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

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Abstract

This paper compares the empirical fit of a Taylor rule featuring constant versus time-varying inflation target by estimating a Generalized New Keynesian model under positive trend inflation while allowing for indeterminacy. The estimation is conducted over two different periods covering the Great Inflation and the Great Moderation. We find that the rule embedding time variation in target inflation turns out to be empirically superior and determinacy prevails in both sample periods. Counterfactual simulations point toward both 'good policy' and 'good luck' as drivers of the Great Moderation. We find that better monetary policy, both in terms of a more active response to inflation gap and a more anchored inflation target, has resulted in the decline in inflation gap volatility and predictability. In contrast, the reduction in output growth variability is mainly explained by reduced volatility of technology shocks.

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). The Great Moderation is also associated with changes in the predictability of inflation. For instance, Stock and Watson (2007) document that inflation has become *absolutely* easier, but *relatively* harder to forecast, in the Volcker-Greenspan era.[1] What are the

JEL codes* **C11; **C52; C62; E31**; **E32**; **E52; E58.** *Keywords*: Monetary policy; Great Inflation; Great Moderation; Equilibrium Indeterminacy; Generalized New Keynesian Phillips curve; Taylor rules; Time-varying inflation target; Good policy; Good luck; Sequential Monte Carlo.

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[1] Forecasting inflation has become *absolutely* easier because of its reduced volatility while predicting inflation has become *relatively* harder due to its reduced persistence.

reasons behind this shift 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).

On the other hand, the empirical plausibility of a link between good systematic monetary policy and macroeconomic stability has been advocated by Clarida, Gali and Gertler (2000), Lubik and Schorfheide (2004), and Boivin and Giannoni (2006) among several others. This literature suggests that dovish monetary policy may have steered the economy into an indeterminate equilibrium during the 1970s resulting in the Great Inflation. However, these authors find that a switch toward a more hawkish policy since the early 1980s brought about a stable and determinate environment. Importantly, these studies only consider a constant zero inflation target. However, the view of a constant inflation target is disputed by many. Amongst them, Kozicki and Tinsley (2005, 2009), Cogley and Sargent (2005a), Ireland (2007), Stock and Watson (2007), Cogley and Sbordone (2008), Leigh (2008), Cogley, Primiceri and Sargent (2010), Castelnuovo (2010), Coibion and Gorodnichenko (2011), Bjornland, Leitemo and Maih (2011), and Castelnuovo, Greco and Raggi (2014) find evidence in favor of a time-varying inflation target.

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 constant target or allowed for time-varying target inflation while restricting the model to determinacy in isolation.[2]Unfortunately, the assumption of a constant versus time-varying target inflation 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 inflation gap depends on whether the Fed is responding to deviations from a constant target or time-varying target. This then affects the probability of being in a determinate or indeterminate regime. Furthermore, Cogley, Primiceri and Sargent (2010) and Castelnuovo (2010) suggest that a better anchoring of the inflation target is the single-most important factor behind the U.S. inflation dynamics.

This paper employs full-information likelihood-based Bayesian estimation techniques to estimate a Generalized New Keynesian (GNK) model featuring both positive trend inflation and time-varying target inflation while allowing for indeterminacy. The estimation is conducted over two different periods: the Great Inflation, a sam-

[2]One exception is Coibion and Gorodnichenko (2011) who use a limited information single-equation approach to estimate a Taylor rule with time-varying coefficients which allow them to extract a measure of trend inflation and construct a time-series for the probability of determinacy for the U.S. economy. However, (in-)determinacy is 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. Moreover, Coibion and Gorodnichenko (2011) estimate a constant term of the Taylor rule which contains not only the trend inflation but also the equilibrium real interest rate and the Fed's targets for real GDP growth and the output gap. Consequently, the level of trend inflation is not separately indentified and hence they need to make additional assumptions.

ple ending in 1979:II, and the Great Moderation, a period beginning in 1984:I. In contrast to the existing literature, we distinguish between trend inflation and time-varying target inflation. Trend inflation, a term coined by Ascari (2004), stands 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 (NKPC). Allowing for positive trend inflation is crucial 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. As a result, the inflation rate becomes less sensitive to current economic conditions and hence monetary authority should respond more strongly to inflation to induce a reduction in output that achieves a given change in inflation thereby widening the indeterminacy region. On the other hand, we assume target inflation to be time-varying and follow a persistent exogenous autoregressive process whose unconditional mean is equal to trend inflation. Following Sargent (1999), Cogley and Sargent (2005b), Primiceri (2006), Sargent, Williams and Zha (2006), Ireland (2007) and Cogley, Primiceri and Sargent (2010), time-varying target inflation can be interpreted as the short-term goal pursued by the Fed conditional on economic situation and its knowledge about the inflation-output volatility trade-off. In contrast, trend inflation stands for the Fed's long-run target compatible with its long-run goals such as inflation stability and sustainable economic growth.

We estimate the model under the assumption of a constant inflation target, that is equal to trend inflation, over the two different regions of the parameter space, i.e. determinacy and indeterminacy., following the methodology proposed in Lubik and Schorfheide (2004).[3] This sets up a baseline scenario which lets us compare our findings to those in the existing literature. Next, we estimate the model featuring a stochastic time-varying target inflation, again allowing for indeterminacy. Our findings read as follows.

First, when considering the model with constant positive target inflation, we can neither rule in nor rule out indeterminacy before 1979 while determinacy unambiguously prevails after 1982. This stands in contrast to Hirose, Kurozumi and Van Zandwaghe (2017) who estimate a similar model allowing for positive constant trend inflation and find that the U.S. economy was unambiguously in the indeterminacy region of the parameter space before 1979 and there is a switch to determinacy after 1982. While these authors employ a model with firm-specific labour following Kurozumi and Van Zandwaghe (2017), we use a model with homogenous labor following Ascari and Ropele (2009) and Ascari and Sbordone (2014) in our benchmark specification. Moreover, when using firm-specific labor, we also find that the pre-Volcker period is unambiguously characterized by indeterminacy. Kurozumi and Van Zandwaghe (2017) show that the model with firm-specific labor is more susceptible to indeterminacy induced by high trend inflation than the model with homogeneous labor which explains the difference.

Yet, the upshot completely differs when we allow for a time-varying target in-

[3] This methodology has been used in previous studies, such as Benati and Surico (2009), Bhattarai, Lee and Park (2012, 2016), Doko Tchatoka, Groshenny, Haque and Weder (2017) and Hirose (2007, 2008, 2013, 2014).

flation ala Cogley and Sargent (2005a), Ireland (2007), Stock and Watson (2007), Cogley and Sbordone (2008), Cogley, Primiceri and Sargent (2010) and Bjornland, Leitemo and Maih (2011). When making this choice, the posterior probability of our sample concentrates all of its mass in the determinacy region for both pre-1979 and post-84 sample periods. This result suggests that the Federal Reserve policy, even during the pre-Volcker period, has been prudent enough to generate a unique rational expectations equilibrium. Given these opposing results, it is essential to compare the empirical fit of the model under constant vs. time-varying target inflation. Using posterior odds ratio to compare the two models, we then find evidence in favor of the model featuring time variation in the target inflation for both the sample periods.

