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Abstract

How and under what circumstances can adjusting the inflation target serve as a stabilization-policy tool and contribute to welfare improvement? We answer these questions quantitatively with a standard New Keynesian model that includes cost-push type shocks. Our proposed inflation target rule calls for the target to be adjusted in a persistent manner and in the opposite direction to the realization of a cost-push shock, which is essentially a makeup strategy. The inflation target rule, combined with a Taylor-type rule, significantly reduces inflation fluctuations originating from cost-push shocks and mitigates the stabilization trade-off, resulting in a similar level of welfare to that associated with the Ramsey optimal policy.

Keywords: Cost-push shocks; Inflation-output trade-off; Makeup strategy; Medium-run inflation targeting; Welfare analysis; Monetary policy; Nominal wage rigidity; Capital accumulation; Flat Phillips curve;

JEL classification: E12; E32; E58; E61;

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1 Introduction

The constancy of the central bank's inflation target has been one of the most enduring features in stabilization policy studies in the literature. These studies, whether they focus on positive or normative aspects of monetary policy, assume that the central bank stabilizes inflation around a constant, long-run target. From an empirical standpoint, however, several studies have documented that historically trend inflation has not been constant, see e.g., Kozicki and Tinsley (2003), Ireland (2007), and Cogley, Primiceri and Sargent (2010) for studies using U.S. data. Time-varying trend inflation can be interpreted as adjustments to the central bank's implicit inflation target (or to the public's inflation-target expectations). This observation raises the question of whether such adjustments play an important role in central bank's stabilization policy. How and under what circumstances are these adjustments warranted and possibly welfare-improving?

In this paper we investigate the role of inflation target adjustment in central banks' stabilization policy. We propose a scenario, as in Ireland (2007), where the central bank's inflation target is endogenous and depends on the state of the economy. In particular, the adjustment of the target is conditional on the realization of cost-push shocks.[1] It is well known that cost-push shocks create a trade-off between inflation and output-gap stabilization. In this paper, we refer to these types of shocks as "cost-push shocks" but they potentially represent any shock that creates such a trade-off including variations in tax, changes in desired price markups by firms and wage markups by households, and oil price shocks.[2]

We show that adjustment of the inflation target, done properly, improves the central bank's policy-stabilization trade-off and can lead to a substantial welfare improvement. In fact, despite the existence of cost-push shocks, an interest-rate rule with an optimal inflation target adjustment is able to closely replicate the Ramsey allocation. The extent of the improvement in the policy trade-off and the welfare gain are above and beyond what is

[1] Ireland (2007) assumes that adjustment of the inflation target is conditional on the realization of cost-push shocks as well as technology shocks and that the central bank stabilizes inflation around the time-varying target. Unlike Ireland (2007), however, we focus on the normative aspects of such adjustments, instead of the positive aspects.

[2] See Clarida, Galí and Gertler (1999), Erceg, Henderson and Levin (2000), Steinsson (2003), Smets and Wouters (2007), and Natal (2012) for details. Blanchard and Galí (2007) note that such a trade-off means the "divine coincidence" no longer holds with respect to these shocks.

attainable in the conventional Taylor-type-rule policy environment with a constant, long-run inflation target.

The theoretical framework used for our analysis is a simple, microfounded New Keynesian model, along the lines of Rotemberg and Woodford (1997) and Steinsson (2003). The baseline model has two standard market distortions: the relative-price distortion arising from nominal price rigidity and the average markup distortion due to firms' monopoly power. Aggregate fluctuations are driven by productivity, government spending, and cost-push (markup) shocks. Despite its simplicity, our model is rich enough to capture important implications of larger-scale, empirically-driven models used to analyze the effects of monetary policy. We also consider extended versions of the model that include capital accumulation and nominal wage rigidity. Our main findings hold true in those models, as long as there exists a trade-off between different stabilization goals. The cost-push shock itself in our model can be treated as a familiar and convenient proxy for any shock that creates such a trade-off.[3]

We first show that in the face of cost-push shocks, it is not possible to achieve a similar welfare level to that associated with the Ramsey policy in an environment in which the monetary authority conducts policy through a standard Taylor-type rule with a constant inflation target. In particular, there still exists a non-trivial welfare cost, relative to the optimal Ramsey allocation, even under an optimized, implementable Taylor-type rule. Note that if only productivity and government spending shocks exist, there is no stabilization trade-off and the central bank can stabilize inflation and output at the same time. As shown by Schmitt-Grohé and Uribe (2007), in such an environment an optimized Taylor rule with a constant inflation target can mimic the Ramsey allocation quite well.

We then consider our proposed policy. In addition to adjusting the nominal interest-rate using a Taylor rule, the monetary authority also adjusts the inflation target in response to cost-push shocks. We allow this adjustment to be temporal, using a persistent inflation target that follows an autoregressive process. This implies that the nominal interest rate now responds to the inflation gap, defined by the difference between actual inflation and the

[3] Smets and Wouters (2007) find that cost-push shocks in their model, in the form of wage markup and price markup shocks, are largely responsible for inflation fluctuations in the postwar U.S. economy.

medium-run inflation target, as well as the output gap.

The optimal target adjustment calls for changing the inflation target in the opposite direction to the realization of cost-push shocks. That is, we find that when there is a positive cost-push shock that raises inflation and leads to a negative output gap on impact, it is optimal for the monetary authority to *decrease* the inflation target as a makeup strategy. For any inflation rate above the initial target, a decreased target in turn leads to a bigger inflation gap compared to that in the standard Taylor rule and translates to a more aggressive response to the cost-push shock through a larger increase in the nominal interest rate. This policy combination leads to lower inflation expectations, resulting in significant welfare gains because inflation variability is sufficiently reduced without generating too large of an increase in output gap variability. These results are robust to various extensions and changes to the model such as capital accumulation, nominal wage rigidity, and different interest-rate rules.

From a positive standpoint, several studies such as Bomfim and Rudebusch (2000), Orphanides and Wilcox (2002), and Ireland (2007) discuss the possibility that over the postwar period the Federal Reserve consistently translated adverse supply shocks (positive cost-push shocks) into more persistent inflation (a higher inflation target).[4] Our finding implies that such an action is unwarranted and welfare-reducing.

We also note that this more-aggressive response to cost-push shocks in our target rule is not equivalent to simply increasing the inflation feedback coefficient in the Taylor-type rule from a welfare perspective. Even when the cost-push shock is the dominant driving process in the economy, it may not be optimal to increase the inflation feedback coefficient beyond a certain value because (i) the variability of the output gap is also a relevant determinant of welfare and (ii) the welfare loss from increasing the variation in the output gap may dominate the welfare gain from reducing the variation in inflation for too large values of the inflation coefficient in the Taylor-type rule.[5] In particular, we show that even when we allow for a wider range of possible values of the Taylor-type rule feedback coefficients, it is

[4] Ireland (2007), however, finds that in the postwar U.S. economy a model with the endogenous movements in the inflation target is statistically indistinguishable from the exogenous inflation target model. Garnier, Mertens and Nelson (2015) obtain the same result using unobserved components models of trend inflation and the inflation gap in the U.S. economy.

[5] Woodford (2002) and Benigno and Woodford (2005) derive a welfare-based loss function and show that it depends on the variability of inflation and an output-gap measure. See also our discussion in Section 4.

not possible to achieve a similar welfare level to that associated with our optimized inflation target rule. Thus, the apparent improvement in the trade-off between inflation and output-gap stabilization is mainly attributable to the adjustment of the inflation target, and not because of any implementability restriction on the policy coefficients.

Our investigation also reveals that the extent of the welfare gain from the inflation target adjustment depends on the slope of the Phillips curve. Various studies in the literature have documented a flattening of the Phillips curve for the U.S. and other advanced economies in recent years.[6] One possible reason for this flattening is the increase in the degree of nominal rigidity, e.g., the probability of price fixity in the familiar Calvo (1983) model, as pointed out by Blanchard (2016). A flatter Phillips curve makes the task of an inflation-targeting monetary authority more difficult, as inflation becomes less responsive to output-gap fluctuations. We show that the welfare gain from adjusting the inflation target is larger when the slope of the Phillips curve is flatter.

