1 P_{i,t}{}^{1-\varepsilon} di \right]^{\frac{1}{1-\varepsilon}} \Rightarrow \\ 1 &= \left[\xi \left(\pi^{1-\mu} \pi_{t-1}^{\mu}\right)^{\omega(1-\varepsilon)} \pi_t^{\varepsilon-1} + (1-\xi) \left(\frac{P_{i,t}^{*}}{P_t}\right)^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}} \\ p_{i,t}^{*} &= \left[\frac{1 - \xi \pi^{(1-\varepsilon)(1-\mu)\omega} \pi_{t-1}^{(1-\varepsilon)\mu\omega} \pi_t^{\varepsilon-1}}{1-\xi} \right]^{\frac{1}{1-\varepsilon}}. \end{aligned}$$

Lastly, define price dispersion $S_t \equiv \int_0^1 (\frac{P_{i,t}}{P_t})^{-\varepsilon} di$. Under the Calvo price mechanism, the above expression can be written recursively as:

$$S_t = (1-\xi) p_{i,t}^{*}{}^{-\varepsilon} + \xi \pi^{-\varepsilon\omega(1-\mu)} \pi_{t-1}^{-\varepsilon\omega\mu} \pi_t^{\varepsilon} S_{t-1}$$

1.2.4 Recursive formulation of the optimal price-setting equation

The joint dynamics of the optimal reset price and inflation can be compactly described by rewriting the first-order condition for the optimal price in a recursive formulation as follows:

$$p^*_{i,t} = \frac{\varepsilon}{(\varepsilon-1)}\frac{\Psi_t}{\phi_t},$$

where Ψ_t and ϕ_t are auxiliary variables defined as:

$$\Psi_t = E_t \sum_{j=0}^{\infty} (\xi\beta)^j \pi^{\varepsilon}_{t|t+j} \frac{W_{t+j}}{P_{+j}} \left[\frac{Y_{t+j}}{A_{t+j}}\right] \lambda_{t+j} \pi^{-\varepsilon(1-\mu)\omega j} \pi^{-\varepsilon\mu\omega}_{t-1|t+j-1}$$

and

$$\phi_t = E_t \sum_{j=0}^{\infty} (\xi\beta)^j \pi^{\varepsilon-1}_{t|t+j} Y_{t+j} \lambda_{t+j} \pi^{(1-\mu)(1-\varepsilon)\omega j} \pi^{\mu\omega(1-\varepsilon)}_{t-1|t+j-1}.$$

We can rewrite the infinite sums that appear in the numerator and denominator of the above equation in recursive formulation as:

$$\Psi_t = w_t \frac{Y_t}{A_t} \lambda_t + \xi\beta\pi^{-\varepsilon(1-\mu)\omega} \pi_t^{-\varepsilon\mu\omega} E_t \left[\pi^{\varepsilon}_{t+1} \Psi_{t+1}\right],$$

and

$$\phi_t = Y_t \lambda_t + \xi\beta\pi^{(1-\mu)(1-\varepsilon)\omega} \pi_t^{\mu\omega(1-\varepsilon)} E_t \left[\pi^{\varepsilon-1}_{t+1} \phi_{t+1}\right],$$

where in defining these two auxiliary variables, we used the definition $\lambda_t = \frac{d_t}{C_t - hC_{t-1}} = \frac{d_t}{Y_t - hY_{t-1}}$ and $w_t = \frac{W_t}{P_t}$.

1.3 Monetary Policy

Lastly, the central bank's policy is described by a Taylor rule

$$\log R_t = \rho_r \log R_{t-1} + (1-\rho_r) \left[\begin{array}{c} \log r + \psi_\pi(\log \pi_t - \log \pi^*_t) + \psi_x \log x_t + \\ \psi_{\Delta y}\left(\log \frac{Y_t}{Y_{t-1}} - \log g\right) \end{array} \right] + \epsilon_{r,t} \qquad 0 \leq \rho_r < 1,$$