Having established the finding that time-varying target inflation empirically outperforms constant target inflation, we then perform theoretical and counterfactual simulations to disentangle the role played by 'good policy' and 'good luck' in explaining the Great Moderation. First and foremost, the estimated model is able to qualitatively replicate the observed drop in inflation gap and output growth volatility and the drop in inflation gap predictability. Second, counterfactual exercises suggest that better monetary policy, both in terms of a stronger response to inflation gap and a better anchoring of the inflation target, has dampened most of the fluctuations in inflation gap and contributed to the decline in inflation gap predictability. In contrast, 'good policy' alone fails to explain the reduced volatility of output growth which is explained by a reduction in the volatility of technology shocks. Hence, both 'good policy' and 'good luck' interpretations are required to explain the joint decline in the variability of real activity and inflation over time.

Perhaps most closely related to our work are Cogley, Primiceri and Sargent (2010), Castelnuovo (2010), Castelnuovo, Greco and Raggi (2014), and Hirose, Kurozumi and Van Zandwaghe (2017). Both Cogley, Primiceri and Sargent (2010) and Castelnuovo (2010) estimate a New Keynesian model log-linearized around a zero-inflation steady state and perform counterfactual simulations to assess the role played by 'good policy' vs. 'good luck'. We depart from them along the following dimensions. First, we estimate a model log-linearized around a positive steady state inflation as it has been shown to substantially alter the NKPC relationship and therefore inflation dynamics and determinacy regions. Moreover, Ascari, Castelnuovo and Rossi (2011) and Hirose, Kurozumi and Van Zandwaghe (2017) has shown that a model with positive steady state inflation fits better than its simple New Keynesian counterpart which is log-linearized around zero inflation steady state. Second, we compare the fit of constant vs. time-varying target while also allowing for indeterminacy. Finally, we employ the Sequential Monte Carlo (SMC) algorithm developed by Herbst and Schorfheide (2014, 2015) while they employ Random-Walk Metropolis Hastings (RWMH) algorithm. SMC algorithm has been shown to be better suited for multi-modal and irregular posterior distributions than the widely used RWMH algorithm.

Castelnuovo, Greco and Raggi (2014) estimate regime-switching policy rules featuring time-varying target inflation and compare it to a specification with fixed target. Like us, the authors find support in favor of time variation in inflation target. However, they 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 identifies a switch to an active regime soon after Paul Volcker's appointment as Chairman of the Federal Reserve. Using a partial equilibrium approach to characterize the likelihood of determinacy is not innocuous as Ascari and Ropele (2007) show that allowing for positive trend inflation in a structural model alters the NKPC, widens the indeterminacy region and the Taylor principle is no longer sufficient to guarantee a unique rational expectations equilibrium. Hence, what they label as 'active' could still imply multiple equilibria. In contrast, we employ full-information likelihood-based structural estimation to estimate a GNK model allowing for both positive steady state trend inflation and time-varying target inflation.

Finally, Hirose, Kurozumi and Van Zandwaghe (2017) estimate a GNK model very similar to ours but one that features constant target inflation. They find that pre-Volcker is ostensibly 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.[4] In contrast, we estimate a similar model allowing for time-varying target inflation and document that it empirically fits better (or at least no worse in the case of firm-specific labor) than a policy rule featuring constant target and favors determinacy in both sample periods. Moreover, unlike them, we then go on to conduct counterfactual simulations to understand the driver of the Great Moderation. To the best of our knowledge, 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 Fed's target inflation. The finding that even the pre-Volcker period could possibly be characterized by a unique equilibrium is a novel result.[5]

2 Model

The estimation is based on a version of Ascari and Sbordone's (2014) Generalized New Keynesian model. The model consists of an intertemporal 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

[4] Arias, Ascari, Branzoli and Castelnuovo (2017) corroborate these findings as well as those in Coibion and Gorodnichenko (2011) by revisiting the relation between the sytematic component of monetary policy, trend inflation and determinacy by employing a medium-scale DSGE model. However, due to the complexities arising from the medium-scale nature of their model, they stop short by estimating the model over the period 1984:I - 2008:II focusing on determinacy alone.

[5] An exception is Orphanides (2004) who finds an active response to expected inflation in a Taylor-type rule estimated for the pre-1979 period, thereby claiming that self-fulfilling expectations cannot be a source of macroeconomic instability during the Great Inflation. However, Ascari and Ropele (2007, 2009) show that an active response to inflation does not guarante equilibrium determinacy when allowing for positive trend inflation. Moreover, Orphanide's (2004) finding is based on a single-equation framework, whereas we use full-information structural estimation (recall that indeterminacy is the property of a system).

economic conditions; (ii) it alters the determinacy properties of the model; and (iii) trend inflation generates more endogenous persistence of inflation and output even in the determinacy case.[6] Unlike Ascari and Sbordone (2014), we assume stochastic growth modelled as the technology level following a unit root process. We also replace their labor supply disturbance by a discount factor shock, d_t, as our stand-in for demand shocks and introduce external habit formation in consumption preferences to generate output persistence. In light of the result of Cogley and Sbordone (2008) that there is no empirical support for intrinsic inertia in their GNK Phillips curve, the model is estimated in the absence of rule-of-thumb price-setting. Also, our Taylor rule involves responses to the output gap and the output growth instead of log-deviations of output from the steady state. This then makes our setup similar to Hirose, Kurozumi and Van Zandweghe (2017). One important distinction of our model is that we allow for time variation in the Federal Reserve's inflation target.[7]

2.1 The log-linearized model

The log-linearized equilibrium conditions are given by the following equations[8]

$$\begin{aligned} y_t \;=\; & \left(\frac{h}{g+h}\right)[y_{t-1}-g_t]+\left(\frac{g}{g+h}\right)[E_t y_{t+1}+E_t g_{t+1}]-\left(\frac{g-h}{g+h}\right)[r_t-E_t\pi_{t+1}] \\ & +\left(\frac{g-h}{g+h}\right)[d_t-E_t d_{t+1}] \end{aligned} \tag{1}$$

$$\pi_t=\kappa E_t\pi_{t+1}+\vartheta\left[\varphi s_t+(1+\varphi)y_t\right]+\chi\left(\frac{h}{g-h}\right)[y_t-y_{t-1}+g_t]-\varpi E_t\psi_{t+1}+\varpi d_t \tag{2}$$

$$\psi_t=(1-\xi\beta\pi^{\varepsilon})\left[\varphi s_t+(1+\varphi)y_t+d_t\right]+\xi\beta\pi^{\varepsilon}\left[E_t\psi_{t+1}+\varepsilon E_t\pi_{t+1}\right] \tag{3}$$

$$s_t=\varepsilon\xi\pi^{\varepsilon-1}\left(\frac{\pi-1}{1-\xi\pi^{\varepsilon-1}}\right)\pi_t+\xi\pi^{\varepsilon}s_{t-1} \tag{4}$$

$$r_t=\rho_r r_{t-1}+(1-\rho_r)\left\{\psi_\pi\left(\pi_t-\pi_t^*\right)+\psi_x x_t+\psi_{\Delta y}\left(y_t-y_{t-1}+g_t\right)\right\}+\epsilon_{r,t} \tag{5}$$

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 $\varpi\equiv\beta(1-\pi)(1-\xi\pi^{\varepsilon-1})$ and lower case letters denote log-deviations from steady state. Here y_t stands for detrended output, r_t denotes the

[6] The plain-vanilla New Keynesian model features a poor internal propagation mechanism. As a result the posterior mass might be biased toward the indeterminacy region. However, trend inflation generates more endogenous persistence of inflation and output even under determinacy thus making the indeterminacy test less susceptible to bias. See the discussion between Beyer and Farmer (2007) and Lubik and Schorfheide (2007).

