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

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This paper estimates a New Keynesian model with trend inflation and contrasts Taylor rules featuring fixed versus time-varying inflation target. The estimation is conducted over the Great Inflation and the Great Moderation periods, while allowing for indeterminacy. 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.

JEL Codes: C11, C52, C62, E31, E32, E52.

1. Introduction

The post–World War II U.S. economy includes two particular eras: the Great Inflation and the Great Moderation. 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

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period (McConnell and Perez-Quiros 2000; Blanchard and Simon 2001; and Stock and Watson 2003). But 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 exogenous shocks hitting the economy—has been supported by a number of authors, including Stock and Watson (2003), 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 (Clarida, Galí, and Gertler 2000; Lubik and Schorfheide 2004) and an enhanced stability of the Federal Reserve's inflation target (Ireland 2007; Cogley, Primiceri and Sargent 2010).

The empirical plausibility of a link between monetary policy and macroeconomic instability in the 1970s was established by Clarida, Galí, and Gertler (2000) and further advocated by Lubik and Schorfheide (2004), who argue that U.S. monetary policy in the 1970s failed to respond sufficiently strongly to inflation, thereby generating indeterminacy.[1] Consequently, self-fulfilling inflation expectations are regarded as the driver of the high-inflation episode in the 1970s. According to this view, the switch from a passive to an active response to inflation has brought about a stable and determinate environment since the early 1980s.[2] 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

[1]Here *indeterminacy* refers to the multiplicity of rational expectations equilibria, such that there are infinite number of paths toward a unique steady state, and that the economy can be unexpectedly volatile due to self-fulfilling beliefs or sunspot shocks. In contrast, an equilibrium that is locally isolated and uniquely determined by preferences and technologies is called *determinate*. See Farmer (1999) for a formal definition.

[2]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 1 percent increase in inflation, the central bank should raise the nominal interest rate by more than 1 percentage point to ensure determinacy. Otherwise, it is labeled as *passive*.

decline in persistence and predictability of inflation around the time of the Volcker disinflation.

While existing studies focusing on indeterminacy only consider a fixed inflation target, a large part of the literature finds that time-varying target is empirically important in capturing the low-frequency movements of the inflation rate.[3] For example, Cogley and Sbordone (2008) structurally decompose inflation dynamics into a time-varying long-run component (i.e., trend inflation) and a short-run one (i.e., the inflation gap, given by the difference between inflation and trend inflation). Their main finding is that time-varying trend inflation captures the low-frequency variation in inflation dynamics, while the short-run inflation gap fits well into a purely forward-looking equation—the New Keynesian Phillips curve (NKPC)—without the need of any ad hoc intrinsic inertia. Moreover, 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 gap volatility and persistence during the Great Moderation. These findings square well with Milton Friedman's dictum that "Inflation is always and everywhere a monetary phenomenon." (Friedman 1968, p. 39). In fact, Ireland (2007) argues that Friedman's "always and everywhere" dictum strongly suggests that persistent movements in inflation, as observed in the data, could not have taken place without ongoing shifts in the Federal Reserve's inflation target. However, the Federal Reserve only explicitly revealed its inflation target in 2012 and did not have an explicit target until then. Hence, one must rely on a statistical or an econometric model to extract information about the Federal Reserve's inflation target from data on observed variables.

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 target, or allowed for time-varying inflation target, while restricting the model to determinacy alone.[4] Unfortunately, the assumption of a fixed versus time-varying inflation target is not innocuous for both (in)determinacy

[3] See Cogley and Sargent (2005a); Kozicki and Tinsley (2005, 2009); Ireland (2007); Cogley and Sbordone (2008); Cogley, Primiceri, and Sargent (2010); Justiniano, Primiceri, and Tambalotti (2013), to name just a few.

[4] One exception is Coibion and Gorodnichenko (2011), which we discuss below.

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 responds to deviations from a fixed target or time-varying target. This feature then affects the probability of being in a determinate or indeterminate regime. 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 also allowing for both indeterminacy and time-varying inflation target.[5] Notwithstanding, the paper does distinguish between trend inflation and time-varying inflation target, as in Aruoba and Schorfheide (2011). On one hand, 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 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. A fixed inflation target is simply equal to trend inflation in the model. On the other hand, following Sargent (1999), Cogley and Sargent (2005b), Primiceri (2006), and Sargent, Williams and Zha (2006), time-varying inflation target can be interpreted as the short-term goal pursued by the Federal Reserve owing to its changing beliefs about the inflation-output trade-off. Another interpretation is that the Federal Reserve opportunistically transformed supply shocks into persistent inflation changes in order to limit output losses in the 1970s, when shocks were mainly adverse. In contrast, the Federal Reserve acted in order to bring down inflation in the 1980s and 1990s, when shocks were mainly favorable (see Ireland 2007 and references cited therein). Along these lines, time-varying inflation target is assumed to follow a persistent exogenous process as in Ireland (2007) and Cogley, Primiceri, and Sargent (2010), but one whose unconditional mean

[5] Ascari, Bonomolo, and Lopes (2019) also allow for temporarily unstable paths in a simple New Keynesian model with fixed zero inflation target, while this paper requires all solutions to be stable, in line with previous contributions in the literature.

is equal to the steady state or trend inflation. Hence, we formalize neither the decisional process by the Federal Reserve to vary its target over time nor the learning process which possibly induced the evolution of such target. Nonetheless, the paper provides a quantitative assessment of the relevance of inflation target shocks hitting the low-frequency component of inflation, particularly for (in)determinacy.[6]

The estimation is conducted over two different periods covering the Great Inflation (1960:Q1–1979:Q2) and the Great Moderation (1984:Q1–2008:Q2). The paper finds that when considering the model with a fixed inflation target, indeterminacy cannot be ruled out before 1979 while determinacy prevails after 1984, which is in line with the existing empirical literature (Lubik and Schorfheide 2004; Hirose, Kurozumi, and Van Zandweghe 2020). Yet, this outcome differs when allowing for a time-varying inflation target. This time the posterior density favors determinacy for both the pre-1979 and post-1984 subsamples. This result suggests that monetary policy, even during the pre-Volcker period, was likely to be sufficiently active to ensure determinacy. Using the Bayes factor to compare the two specifications, the paper then reports evidence in favor of time variation in the inflation target process. What is driving the determinacy 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. For a given historical path of the nominal interest rate, the response of the nominal rate to the inflation gap turns out to be higher in case of a time-varying target, which leads to determinacy. Moreover, as Cogley, Primiceri, and Sargent (2010) discuss, inflation target shocks induce persistent responses in the inflation gap, which helps to capture the highly persistent inflation dynamics in the 1970s. As such, the model does not require the richer endogenous inflation dynamics that arise under indeterminacy to explain the Great Inflation episode. Therefore, unlike the literature's preponderant view, this finding works against self-fulfilling inflation expectations (i.e., sunspots) as an explanation of the Great Inflation episode.