Our finding is also potentially relevant to the current economic environment of low inflation rates under a flat Phillips curve, especially in advanced economies such as the U.S. and the Euro area. Blanchard (2016) argues that the flat Phillips curve raises serious challenges for monetary policy and may require very flexible inflation targeting. However, he does not propose how to implement flexible inflation targeting in practice or consider its welfare implications. If a *negative* realization of a cost-push shock or similar shocks contributes to the low-inflation environment, our finding suggests that an appropriate policy response is to simply *increase* the medium-run inflation target. In a broader context, the finding in our paper can also serve as a justification for the practice of central banks in several countries of regularly readjusting and announcing their medium-run inflation targets.[7] For example, in September 2016, the Bank of Japan introduced an inflation-overshooting commitment, under which it aims to exceed the inflation target of 2% and stay above the target in a stable manner. The Bank of Japan plans to make policy adjustments conditional on developments in economic activity and prices, as well as financial conditions, in order to achieve its inflation target of 2% in the long run. Though motivated by a different set of objectives,

[6] See e.g., Roberts (2006), Kuttner and Robinson (2010), and Blanchard (2016).

[7] A non-exhaustive list of countries currently practising this policy includes Brazil, India, Indonesia, Nigeria, and South Korea.

our finding suggests that such a conditional adjustment might be welfare-improving.

The rest of this paper is organized as follows. Section 2 presents the model used for welfare analysis and its calibration. Section 3 introduces monetary policy rules and discusses a measure of household welfare. Section 4 conducts welfare analysis for our proposed policy of adjusting the inflation target compared to the Taylor-type rule. Section 5 provides some extensions and robustness analysis. Section 6 concludes.

2 Model and calibration

We consider a New Keynesian model along the lines of Rotemberg and Woodford (1997) and Steinsson (2003). The baseline model consists of a representative household, a continuum of monopolistically-competitive firms producing differentiated varieties, and a monetary policy authority. Our baseline model is closest to the cashless model in Schmitt-Grohé and Uribe (2007), although we abstract from capital accumulation and fiscal policy.[8] Aggregate fluctuations are driven by three exogenous shocks: productivity, government purchase, and cost-push shocks. As we discussed, the inclusion of a cost-push shock is important because it creates a trade-off between inflation stabilization and output-gap stabilization, as in Steinsson (2003) and is consistent with empirical findings in the literature.

2.1 Households

The representative household maximizes a discounted sum of utilities of the form

$$E_t \sum_{s=0}^{\infty} \beta^s \frac{\left[C_{t+s}(1-N_{t+s})^{\gamma}\right]^{1-\sigma}-1}{1-\sigma}, \tag{1}$$

where $\beta \in (0,1)$ is the discount factor and N_t denotes the household's labor supply. The consumption index C_t is a Dixit-Stiglitz CES aggregator of differentiated consumption goods

[8] We abstract from fiscal policy dynamics by assuming that it follows a passive policy, in the sense of Leeper (1991). Schmitt-Grohé and Uribe (2007) find that monetary distortions are not quantitatively important in comparison to cashless economy and passive fiscal policy is optimal. We also consider extended models involving capital accumulation and nominal wage rigidity in Appendix C and show that our results are robust to the extensions.

or varieties, given by

$$C_t = \left[\int_0^1 C_t(i)^{1/(1+\theta_t)} di \right]^{1+\theta_t}, \tag{2}$$

where $\theta_t = 1/(\eta_t - 1)$ is the firms' average markup at time t and η_t is the elasticity of substitution across varieties. The average markup follows

$$\log(\theta_t) = (1 - \rho_\theta) \log(\bar{\theta}) + \rho_\theta \log(\theta_{t-1}) + \varepsilon_{\theta,t}, \tag{3}$$

with $\varepsilon_{\theta,t} \sim i.i.d.N(0, \sigma_\theta^2)$.

Households earn nominal wage W_t by supplying N_t and have access to a domestic bond market where the riskless one-period nominal government bonds, B_t, are traded. These bonds pay the gross interest rate R_t. Households also receive firms' profits, Π_t^{prof}, and government transfers or taxes, T_t. Thus, the one-period budget constraint is given by

$$\int_0^1 P_t(i) C_t(i) di + B_t \leq R_{t-1} B_{t-1} + W_t N_t + \Pi_t^{prof} + T_t, \tag{4}$$

where $P_t(i)$ denotes the nominal price of variety i. Solving the household's problem and taking first-order approximations of the resulting efficiency conditions around the long-run steady-state equilibrium yield a standard consumption Euler equation. Additional details on the households' optimality conditions are contained in Appendix A.

2.2 Firms

Each monopolistically-competitive firm uses labor to produce a differentiated variety i, with a production function

$$Y_t(i) = z_t N_t(i), \tag{5}$$

where $Y_t(i)$ is the production of good i and z_t is the aggregate productivity shock, which is assumed to follow a univariate autoregressive process

$$\log(z_t) = \rho_z \log(z_{t-1}) + \varepsilon_{z,t}, \tag{6}$$

with $\varepsilon_{z,t} \sim i.i.d.N(0, \sigma_z^2)$.

Following Calvo (1983) and Yun (1996), only a $(1-\alpha) \in [0,1)$ fraction of firms are allowed to optimally adjust their prices in any given time period. We assume that an α fraction of firms that are not allowed to optimally reset their prices simply index their prices to the steady-state gross inflation, $\overline{\Pi}$, which coincides with the monetary authority's time-invariant long-run inflation target. Thus, each optimizing firm i chooses an identical optimal nominal price, $\tilde{P}_t(i) = \tilde{P}_t$, to maximize the expected discounted sum of profits

$$\sum_{s=0}^{\infty} \alpha^s Q_{t,t+s} \left[\tilde{P}_t(i) \bar{\Pi}^s Y_{t+s}(i) - W_{t+s}(i) N_{t+s}(i) \right], \tag{7}$$

where $Q_{t,t+s} = \beta^s \frac{\lambda_{t+s}/P_{t+s}}{\lambda_t/P_t}$ is the nominal stochastic discount factor between time t and $t+s$ and λ_t is the marginal utility of consumption.

The resulting first-order condition of the firms' optimal pricing problem and the associated aggregate-price level equation

$$P_t = \left[(1-\alpha)(\tilde{P}_t)^{-\frac{1}{\theta_t}} + \alpha \left(\overline{\Pi} P_{t-1} \right)^{-\frac{1}{\theta_t}} \right]^{-\theta_t}$$

make up the pricing block of the model. Taking first-order approximations of these equations around the long-run steady-state equilibrium leads to the following New Keynesian Phillips curve (NKPC) equation (see Appendix A for more details):

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \lambda \widehat{mc}_t + \hat{u}_t, \tag{8}$$

where $\lambda \equiv \frac{(1-\alpha\beta)(1-\alpha)}{\alpha}$, $\hat{u}_t$ is the reduced-form cost-push shock, which is a function of the shock to the average markup $(\hat{\theta}_t)$,[9] and $\widehat{mc}_t$ is log deviation of the real marginal cost. Alternatively, we can write the NKPC as a function of the output gap, $x_t \equiv Y_t/Y_t^*$:

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \kappa \hat{x}_t + \hat{u}_t. \tag{9}$$

The coefficient on the output gap, i.e., the slope of the NKPC, is $\kappa = \left[(1-\bar{g})^{-1} + \frac{\bar{N}}{1-\bar{N}} \right] \lambda$, with $\bar{g}$ and $\bar{N}$ denoting the steady-state government spending-output ratio and steady-state

[9] That is, $\hat{u}_t \equiv \frac{(1-\alpha\beta\rho_\theta)(1-\alpha)}{\alpha} \frac{1}{\bar{\eta}-1} \hat{\theta}_t$.

labor, respectively. Following Woodford (2003), we define potential output, Y_t^*, as the output level under the flexible-price equilibrium with a constant average markup.

2.3 The monetary authority and government

The monetary authority follows a standard Taylor-type rule in which the authority engages in interest-rate smoothing and responds to deviations of inflation from an inflation target, as well as the output gap. We first present our benchmark rule in which the inflation target is defined by the long-run inflation target (i.e., the steady-state inflation rate). We then introduce our additional policy tool in which the inflation target is adjusted in response to cost-push shocks.