where x_t is the output gap, $\epsilon_{r,t}$ is an i.i.d. monetary policy shock, $r \geq 1$ is the steady state gross policy rate. The parameters ψ_π, ψ_x and $\psi_{\Delta y}$ govern the central bank's responses to the inflation gap, the output gap and output growth respectively, and $\rho_r \in [0,1]$ is the degree of policy rate smoothing . Here π^*_t denotes the time varying inflation target that is assumed to follow an exogenous autoregressive process

$$\log \pi^*_t = (1-\rho_{\pi^*}) \log \pi + \rho_{\pi^*} \log \pi^*_{t-1} + \epsilon_{\pi^*,t},$$

where $\epsilon_{\pi^*,t}$ is a zero-mean, serially uncorrelated innovation that is normally distributed with standard deviation σ_{π^*}. Under fixed inflation target, I assume that the policy rules becomes

$$\log R_t = \rho_r \log R_{t-1} + (1-\rho_r) \left[\begin{array}{c} \log r + \psi_\pi (\log \pi_t - \log \pi) + \psi_x \log x_t + \\ \psi_{\Delta y} \left(\log \frac{Y_t}{Y_{t-1}} - \log g \right) \end{array} \right] + \epsilon_{r,t},$$

where this time the central bank's inflation target is equal to steady-state inflation or trend inflation, π.

Finally, the output gap is defined as

$$x_t = \frac{Y_t}{Y_t^n},$$

where Y_t^n is the natural rate of output. By considering flexible prices, the law of motion for Y_t^n is given by

$$\left(\frac{Y_t^n}{A_t} \right)^{1+\varphi} = \frac{\varepsilon - 1}{\varepsilon d_n} + h \left(\frac{Y_t^n}{A_t} \right)^{\varphi} \frac{Y_{t-1}^n}{A_t}.$$

2 Parameter Estimates

Table A1: Posterior distributions (Fixed target)

	Posterior Mean [90% interval] 1966 : I − 1979 : II	Posterior Mean [90% interval] 1984 : I − 2008 : II
ψ_π	1.18 [0.88,1.48]	3.11 [2.40,3.89]
ψ_x	0.11 [0.00,0.23]	0.12 [0.00,0.24]
$\psi_{\Delta y}$	0.14 [0.01,0.27]	0.71 [0.40,1.03]
ρ_r	0.42 [0.25,0.61]	0.78 [0.73,0.83]
π^*	1.39 [1.15,1.63]	0.67 [0.58,0.76]
r^*	1.63 [1.38,1.88]	1.44 [1.21,1.66]
g^*	0.52 [0.36,0.67]	0.51 [0.40,0.63]
h	0.45 [0.34,0.57]	0.43 [0.32,0.53]
ξ	0.50 [0.37,0.65]	0.62 [0.52,0.74]
ρ_d	0.79 [0.69,0.89]	0.90 [0.87,0.94]
ρ_g	0.23 [0.14,0.34]	0.22 [0.12,0.31]
σ_r	0.37 [0.29,0.46]	0.20 [0.16,0.23]
σ_d	0.66 [0.35,0.96]	1.55 [1.14,1.94]
σ_g	1.45 [1.11,1.75]	0.76 [0.61,0.89]
σ_ζ	0.57 [0.24,0.92]	0.54 [0.24,0.85]
$M_{r,\zeta}$	0.17 [−1.58,1.81]	−0.06 [−1.68,1.65]
$M_{d,\zeta}$	0.03 [−1.61,1.80]	0.05 [−1.52,1.73]
$M_{g,\zeta}$	−0.05 [−1.68,1.54]	0.00 [−1.65,1.70]
$\log p(X_T)$	−124.87	−32.31
$P\{\theta_S \in \Theta^D \vert X_T\}$	0.60	1.00

$\log p(X_T)$ represents the log marginal data density and $P\{\theta_S \in \Theta^D|X_T\}$ denotes the posterior probability of determinacy of equilibrium.