[6]For models in which inflation target evolves partly or fully endogenously, see Ireland (2007), Zanetti (2014), and Eo and Lie (2020).

The structure of the paper is as follows. Section 2 presents a brief overview of some closely related papers to provide further background and motivation. Section 3 sketches the model and its solution. Section 4 presents the econometric strategy, while Section 5 documents the estimation results. Robustness checks are performed in Section 6. Finally, Section 7 concludes.

2. Related Literature

Closely related to this paper are studies by Castelnuovo (2010), Cogley, Primiceri, and Sargent (2010), Aruoba and Schorfheide (2011), Coibion and Gorodnichenko (2011), Ettmeier and Kriwoluzky (2020), and Hirose, Kurozumi, and Van Zandweghe (2020), among others. Both Castelnuovo (2010) and Cogley, Primiceri, and Sargent (2010) estimate a New Keynesian model with time-varying inflation target using standard Bayesian Markov chain Monte Carlo (MCMC) techniques, while restricting the parameter space to determinacy, and perform counterfactual simulations to assess the drivers of the Great Moderation. This paper, on the other hand, estimates the model over the entire stable region of the parameter space using sequential Monte Carlo (SMC) techniques; that is, 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.

Coibion and Gorodnichenko (2011) use a single-equation approach to estimate a Taylor rule with time-varying coefficients using real-time data and 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 New Keynesian model with firm-specific labor and trend inflation. 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 dynamic stochastic general equilibrium (DSGE) model, as they point out.

Aruoba and Schorfheide (2011) develop and estimate a two-sector model comprising search-based monetary frictions and a standard New Keynesian economy with price rigidities. They study the steady-state welfare implications of the estimated model and suggest that distortions created by monetary frictions may be of similar magnitude as the distortions created by price stickiness in standard New Keynesian models. Although the focus of their paper is quite different, some of the features of their estimated model are quite similar to this study. In particular, both this paper and that of Aruoba and Schorfheide (2011) log-linearize the model around a non-zero steady-state inflation or trend inflation and assume an exogenous time-varying inflation target in the monetary policy rule.[7]

Hirose, Kurozumi, and Van Zandweghe (2020) estimate a New Keynesian model with firm-specific labor and a fixed inflation target (equal to trend inflation) using the same SMC methodology 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.[8] In contrast, this paper estimates a similar model with homogenous labor while also allowing for time variation in the inflation target process. The paper documents that a time-varying inflation target empirically fits better than a constant target and determinacy prevails in both sample periods.

In a recent paper, Ettmeier and Kriwoluzky (2020) also use the same SMC methodology and estimate a New Keynesian model with monetary and fiscal policy interactions. By estimating the model over the entire parameter space, Ettmeier and Kriwoluzky (2020) find that the pre-Volcker macroeconomic dynamics were driven by both a passive monetary/passive fiscal (indeterminate) regime and an active fiscal/passive monetary (determinate) regime. They show

[7] Aruoba and Schorfheide (2011) assume a random walk for the inflation target process, while this paper assumes a highly persistent but stationary process as in Cogley, Primiceri, and Sargent (2010).

[8] Arias et al. (2020) corroborate these findings by revisiting the relation between the sytematic component of monetary policy, trend inflation, and determinacy within a medium-scale DSGE model.

that due to fiscal dominance arising from the active fiscal/passive monetary regime, fiscal policy actions (in particular government spending) were critical in the inflation build-up in the 1970s. In contrast, this paper abstracts from fiscal policy actions and its interactions with monetary policy and instead focuses on evaluating monetary policy rules featuring fixed versus time-varying inflation target, while also analyzing its implications for (in)determinacy, through the lens of a generalized New Keynesian (GNK) model with non-zero steady-state inflation and no ad hoc backward-looking price indexation.[9] Ettmeier and Kriwoluzky's (2020) model, which is based on Bhattarai, Lee, and Park (2016), features indexation of non-reoptimized prices to both lagged inflation and steady-state inflation, thereby completely mitigating the effects of non-zero steady-state inflation on model dynamics (see Coibion and Gorodnichenko 2011 and Ascari and Sbordone 2014). However, Hirose, Kurozumi, and Van Zandweghe (2020) show that a GNK model with no price indexation fits the post-war U.S. data substantially better, which is also in line with Cogley and Sbordone's (2008) argument. An interesting avenue for future research would be to incorporate non-zero trend inflation without any backward-looking indexation into a model with monetary-fiscal interactions and empirically reexamine the drivers of the Great Inflation and subsequent Great Moderation.[10]

The finding that the pre-Volcker period could possibly be characterized by a unique equilibrium coincides with those of Orphanides (2004), Bilbiie and Straub (2013), and Haque, Groshenny, and Weder (2021). Orphanides (2004) finds an active response to expected inflation in a Taylor-type rule estimated for the pre-1979 period using real-time data, as opposed to ex post revised data, thereby claiming that self-fulfilling inflation expectations could not have been 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; that

[9]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.

[10]Ascari, Florio, and Gobbi (2018) study the long-run Taylor principle in a model with positive trend inflation and Markov-switching monetary and fiscal policies and find an important role for trend inflation.

is, interest rate increases become expansionary. Accordingly, they document passive monetary policy during the pre-Volcker period as being consistent with equilibrium determinacy. Haque, Groshenny, and Weder (2021) document that commodity price shocks, in an environment characterized by a high degree of real wage rigidities, generated a trade-off for the Federal Reserve in terms of stabilizing inflation and the output gap during the 1970s. Faced with this trade-off, they find that the Federal Reserve responded aggressively to inflation and negligibly to the output gap in the pre-Volcker period, such that its conduct did not lead to indeterminacy.

3. Model

The estimation is based on a version of Ascari and Sbordone's (2014) generalized New Keynesian (GNK) model. The model economy 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 a 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), this paper assumes stochastic trend growth modeled as the technology level following a unit-root process; replaces their labor supply disturbance with a discount factor shock, which is a stand-in for a demand-type 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 model is estimated in the absence of rule-of-thumb price setting. Finally, the Taylor rule features responses to the inflation gap, the output gap, and output growth and also allows for interest rate smoothing.