- Benchmark: the long-run inflation targeting rule

$$\log(R_t/\bar{R}) = \phi_R \log(R_{t-1}/\bar{R}) + (1-\phi_R)\left[\phi_\pi \log(\Pi_t/\bar{\Pi}) + \phi_y \log(Y_t/Y_t^*)\right], \qquad (10)$$

where Π_t is the quarterly rate of inflation and $\bar{R}$ is the steady state nominal interest rate. We allow for interest-rate smoothing in the policy rule, with ϕ_R denotes the smoothing parameter. In addition to matching the actual behavior of central banks in many developed economies, many authors (see e.g., Levin, Wieland and Williams (1999), Williams (1999), and Woodford (1999)) argue that a high degree of interest rate inertia may be consistent with optimal policy. We examine the welfare implication of interest-rate smoothing in Section 5.4.

Alternatively, as in Ireland (2007), we consider that instead of using the long-run constant inflation target, the monetary authority reacts to the deviation of inflation from the potentially time-varying, medium-run inflation target, which is adjusted in response to cost-push shocks.[10]

[10] Ireland (2007) also considers the inflation target's response to a technology shock, but we do not take it into account in our policy framework because this shock does not create a trade-off between inflation and output stabilization.

- Proposed policy: the medium-run inflation targeting rule

$$\log(R_t/\bar{R}) = \phi_R \log(R_{t-1}/\bar{R}) + (1-\phi_R)\left[\phi_\pi \log(\Pi_t/\Pi_t^*) + \phi_y \log(Y_t/Y_t^*)\right] \quad (11)$$

$$\log(\Pi_t^*) = \log(\bar{\Pi}) + \mu_{\pi^*} \upsilon_{\pi^*,t} \quad (12)$$

where $\upsilon_{\pi^*,t} = \rho_{\pi^*}\upsilon_{\pi^*,t-1} + \varepsilon_{\theta,t}$ and $\varepsilon_{\theta,t}$ is the innovation in the markup shock, as previously defined in (3). The medium-run inflation targeting rule (MRIT) in (12) shows that the medium-run inflation target, $\pi_t^* \equiv \log(\Pi_t^*)$, is the sum of two distinct components. The first component, $\bar{\pi} \equiv \log(\bar{\Pi})$, is the long-run inflation target. The second component, $\mu_{\pi^*}\upsilon_{\pi^*,t}$, constitutes the endogenous adjustment of the target, where its evolution is directly controlled by the monetary authority through the coefficients μ_{π^*} and ρ_{π^*}. The μ_{π^*} coefficient can be interpreted as the instantaneous response to the markup shock, while ρ_{π^*} can be thought of as the smoothness parameter, i.e., how the monetary authority spreads the target adjustment across multiple periods.

The government issues one-period nominal risk-free bonds, makes transfers, imposes taxes, and faces an exogenous expenditure stream, G_t. Thus, the one-period government budget constraint is given by

$$B_t = R_{t-1}B_{t-1} + P_tG_t + T_t. \quad (13)$$

Government spending is assumed to follow a univariate autoregressive process of the form

$$\log(G_t/\bar{G}) = \rho_g \log(G_{t-1}/\bar{G}) + \varepsilon_{g,t}, \quad (14)$$

with $\varepsilon_{g,t} \sim i.i.d.N(0, \sigma_g^2)$.

2.4 Competitive equilibrium

The stationary equilibrium in our economy is characterized by prices and quantities that satisfy the optimality conditions of the households and firms, in addition to a monetary policy rule and the aggregate market clearing condition for goods, labor, and assets. Aggregate

Table 1: Calibration: baseline model

Parameter	Value	Description
σ	2.00	preference parameter
γ	3.86	preference parameter
β	$1.04^{-1/4}$	quarterly discount rate
$\bar{\theta}$	0.25	steady-state price markup 25%; price elasticity of demand 5
$\bar{G}/\bar{Y}$	0.17	steady-state government spending to output ratio
α	0.80	share of firms that cannot change their price each period
ϕ_π	1.50	inflation reaction
ϕ_y	0.50	output gap reaction
ϕ_R	0.80	interest-rate smoothing
ρ_z	0.95	persistence of productivity shock
ρ_θ	0.64	persistence of cost-push shock
ρ_g	0.56	persistence of government spending
σ_z	0.007	standard deviation of productivity innovation
σ_θ	0.115	standard deviation of cost-push innovation
σ_g	0.224	standard deviation of government spending innovation

employment is given by the sum of employment across firms:

$$N_t = \int_0^1 N_t(i)di. \tag{15}$$

We assume that the government minimizes the cost of producing G_t. Thus, the public good demand for each intermediate good i is given by $G_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\frac{1+\theta_t}{\theta_t}} G_t$. Thus, aggregate demand is given by

$$Y_t = C_t + G_t \tag{16}$$

where $Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\frac{1+\theta_t}{\theta_t}} Y_t$ and $Y_t(i) = C_t(i) + G_t(i)$. We provide the complete equilibrium equations in Appendix A.

2.5 Calibration

Table 1 presents the model's calibration, based on the U.S. economy. The choice of γ implies that the steady-state labor $\bar{N}$ is 0.20. $\bar{\eta} = 5$ corresponds to the steady-state average price markup of $\bar{\theta} = 0.25$. The steady-state ratio of government spending to output is $\bar{G}/\bar{Y} = 0.17$.

These values are consistent with the calibrated values of structural parameters in Schmitt-Grohé and Uribe (2007). The steady-state gross inflation, or the long-run inflation target, is $\bar{\Pi} = 1$. This zero net inflation coincides with the (Ramsey) optimal steady-state inflation in our model.[11] The Calvo parameter α, which is a key parameter for the welfare analysis in the next section, is set to 0.8, implying an average duration of price fixity of 5 quarter.[12] This calibrated Calvo parameter corresponds to the NKPC slope of $\lambda = 0.052$ in (8) when marginal cost is used as the driving process for inflation and the NKPC slope of $\kappa = 0.084$ in (9) when the output gap is used.

Following the real business cycle literature, the persistence parameter ρ_z and the standard deviation σ_z for the productivity shock are taken to be 0.95 and 0.007, respectively. For monetary policy, we assume the standard Taylor-rule coefficients of $\phi_\pi = 1.5$ and $\phi_y = 0.5$ with interest rate smoothing $\phi_R = 0.8$ for the baseline case. This value of ϕ_R is consistent with the estimate in Smets and Wouters (2007). The remaining four parameters for the structural shock processes, ρ_g, ρ_θ, σ_g, and σ_θ are set to closely match four moments of economic variables under the baseline model to the same moments for the postwar U.S. economy: the standard deviations of inflation, the output gap, and the nominal interest rate and the correlation between inflation and the output gap. The first three moments are closely related to the utility-based welfare loss function, often represented by the weighted sum of their variances, see e.g., Rotemberg and Woodford (1997), Rudebusch and Svensson (1999), Woodford (2003), and Steinsson (2003) among others. In our cashless model, only the variances of inflation and output gap affect welfare. We additionally consider the correlation between inflation and the output gap because it is related to the magnitude of the trade-off between inflation and output gap stabilization. Kiley (2013) shows that the estimate of the welfare-relevant output gap from the Federal Reserve Board's estimated New Keynesian DSGE model of the U.S. economy is similar to the gap from the Congressional Budget Office

[11] The model contains two market distortions: the relative-price distortion due to sticky prices and the average markup distortion arising from firms' monopoly power. As shown in various studies, e.g., Benigno and Woodford (2005), Khan, King and Wolman (2003), King and Wolman (1999), and Woodford (2002), zero inflation minimizes both distortions and constitutes the optimal policy.

[12] Estimates in the literature of the Calvo parameter range from 0.72 to 0.83 for the postwar U.S. economy. For example, they are found to be 0.83 in Levin et al. (2005), 0.79 for a DSGE-VECM model, 0.83 for a DSGE model in Del Negro et al. (2007), and 0.72 in Herbst and Schorfheide (2014). The average of these estimates is 0.79, which is quite close to our calibrated parameter value of $\alpha = 0.8$.