Table A2: Posterior distributions
(Alternative measure of inflation)

	Posterior Mean [90% interval]			
	$1966:I-1979:II$		$1984:I-2008:II$	
	Fixed Target	Time-varying Target	Fixed Target	Time-varying Target
ψ_π	0.99 [0.77,1.21]	1.63 [0.96,2.28]	2.43 [1.90,3.00]	2.56 [1.83,3.22]
ψ_x	0.09 [0.00,0.20]	0.16 [0.00,0.31]	0.12 [0.00,0.24]	0.11 [0.00,0.24]
$\psi_{\Delta y}$	0.15 [0.01,0.28]	0.17 [0.01,0.30]	0.63 [0.26,0.94]	0.55 [0.14,0.83]
ρ_r	0.47 [0.30,0.61]	0.52 [0.33,0.71]	0.75 [0.68,0.82]	0.75 [0.66,0.83]
π^*	1.50 [1.22,1.75]	1.42 [1.04,1.74]	0.85 [0.73,0.98]	0.86 [0.70,1.04]
r^*	1.64 [1.39,1.90]	1.57 [1.25,1.86]	1.45 [1.21,1.69]	1.44 [1.21,1.70]
g^*	0.51 [0.35,0.67]	0.52 [0.35,0.66]	0.51 [0.39,0.61]	0.51 [0.40,0.62]
h	0.44 [0.32,0.57]	0.41 [0.31,0.54]	0.37 [0.27,0.46]	0.38 [0.29,0.49]
ξ	0.59 [0.46,0.69]	0.57 [0.42,0.74]	0.38 [0.27,0.49]	0.37 [0.26,0.49]
ρ_d	0.83 [0.72,0.91]	0.75 [0.59,0.89]	0.92 [0.89,0.95]	0.91 [0.87,0.94]
ρ_g	0.26 [0.15,0.39]	0.26 [0.13,0.40]	0.21 [0.13,0.29]	0.21 [0.13,0.29]
ρ_{π^*}	–	0.94 [0.91,0.98]	–	0.94 [0.91,0.99]
σ_r	0.32 [0.26,0.40]	0.33 [0.26,0.43]	0.25 [0.19,0.31]	0.25 [0.19,0.32]
σ_d	0.58 [0.32,0.85]	0.73 [0.27,0.96]	1.51 [1.00,1.98]	1.40 [0.96,1.74]
σ_g	1.42 [1.06,1.76]	1.26 [0.96,1.76]	0.68 [0.57,0.79]	0.68 [0.57,0.80]
σ_{π^*}	–	0.08 [0.02,0.15]	–	0.02 [0.00,0.04]
σ_ζ	0.59 [0.23,0.96]	0.55 [0.24,0.86]	0.55 [0.24,0.86]	0.58 [0.24,0.93]
$M_{r,\zeta}$	0.06 [−1.64,1.70]	0.04 [−1.51,1.77]	0.01 [−1.60,1.66]	−0.03 [−1.71,1.55]
$M_{d,\zeta}$	0.18 [−1.44,1.96]	−0.08 [−1.68,1.61]	0.03 [−1.59,1.71]	0.02 [−1.73,1.59]
$M_{g,\zeta}$	−0.24 [−1.91,1.34]	−0.18 [−1.78,1.49]	0.01 [−1.63,1.60]	0.03 [−1.64,1.69]
$M_{\pi^*,\zeta}$	–	−0.01 [−1.68,1.62]	–	−0.01 [−1.64,1.65]
$\log p(X_T)$	−122.00	−118.19	−89.28	−92.46
$P\{\theta_S \in \Theta^D \vert X_T\}$	0.24	0.81	1.00	1.00

$\log p(X_T)$ represents the log marginal data density and $P\{\theta_S \in \Theta^D|X_T\}$ denotes the posterior probability of determinacy of equilibrium.