3.1 The Log-Linearized Model

The log-linearized equilibrium conditions are given by the following equations.[11]

$$\widehat{y}_t = \left(\frac{h}{g+h}\right)[\widehat{y}_{t-1} - \widehat{g}_t] + \left(\frac{g}{g+h}\right)[E_t\widehat{y}_{t+1} + E_t\widehat{g}_{t+1}] - \left(\frac{g-h}{g+h}\right)[\widehat{r}_t - E_t\widehat{\pi}_{t+1}] + \left(\frac{g-h}{g+h}\right)\left[\widehat{d}_t - E_t\widehat{d}_{t+1}\right], \quad (1)$$

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

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

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

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

$$\widehat{x}_t = \widehat{y}_t - \widehat{y}_t^n, \quad (6)$$

$$\widehat{y}_t^n = \frac{h}{g(1+\varphi) - h\varphi}\left(\widehat{y}_{t-1}^n - \widehat{g}_t\right), \quad (7)$$

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 the steady

[11] A full description of the model is relegated to the online appendices, available at http://www.ijcb.org.

state. Here y_t and y_t^n stand for output and natural level of output, respectively; x_t is the output gap; r_t denotes the nominal interest rate; π_t denotes the inflation rate; π_t^* represents the Federal Reserve's time-varying inflation target; s_t denotes the resource cost due to relative price dispersion; Ψ_t is an endogenous auxiliary variable that appears in the Phillips curve in expectations, and thus drives inflation in response to expected changes in future demand and price dispersion; and E_t represents the expectations operator. Equation (1) is the dynamic IS curve, reflecting a Euler equation, where $h \in [0, 1]$ represents the degree of habit persistence and g stands for the steady-state gross rate of technological progress, which is also equal to the steady-state balanced growth rate. Equations (2), (3), and (4) 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 $\varphi \geq 0$ is the inverse elasticity of labor supply. Equation (4) is a recursive log-linearized expression for the price dispersion measure under the Calvo pricing mechanism. A few things should be noted here. First, the supply side of the GNK model includes three dynamic equations—(2), (3), and (4)—rather than one as in the simple NK model approximated around a zero steady-state inflation. Setting $\pi = 1$ in these three equations yields the standard NKPC. Second, s_t is a backward-looking variable, so its inclusion adds inertia to the adjustment of inflation. Therefore, the dynamics of the GNK model is richer, as discussed in Ascari and Sbordone (2014). Finally, to close the model, Equation (5) represents monetary policy actions—that is, 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, output gap, output growth, and 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. Equation (6) is the definition of the output gap, while the law of motion for the natural level of output is given by Equation (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 follows an $AR(1)$ process:

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

and

$$\log \pi_t^* = (1-\rho_{\pi^*})\log \pi + \rho_{\pi^*} \log \pi_{t-1}^* + \epsilon_{\pi^*,t} \qquad 0<\rho_{\pi^*}<1, \quad (8)$$

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, that is with no inflation target shock ($\sigma_{\pi^*}=0$), Equation (8) drops out and the policy rules boils down to

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

in which the central bank's target becomes equal to a constant steady-state or trend inflation π. In other words, the model with a time-varying inflation target nests the one with a fixed target in the absence of inflation target shocks.

3.2 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

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

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 that of Sims (2002). However, it has the added advantage of being explicit in dealing with expectation errors, since it makes the solution suitable for solving and estimating models featuring multiple equilibria. In particular, under indeterminacy, η_t becomes a linear function of the fundamental shocks ϵ_t and the purely extrinsic sunspot disturbances ζ_t. The full set of solutions to the LRE model entails

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

where $\Phi(\theta)$, $\Phi_\epsilon(\theta, \widetilde{M})$, and $\Phi_\zeta(\theta)$[12] are the coefficient matrices.[13] 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 model dynamics through endogenous expectation errors; and (ii) 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 solution 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 indeterminacy regions.[14] Finding an analytical solution to the boundary in this model is infeasible, and hence, following Justiniano and Primiceri (2008) and Hirose (2020), the paper resorts to a numerical procedure to find the boundary by perturbing the parameter ψ_π in the monetary policy rule.

3.3 Equilibrium Determinacy and Trend Inflation

Before moving onto the empirical investigation, this subsection revisits how the determinacy properties of the model are altered by trend inflation. 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 alters the determinacy region. Since analytical solution is infeasible unless one assumes indivisible labor, the determinacy results shown here are numerical.[15]

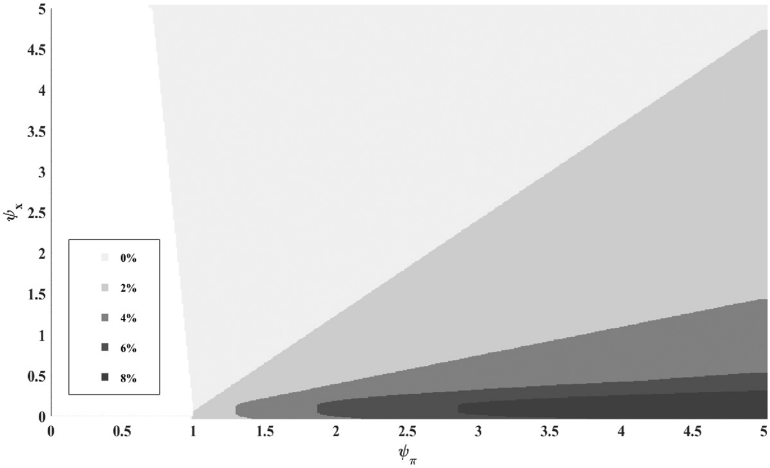
[12] Lubik and Schorfheide (2003) express this term as $\Phi_\zeta(\theta, M_\zeta)$, where M_ζ is an arbitrary matrix. For identification purpose, the paper imposes their normalization such that $M_\zeta = I$.

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

[14] This methodology has been used in previous studies, such as Benati and Surico (2009), Hirose (2007, 2008, 2013, 2020), and Doko Tchatoka et al. (2017).

[15] The parameter values and the policy rule used in the numerical computation are similar to Ascari and Sbordone (2014). In particular, $\beta = 0.99$, $\varepsilon = 11$,

Figure 1. Determinacy Region and Trend Inflation



Note: Shaded area corresponds to determinacy regions for different levels of trend inflation.

The determinacy region shrinks with trend inflation, as documented by Ascari and Ropele (2009) and Ascari and Sbordone (2014).[16] 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 case of positive trend inflation, Coibion and Gorodnichenko (2011) show that both interest rate smoothing and stronger response to output growth, as opposed to the output gap, are stabilizing and therefore widen the determinacy region. Finally, it is important to note that allowing for an exogenous stochastic time-varying inflation target, as done in this paper, does not alter the (in)determinacy regions of the parameter space.