[7] Moreoever, following Ascari and Sbordone (2014), we assume homogenous labor whereas Hirose, Kurozumi and Van Zandwaghe (2017) assume firm-specific labor.

[8] A full description of the model is delegated to the Appendix to conserve space.

nominal interest rate, π_t symbolizes inflation, π_t^* represents the Federal Reserves 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 change which is also equal to the steady state gross rate of balanced growth. Eq. (2) and (3) represents the generalized New Keynesian 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 labour supply. Eq. (2) boils down to a standard NKPC when trend inflation is zero (i.e. $\pi = 1$) and that also implies $\psi_t = 0$. 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 inflation gap, the output gap, the output growth rate and the degree of inertia in interest rate setting. The term $\epsilon_{r,t}$ is an exogenous transitory monetary policy shock whose standard deviation is given by σ_r. Under constant target inflation, we assume that the policy rules becomes

$$r_t = \rho_r r_{t-1} + (1-\rho_r)\left\{\psi_\pi \pi_t + \psi_x x_t + \psi_{\Delta y}\left(y_t - y_{t-1} + g_t\right)\right\} + \epsilon_{r,t}, \qquad (6)$$

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

The other fundamental disturbances involve a preference shock d_t, a non-stationary technology shock g_t, and target inflation shock π_t^*. Each of these three shocks are assumed to follow $AR(1)$ processes:

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

$$g_t = \rho_g g_{t-1} + \epsilon_{g,t} \qquad 0 < \rho_g < 1,$$

and

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

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

To solve the model, we apply the method proposed by Lubik and Schorfheide (2003). Let us denote by η_t the vector of one-step ahead expectation errors. Moreover, define ϱ_t as the vector of endogenous variables and ε_t as vector of fundamental shocks. Then, the linear rational expectation system can be compactly written as

$$\Gamma_0(\theta)\varrho_t = \Gamma_1(\theta)\varrho_{t-1} + \Psi(\theta)\varepsilon_t + \Pi(\theta)\eta_t \qquad (7)$$

where $\Gamma_0(\theta)$, $\Gamma_1(\theta)$, $\Psi(\theta)$, and $\Pi(\theta)$ are appropriately defined coefficient matrices. We follow Sims' (2002) solution algorithm that was revisited by Lubik and Schorfheide

(2003). This has the 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 will be a linear function of the fundamental shocks and the purely extrinsic sunspot disturbances, ζ_t. Hence, the full set of solutions to the LRE model entails

$$\varrho_t = \Phi(\theta)\varrho_{t-1} + \Phi_\varepsilon(\theta, \widetilde{M})\varepsilon_t + \Phi_\zeta(\theta)\zeta_t \tag{8}$$

where $\Phi(\theta)$, $\Phi_\varepsilon(\theta, \widetilde{M})$ and $\Phi_\zeta(\theta)$[9] are the coefficient matrices.[10] 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) pure extrinsic non-fundamental disturbances can affect 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 Lubik and Schorfheide (2004) we replace $\widetilde{M}$ with $M^*(\theta)+M$ and in the subsequent empirical analysis set the prior mean for M equal to zero. The particular solution employed in their paper selects $M^*(\theta)$ by using a least squares criterion to minimize the behavior of the model under determinacy and indeterminacy by assuming that it remains unchanged across the boundary. "Behavior" needs be described in some meaningful way and we follow them by choosing $M^*(\theta)$ such that the response of the endogenous variables to fundamental shocks, $\partial\varrho_t/\partial\varepsilon_t'$, are continuous at the boundary between the determinacy and the indeterminacy region. Analytical solution for the boundary in this model is unavailable and hence, following Justiniano and Primiceri (2008) and Hirose (2014), we resort to a numerical procedure for the model to find the boundary by perturbing the parameter ψ_π in the monetary policy rule.

3 Econometric strategy

3.1 Bayesian estimation with Sequential Monte Carlo (SMC) algorithm

We use Bayesian techniques for estimating the parameters of the model and test for indeterminacy using posterior model probabilities. In our estimation, we employ the Sequential Monte Carlo (SMC) algorithm proposed by Herbst and Schorfheide (2014, 2015) which is particularly suitable for irregular and non-elliptical posterior distributions. Another practical advantage of using an importance sampling algorithm like SMC is that the process does not require one to find the mode of the posterior distribution, a task that can prove to be difficult particularly under indeterminacy.[11]

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

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

[11] See also Hirose, Kurozumi and Van Zandwaghe (2017) who are the first ones to apply Bayesian estimation using SMC algorithm to test for indeterminacy using Lubik and Schorfheide's (2003, 2004) methodology.

First priors are described by a density function of the form

$$p(\theta_S|S).$$

Here $S \in \{D, I\}$ where D and I stand for determinacy and indeterminacy respectively, θ_S represents the parameter of the model S, $p(.)$ stands for probability density function. Next, the likelihood function describes the density of the observed data:

$$\mathcal{L}(\theta_S|X_T, S) \equiv p(X_T|\theta_S, S)$$

where X_T are the observations until period T. By using Bayes theorem we can combine the prior density and the likelihood function to get the posterior density:

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

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

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

This paper employs the SMC algorithm of Herbst and Schorfheide (2014, 2015) to build a particle approximation of the posterior distribution through tempering the likelihood. A sequence of tempered posteriors is defined as

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

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

The algorithm generates weighted draws from the sequence of posteriors $\{\pi_n(\theta)\}_{n=1}^{N_\phi}$, 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.

Note that in the first stage, i.e. when $n = 1$, ϕ_1 is zero. Hence, the prior density serves as an efficient proposal density for $\pi_1(\theta)$. That is, the algorithm is initialized by drawing the initial particles from the prior. Likewise, the idea is that the density of $\pi_n(\theta)$ may be a good proposal density for $\pi_{n+1}(\theta)$.

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 tempering schedule. In our estimation, the tuning parameters N, N_ϕ and τ are fixed ex ante. We use $N = 10,000$ particles and $N_\phi = 200$ stages. Also, τ, which is the parameter that controls the tempering schedule, is set at 2 following Herbst and Schorfheide (2015).

Resampling Resampling is necessary to avoid particle degeneracy. A rule-of-thumb measure of this degeneracy, proposed by Herbst and Schorfheide (2014, 2015), is given by the reciprocal of the uncentered variance of the particles and is called the effective sample size (ESS). Following them, we use systematic resampling whenever $ESS_n < \frac{N}{2}$.

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

3.2 Data

To estimate the parameters of the model and test for indeterminacy, we employ three U.S. quarterly time series: per capita real GDP growth rate, quarterly growth rate of the GDP deflator, and the Federal funds rate.[12] To compare the fit of constant versus time-varying target inflation and to test for indeterminacy we estimate the model over two sample periods. The first, $1966 : I - 1979 : II$, corresponds to the Great Inflation period before the Volcker chairmanship. The second period, $1984 : I - 2008 : II$, corresponds to the Great Moderation period characterized by dramatically milder macroeconomic volatilities. The second sample ends before the onset of the zero lower bound as the solution and estimation strategy is not designed to deal with it. The measurement equation relating the relevant elements of ϱ_t to the three observables is given by

$$\begin{bmatrix} 100\Delta \log Y_t \\ 100\Delta \log \Pi_t \\ R_t \end{bmatrix} = \begin{bmatrix} g^* \\ \pi^* \\ r^* \end{bmatrix} + \begin{bmatrix} y_t - y_{t-1} + g_t \\ \pi_t \\ r_t \end{bmatrix}$$

where $g^* = 100(g - 1)$, $\pi^* = 100(\pi - 1)$ and $r^* = 100(r - 1)$.