(CBO). Thus, we calculate these moments using postwar U.S. data of CPI inflation, the CBO output gap, and the federal funds rate.[13] The standard deviations of CPI inflation, the CBO output gap, and the federal funds rate are 3.24, 2.37, and 3.40, respectively, while those for the calibrated model are 3.24, 2.37, and 3.15, respectively.[14] The correlation between CPI inflation and the CBO output gap is 0.06 while that for the calibrated model is 0.07. Thus, our calibration of the baseline model successfully reproduces the key moments for our analysis.

3 Monetary policy and welfare

We conduct welfare analysis for four different policies in comparison to the Ramsey optimal policy:

(i) Taylor rule: the standard Taylor rule ($\phi_\pi = 1.5, \phi_y = 0.5, \phi_R = 0.8$) without the MRIT;

(ii) Taylor-MRIT rule: the optimal MRIT conditional on the Taylor rule;

(iii) Optimized Taylor rule: the optimal implementable Taylor rule without the MRIT;

(iv) Optimized Taylor-MRIT rule: the optimal implementable Taylor rule with the MRIT.

The Taylor-MRIT rule (ii) entails a monetary authority that adjusts the medium-run inflation target by choosing the parameter values μ_{π^*} and ρ_{π^*} in (12) to maximize the welfare of the representative household, conditional on the Taylor rule coefficients $\phi_\pi = 1.5$, $\phi_y = 0.5$, and $\phi_R = 0.8$. Under the optimized Taylor rule (iii), the monetary authority simply chooses the welfare-maximizing values of ϕ_π, ϕ_y and ϕ_R in (10), without adjusting the medium-run inflation target. In policy (iv), all five policy parameters may be optimized. Formally, for policies (ii), (iii), and (iv) we search for the relevant policy parameters that maximize the

[13] We use the sample period of 1949:Q1 to 2008:Q4. The CBO output gap is available from 1949:Q1. The federal funds rate is available from 1954:Q3. Thus, we use the three month Treasury Bill rate for the period before 1954:Q3. Note that the correlation between the federal funds rate and the three month Treasury Bill rate is 0.99 for the sample period of 1954:Q3 to 2008:Q4.

[14] The standard deviations of inflation and the nominal interest rate are calculated using annualized rates.

unconditional expectation of lifetime utility, $E(V_t)$, where

$$V_t = E_t \sum_{s=0}^{\infty} \beta^s U(C_{t+s}, N_{t+s}) \tag{17}$$

and E denotes the unconditional expectation operator.[15] For the welfare measure in (17) to adequately capture the effect of uncertainty, we compute the second-order accurate solution to the equilibrium policy functions, including for V_t.[16]

Following Schmitt-Grohé and Uribe (2007), in searching for the optimal values of the Taylor parameters, we restrict $\phi_\pi \in (1, 3]$ and $\phi_y \in (0, 3]$ for policies (iii) and (iv). Schmitt-Grohé and Uribe (2007) argue that policy coefficients larger than 3 would be difficult for policymakers to communicate to the public. We also rule out those parameter values that yield an indeterminate equilibrium. In addition, we restrict $|\mu_{\pi^*}| < 0.15$ and $\rho_{\pi^*} \in [0, 1)$ when searching for the optimized coefficients in policies (ii) and (iv). The restriction on the value of μ_{π^*} is somewhat arbitrary. However, an excessively large value of μ_{π^*} may undermine the credibility of the monetary authority in delivering the stated objectives for the same reason as Taylor-type rule parameters greater than 3.[17]

3.1 The Ramsey policy

To evaluate and compare the various policy rules above we use the time-invariant (timeless perspective) stochastic Ramsey optimal policy. Under the Ramsey policy, the policy authority acts benevolently and searches for the allocation that maximizes the welfare of the representative agent. Following the standard approach in the literature, we abstract from any specific form of the policy rule and search instead for the optimal Ramsey allocation.[18] In addition, as in the competitive equilibrium, the Ramsey equilibrium is solved up to a

[15] Our results continue to hold if, instead, the policy parameters used are those that maximize the conditional expectation, $E_0 V_0$, i.e., conditional on the initial state of the economy being the nonstochastic steady state.

[16] See Schmitt-Grohé and Uribe (2004) for a discussion on why a second-order approximation to the equilibrium solution is needed for an accurate welfare computation. Also see Johnston, King and Lie (2014) for the detail of the solution method that we use.

[17] We sidestep this possible credibility issue in this paper and leave it for future research.

[18] See, for example, Erceg, Henderson and Levin (2000), Khan, King and Wolman (2003), Lie (2015), and Schmitt-Grohé and Uribe (2007).

second-order approximation. Appendix A contains additional details on the derivation and computation of the Ramsey policy. Armed with the Ramsey policy, we can then calculate the conditional and unconditional welfare costs of any alternative policy relative to the Ramsey policy, which is described in the following section.

3.2 Welfare cost measure

As in Schmitt-Grohé and Uribe (2007), we define the welfare cost of implementing an alternative policy as the fraction of consumption that the representative household would be willing to give up under the Ramsey policy environment to be equally well off, as under the alternative policy environment. Specifically, let $\{C_t^r, N_t^r\}$ and $\{C_t^a, N_t^a\}$ be the state-contingent plans for consumption and labor under the Ramsey policy and under the alternative policy, respectively. The conditional welfare cost, λ_c, is implicit in the expression

$$E_0 \sum_{t=0}^{\infty} \beta^t U(C_t^a, N_t^a) = E_0 \sum_{t=0}^{\infty} \beta^t U((1-\lambda_c)C_t^r, N_t^r).$$

The expectation operator above makes clear that the welfare cost is conditional on the initial state at time $t = 0$, which we assume to be the deterministic steady state under the Ramsey policy. The deterministic steady state under the alternative policy is assumed to be identical to that under the Ramsey policy. Similarly, the unconditional welfare cost, λ_u, can be obtained from

$$E \sum_{t=0}^{\infty} \beta^t U(C_t^a, N_t^a) = E \sum_{t=0}^{\infty} \beta^t U((1-\lambda_u)C_t^r, N_t^r).$$

Here, E is the unconditional expectation operator. For the specific form of the utility function and the calibrated parameters in Table 1, we can then calculate the second-order approximations to λ_c and λ_u for any alternative policy rule.[19]

[19] In fact, since our utility function in (1) is identical to that in Schmitt-Grohé and Uribe (2007), we obtain the same expressions for both λ_c and λ_u — see equations (38) and (39) in the expanded version of their paper, Schmitt-Grohé and Uribe (2006).

Table 2: Baseline model: welfare costs of various policies

	Policy Parameters					Conditional Welfare Cost	Unconditional Welfare Cost	$\sigma(\hat{\pi}_t)$	$\sigma(\hat{x}_t)$	$\sigma(\hat{R}_t)$
	ϕ_π	ϕ_y	ϕ_R	μ_{π^*}	ρ_{π^*}	$\lambda_c \times 100$	$\lambda_u \times 100$			
(i) Taylor rule	1.50	0.50	0.80	—	—	0.298	0.312	3.240	2.368	3.150
(ii) Taylor-MRIT	1.50	0.50	0.80	-0.084	0.72	0.106	0.109	1.648	3.378	3.596
(iii) Optimized Taylor	3.00	0.16	0.80	—	—	0.183	0.186	2.317	3.028	3.239
(iv) Optimized Taylor-MRIT	3.00	2.48	0.80	-0.150	0.72	0.035	0.034	1.242	2.920	5.846

Notes: (1) The conditional and unconditional welfare costs are in terms of percent consumption loss relative to the Ramsey allocation. (2) The standard deviation $\sigma(\cdot)$ is expressed in percent (annualized for inflation and nominal interest rate). (3) For the Taylor-MRIT rule (ii), we search for μ_{π^*} and ρ_{π^*} that maximize the unconditional welfare, while fixing $\phi_\pi = 1.5$, $\phi_y = 0.5$, and $\phi_R = 0.80$. (4) For the optimized Taylor-MRIT rule, we search for optimal ϕ_π, ϕ_y, and μ_{π^*}, while fixing ρ_{π^*} to the optimized value found in rule (ii) and $\phi_R = 0.80$. (5) We restrict $1 \leq \phi_\pi \leq 3$, $0 \leq \phi_y \leq 3$, and $|\mu_{\pi^*}| \leq 0.15$ when searching for optimized coefficients. (6) Under the Ramsey policy, $\sigma(\hat{\pi}_t) = 1.187$, $\sigma(\hat{x}_t) = 2.492$, $\sigma(\hat{R}_t) = 11.90$.