$\xi = 0.75$, $h = 0$ implying no habit formation in consumption, and $g = 1.005$ such that the steady-state growth rate of real per capita GDP is 2 percent per year. The policy rule is a simple Taylor rule of the form $r_t = \psi_\pi \pi_t + \psi_x x_t$.

[16]The figure is similar to Figure 4 in Ascari and Ropele (2009) and Figure 11 in Ascari and Sbordone (2014).

4. Econometric Strategy

4.1 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 Monte Carlo (SMC) algorithm proposed by Herbst and Schorfheide (2014, 2015), which is particularly suitable for irregular and non-elliptical posterior distributions.[17]

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 estimate the model twice—first under

[17] See Hirose, Kurozumi, and Van Zandweghe (2020), who were the first to apply Bayesian estimation using the SMC algorithm to test for indeterminacy following Lubik and Schorfheide's (2003, 2004) methodology.

determinacy, and then under indeterminacy—and then compare the fit of the model under the two 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.[18] The likelihood function is then given by

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

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, which equals 1 if $\theta_S \in \Theta^S$ and zero otherwise; and $p^D(X_T|\theta_D, D)$ and $p^I(X_T|\theta_I, I)$ 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

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

where ϕ_n is the tempering schedule, which 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 reweighted to reflect the density in iteration n. Next, in the *selection* step, any

[18] Ettmeier and Kriwoluzky (2020) and Hirose, Kurozumi, and Van Zandweghe (2020) also use SMC to estimate their model over the 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).

particle degeneracy is eliminated by resampling the particles. Finally, in the *mutation* step, the particles are propagated forward using a Markov transition kernel in order 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 $\Pi_n(\theta_S)$ is 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 $N = 10,000$ particles and $N_\phi = 200$ stages. The parameter that controls the tempering schedule, denoted by τ, 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 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. First, it allows for 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.[19] 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"; that is, 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 reweighting 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; that is, 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.

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 estimated under indeterminacy along the lines of Lubik and Schorfheide (2004), the evaluation of the likelihood function is computationally very costly because it requires running a model solution procedure that bridges the gap between the impact response of the variables to fundamental shocks at the boundary between determinacy and indeterminacy (by picking $M^*(\theta)$). Whenever analytical solution to the boundary is not available, this requires numerically tracing the boundary for every draw at every stage. Thus, gains from parallelization can be quite large.

4.2 Data

The paper uses 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, 1960:Q1–1979:Q2,

[19]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.

corresponds to the Great Inflation period. The second one, 1984:Q1–2008:Q2, corresponds to the Great Moderation period, which is characterized by dramatically milder macroeconomic volatilities. The measurement equations relating the relevant elements of ϱ_t to the three observables are given by

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

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

4.3 Calibration and Prior Distributions

Some parameters are fixed before the estimation. The elasticity of substitution among intermediate goods and the inverse of the labor-supply elasticity are fixed at $\varepsilon = 11$ and $\varphi = 1$, respectively. The former value corresponds to a steady-state markup of 10 percent, which is consistent with the estimate of Basu and Fernald (1997).[20] The latter value is a standard one in the macroeconomic literature.[21] The remaining parameters are estimated.[22] 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 ψ_x and output growth $\psi_{\Delta y}$ are both centered at 0.125 with standard deviation 0.10. The paper uses beta distribution 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 ρ_d. The autoregressive parameter of the total factor productivity (TFP) shock ρ_g follows a beta distribution

[20] More recent estimates by Edmond, Midrigan, and Xu (2018) suggest that aggregate markups could be as high as 25 percent. Hence, to check the robustness of the results, the elasticity of substitution among intermediate goods is alternatively set at $\varepsilon = 5$, corresponding to a steady-state markup of 25 percent. The online appendices show that the results remain robust.

[21] See, for instance, Hirose, Kurozumi, and Van Zandweghe (2020), who also set $\varphi = 1$.

[22] For the subjective discount factor β, the steady-state condition $\beta = \frac{\pi g}{r}$ is used in estimation.

Table 1. Prior and Posterior Distributions

			1960:Q1–1979:Q2	1984:Q1–2008:Q2
Name	**Density**	**Prior Mean (Std. Dev.)**	**Posterior Mean [90% Interval]**	**Posterior Mean [90% Interval]**
ψ_π	Gamma	1.10 (0.50)	2.29 [1.42,2.89]	4.04 [3.08,4.95]
ψ_x	Gamma	0.125 (0.10)	0.12 [0.00,0.25]	0.13 [0.00,0.26]
$\psi_{\Delta y}$	Gamma	0.125 (0.10)	0.16 [0.02,0.28]	0.38 [0.08,0.64]
ρ_r	Beta	0.50 (0.20)	0.41 [0.23,0.65]	0.71 [0.62,0.80]
π^*	Normal	0.98 (0.50)	1.18 [0.86,1.51]	0.69 [0.52,0.85]
r^*	Gamma	1.60 (0.25)	1.49 [1.18,1.79]	1.46 [1.19,1.69]
g^*	Normal	0.50 (0.10)	0.54 [0.38,0.68]	0.51 [0.40,0.62]
h	Beta	0.50 (0.10)	0.39 [0.31,0.51]	0.40 [0.31,0.50]
ξ	Beta	0.50 (0.10)	0.39 [0.27,0.57]	0.49 [0.36,0.61]
ρ_d	Beta	0.70 (0.10)	0.79 [0.67,0.88]	0.92 [0.89,0.95]
ρ_g	Beta	0.40 (0.10)	0.17 [0.11,0.26]	0.17 [0.11,0.24]
$\rho_{\pi*}$	Beta	0.95 (0.025)	0.96 [0.93,0.99]	0.95 [0.91,0.98]
σ_r	Inv-Gamma	0.60 (0.20)	0.39 [0.27,0.48]	0.21 [0.16,0.26]
σ_d	Inv-Gamma	0.60 (0.20)	0.71 [0.39,0.95]	1.69 [1.20,2.18]
σ_g	Inv-Gamma	0.60 (0.20)	1.28 [1.07,1.55]	0.71 [0.59,0.83]
$\sigma_{\pi*}$	Uniform	0.075 (0.0433)	0.08 [0.04,0.13]	0.04 [0.03,0.06]
σ_ζ	Inv-Gamma	0.60 (0.20)	0.57 [0.24,0.90]	0.57 [0.25,0.93]
$M_{r,\zeta}$	Normal	0.00 (1.00)	0.02 [–1.71,1.62]	0.02 [–1.64,1.65]
$M_{d,\zeta}$	Normal	0.00 (1.00)	–0.08 [–1.66,1.65]	0.00 [–1.63,1.63]
$M_{g,\zeta}$	Normal	0.00 (1.00)	–0.01 [–1.70,1.65]	0.06 [–1.54,1.61]
$M_{\pi*,\zeta}$	Normal	0.00 (1.00)	0.00 [–1.63,1.65]	0.01 [–1.62,1.71]

Note: The prior probability of determinacy is 0.498. The inverse gamma distributions are of the form $p(\sigma|\nu,\varsigma) \propto \sigma^{-\nu-1}e^{-\nu\varsigma^2/2\sigma^2}$, where $\nu = 4$ and $\varsigma = 0.45$.