3.3 Calibrated parameters

We calibrate a subset of the model parameters. We set the discount factor β to 0.99, the steady-state markup at ten percent (i.e. $\varepsilon = 11$), and the inverse of the labor-supply elasticity to one. Following Cogley, Primiceri and Sargent (2010), we also fix the autoregressive parameter of the target inflation shock $\rho_{\pi^*} = 0.995$, in order to have a highly persistent autoregressive process.[13] We estimate all the remaining parameters.

[12] These variables are standard for estimating small-scale DSGE models. See, for instance, Cogley, Primiceri and Sargent (2010), Hirose, Kurozumi and Van Zandwaghe (2017).

[13] Alternatively, one may follow Ireland (2007) by assuming the target inflation shock follows a unit-root process. Instead, we calibrate it at $\rho_{\pi^*} = 0.995$ as Cogley, Primiceri and Sargent (2010) show that a unit-root target inflation may counterfactually imply low inflation gap predictability.

3.4 Prior distribution

The specification of the prior distribution is summarized in Table 1. 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 output gap and output growth are centered at 0.125 with standard deviation 0.10. We use Beta distribution with mean 0.50 for the smoothing coefficient ρ_r, the Calvo probability ξ and habit h, and 0.70 for the persistence of the discount factor shock. The autoregressive parameter of the TFP shock is centered at 0.40 since this process already includes a unit-root. 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 0.50 and standard deviation 0.20. The exception is the standard deviation of the innovation to the inflation target which is an important parameter in our analysis. Following Cogley, Primiceri and Sargent (2010) we adopt a weakly informative uniform prior on $(0, 0.15)$.

Finally, we follow Lubik and Schorfheide (2004) by having the coefficient of the vector M follow standard normal distributions. Hence, the prior is centered around the baseline solution of Lubik and Schorfheide (2004) The choice of the prior 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

This section presents the empirical analysis. First, our findings in terms of model comparison are documented. Next, we discuss the parameter estimates, the estimated inflation target and the forecast error variance decomposition.

4.1 Model comparison

This subsection begins by comparing the empirical performance of the model with constant vs. time-varying target inflation. Table 2 collects our results. To assess the quality of the model's fit to the data we use log marginal data densities and the posterior model probabilities for both parametric regions. The SMC algorithm-based approximation of the marginal data density is given by

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

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

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

Following a vast literature initiated by Clarida, Gali and Gertler (2000) and studied further by Lubik and Schorfheide (2004) and Boivin and Giannoni (2006) among others, we begin by assuming constant positive target inflation. Our estimation implies that the evidence for (in-)determinacy for pre-Volcker is mixed while determinacy prevails after 1984. Phrased alternatively, we cannot dismiss the possibility of indeterminacy in the first sub-sample. Indeed, when assuming firm-specific labor instead of homogenous labor as in Hirose, Kurozumi and Van Zandwaghe (2017), pre-Volcker is unambiguously characterized by indeterminacy (as shown in a later section).

However, the view of a constant inflation target is disputed by many. Amongst them, Kozicki and Tinsley (2005, 2009), Cogley and Sargent (2005a), Ireland (2007), Stock and Watson (2007), Cogley and Sbordone (2008), Leigh (2008), Cogley, Primiceri and Sargent (2010), Castelnuovo (2010), Coibion and Gorodnichenko (2011), Bjornland, Leitemo and Maih (2011) and Castelnuovo, Greco and Raggi (2014) find evidence in favor of a time-varying inflation target. Hence, following this literature, next we allow for time variation in the inflation target pursued by the Fed and the results are drastically different. Both pre-Volcker and post-84 sample periods can ostensibly be characterized by determinacy as the posterior concentrates all of its mass in the determinacy region. This finding suggests that the Federal Reserve policy, even during the Great Inflation period, was sensible and did not open the door for any self-fulfilling fluctuations.

Given such opposing findings with regard to constant vs. time-varying target, it is necessary to compare the fit of the two specifications. In terms of posterior odds ratio, the marginal likelihood points toward the empirical superiority of the model taking time variation in target inflation into account. The Bayes factor involving constant target and time-varying target reads about 25 for pre-Volcker and about 10 for post-84 sample periods. This suggests a "positive" evidence in favor of the model where the Fed follows a time-varying target.[14]

4.2 Parameter estimates

Table 3 reports the posterior estimates of the parameters under time-varying target inflation. As seen in the table, the policy parameters have changed substantially between the two periods. In line with the findings of Hirose, Kurozumi and Van Zandwaghe (2017), the policy response to inflation gap almost doubled, the policy response to output growth increased by a factor of 3, and trend inflation fell considerably by a third. Moreover, like Cogley, Primiceri and Sargent (2010), we find that the innovation variance of the two shocks: $\epsilon_{\pi^*,t}$ and $\epsilon_{r,t}$, have declined quite notably. According to our estimates, the innovation variance fell by about 50 percent, from 0.08 to 0.04 for the target inflation shock, and from 0.36 to 0.19 for the policy-rate shock. However, unlike Cogley, Primiceri and Sargent (2010) who find a moderate increase in the responsiveness to inflation gap, we find quite a substantial increase across the two periods. This suggests that both the systematic response to inflation

[14] 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.

gap and a better anchoring of inflation target might have played a key role in the decline in inflation volatility and predictability after 1980.

Among the structural parameters, habit h and Calvo probability ξ do not change across the two periods. This is of some comfort as these parameters are supposed to be invariant to changes in monetary policy.[15] Among the non-policy shocks, there is an increase in the persistence and volatility of the discount factor shock, a finding we share with Hirose, Kurozumi and Van Zandwaghe (2017). However, we find a decline in the volatility of technology shocks, a finding in line with Smets and Wouters (2007).

4.3 Federal Reserve's inflation target

At this stage, we would first like to assess the model-implied evolution of the Federal Reserve's inflation target. Recall that π_t^* is treated as a latent variable in our likelihood-based estimation of the model. Here, we use Kalman smoother to obtain ex-post estimates of π_t^* based on the observations that are included in the construction of the likelihood function. As such this serves as an external validity check. Figure 1 plots the smoothed estimates of the (latent) target inflation process on top of actual annualized quarterly inflation of the GDP deflator. As seen in the figure, target inflation began rising in the mid-1960s and jumped up to 7% in the aftermath of the 1973 oil crisis. Subsequently, it dropped significantly during the Volcker disinflation and somewhat settled around 2.5% since the mid-1980s. The figure suggests that our estimated inflation target is similar to one proposed by Ireland (2007), Leigh (2008), Cogley, Primiceri and Sargent (2010), Auroba and Schorfheide (2011), Castelnuovo, Greco and Raggi (2014).

4.4 Forecast error variance decomposition

In this section, we assess the role of the various shocks by appealing to forecast error variance decomposition (FEVD) exercise. The FEVDs are constructed by computing the contribution of each shock in explaining the forecast errors of the variables of interest. Our computations, conditional on the estimated posterior means, refer to several horizons ranging from 1-step ahead up to ∞-step ahead to assess the contribution of each shock at various business cycle frequencies as well as the unconditional variances. Tables 4 and 5 report our results for the two sub-samples.