Table A3: Posterior distributions
(Alternative calibration)

	Posterior Mean [90% interval]			
	$1966:I-1979:II$		$1984:I-2008:II$	
	Fixed Target	Time-varying Target	Fixed Target	Time-varying Target
ψ_π	1.09 [0.73,1.41]	2.12 [1.58,2.65]	2.51 [1.77,2.93]	3.19 [2.05,3.97]
ψ_x	0.07 [0.01,0.13]	0.11 [0.01,0.20]	0.12 [0.00,0.27]	0.10 [0.00,0.20]
$\psi_{\Delta y}$	0.38 [0.10,0.61]	0.17 [0.01,0.32]	0.96 [0.60,1.20]	0.56 [0.08,0.96]
ρ_r	0.65 [0.55,0.73]	0.65 [0.54,0.76]	0.81 [0.75,0.85]	0.79 [0.72,0.84]
π^*	1.26 [1.01,1.48]	1.25 [1.07,1.44]	0.68 [0.57,0.81]	1.28 [0.74,1.65]
r^*	1.54 [1.29,1.78]	1.55 [1.31,1.80]	1.42 [1.20,1.63]	1.89 [1.39,2.27]
g^*	0.52 [0.36,0.67]	0.57 [0.45,0.71]	0.52 [0.38,0.64]	0.49 [0.37,0.61]
h	0.47 [0.35,0.60]	0.41 [0.29,0.54]	0.49 [0.38,0.61]	0.49 [0.37,0.61]
ξ	**0.75**	**0.75**	**0.75**	**0.75**
ρ_d	0.83 [0.73,0.94]	0.71 [0.59,0.82]	0.89 [0.84,0.93]	0.88 [0.82,0.92]
ρ_g	0.35 [0.20,0.49]	0.39 [0.22,0.54]	0.28 [0.16,0.43]	0.36 [0.21,0.53]
ρ_{π^*}	–	**0.995**	–	**0.995**
σ_r	0.32 [0.26,0.39]	0.28 [0.23,0.33]	0.18 [0.15,0.21]	0.16 [0.14,0.19]
σ_d	1.08 [0.53,1.57]	1.90 [1.35,2.51]	1.54 [1.10,1.83]	1.80 [1.20,2.23]
σ_g	1.50 [1.05,1.93]	0.47 [0.25,0.71]	0.88 [0.69,1.06]	0.59 [0.29,0.94]
σ_{π^*}	–	0.12 [0.08,0.15]	–	0.07 [0.01,0.11]
σ_ζ	0.57 [0.25,0.91]	0.58 [0.24,0.93]	0.58 [0.23,0.91]	0.58 [0.24,0.94]
$M_{r,\zeta}$	0.15 [−1.54,1.76]	−0.02 [−1.69,1.56]	0.04 [−1.72,1.66]	0.13 [−1.47,1.76]
$M_{d,\zeta}$	0.36 [−1.38,2.00]	−0.03 [−1.63,1.66]	0.00 [−1.71,1.58]	−0.06 [−1.66,1.66]
$M_{g,\zeta}$	−0.67 [−2.29,1.06]	0.00 [−1.62,1.67]	0.01 [−1.67,1.69]	−0.01 [−1.72,1.67]
$M_{\pi^*,\zeta}$	–	−0.02 [−1.64,1.59]	–	0.01 [−1.71,1.65]
$\log p(X_T)$	−128.17	−120.82	−30.24	−32.21
$P\{\theta_S \in \Theta^D \vert X_T\}$	0.12	0.99	0.99	1.00

$\log p(X_T)$ represents the log marginal data density and $P\{\theta_S \in \Theta^D | X_T\}$ denotes the posterior probability of determinacy of equilibrium.

Table A4: Posterior distributions
(Firm-specific labor)