Table 2. Determinacy versus Indeterminacy

Sample	Inflation Target	Log-Data Density	Probability of Determinacy
1960:Q1–1970:Q2	Fixed	–152.08	0.20
	Time Varying	–144.29	1.0
1984:Q1–2008:Q2	Fixed	–32.58	1.0
	Time Varying	–27.58	1.0

Note: The table shows the SMC-based approximations of log marginal data densities and the posterior probabilities of determinacy.

centered at 0.40, since this process already includes a unit root, while that of the inflation target shock ρ_{π^*} is assumed to be highly persistent and is centered at 0.95. The priors for the quarterly net steady-state rates of output growth, inflation, and nominal interest rate, denoted by g^*, π^*, and r^*, respectively, are distributed roughly around their average values over the entire sample period.

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 σ_{π^*}, which is an important parameter in the analysis, as it governs the rate at which π^*_t drifts. 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 about 50 percent, which is quite even and suggests no prior bias toward either determinacy or indeterminacy.

5. Estimation Results

5.1 Model Comparison

Table 2 collects the results for the empirical performance of the model with fixed and time-varying inflation targets. To assess the quality of the models' 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 approximation of the marginal data density as a byproduct in the *correction* step, which 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

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

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:

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

Table 2 shows that in case of a fixed inflation target, indeterminacy cannot be ruled out in the pre-Volcker period, while determinacy unambiguously prevails after 1984. Nevertheless, the fact that the posterior probability of determinacy in the pre-Volcker period is around 20 percent in the case of a fixed inflation target is a priori unexpected, given the empirical findings of Lubik and Schorfheide (2004) and Hirose, Kurozumi, and Van Zandweghe (2020), who show the pre-Volcker period to be explicitly characterized by indeterminacy. However, this is a result of estimating a GNK model with trend inflation and homogenous labor while using the GDP deflator to measure inflation. In fact, upon further investigation, the paper finds that when using CPI to measure inflation instead of the GDP deflator (as in Lubik and Schorfheide 2004), or assuming firm-specific labor instead of homogenous labor (as in Hirose, Kurozumi, and Van Zandweghe 2020), strong evidence for indeterminacy reemerges, and the 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 entire 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.[23] Phrased alternatively, it suggests that monetary policy did not result in sunspot fluctuations during the Great Inflation period, given time variation in the inflation target.

In terms of posterior odds ratio, the marginal likelihood points toward the empirical superiority of the specification featuring time variation in the inflation target in both subsamples. In particular, the Bayes factor or KR ratio involving fixed versus time-varying target is about 16 in the pre-Volcker period, and points toward "very strong" evidence in favor of the model in which the Federal Reserve follows a time-varying inflation target.[24,25]

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 is driving this result? On one hand, Lubik and Schorfheide (2004) and Fujiwara and Hirose (2012) argue that a model under indeterminacy can generate richer persistent inflation dynamics compared with determinacy because fewer autoregressive roots are suppressed. On the other hand, as documented by Cogley, Primiceri, and Sargent (2010), inflation target

[23]The post-1984 period remains explicitly characterized by determinacy.

[24]We report the Bayes Factor or KR ratio as suggested in Kass and Raftery (1995), calculated as 2(log-data density H1 − log-data density H0), where the null hypothesis (H0) is always the less-preferred model (while the alternative hypothesis, H1, is the preferred one). Hence, we weight evidence against the null hypothesis.

[25]According to Kass and Raftery (1995), values of KR below 2 are "not worth more than a bare mention," between 2 and 6 suggest "positive" evidence in favor of one of the two models, between 6 and 10 suggest "strong" evidence, and larger than 10 suggest "very strong" evidence.

shocks induce persistent responses in the inflation gap, which help to capture the highly persistent inflation dynamics in the 1970s. 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 no longer requires the richer inflation dynamics that arise under indeterminacy in order to explain the Great Inflation episode, and therefore we find the pre-Volcker period to be characterized by determinacy. Moreover, 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. 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 case of a time-varying target, which leads to determinacy.

5.2 Parameter Estimates and the Federal Reserve's Inflation Target

Table 1 reports the posterior means and the 90 percent highest posterior density intervals based on 10,000 particles from the final stage of the SMC algorithm under time-varying inflation target (the specification that fits better).[26] 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 above 2, which shows why the posterior favors determinacy under a time-varying target. Moving across the sample, the policy responses to the inflation gap and output growth and inertia in interest rate setting all increased, while trend inflation fell considerably.

The estimated response to the inflation gap is in line with the results of Fernández-Villaverde and Rubio-Ramírez (2008), who estimate a DSGE model with time-varying structural parameters. Fernández-Villaverde and Rubio-Ramírez (2008) find that the response to inflation was slightly above 1 during the 1950s, 1960s, and early 1970s, and then dramatically increased in the mid-1970s and especially after Volcker's appointment as the Federal Reserve Chairman, with the average response to inflation being roughly

[26]The online appendices report parameter estimates under a fixed target.

around 4 during the 1980s and 1990s.[27] They also find substantial variation in the estimated inflation target, with the target rising in the late 1960s and 1970s and falling after the Volcker disinflation, which is similar in pattern to what this paper finds, as discussed later. Fernández-Villaverde and Rubio-Ramírez (2010) and Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez (2010) also find evidence of changes in monetary policy through the lens of estimated non-linear DSGE models with both time-varying parameters and stochastic volatilities. Both these papers find that the response to inflation started above 1 and increased during the 1960s, before collapsing below 1 and therefore violating the Taylor principle during the Burns-Miller Chairmanship in the 1970s. Thereafter, the response increased strongly with the arrival of Volcker. However, Fernández-Villaverde and Rubio-Ramírez (2010) and Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez (2010) find that the response to inflation was again below 1 during most of Greenspan's tenure, which is at odds with the findings of this paper and others in the literature that monetary policy was strongly active during the Great Moderation (Clarida, Galí, and Gertler 2000; Lubik and Schorfheide 2004; Boivin and Giannoni 2006). Nevertheless, Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez (2010) find that their estimates still guarantee local equilibrium determinacy even though the response to inflation temporarily violates the Taylor principle, as the agents still expect the Taylor principle to be satisfied on average. Hence, Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez (2010) suggest that equilibrium was determinate even during the turbulent 1970s, while they blame the instability of the Great Inflation on bad shocks or bad luck. One possible explanation for the difference between the estimated response to inflation in the current paper and Fernández-Villaverde and Rubio-Ramírez (2010) and Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez (2010), apart from time-varying parameters and stochastic volatilities, is the absence of a time-varying inflation target in the latter studies.[28]