First of all, the results show that technology shocks play a dominant role in explaining the fluctuations in output growth for both the sample periods accounting for over 90% of the fluctuations across all forecast horizons. This stands in contrast to Ireland (2004), who finds a secondary role for technology shocks and concludes

[15] Kurozumi (2016) shows that when the degree of price stickiness is endogenously determined in the Calvo model, the probability of price adjustment rises with trend inflation and this mitigates the effect of higher trend inflation on the likelihood of indeterminacy. However, following Ascari and Ropele (2007, 2009), Coibion and Gorodnichenko (2011) and Ascari and Sbordone (2014), we assume that price stickiness is exogenously determined. As such, one would expect the Calvo probability to be a structural parameter that is invariant to policy changes. Incorporating endogenous price stickiness into the existing empirical investigation is an interesting extension which we leave for future research.

that other shocks appear to be more important (or at least as important) than the technology shock in the New Keynesian model. One key difference between our model and Ireland's (2004) is that we log-linearize the model around a positive steady state trend inflation while Ireland (2004) assumes zero inflation in the steady state. This modeling assumption is not innocuous as Ascari and Sbordone (2014) show that trend inflation substantially affects the propagation of technology shocks.[16] Our finding resurrects the link between current generation of New Keynesian models and the real-business cycle models from which they were originally derived.

Yet technology shocks play a negligible role in explaining the fluctuations of the nominal variables. Here we focus on both mean-based and target-based gap. Mean-based inflation gap is defined as the difference between inflation and the central bank's long-run inflation target which is also the steady state inflation in the model; whereas target-based inflation gap is the difference between inflation and the central bank's time-varying short run inflation objective. Importantly, the target inflation shock plays a considerable role as regards the inflation gap and policy rate, mainly at medium to low frequency. This corroborates the results in Castelnuovo (2010) who finds a similar role for inflation target shocks. As pointed out by Castelnuovo (2010), this finding is not necessarily a consequence of the calibration imposed on the autoregressive parameter for target inflation ($\rho_{\pi^*} = 0.995$) since the volatility of the process, which is estimated, clearly matters as well. Moreover, while being relevant for the unconditional FEVDs of mean-based inflation gap (given its high persistence), the role of such a calibration is less obvious for the FEVD of target-based gap even at lower frequencies.

As regards the policy-rate shock and the preference shock, the contribution is considerable in explaining the fluctuations in inflation gap and policy rate at shorter horizons. For instance, the preference shock is most important in driving movements in the nominal interest rate at higher frequencies.

Finally, it is also interesting to compare the differences in the relevance of the shocks across sub-samples. As mentioned above, technology shock is the key driver of fluctuations in output growth in both sample periods. While in the Great Inflation era target inflation shocks play a dominant role in explaining the fluctuations of target-based inflation gap and the policy rate, however, when moving to the Great Moderation sub-sample we find notable difference. The variance decompositions reveal that both preference and policy-rate shocks are important in explaining movements in target-based inflation gap even at longer horizons. Moreover, for policy rate fluctuations, preference shocks play a key role at all horizons.

Overall, the variance decomposition exercise suggests that the decline in the innovation variance of target inflation shocks might have played a significant role with regard to the decline in inflation gap volatility while technology shocks might have been more important for the decline in output growth volatility.

[16] See Figure 13 in the published paper.

5 Time-varying inflation target: relation to the literature

How does our implicit inflation target compare with the evidence in the literature? Figure 2 compares our inflation target estimate with a selection of other proposed measures: Kozicki and Tinsley (2005), Ireland (2007), Leigh (2008), Cogley, Primiceri and Sargent (2010), Auroba and Schorfheide (2011), and Castelnuovo, Greco and Raggi (2014).[17] Each panel plots GDP deflator inflation rate as well.

Several notable findings arise. First of all, there is a striking difference between our estimated target and Kozicki and Tinsley's (2005). Kozicki and Tinsley (2005) 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 between our estimate and theirs 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), we find that the co-movement between the two series is very similar: with a correlation of 0.98 and 0.83 for pre-Volcker and post-1984 sub-sample respectively.[18]However, Figure 2.4 documents clear evidence of a gap between the two target inflation 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 shortcoming by explicitly modelling inflation's long-run value (by log-linearizing around a positive steady state) on top of its dynamics.

Next, our implicit inflation target is close to those of Ireland (2007)[19], Auroba 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 0.96 respectively.[20]However, our estimated target turns out to be much smoother and somewhat different than theirs. In particular, since the early 2000s, there is a clear divergence between the estimates. During this period, our estimate turns out to be higher than the alternative measures as well as actual inflation itself. This finding is intuitive and captures the fear of deflation among policymakers at that time which led to extra easy monetary policy and lowering of the Federal Funds rate.[21]As noted by Eggertsson and Woodford (2003), keeping interest rates too low for too long is equivalent to a rise in the time-varying inflation target.

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[17]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; Auroba and Schorfheide (2011) - *American Economic Review* (website), their paper, zip file under "Additional Materials - Download Data Set", "inflation-target.xls" file, "filtered f2 estimates".

[18]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.

[19]Ireland (2007) studies different target inflation processes, including some which allow for a systematic reaction to structural shocks hitting the economy. Figure 2.2 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).

[20]The numbers again relate to mutually overlapping periods, in this case, 1966:I - 1979:II.

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

Our estimates are also strikingly similar to Leigh (2008) who estimates the implicit inflation target using a time-varying parameter Taylor rule and the Kalman filter focusing on post-1980 sample period alone.[22] As in Leigh (2008, p. 2022-23), we can divide our time-varying implicit inflation target for the post-1984 sub-sample 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 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.

Finally, as a note of caution, one must be careful when drawing these comparisons. As Castelnuovo, Greco and Raggi (2014) point out, the differences could be due to differences in investigated samples, data transformation, structure imposed on the data and vintage of the data.

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

What are the reasons behind the decline in macroeconomic volatility and inflation gap predictability? In this section, we follow Cogley, Primiceri and Sargent (2010) and Castelnuovo (2010) to conduct counterfactual exercises to disentangle the role played by 'good policy' and 'good luck'. In comparison to these studies, our exercise is still meaningful as we depart from them by estimating a model log-linearized around a positive steady state inflation rate. This has been shown by Ascari and Ropele (2007, 2009) and Ascari and Sbordone (2014) to substantially alter the NKPC relationship and hence the inflation dynamics. This further allows us to analyze both mean-based and target-based inflation gap.

Table 6 summarizes the model's implications for the volatility and predictability of inflation gap and the volatility of output growth at the posterior mean of the model parameters. First and foremost, the estimated model is able to replicate the observed drop in output growth and inflation gap volatility.[23]We find a fall of output growth variability of 37%, and a drop of mean-based and target-based inflation gap volatility of about 70% and 76% respectively. The data we use in estimation implies a fall of the standard deviation of output growth of about 50% and that of inflation of about 60%. Even though the estimated model is slightly off-target, our figures are very similar 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.

We also focus on the persistence of inflation gap using the R_j^2 statistic proposed

[22] Leigh (2008) focuses on estimating the implicit target based on both core PCE inflation and GDP/GNP implicit deflator inflation. Figure 2.3 plots the one labelled as "Estimate of GDP/GNP deflator target (real-time forecasts)" (see Figure 5, page 2028 in the published paper).