4 The optimality of medium-run inflation target adjustment in the face of cost-push shocks

In this section, we evaluate the various policies discussed in the previous section. We analyze how and why adjusting the medium-run inflation target in the face of cost-push shocks may lead to a more optimal equilibrium allocation and improve households' welfare.

4.1 Welfare under medium-run inflation targeting

Table 2 reports the conditional and unconditional welfare cost measures, λ_c and λ_u, in comparison to the Ramsey policy. We find that the Taylor rule (i) yields conditional and unconditional welfare costs of 0.298% and 0.312% of consumption relative to the Ramsey policy. This is in fact quite a sizable business-cycle cost and is comparable to the finding in Schmitt-Grohé and Uribe (2007).

We next study the implication of our proposed policy, the Taylor-MRIT rule (ii), where the monetary authority can additionally adjust the medium-run inflation target in response to cost-push shocks over time. Our numerical search finds optimal MRIT coefficients of $\mu_{\pi^*} = -0.084$ and $\rho_{\pi^*} = 0.72$.[20] The negative value of μ_{π^*} implies that the monetary

[20] When we use the conditional welfare function as the criterion, the optimal parameter values that maximize $E_0(V_0)$ are $\mu_{\pi^*} = -0.080$ and $\rho_{\pi^*} = -0.73$, with $\lambda_c \times 100 = 0.106$ and $\lambda_c \times 100 = 0.109$. The

authority decreases the medium-run inflation target when inflation increases due to a positive realization of cost-push shock. All else equal, this policy action leads to a bigger inflation gap (Π_t/Π_t^*) compared to the standard Taylor rule (i) in (10) without the MRIT adjustment. The bigger inflation gap translates to a more aggressive response to the cost-push shock through a larger increase in the nominal interest rate, as evident from (11). In addition, the substantial inertia in the Taylor-MRIT rule means that the monetary authority needs to react to a realization of the cost-push shock in a highly persistent manner. This smoothing adjustment can be explained by the persistent effect of the cost-push shock on inflation.

The welfare gain from the MRIT adjustment is significant. The Taylor-MRIT rule (ii) yields conditional and unconditional welfare costs of 0.106% and 0.109% of consumption relative to the Ramsey policy. When compared to the welfare costs associated with the Taylor rule (i), the welfare gain implies that agents would be willing to give up more than 20 basis points of their consumption stream under the Taylor-MRIT rule (ii) to be as well off as under the Taylor rule (i). Alternatively, using the unconditional cost measure, we can say that the welfare gain from adopting the Taylor-MRIT rule over the Taylor rule is 65%.[21] To better understand the reason for the welfare gain, we compute the standard deviations of inflation ($\sigma(\hat{\pi}_t)$), the output gap ($\sigma(\hat{x}_t)$), and the nominal interest rate ($\sigma(\hat{R}_t)$). The standard deviations $\sigma(\hat{\pi}_t)$ and $\sigma(\hat{x}_t)$ for the Taylor rule (i) are 3.24 and 2.37, respectively, while they are 1.65 and 3.38 for the Taylor-MRIT rule (ii). These calculations show that the MRIT, which allows for a more aggressive reaction to inflation due to cost-push shocks, reduces inflation volatility by a factor of two, but only increases the volatility of the output gap by about 43%. This, coupled with the fact that inflation variation carries a much larger weight in the utility-based welfare measure relative to the output-gap variation, is the source of the significant welfare gain.[22]

In addition to increasing output-gap volatility, another potential cost of adjusting the MRIT in policy (ii) may arise from higher nominal interest-rate volatility: $\sigma(\hat{R}_t)$ is 3.60 in rule (ii) versus 3.15 in rule (i) under the standard Taylor rule. This potential cost, however,

welfare ranking across policy rules is also identical. Hence, the results are robust to the choice of the welfare criterion.

[21] We find the welfare gain based on (0.312-0.109)/0.312 = 0.65.

[22] This much-larger weight on inflation variation can be seen by deriving the welfare-theoretic loss function, as in Woodford (2003) and Benigno and Woodford (2005). We also illustrate this in Appendix D in the paper.

does not affect welfare since in our cashless model the welfare function only depends on the volatility of inflation and the output gap, as shown in Rotemberg and Woodford (1999), Woodford (2003), and Benigno and Woodford (2005). We show later that even when we put some weight on nominal interest-rate volatility in the welfare loss function, the welfare gain from the huge reduction in inflation volatility dominates the cost of higher output-gap and nominal interest-rate volatilities.

We next investigate whether the optimized Taylor rule (iii) can produce a welfare gain comparable to the Taylor-MRIT rule (ii). In the first instance we only search for optimal values of ϕ_π and ϕ_y, while fixing ϕ_R to its calibrated value of 0.8. In Section 5.4, we explore the welfare implication of interest rate smoothing. We find that the best implementable Taylor-type rule requires an aggressive response to inflation and a somewhat muted response to the output gap fluctuation. The optimized Taylor rule entails $\phi_\pi = 3$, which is the largest allowable value, and $\phi_y = 0.16$.

Our finding on the optimality of applying the largest allowable value for the inflation coefficient is consistent with that in Schmitt-Grohé and Uribe (2007). It reflects the fact that inflation variation is the most important element of the welfare function: a higher value of ϕ_π reduces the volatility of inflation arising from all three shocks. We find, however, the optimal ϕ_y is not zero, in contrast to their finding. This discrepancy comes from two important differences between our economy and the one considered in Schmitt-Grohé and Uribe (2007): the presence of cost-push shocks in our model and the assumption that the monetary authority responds to the deviation of output from its natural output level (i.e., the output gap), instead of deviations from the constant steady-state level. Since it is the volatility of the output *gap* that matters for welfare instead of output, the optimal ϕ_y may no longer be zero. Despite this, ϕ_y should not be too large, as responding too strongly to output-gap fluctuations may be suboptimal because it may lead to higher inflation volatility coming from cost-push shocks. Thus, the existence of the policy stabilization trade-off between inflation and the output-gap due to the presence of cost-push shocks is responsible for the low optimal value of ϕ_y relative to ϕ_π — here, the trade-off is resolved in favor of inflation stabilization. If there is no cost-push shock, and productivity and government spending shocks are the only source of aggregate fluctuations, the inflation and the output-gap respond to them in the same direction. This means it does not matter whether the monetary authority reacts strongly to inflation or output-gap fluctuations.[23]

In terms of welfare implications, the optimized Taylor-rule (iii) still yields non-negligible conditional and unconditional welfare costs of 0.183% and 0.186%, respectively, under fixed $\phi_R = 0.8$. Thus, relative to the Taylor-MRIT rule (ii), the welfare gain from the optimized Taylor-rule (iii) over the standard Taylor rule (i) is smaller. The standard deviation of inflation in the optimized Taylor-rule is about 40% larger compared to that in the Taylor-MRIT rule, while the standard deviation of the output gap is only about 10% smaller. Hence, it appears that adjusting the medium-run inflation target leads to a better trade-off between inflation and output-gap variations. We investigate this important finding in the next section.