	Posterior Mean [90% interval]			
	$1966:I-1979:II$		$1984:I-2008:II$	
	Fixed Target	Time-varying Target	Fixed Target	Time-varying Target
ψ_π	0.91 [0.30,1.57]	2.12 [0.73,3.32]	2.67 [1.88,3.31]	3.08 [2.14,3.98]
ψ_x	0.28 [0.05,0.45]	0.25 [0.02,0.43]	0.08 [0.00,0.17]	0.16 [0.00,0.32]
$\psi_{\Delta y}$	0.12 [0.00,0.26]	0.17 [0.00,0.32]	0.82 [0.48,1.04]	0.64 [0.29,0.95]
ρ_r	0.77 [0.67,0.88]	0.76 [0.67,0.85]	0.83 [0.78,0.86]	0.81 [0.75,0.86]
π^*	1.52 [1.15,1.87]	1.43 [1.10,1.77]	0.71 [0.59,0.85]	0.84 [0.54,1.24]
r^*	1.67 [1.36,1.96]	1.66 [1.31,1.95]	1.44 [1.17,1.70]	1.49 [1.19,1.84]
g^*	0.44 [0.19,0.66]	0.49 [0.26,0.67]	0.44 [0.25,0.60]	0.42 [0.24,0.58]
h	0.54 [0.40,0.68]	0.55 [0.41,0.71]	0.57 [0.48,0.69]	0.60 [0.49,0.70]
ξ	0.53 [0.46,0.60]	0.53 [0.47,0.60]	0.48 [0.41,0.56]	0.48 [0.38,0.58]
ρ_d	0.48 [0.14,0.76]	0.44 [0.15,0.71]	0.92 [0.87,0.95]	0.90 [0.85,0.94]
ρ_g	0.67 [0.36,0.96]	0.62 [0.31,0.92]	0.23 [0.04,0.45]	0.32 [0.03,0.71]
ρ_{π^*}	–	0.95 [0.92,0.99]	–	0.96 [0.93,0.99]
σ_r	0.27 [0.23,0.33]	0.28 [0.24,0.34]	0.17 [0.15,0.20]	0.16 [0.14,0.19]
σ_d	1.54 [0.26,2.93]	1.93 [0.30,3.13]	2.32 [1.53,2.94]	2.11 [1.49,2.69]
σ_g	0.57 [0.29,0.93]	0.55 [0.27,0.96]	1.16 [0.82,1.47]	1.04 [0.45,1.45]
σ_{π^*}	–	0.10 [0.06,0.15]	–	0.06 [0.02,0.09]
σ_ζ	0.38 [0.29,0.48]	0.55 [0.25,0.91]	0.60 [0.28,0.93]	0.62 [0.28,0.98]
$M_{r,\zeta}$	−0.26 [−1.00,0.42]	−0.02 [−1.50,1.45]	0.00 [−1.59,1.67]	−0.10 [−1.73,1.58]
$M_{d,\zeta}$	−0.01 [−0.52,0.46]	−0.05 [−1.59,1.40]	0.11 [−1.52,1.74]	−0.20 [−1.86,1.39]
$M_{g,\zeta}$	0.25 [−0.33,0.74]	0.00 [−1.64,1.42]	0.06 [−1.56,1.79]	0.08 [−1.55,1.77]
$M_{\pi^*,\zeta}$	–	−0.07 [−1.58,1.62]	–	−0.02 [−1.64,1.61]
$\log p(X_T)$	−120.23	−119.67	−48.42	−50.89
$P\{\theta_S \in \Theta^D \vert X_T\}$	0.00	0.80	1.00	1.00

$\log p(X_T)$ represents the log marginal data density and $P\{\theta_S \in \Theta^D|X_T\}$ denotes the posterior probability of determinacy of equilibrium.

Table A5: Posterior distributions
(Lubik and Schorfheide, AER 2004)