[23] We compute the population standard deviation of the variables by numerically solving the Lyapunov equation associated with the state-space representation of the model.

by Cogley, Primiceri and Sargent (2010).[24] To measure persistence at a given date t, these authors propose to calculate the fraction of the total variation in inflation gap that is due to shocks inherited from the past relative to those that will occur in the future. They suggest that this is equivalent to one minus the fraction of the total variation due to future shocks. Since future shocks account for the forecast error, they express this as one minus the ratio of the conditional variance to the unconditional variance where j denotes the forecast horizon. Table 6 reports R_j^2 statistic for inflation gap predictability for forecast horizons of one, four and eight quarters following Cogley, Primiceri and Sargent (2010). However, since we allow for positive steady state trend inflation, we consider both mean-based and target-based inflation gap. Some interesting results arise. Similar to the findings reported in Cogley, Primiceri and Sargent (2010), there has been a marked decline in the persistence of time-varying target-based gap at all three horizons. However, it is remarkably muted for mean-based inflation gap. This shows that the persistence of these two series is considerably different, a finding that is in line with the autocorrelation of the two series based on pre and post-Volcker data reported in Ascari and Sbordone (2014).[25]Moreover, our finding is also in line with Benati (2008) who fails to detect a change in raw inflation persistence in the U.S. around the time of the Volcker stabilization. Importantly, both mean-based inflation gap and raw inflation remained persistent as target inflation continued to drift after the Volcker disinflation. Instead, it is time-varying target-based inflation gap that has become less persistent. Hence, our results shed further light on the findings of Cogley and Sargent (2002, 2005a), Cogley, Primiceri and Sargent (2010) on the one hand and Benati (2008) on the other.

6.1 Counterfactuals

Next we conduct counterfactual exercises designed to disentangle the role played by 'good policy' and 'good luck' in explaining the Great Moderation where we closely follow the counterfactual scenarios studied in Cogley, Primiceri and Sargent (2010) and Castelnuovo (2010). Following these authors, we divide the experiment into two broad categories. First, we combine the parameters pertaining to the Taylor rule, i.e. ψ_π, ψ_x, $\psi_{\Delta y}$, ρ_r, π^*, σ_r, σ_{π^*}, of the post-84 sub-sample with the private sector parameters of the pre-79 period which is called 'Policy 2, Private 1'. This is designed to capture the role of better monetary policy in reducing the volatility of inflation gap (both mean-based and target-based) and output growth and the persistence of the target-based inflation gap series. We also inspect the policy parameters in detail to gain further insights. In the second category, we combine private sector parameters of the second sub-sample with the policy parameter of the first. This scenario, labelled 'Policy 1, Private 2', is designed to study the contribution of non-policy factors.

[24] Using this measure of persistence based on short- and medium-term predictability within a simple New Keynesian model, Benati and Surico (2008) show that a more aggressive poliy stance towards inflation causes a decline in inflation predictability. However, they estimate the model for the Great Moderation period only, thus stopping short of using the methodology of Lubik and Schorfheide (2003, 2004) to allow for indeterminacy and estimate the model during the Great Inflation period as well.

[25] See their Table 1, page 688.

Table 7 reports the counterfactual results for the volatility of output growth and the two inflation gap series. We report the standard deviations and the percentage deviations with respect to the pre-Volcker scenario. First and foremost, we find that better monetary policy, both in terms of systematic component and a better anchoring of inflation target, is likely to have played a major role in the decline of inflation gap volatility (Policy 2, Private 1). However, better monetary policy alone cannot explain the decline in output growth variability, a finding we share with Castelnuovo (2010) who looks at output gap instead. We find that 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 required to jointly explain the reduction in output growth and inflation gap volatility.

Digging further into better monetary policy, we find that both stronger response to inflation gap (ψ_π) and better anchored inflation objective, i.e. a reduction in the volatility of target inflation shocks (σ_{π^*}), are key ingredients in the reduction of inflation gap variability. This stands in contrast to Cogley, Primiceri and Sargent (2010) and Castelnuovo (2010) who both find that a stronger response to inflation during the Great Moderation period only plays a minor role. Interestingly, we also find that the decline in the Fed's long-run inflation target (π^*) plays a negligible role in the reduction of inflation gap volatility. That a reduction in π^* is negligible for the reduced variability of target-based inflation gap is *a-priori* expected as π^* cancels out when looking at log-deviations of the inflation gap, $\pi_t - \pi_t^*$. However, that it is quantitatively unimportant for variability of mean-based inflation gap as well is much less obvious given the qualitative result in Ascari and Sbordone (2014) that trend inflation affects the volatility of macroeconomic variables.

We also conduct counterfactual exercises as regards the decline in inflation gap persistence using the same R_j^2 statistic. Here we focus on time-varying target-based inflation gap alone as the decline in the persistence of mean-based gap is rather muted. Table 8 reports our results. The main message from these experiments goes hand in hand with the counterfactuals related to volatility reduction. In particular, we find that better monetary policy, once again in terms of both systematic component and reduced variability of target inflation shocks, are key drivers of the decline in the inflation gap predictability. Moreover, the decline in the Fed's long-run inflation target, i.e. π^*, plays a quantitatively negligible role.

7 Further investigation

In contrasting constant vs. time-varying target inflation, our analysis so far has relied on a Generalized New Keynesian model with homogenous labor following Ascari and Ropele (2009) and Ascari and Sbordone (2014). We find that time-varying target inflation empirically fits better than a model featuring constant target inflation and determinacy prevails in both pre-Volcker as well as post-1984 sample periods. However, Kurozumi and Van Zandwaghe (2017) show that a similar model with firm-specific labor is more susceptible to indeterminacy induced by high trend inflation than a model with homogenous labor. Hence, we conduct further investigation along this dimension and estimate the model of Hirose, Kurozumi and Van Zandwaghe (2017) who employ firm-specific labor following Kurozumi and Van Zandwaghe (2017). In order to establish a valid comparison, we use the exact same set of priors, observables and sample periods as they do.[26]However, to achieve identification between the target inflation process and the policy-rate shock, we assume that the latter follows a transitory i.i.d. process while the former is a highly persistent AR(1) process as before. Table 9 collects our results for the marginal data densities and the posterior model probabilities.

In line with Hirose, Kurozumi and Van Zandwaghe (2017), we find that the pre-Volcker period is unambiguously characterized by indeterminacy while the post-1982 period is characterized by determinacy under the assumption of a constant target inflation. However, when we allow for time-varying target inflation, determinacy prevails for both the sample periods. When comparing the fit of constant vs. time-varying target, we see that it is comparable for the pre-Volcker period while time-varying target fits better in the post-1982 period. Given that firm-specific labor makes the model more prone to indeterminacy due to higher trend inflation, this set of results somewhat mitigates, yet does not completely overturn, our findings. The hypothesis that the Fed might have pursued a time-varying inflation target and as a consequence determinacy might have prevailed even in the pre-Volcker period is a possibility that cannot be empirically ruled out.

8 Conclusion

This paper compares Generalized New Keynesian monetary DSGE models under constant vs. time-varying inflation target pursued by the Fed. While allowing for indeterminacy, we assess the empirical fit of these two different specifications for the period $1966 : I - 1979 : II$ and $1984 : I - 2008 : II$. Several notable findings arise. First, when considering the model with constant inflation target, we find that indeterminacy cannot be ruled out in the pre-Volcker period while there is a switch to determinacy after Volcker disinflation. However, we find that determinacy unambiguously prevails in both the sample periods when we model the Fed as following a time-varying inflation target. Interestingly, the data support the model with time variation in the Fed's inflation objective as empirically superior with respect to the standard constant target model. To the best of our knowledge, this paper is the first one to test for indeterminacy using a full–information structural approach while comparing the fit of constant vs. time-varying target. The finding that even pre-Volcker could possibly be characterized by determinacy is a novel result. Furthermore, counterfactual simulations suggest that both 'good policy' and 'good luck' are required to explain the Great Moderation. We find that better monetary policy, both in terms of a more active response to inflation gap and a more anchored inflation target, has resulted in the decline of inflation gap volatility and predictability. In contrast, technology shocks are likely to have played a key role in the reduction of output growth

[26]The pre-1979 period in Hirose, Kurozumi and Van Zandwaghe (2017) is the same as ours, 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 our findings.

volatility.