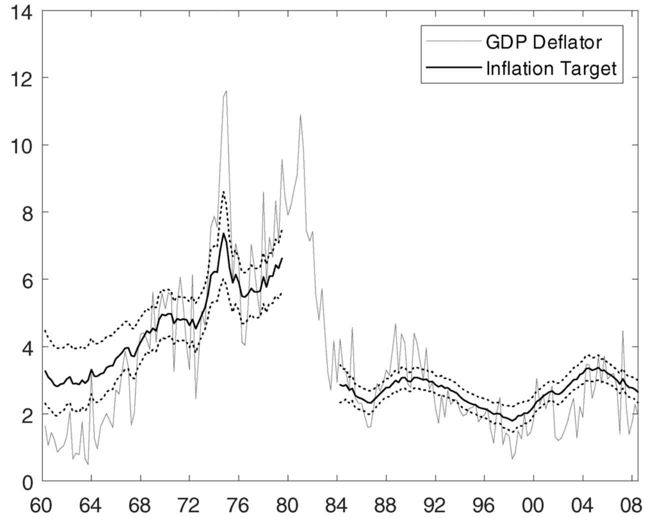
[27] See Figure 2.2 and 2.3 in Fernández-Villaverde and Rubio-Ramírez (2008).

[28] Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez (2010) point out the difficulties of estimating a time-varying inflation target in the context of their non-linear DSGE model solved with perturbation methods.

In terms of the policy shocks, the innovation variance of the two shocks, $\epsilon_{\pi^*,t}$ and $\epsilon_{r,t}$, both declined, which is in line with the findings of Cogley, Primiceri, and Sargent (2010). According to the posterior mean estimates, the innovation variance fell from 0.08 to 0.04 for the inflation target shock, and from 0.39 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 a better anchoring of the inflation target may have played a key role in the decline of inflation volatility and persistence during the Great Moderation period.

Turning to the deep parameters, the degree of habit formation remains stable, roughly around 0.40 for both subsamples. The posterior mean for the degree of price stickiness ξ turns out to be 0.39 in the pre-Volcker period and increases to 0.49 in the post-84 period, which are smaller than the estimates reported in Smets and Wouters (2007), Fernández-Villaverde and Rubio-Ramírez (2008), Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez (2010), and Justiniano, Primiceri, and Tambalotti (2010). For example, allowing for time variation in the estimated Calvo parameter, Fernández-Villaverde and Rubio-Ramírez (2008) find an estimate of around 0.8 in the 1950s. Thereafter, the estimate drops somewhat in the 1960s and 1970s, before rising steadily again since the late 1970s and reaching above 0.8 during the 1990s. However, the microeconomic evidence on the average duration of prices suggests different degrees of price stickiness. For example, Bils and Klenow (2004) find that firms update prices every four to five months, roughly corresponding to $\xi = 0.40$, while Nakamura and Steinsson (2008) find longer duration ranging between 8 and 11 months on average, which roughly corresponds to $\xi = 0.70$. In any case, it turns out that the estimated degree of price stickiness has increased in the second period, which is in line with the findings of Smets and Wouters (2007) and Fernández-Villaverde and Rubio-Ramírez (2008). As they point out, this finding is consistent with the idea that low and stable inflation may reduce the cost of not adjusting prices and therefore lengthen the average price duration, thereby leading to a flatter Phillips curve. Nevertheless, the main result documented in this paper, regarding the role of time-varying inflation target in driving equilibrium determinacy

Figure 2. Inflation and the Federal Reserve's Inflation Target



Note: The solid dark line, labeled "Inflation Target," plots the mean of the target estimates based on the posterior draws of the parameters and the dotted lines show the 5th and 95th percentiles.

during the Great Inflation, does not depend on the estimated low value of the Calvo parameter, as shown in the robustness section.

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 (2020). 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).

Before moving on to study the drivers of the Great Moderation, Figure 2 plots the model-implied evolution of the Federal Reserve's inflation target on top of the actual GDP deflator inflation rate. 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.[29] The inflation target was

[29]The solid dark line, labeled "Inflation Target," shows the mean of the target estimates based on the posterior draws of the parameters, and the dotted lines show the 5th and 95th percentiles.

low—even if higher than realized inflation—at the beginning of the 1960s. Thereafter, the inflation target began rising in the mid-1960s and jumped higher in the aftermath of the 1973 oil crisis. The upward trend in the inflation target in the 1970s may be interpreted as "a systematic tendency for Federal Reserve policy to translate the short-run price pressures set off by adverse supply shocks into more persistent movements in the inflation rate itself—part of an effort by policymakers to avoid at least some of the contractionary impact those shocks would otherwise have had on the real economy." (Ireland 2007, p. 1853). Subsequently, it dropped remarkably during the Volcker-disinflation period and somewhat settled around 2.5 percent since the mid-1980s. As in Leigh (2008, pp. 2022–23), the time-varying implicit inflation target for the post-1984 subsample can be divided into separate chunks: (i) "the opportunistic approach to disinflation"—a period covering from the mid-1980s to mid-1990s—during which, according to Orphanides and Wilcox (2002), the Federal Reserve 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, which led to a lowering of the federal funds rate, while the inflation target rose above actual inflation.[30] Overall, visual inspection suggests that the estimated target is similar to those previously reported by Ireland (2007), Leigh (2008), Cogley, Primiceri, and Sargent (2010), Aruoba and Schorfheide (2011), and Castelnuovo, Greco, and Raggi (2014), among others.

6. Robustness Analysis

The paper conducts robustness checks along the following dimensions: (i) alternative measure of inflation as observable in the estimation, (ii) firm-specific labor, (iii) estimating the NK model of Lubik and Schorfheide (2004) while allowing for a time-varying inflation

[30]The early 2000s was a period of low interest rates and, 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. For alternative interpretation of monetary policy during the 2000s, see Groshenny (2013), Belongia and Ireland (2016), and Doko Tchatoka et al. (2017).