4.2 The trade-off between stabilizing inflation and the output gap

The extent of the inflation-output trade-off is an important consideration when conducting monetary policy. The greater the trade-off is, the more difficulty the monetary authority faces in stabilizing inflation and the output gap. We argue that the ability of the monetary authority to adjust the medium-run inflation target in the face of cost-push shocks leads to a more favorable inflation-output trade-off. This improvement in the trade-off leads to welfare gain, above and beyond what is attainable in the standard Taylor-rule policy. This source of inflation-output trade-off improvement, to the best of our knowledge, is a new result in the literature.[24]

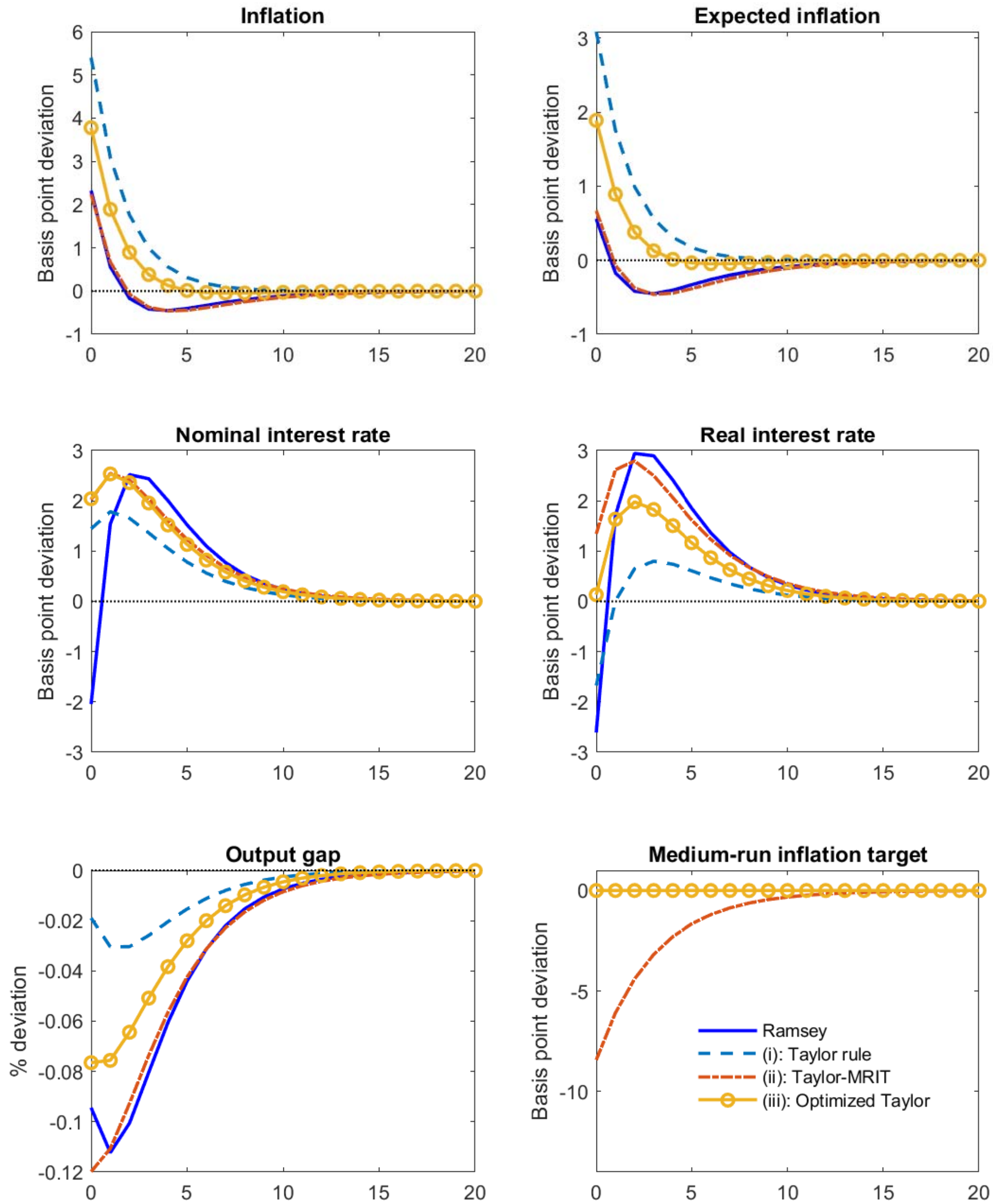
4.2.1 The improvement in the trade-off

We first show this improvement by comparing the impulse responses to a 1% cost-push shock for various policies described above. As depicted in Figure 1, a positive cost-push shock raises inflation and lowers the output gap on impact under all policies, including the

[23] In fact, without the cost-push shock ($\sigma_\theta = 0$), we find that the optimized Taylor-type rule entails $\phi_\pi = \phi_y = 3$.

[24] Other sources have been identified in the literature. For example, Clarida, Galí and Gertler (1999) show that adopting a pre-commitment policy leads to an improved inflation variability-output variability compared to a discretionary policy.

Figure 1: Impulse response functions to a 1% cost-push shock



Notes: In generating the impulse responses, we calibrate the size of the innovation to the average markup, $\varepsilon_{\theta,t}$ in (3), so that u_t in (9) increases by one percent on impact relative to its steady-state value. The policy coefficients for rules (i), (ii), and (iii) are presented in Table 2.

Ramsey policy.[25] Under the Taylor rule (i), inflation jumps the highest on impact and reverts

[25]Under the Ramsey policy, complete price stability in response to a cost-push shock is not optimal. This partial accommodation of the inflationary pressure is optimal because in addition to inflation variation, the

back to the steady-state level slowly. The optimized Taylor rule (iii) with $\phi_\pi = 3$, $\phi_y = 0.16$, and $\phi_R = 0.8$ produces only marginally smaller inflation fluctuations than the Taylor rule (i). This, however, is enough to make the welfare costs smaller in the optimized Taylor rule in spite of larger output gap fluctuations (bottom left panel), reflecting the fact that inflation variation is more important than output-gap variation for welfare.

Meanwhile, under the Taylor-MRIT rule (ii) the response of inflation almost perfectly matches that under the Ramsey policy throughout all periods. Inflation increases by less on impact compared to rules (i) and (iii), and unlike those two policies, both the Ramsey policy and the Taylor-MRIT rule (ii), as makeup strategies, induce a period of the inflation rate below its target following an inflationary cost-push shock. The output gap, on the other hand, is less stabilized under the Taylor-MRIT rule, consistent with the results in Table 2. However, output-gap movements closely match those under Ramsey, and hence constitute a near-optimal response to the cost-push shock.

One way to assess the relative improvement in the inflation-output trade-off is to calculate output-gap variation relative to inflation variation when the monetary authority switches from the Taylor-rule (i) to an alternative rule (j), for j=ii, iii, and iv, as

$$\epsilon_{(j)} = -\frac{\log(\sigma(\hat{x}_t)_{(j)}/\sigma(\hat{x}_t)_{(i)})}{\log(\sigma(\hat{\pi}_t)_{(j)}/\sigma(\hat{\pi}_t)_{(i)})}, \tag{18}$$

where $\sigma(\hat{x}_t)_{(j)}$ and $\sigma(\hat{\pi}_t)_{(j)}$ are the standard deviations of the output gap and inflation, respectively, under the monetary policy rule (j). The standard deviations represent the variations in inflation and the output gap. As reported in Table 2, switching from the Taylor rule (i) to each alternative rule of (ii)-(iii) always improves welfare, decreases the standard deviation of inflation, and increases variation in the output gap. Thus, a larger value in (18) implies a smaller trade-off improvement. Using (18) and the standard deviations reported in Table 2, we find $\epsilon_{(ii)} = 0.53$ and $\epsilon_{(iii)} = 0.72$. The calculated value of $\epsilon_{(ii)} = 0.53$ implies, for example, that reducing inflation variation by one percent through switching from the Taylor-rule (i) to the Taylor-MRIT rule (ii) requires increasing output-gap variation by 0.53 percent. Thus, adopting MRIT using rule (ii) has a larger inflation-output trade-off

welfare function also depends on output-gap variation.

improvement compared to the optimized Taylor rule (iii).