We chose to make these arguments by assuming that trend inflation is positive but constant while the Fed pursues a time-varying inflation target. This choice enables us to keep the analysis simple yet related to existing research. However, one could depart instead by log-linearizing the equilibrium conditions around a steady state characterized by drifting trend inflation which would result in a New Keynesian Phillips curve with drifting coefficients. Monetary DSGE models with time-varying coefficients and stochastic volatilities have been estimated by Fernandez-Villaverde and Rubio-Ramiresz (2007a,b) and Fernandez-Villaverde, Guerron-Quintana and Rubio-Ramirez (2010). We wish to pursue these lines of research in the future.

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Table 1 - Prior distributions for parameters.

Parameter	Range	Density	Prior Mean	St. Dev
ψ_{π}		Gamma	1.10	0.50
ψ_x		Gamma	0.125	0.10
$\psi_{\Delta y}$		Gamma	0.125	0.10
ρ_r		Beta	0.50	0.20
π^*		Normal	0.976	0.50
r^*		Gamma	1.612	0.25
g^*		Normal	0.50	0.10
h		Beta	0.50	0.10
ξ		Beta	0.50	0.10
ρ_d		Beta	0.70	0.10
ρ_g		Beta	0.40	0.10
σ_r		Inv-Gamma	0.50	0.20
σ_d		Inv-Gamma	0.50	0.20
σ_g		Inv-Gamma	0.50	0.20
σ_{π^*}		Uniform	0.075	0.0433
σ_{ζ}		Inv-Gamma	0.50	0.20
$M_{r,\zeta}$		Normal	0.00	1.00
$M_{d,\zeta}$		Normal	0.00	1.00
$M_{g,\zeta}$		Normal	0.00	1.00
$M_{\pi^*,\zeta}$		Normal	0.00	1.00

Notes: The inverse gamma priors are of the form
$p(\sigma|\upsilon,\varsigma) \propto \sigma^{-\upsilon-1} e^{-\frac{\upsilon\varsigma^2}{2\sigma^2}}$ where where $\nu = 4$ and $\varsigma = 0.38$.
The prior probability of determinacy is 0.48.

Table 2: Determinacy versus Indeterminacy

Sample	Target inflation	Log-data density		Probability	
		Determinacy	Indeterminacy	Determinacy	Indeterminacy
1966:I-1979:II	Constant	-126.22	-126.25	0.51	0.49
	Time-varying	-122.99	-128.58	1	0
1984:I-2008:II	Constant	-29.75	-41.76	1	0
	Time-varying	-27.52	-53.29	1	0

Table 3: Posterior estimates for DSGE parameters under time-varying target

	Pre-1979 period		Post-1984 period	
Parameter	Mean	[5th pct, 95th pct]	Mean	[5th pct, 95th pct]
ψ_π	2.01	$[1.32, 2.60]$	3.94	$[3.03, 4.88]$
ψ_x	0.12	$[0.02, 0.29]$	0.13	$[0.02, 0.34]$
$\psi_{\Delta y}$	0.15	$[0.03, 0.33]$	0.45	$[0.14, 0.76]$
ρ_r	0.51	$[0.24, 0.72]$	0.75	$[0.65, 0.81]$
π^*	1.31	$[0.93, 1.67]$	0.85	$[0.51, 1.22]$
r^*	1.57	$[1.22, 1.90]$	1.55	$[1.24, 1.90]$
g^*	0.54	$[0.37, 0.68]$	0.51	$[0.40, 0.62]$
h	0.42	$[0.31, 0.55]$	0.42	$[0.32, 0.53]$
ξ	0.53	$[0.33, 0.74]$	0.53	$[0.39, 0.65]$
ρ_d	0.74	$[0.59, 0.85]$	0.92	$[0.88, 0.95]$
ρ_g	0.27	$[0.14, 0.49]$	0.18	$[0.12, 0.27]$
σ_r	0.36	$[0.25, 0.52]$	0.19	$[0.15, 0.24]$
σ_d	1.19	$[0.37, 2.20]$	1.84	$[1.24, 2.74]$
σ_g	1.04	$[0.32, 1.73]$	0.73	$[0.61, 0.89]$
σ_{π^*}	0.08	$[0.02, 0.14]$	0.04	$[0.02, 0.05]$

Results based on 10,000 particles from the final stage in the SMC algorithm.

Table 4: Forecast Error Variance Decompositions: Pre-1979 Sub-sample

Quarters Ahead	Policy Shock	Preference Shock	Technology Shock	Target Inflation Shock
		Output Growth		
1	3.54	2.53	93.92	0.02
4	3.74	2.60	93.41	0.25
8	3.74	2.60	93.40	0.25
20	3.74	2.60	93.40	0.25
40	3.74	2.60	93.40	0.25
∞	3.74	2.60	93.40	0.26
		Inflation Gap (Mean-based)		
1	22.72	44.39	0.61	32.28
4	13.25	33.16	1.10	51.69
8	9.24	24.53	0.77	65.47
20	5.08	13.55	0.42	80.95
40	3.10	8.27	0.26	88.37
∞	1.13	3.00	0.09	95.78
		Inflation Gap (Target-based)		
1	28.45	55.58	0.76	15.22
4	20.44	52.37	1.70	25.49
8	17.04	45.26	1.42	36.29
20	12.01	32.01	1.00	54.98
40	8.47	22.57	0.70	68.26
∞	3.64	9.70	0.30	86.36
		Interest Rate		
1	24.28	60.68	0.87	14.17
4	8.26	63.00	0.32	28.43
8	5.85	50.99	0.23	42.93
20	3.57	31.46	0.14	64.83
40	2.30	20.30	0.10	77.31
∞	0.89	7.81	0.03	91.26

Table 5: Forecast Error Variance Decompositions: Post-1984 Sub-sample

Quarters Ahead	Policy Shock	Preference Shock	Technology Shock	Target Inflation Shock
		Output Growth		
1	2.14	1.29	96.54	0.02
4	2.25	1.38	96.32	0.06
8	2.25	1.38	96.31	0.06
20	2.25	1.38	96.31	0.06
40	2.25	1.38	96.31	0.06
∞	2.25	1.38	96.31	0.06
		Inflation Gap (Mean-based)		
1	35.18	41.25	10.19	13.38
4	27.02	39.62	9.54	23.82
8	22.52	35.99	7.95	33.53
20	16.04	27.49	5.66	50.81
40	11.57	20.03	4.09	64.31
∞	5.16	8.93	1.82	84.10
		Inflation Gap (Target-based)		
1	39.18	45.94	11.35	3.53
4	33.87	49.65	11.96	4.52
8	32.00	51.13	11.30	5.57
20	29.82	51.12	10.53	8.52
40	28.34	49.06	10.01	12.60
∞	23.56	40.79	8.32	27.33
		Interest Rate		
1	20.21	74.43	0.03	5.34
4	4.81	87.13	0.28	7.78
8	2.94	86.74	0.17	10.14
20	2.04	80.52	0.12	17.32
40	1.73	70.98	0.10	27.19
∞	1.11	45.50	0.07	53.33