Table 3. Determinacy versus Indeterminacy (robustness checks)

	Constant Target	Time-Varying Target
	Log-Data Density (Probability of Determinacy)	Log-Data Density (Probability of Determinacy)
Sample: 1960:Q1–1979:Q2		
CPI	–152.32 (0.12)	–144.23 (0.95)
Firm-Specific Labor	–145.31 (0)	–144.07 (0.97)
Lubik and Schorfheide (2004)	–359.59 (0)	–357.92 (0.97)
Calibrate $\rho_{\pi *}$	—	–143.95 (1)
Calibrate ξ	–153.49 (0.19)	–145.87 (0.95)
Calibrate π^*	–149.29 (0)	–147.11 (1)
Sample: 1984:Q1–2008:Q2		
CPI	–89.98 (1)	–92.20 (1)
Firm-Specific Labor	–31.62 (1)	–34.35 (1)
Lubik and Schorfheide (2004)	–238.63 (0.97)	–237.38 (0.99)
Calibrate $\rho_{\pi *}$	—	–28.08 (1)
Calibrate ξ	–30.88 (0.99)	–31.16 (1)

Note: The table shows the SMC-based approximations of log marginal data densities and the posterior probabilities of determinacy for various robustness checks. "CPI" refers to the estimations with CPI inflation data; "Firm-Specific Labor" is the GNK model of Hirose, Kurozumi, and Van Zandweghe (2020); "Calibrate $\rho_{\pi *}$" refers to the estimations where $\rho_{\pi *} = 0.995$; "Calibrate ξ" refers to the estimations where $\xi = 0.75$; "Calibrate π^*" refers to the estimations where $\pi^* = 2$.

target, (iv) calibrating the persistence of the inflation target process, (v) calibrating the degree of price stickiness to a higher level, and (vi) setting the steady-state or trend inflation to a higher value for the Great Inflation sample. Table 3 summarizes the log-data densities and posterior model probabilities.[31] 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. To check the robustness of the results, the paper reestimates the models using CPI to measure inflation, as in Lubik and Schorfheide (2004). The posterior mass lies almost entirely in the indeterminacy region in the pre-Volcker period under a fixed inflation target, with around 90 percent of the draws from the posterior distribution generating indeterminacy. 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 a fixed target fits better in the post-1984 period, implying a larger role played by the decline in the variability of the inflation target in driving the reduction in inflation volatility.

6.2 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. The only difference is that the household now supplies a set of labor services $N_{i,t}$, each of which is specific to intermediate-good firm $i \in [0, 1]$, instead of supplying a homogenous labor service N_t. This leads to a distinct representation of the supply side of the model. Following Hirose, Kurozumi, and Van Zandweghe (2020),

[31] The online appendix reports the parameter estimates.

the log-linearized GNKPC for the model with firm-specific labor is given by[32]

$$\widehat{\pi}_t = \kappa_f E_t \widehat{\pi}_{t+1} + (1+\varphi)\vartheta_f \widehat{y}_t + \vartheta_f \left(\frac{h}{g-h}\right)[\widehat{y}_t - \widehat{y}_{t-1} + \widehat{g}_t] + \widehat{\Psi}_t, \tag{18}$$

$$\widehat{\Psi}_t = \gamma_\psi E_t \widehat{\Psi}_{t+1} + \kappa_\psi \left(E_t \widehat{y}_{t+1} - \widehat{y}_t + E_t \widehat{g}_{t+1} + \varepsilon E_t \widehat{\pi}_{t+1} - \widehat{r}_t\right), \tag{19}$$

where $\kappa_f = \beta\xi\pi^{\varepsilon(1+\varphi)}/\xi\pi^{\varepsilon-1}$, $\vartheta_f = (1-\xi\pi^{\varepsilon-1})(1-\xi\beta\pi^{\varepsilon(1+\varphi)})/\xi\pi^{\varepsilon-1}(1+\varepsilon\varphi)$, $\gamma_\psi = \beta\xi\pi^{\varepsilon-1}$, and $\kappa_\psi = \gamma_\psi\left(\pi^{1+\varepsilon\varphi}-1\right)\left(1-\xi\pi^{\varepsilon-1}\right)/\xi\pi^{\varepsilon-1}(1+\varepsilon\varphi)$.

A few key points are particularly worth noting. First, as shown by Kurozumi and Van Zandweghe (2017), the slope of the GNKPC in the model with firm-specific labor (given by $(1+\varphi)\vartheta_f$) is less than that of the model with homogenous labor (given by $(1+\varphi)\vartheta$), as long as the elasticity of labor supply is finite, i.e., $\varphi > 0$. This reflects strategic complementarity in price setting incorporated by firm-specific 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, Kurozumi and Van Zandweghe (2017) show that the long-run inflation elasticity of output implied by the GNKPC is highly sensitive to trend inflation in the model with firm-specific labor relative to the model with homogenous labor.[33] Higher trend inflation lowers this elasticity and makes the long-run 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. Third, in the model with homogenous labor, the GNKPC depends on price distortion (s_t) as long as the trend inflation rate is non-zero (i.e., $\pi \neq 1$) and the elasticity of labor supply is finite (i.e., $\varphi > 0$). Therefore, the persistence of price distortion, as seen in its law of motion (4), generates endogenously persistent inflation dynamics in

[32]The Euler equation (Equation (1)), the specification of the Taylor rule (Equation (5) or Equation (9)), the definition of the output gap (Equation (6)), the expression for the natural level of output (Equation (7)), and the shock processes (Equation (8)) remain the same as in the model with homogenous labor.

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

the model with homogenous labor, as stressed by Kurozumi and Van Zandweghe (2017). Finally, in case of infinite elasticity of labor supply (i.e., $\varphi = 0$), the GNKPC coincides between the models with firm-specific and homogenous labor, which implies that in that case the two models are equivalent.

Along these lines, the paper estimates a GNK model with positive trend inflation and firm-specific labor following Hirose, Kurozumi, and Van Zandweghe (2020).[34] In order to establish a valid comparison, this paper uses the exact same set of priors as they do. However, to achieve identification between the inflation target process and the policy rate shock, the 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.[35]

In line with Hirose, Kurozumi, and Van Zandweghe (2020), the pre-Volcker period is unambiguously characterized by indeterminacy, while the post-1984 period is characterized by determinacy, under the assumption of a fixed inflation target equal to trend inflation. However, when allowing for a time-varying inflation target, determinacy prevails in both sample periods, as before. In terms of the empirical fit, the model with a time-varying inflation target fits marginally better than one with a fixed target in the pre-Volcker period.[36] 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.

[34] This paper abstracts from price indexation given Hirose, Kurozumi, and Van Zandweghe's (2020) finding that the model with no indexation fits better.