	Posterior Mean [90% interval]			
	$1966:I-1979:II$		$1984:I-2008:II$	
	Fixed Target	Time-varying Target	Fixed Target	Time-varying Target
ψ_1	0.75 [0.59,0.92]	1.62 [1.12,2.25]	2.13 [1.13,2.90]	2.45 [1.39,3.21]
ψ_2	0.14 [0.01,0.30]	0.17 [0.02,0.34]	0.32 [0.04,0.58]	0.35 [0.05,0.65]
ρ_R	0.59 [0.45,0.78]	0.63 [0.51,0.75]	0.84 [0.78,0.89]	0.85 [0.79,0.90]
π^*	4.32 [2.13,6.23]	4.25 [2.20,5.95]	3.50 [2.79,4.11]	3.43 [1.99,4.94]
r^*	1.04 [0.53,1.62]	1.04 [0.58,1.58]	2.92 [2.06,3.72]	2.98 [2.06,3.80]
κ	0.75 [0.33,1.07]	0.71 [0.39,1.02]	0.60 [0.26,0.84]	0.59 [0.26,0.82]
τ^{-1}	1.54 [0.90,2.27]	1.98 [1.23,2.71]	1.89 [1.11,2.76]	1.98 [1.15,2.83]
ρ_g	0.66 [0.53,0.80]	0.81 [0.74,0.87]	0.82 [0.74,0.88]	0.81 [0.72,0.87]
ρ_z	0.82 [0.70,0.90]	0.69 [0.60,0.77]	0.85 [0.75,0.93]	0.87 [0.77,0.94]
ρ_{gz}	0.09 [−0.42,0.70]	0.97 [0.93,0.99]	0.32 [−0.01,0.65]	0.31 [−0.03,0.63]
ρ_{π^*}	–	0.93 [0.90,0.97]	–	0.94 [0.90,0.99]
σ_R	0.23 [0.19,0.27]	0.26 [0.20,0.31]	0.18 [0.14,0.22]	0.16 [0.13,0.20]
σ_g	0.26 [0.17,0.37]	0.24 [0.18,0.31]	0.18 [0.14,0.24]	0.18 [0.14,0.25]
σ_z	1.10 [0.90,1.35]	1.05 [0.87,1.24]	0.62 [0.50,0.78]	0.61 [0.49,0.76]
σ_{π^*}	–	0.10 [0.06,0.15]	–	0.07 [0.02,0.13]
σ_ζ	0.21 [0.12,0.31]	0.26 [0.11,0.41]	0.24 [0.11,0.40]	0.25 [0.10,0.41]
$M_{R,\zeta}$	0.47 [−0.39,1.52]	−0.11 [−1.79,1.54]	0.04 [−1.65,1.67]	−0.02 [−1.66,1.66]
$M_{g,\zeta}$	−1.70 [−2.55,−0.74]	−0.09 [−1.91,1.55]	0.00 [−1.68,1.64]	−0.01 [−1.76,1.60]
$M_{z,\zeta}$	0.73 [0.39,1.05]	0.05 [−1.58,1.58]	0.02 [−1.63,1.69]	−0.02 [−1.68,1.59]
$M_{\pi^*,\zeta}$	–	0.02 [−1.60,1.69]	–	0.03 [−1.66,1.65]
$\log p(X_T)$	−359.59	−357.92	−238.63	−237.38
$P\{\theta_S \in \Theta^D \| X_T\}$	0.00	0.97	0.97	0.99

$\log p(X_T)$ represents the log marginal data density and $P\{\theta_S \in \Theta^D|X_T\}$ denotes the posterior probability of determinacy of equilibrium. Notations for the parameters follow Lubik and Schorfheide (2004).

Table A6: Posteriors distributions
(Higher trend inflation + Time-varying inflation target)

	Posterior Mean [90% interval]
	$1966:I - 1979:II$
ψ_π	2.27 [0.60,3.51]
ψ_x	0.13 [0.02,0.23]
$\psi_{\Delta y}$	0.20 [0.01,0.37]
ρ_r	0.74 [0.66,0.83]
π^*	**2.00**
r^*	2.10 [1.86,2.33]
g^*	0.45 [0.18,0.67]
h	0.58 [0.45,0.73]
ξ	0.49 [0.42,0.61]
ρ_d	0.51 [0.18,0.78]
ρ_g	0.60 [0.28,0.92]
ρ_{π^*}	**0.995**
σ_r	0.29 [0.25,0.35]
σ_d	1.93 [0.29,3.02]
σ_g	0.52 [0.25,0.81]
σ_{π^*}	0.08 [0.02,0.15]
σ_ζ	0.53 [0.27,0.86]
$M_{r,\zeta}$	0.10 [−1.48,1.54]
$M_{d,\zeta}$	−0.06 [−1.53,1.53]
$M_{g,\zeta}$	−0.03 [−1.54,1.48]
$M_{\pi^*,\zeta}$	−0.14 [−1.65,1.59]
$\log p(X_T)$	−121.64
$P\{\theta_S \in \Theta^D \mid X_T\}$	0.80

$\log p(X_T)$ represents the log marginal data density and $P\{\theta_S \in \Theta^D \mid X_T\}$ denotes the posterior probability of determinacy of equilibrium.