Table 6: Implications of the model for inflation gap volatility and predictability and output growth volatility

		St. Dev	R_1^2	R_4^2	R_8^2
Output growth	1966:I-1979:II	0.92	-	-	-
	1984:I-2008:II	0.58	-	-	-
	Percent Change	-37	-	-	-
Mean-based Inflation Gap	1966:I-1979:II	1.76	0.96	0.92	0.88
	1984:I-2008:II	0.52	0.87	0.81	0.77
	Percent Change	-70	-9	-12	-13
Target-based Inflation Gap	1966:I-1979:II	0.98	0.89	0.82	0.79
	1984:I-2008:II	0.24	0.47	0.30	0.26
	Percent Change	-76	-47	-63	-67

Table 7: Counterfactual standard deviations

Scenarios	Output Growth		Mean-based inflation gap		Target-based inflation gap	
	St. Dev	Percent Change	St. Dev	Percent Change	St. Dev	Percent Change
Policy 2, Private 1	0.90	-2	0.59	-66	0.28	-71
ψ_π, ψ_x, $\psi_{\Delta y}$, ρ_r	0.91	-1	1.16	-34	0.43	-56
ψ_π	0.91	-1	1.13	-36	0.35	-64
π^*	0.92	0	1.71	-3	0.93	-5
σ_{π^*}	0.92	0	0.92	-48	0.58	-41
Policy 1, Private 2	0.61	-34	1.77	+1	0.99	+1
σ_g, ρ_g	0.63	-32	1.76	0	0.98	0

Table 8: Counterfactual predictability

Scenarios	Target-based inflation gap					
	R_1^2	Percent Change	R_4^2	Percent Change	R_8^2	Percent Change
Policy 2, Private 1	0.38	-57	0.24	-71	0.23	-71
ψ_π, ψ_x, $\psi_{\Delta y}$, ρ_r	0.57	-36	0.46	-44	0.44	-44
ψ_π	0.77	-13	0.69	-16	0.66	-16
π^*	0.87	-2	0.80	-2	0.77	-3
σ_{π^*}	0.71	-20	0.58	-29	0.55	-30
Policy 1, Private 2	0.91	+2	0.84	+2	0.79	0

Table 9: Determinacy versus Indeterminacy (firm-specific labor)

		Log-data density		Probability	
Sample	Target inflation	Determinacy	Indeterminacy	Determinacy	Indeterminacy
1966:I-1979:II	Constant	-132.27	-120.86	0	1
	Time-varying	-120.68	-123.41	0.94	0.06
1984:I-2008:II	Constant	-47.56	-61.83	1	0
	Time-varying	-45.96	-70.96	1	0

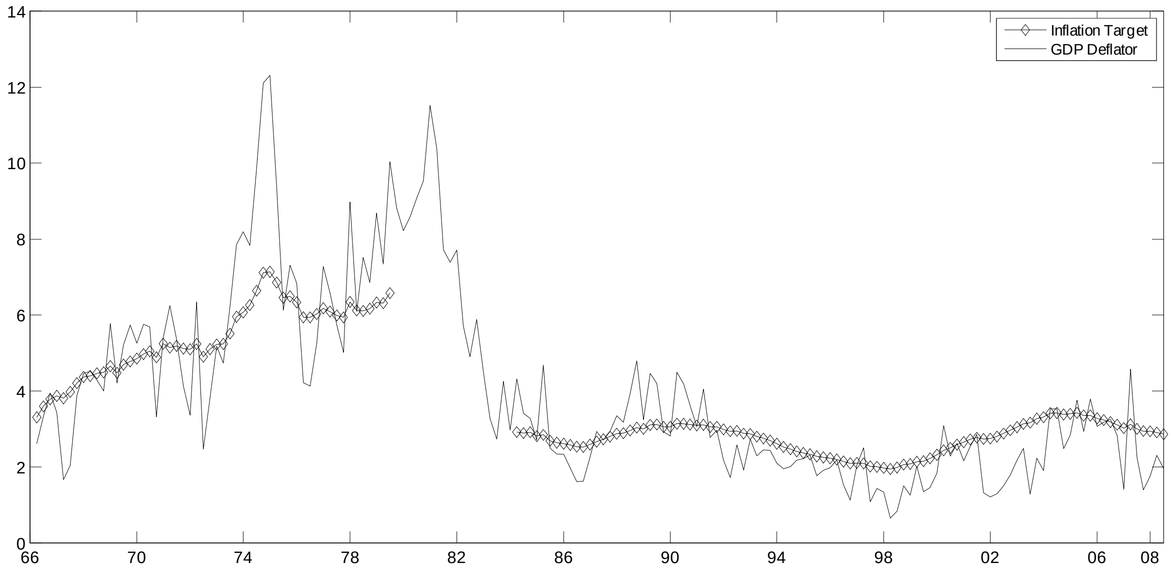

Figure 1: Federal Reserve's Inflation Target

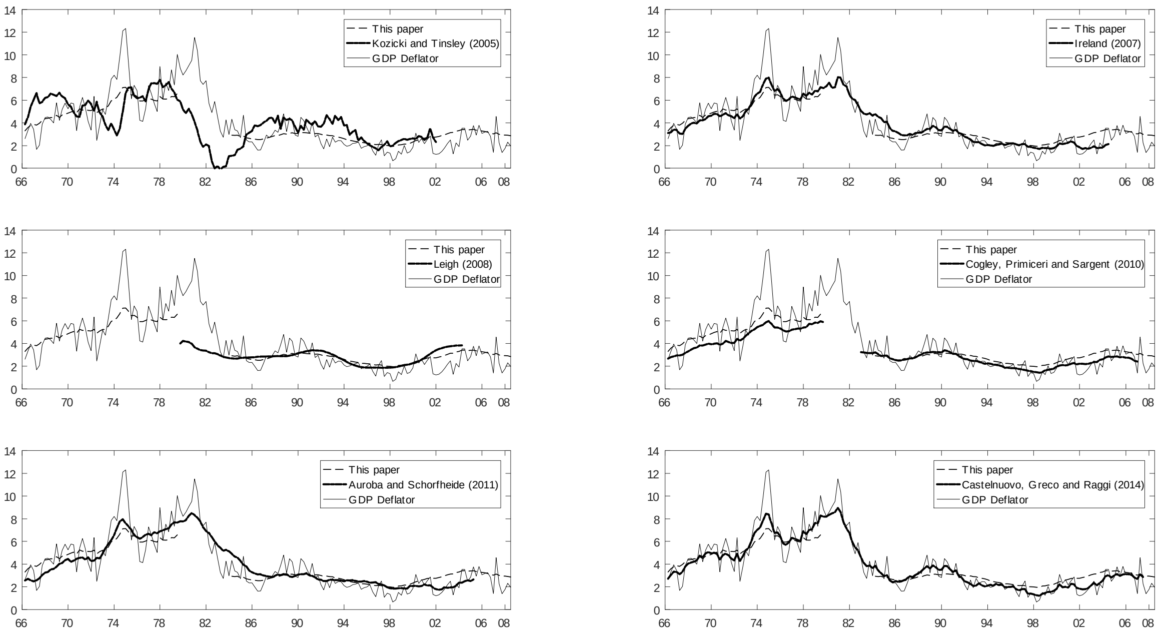

Figure 2: A comparison of inflation target estimates