[35] As in the baseline estimation, the elasticity of substitution among intermediate goods and the inverse of the labor-supply elasticity are fixed at $\varepsilon = 11$ and $\varphi = 1$, respectively

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

6.3 Lubik and Schorfheide (2004)

To bridge the gap with key studies in the literature, the paper also estimates an NK model log-linearized around a zero inflation steady state.[37] 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.[38] In line with Lubik and Schorfheide (2004), the paper considers the following sample periods: a pre-Volcker sample from 1960:Q1 to 1979:Q2 and a post-1982 sample from 1982:Q4 to 1997:Q4 that excludes the Volcker disinflation period. The findings read as follows.

First, in case of a 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),[39] though this paper uses a different algorithm to estimate the DSGE framework over the entire region of the parameter space (Lubik and Schorfheide 2004 use standard MCMC techniques and they split the estimation separately over determinacy and indeterminacy regions). Second, when allowing for a drifting inflation target, determinacy prevails in the pre-Volcker period, which is in line with the benchmark results. Moreover, the model with a time-varying inflation target (determinacy) fits better than the one with a fixed target (indeterminacy). Again, these results raise the possibility that the Federal Reserve

[37]Hirose, Kurozumi, and Van Zandweghe (2020) find that replacing the standard NKPC with a GNKPC alters the estimated cofficients in the Taylor rule, in particular for the policy response to inflation.

[38]Note that, as in Lubik and Schorfheide (2004), the paper also estimates π^*. However, since the model of Lubik and Schorfheide (2004) is log-linearized around a zero-inflation steady state, the estimated π^* only appears in the measurement equation. As such, π^* only pertains to demeaning the inflation data used in the estimation and does not otherwise feed into the model dynamics through steady-state inflation (which is zero in the model), unlike the baseline model log-linearized around a non-zero steady-state inflation.

[39]See Table 2 on page 205 of their paper.

pursued a time-varying inflation target and possibly did not generate indeterminacy in the pre-Volcker period.

6.4 Calibrate ρ_{π^*}

Looking at the posterior distributions of the persistence of the inflation target process (ρ_{π^*}) in Table 1, the posteriors look quite similar to the prior. Hence, it seems that the data might not be sufficiently informative to pin down this parameter. As a result, the paper now calibrates ρ_{π^*}, while estimating the remaining parameters in the model as before.[40] 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. A time-varying target continues to fit better than a constant target and determinacy prevails in both periods, as in the baseline estimations.

6.5 Calibrate ξ

The posterior distributions of ξ in Table 1 suggest that the estimated degree of price stickiness is relatively low. To ensure that the (in)determinacy results are not driven by a low degree of price stickiness, the paper calibrates ξ while estimating the remaining parameters of the model.[41] In particular, the degree of price stickiness is set to 0.75, which is a typical value used in calibration studies and the value used in Ascari and Sbordone (2014). A higher degree of price rigidity makes 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

[40] In the online appendix, I conduct identification analysis of the remaining parameters by first simulating data from the model with a time-varying target under determinacy and then estimating the model with the simulated data over the entire stable region of the parameter space (i.e., over both determinacy and indeterminacy). The results show that the estimation is able to recover the true parameter values for both the structural parameters and shocks, suggesting that the model parameters are relatively well identified.

[41] ρ_{π^*} is also set to 0.995 as above.

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 about 27 percent, such that a priori it is more likely for indeterminacy to prevail.[42] As in the baseline analysis, the estimation finds that a time-varying target continues to fit better and determinacy prevails in the pre-Volcker period, despite the estimation being biased toward indeterminacy. In the post-1984 period, the fit of the model with a fixed target versus a time-varying target are quite similar and both favor determinacy.

6.6 Calibrate π^*

The paper conducts one final check. Recall that in the analysis so far, trend inflation (or steady-state inflation) and the time-varying inflation target are distinct features. There are two counteracting effects at work here. On one hand, the time-varying inflation target captures some of the low-frequency movements of inflation, 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. To address this issue, the paper estimates the GNK model with firm-specific labor in the pre-Volcker period while calibrating the steady-state inflation to a higher level and allowing for a time-varying inflation target.[43] In particular, trend inflation is set to 8 percent

[42]Recall that the prior predictive probability of determinacy in the baseline analysis is around 50 percent, such that, following the literature on testing for indeterminacy, the baseline estimations remain a priori unbiased.

[43]Firm-specific labor is assumed in order to maintain continuity with Coibion and Gorodnichenko (2011). Moreover, as discussed above, the long-run inflation elasticity of output implied by the GNKPC is more sensitive to trend inflation in

(annual level), which roughly corresponds to the highest estimate of Coibion and Gorodnichenko's (2011) time-varying trend inflation measure in the pre-Volcker period. The estimation continues to favor time-varying inflation target and determinacy prevails with a posterior probability of determinacy of 100 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).[44]

7. Conclusion

This paper estimates a New Keynesian model with positive trend inflation while allowing for indeterminacy and time variation in the inflation target pursued by the Federal Reserve. The paper finds that inflation target has been drifting over time and, as a consequence, 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 target is drifting over time is less volatile than the inflation gap with a fixed target. 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 a time-varying target, which leads to determinacy. Second, inflation target shocks induce persistent responses in the inflation gap, as shown by Cogley, Primiceri, and Sargent (2010), which helps to capture the highly persistent inflation dynamics of the 1970s. As a result, the estimated model does not need to resort to the richer dynamics that arise under indeterminacy to explain the Great Inflation episode. One implication of this finding is that self-fulfilling inflation expectations, otherwise known as "sunspots," are not required to explain the high inflation outturns during this episode.

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the model with firm-specific labor, thereby requiring a stronger response to inflation to guarantee determinacy for a given level of trend inflation relative to the model with homogenous labor. Nevertheless, we have also estimated the model with homogenous labor while calibrating trend inflation to 8 percent (annual level) and the results remain robust.

[44]The paper also estimates π^* with the priors centered around the average value for each sample period (instead of the average over the entire sample as in the baseline estimation) for both the homogenous and firm-specific labor model and the results remain robust.

The paper makes these arguments by assuming that trend inflation is positive but constant while the Federal Reserve pursues an exogenous time-varying inflation target. This choice helps to keep the analysis simple yet related and relevant 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 then result in a New Keynesian Phillips curve with drifting coefficients as in Cogley and Sbordone (2008). DSGE models with time-varying coefficients have been estimated by Fernández-Villaverde and Rubio-Ramírez (2008, 2010) and Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez (2010). I plan to pursue these lines of research in the future.

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