To further understand the intuition behind the improvement in the trade-off and the associated welfare gain, the top right panel of Figure 1 plots the impulse response of one-period ahead expected inflation. The ability of the monetary authority in the Taylor-MRIT rule to lower the inflation target following an inflationary cost-push shock leads to much-lower inflation expectations compared to standard Taylor rule (i) and the optimized Taylor rule (iii). Lower expected inflation in turn yields lower current inflation for a given output gap and a given realization of the cost-push shock. These responses in inflation and expected inflation under the Taylor-MRIT rule are reminiscent of those under an optimal pre-commitment policy, i.e., the Ramsey policy. As discussed in Clarida, Galí and Gertler (1999) and Steinsson (2003) for example, in response to an inflationary cost-push shock, the optimal policy under commitment entails lower inflation expectations than the optimal discretionary policy, causing the inflation rate to be below its long-run target in some periods, as depicted in Figure 1. Indeed, the impulse responses of expected inflation under the Taylor-MRIT rule closely match those under Ramsey policy. In a way, one can view proper adjustments in the medium-run inflation target as an additional commitment device, which improves welfare.

On the impulse response of the nominal interest rate, the Taylor-MRIT rule (ii) implies a larger increase in the nominal rate in all periods than in the standard Taylor rule (i). Hence, consistent with the results reported in Table 2, adjusting the medium-run inflation target entails higher nominal interest-rate volatility, although it is comparable to the optimized Taylor rule (iii). The higher volatility does not adversely affect welfare, however, in our cashless model. In fact, the Ramsey allocation necessitates even larger nominal interest rate fluctuations in response to the cost-push shock. It is noteworthy that the nominal rate decreases on impact under Ramsey, instead of increasing as in the other three rules. The Taylor-type rules (i)-(iii) restrict the dynamics of the nominal interest rate as a function of inflation and the output gap and make the impulse response functions die out smoothly over time. However, the Ramsey policy determines the optimal path of the nominal interest rate without any such restrictions. This flexibility helps generate a smaller decline in the output gap in the first period compared to the Taylor-MRIT rule (ii), despite an almost-identical increase in inflation.

4.2.2 The extent of the improvement

How much of an improvement in the inflation-output trade-off can the MRIT policy generate? Can we achieve a similar welfare level to that under Ramsey with such a policy? To answer these questions, we consider the optimized Taylor-MRIT rule (iv), where we search jointly for optimal ϕ_π, ϕ_y, and μ_{π^*}. The coefficient ρ_{π^*} is fixed at 0.72, which is the optimal value under the Taylor-MRIT rule (ii).[26] We also fix $\phi_R = 0.8$.

The last row of Table 2 reports the results. Compared to the Taylor-MRIT rule (ii) in which we fix the Taylor coefficients at $\phi_\pi = 1.5$ and $\phi_y = 0.5$, the welfare costs are now much smaller at 0.034-0.035% of consumption per capita. The optimized Taylor-MRIT rule thus appears to be able to replicate the Ramsey allocation quite well. This policy calls for the maximum allowable value for $\phi_\pi = 3$, a much larger value of $\phi_y = 2.48$ compared to the output-gap coefficient of 0.16 in the optimized Taylor rule (iii), and $\mu_{\pi^*} = -0.15$. Thus, in the face of a positive cost-push shock, the monetary authority responds more aggressively to output gap fluctuations. It is optimal to do so because the monetary authority can now respond to the inflationary pressure by further reducing the medium-run inflation target, i.e., a more negative value of μ_{π^*}. Without the ability to adjust the medium-run inflation target, reacting strongly to the output gap ($\phi_y = 2.48$) would not be optimal, as is apparent from the optimized Taylor rule (iii). In this standard policy environment with a fixed inflation target, a much-more aggressive response to inflation fluctuations originating from cost-push shocks, i.e., a relatively larger value of ϕ_π and a lower value of ϕ_y, is optimal because inflation fluctuations are much more important than output-gap fluctuations in the utility-based welfare measure.

The larger extent of the improvement in the trade-off and the associated larger welfare gain under the optimized Taylor-MRIT rule are apparent if we look at the standard deviations of inflation and the output gap. Not only are $\sigma(\hat{\pi}_t)$ and $\sigma(\hat{x}_t)$ smaller than those under the Taylor-MRIT rule (ii), they are also both smaller than those under the optimized Taylor rule (iii). Moreover, based on (18), we find $\epsilon_{(iv)} = 0.22$. The improvement is much more pronounced for the optimized Taylor-MRIT rule (iv), which leads to a similar welfare level to that associated with the Ramsey policy.

[26] The results do not materially change when we also numerically search for optimal ρ_{π^*}.

4.2.3 Unconstrained Taylor-rule coefficients

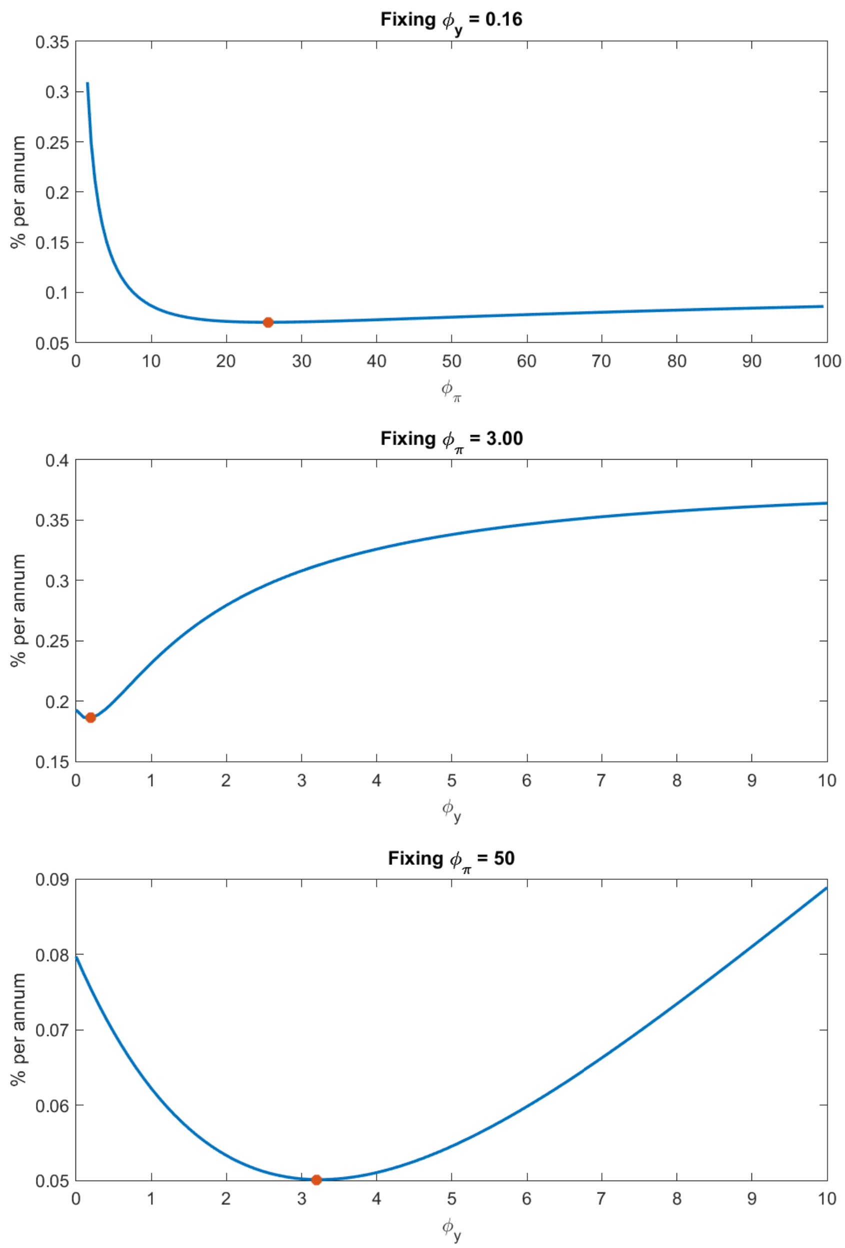
The findings above also raise the question of whether the allocation under the optimized Taylor-MRIT rule (iv) can be achieved solely with an unconstrained Taylor rule, i.e., when we remove the upper limit of ϕ_π and ϕ_y coefficients. If so, the improvement in the inflation-output trade-off under the MRIT policy is just a mirage, arising from an implementability restriction. To investigate this, we look at the implications of various values of ϕ_π and ϕ_y for unconditional welfare costs, while setting $\mu_{\pi^*} = 0$ throughout. The results are shown in Figure 2.

The top panel of Figure 2 depicts the welfare cost when we vary ϕ_π, while fixing $\phi_y = 0.16$, which is the optimal value in the optimized Taylor rule (iii). The panel shows that the unrestricted optimal value of ϕ_π is 25 — above this value, the welfare cost starts increasing again. Intuitively, a too-high value of ϕ_π means that the monetary authority responds too aggressively to inflation fluctuations and too timidly to output-gap fluctuations given the trade-off originating from cost-push shocks. The middle and bottom panels of Figure 2 depict the welfare cost when we vary ϕ_y, given a value of ϕ_π. When the value of ϕ_π is fixed to 3, the optimal ϕ_y value is 0.16. The welfare cost is larger when $0 < \phi_y < 0.16$ since the monetary authority's response to output-gap fluctuations is too timid. On the contrary, when $\phi_y > 0.16$ it responds too aggressively. When ϕ_π is fixed at a larger value of 50 (bottom panel), the optimal value of ϕ_y becomes larger.[27] All in all, the results depicted in Figure 2 imply that the jointly optimized values of ϕ_π and ϕ_y should be finite and relatively small. More importantly, at least for the range of coefficient values considered in Figure 2, the welfare costs appear to be at least 0.05%, which is greater than the welfare cost from the optimized Taylor-MRIT rule (iv). Thus, the improvement in the inflation-output trade-off under the MRIT policy is evident.

Figure 3 offers a more comprehensive, three-dimensional picture of the unconditional welfare costs when we jointly vary $\phi_\pi \in (1, 100]$ and $\phi_y \in (0, 10]$. Again, the figure shows that the joint optimal values of ϕ_π and ϕ_y are finite. The smallest unconditional welfare cost is

[27] This makes sense since in the presence of a policy stabilization trade-off between inflation and output-gap, a more aggressive response to inflation fluctuations calls for a more aggressive response to output-gap fluctuations, albeit to different degrees.

Figure 2: Unconditional welfare costs under the Taylor-type rule

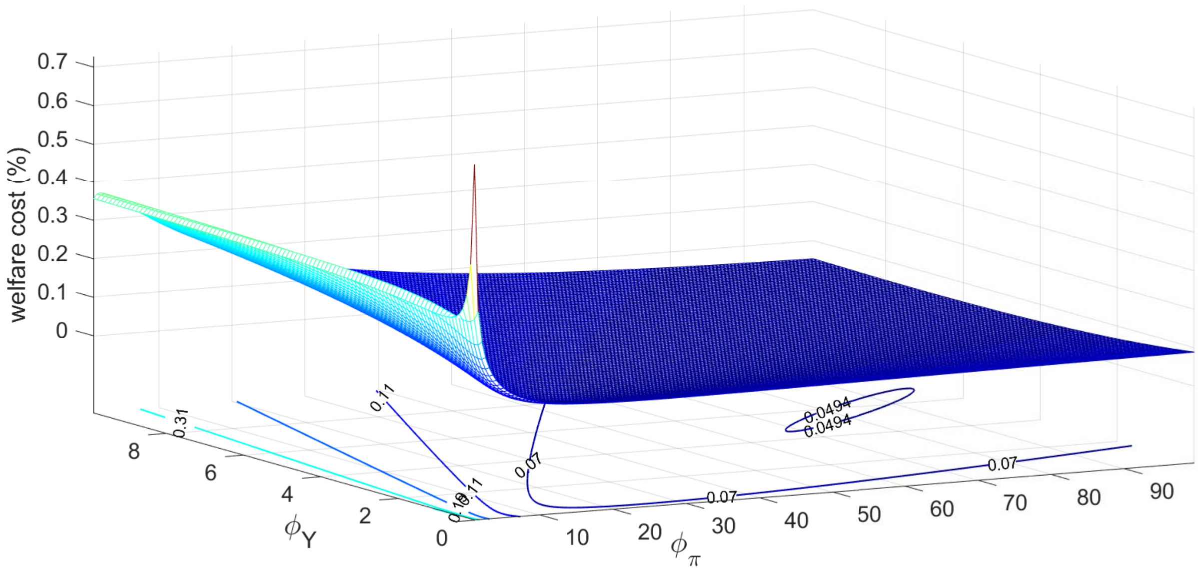


Notes: In each panel, we fix one of policy coefficients, ϕ_π or ϕ_y, and vary the other parameter. The asterisk mark indicates the smallest welfare cost for each setup.

at $\lambda_u = 0.05\%$, which is achieved at $\phi_\pi = 73$ and $\phi_y = 5$.[28] We note that this combination of optimal Taylor-rule coefficients is not unique. For example, one can always achieve a similar

[28] Unlike the result in Schmitt-Grohé and Uribe (2007), it is not possible in our environment to fully replicate the Ramsey allocation (i.e., zero welfare cost) due to the existence of the cost-push shock.

Figure 3: Unconditional welfare costs under the Taylor-type rule for various values of ϕ_π and ϕ_y



Notes: We plot the unconditional welfare costs when we jointly vary the monetary policy coefficients ϕ_π and ϕ_y. All other parameter values are set to those for the baseline model presented in Table 1.

optimal allocation by increasing both ϕ_π and ϕ_y appropriately. Despite this, it is not possible to reduce the welfare cost much beyond $\lambda_u = 0.05\%$. This indicates that the improved inflation-output trade-off under the MRIT policy is not due to the restriction on the values ϕ_π and ϕ_y. Treating the optimized Taylor-MRIT rule (iv) in Table 2 as the best attainable policy, the monetary authority could further reduce the welfare cost by 32% using the MRIT rule.[29] In addition, we search over the policy coefficients under the Taylor-type rule with $\mu_{\pi^*} = 0$ that would lead to the same welfare level associated with the Taylor-MRIT rule (ii). We find that multiple pairs of coefficients—for example, $(\phi_\pi, \phi_y) = (7.5, 0.0), (27.5, 6.5)$—can achieve a similar welfare level, but they require impractically-high inflation-feedback coefficients. The inflation-feedback coefficient of $\phi_\pi = 7.5$ is the lower bound.

[29]That is, $(0.05 - 0.034)/0.05 = 0.27$.

5 Robustness analysis

This section explores the robustness of our results along several key dimensions. We first examine the relationship between the welfare gains from the MRIT policy and the Phillips curve's slope, which is governed by the Calvo parameter. Second, we explore the potential implication of interest rate volatility on the welfare cost. Third, we consider the extent to which our results are sensitive to different Taylor-rule specifications, particularly involving the measure of real activity the monetary authority reacts to. Fourth, we examine the importance of nominal interest-rate smoothing. Fifth and finally, we consider to what extent adding capital accumulation and sticky wages (i.e., richer model features) affects our findings and find that they are robust to the additions.

5.1 The NKPC slope

The flattening of the NKPC since the mid-1980s has been widely documented in the literature.[30] As discussed in Appendix D, the flattening of the NKPC complicates the conduct of monetary policy from three perspectives: (i) the fraction of inflation variation due to cost-push shocks becomes increasingly substantial; (ii) controlling inflation through monetary policy becomes much harder in the face of cost-push shocks; and (iii) inflation becomes completely dominant over the output gap in determining household welfare. For a given monetary policy rule, such an environment results in lower welfare. It is therefore imperative to assess how the extent of the welfare gain from the MRIT policy varies with the slope of the NKPC.

The NKPC slope in (8) is given by $\lambda = (1-\alpha\beta)(1-\alpha)/\alpha$ and is mainly governed by the Calvo parameter α. To establish the relationship between the NKPC slope and the effectiveness of monetary policy, we set $\alpha = 0.70$ for a steep slope and $\alpha = 0.85$ for a flat slope. These values are closely matched to the pre- and post-1980 U.S. economies. For example, Bhattarai, Lee and Park (2016) estimate the Calvo parameter to be 0.67 for 1960:Q1 to 1979:Q2 and 0.84 for 1982:Q4 to 2008:Q2. These Calvo parameter values correspond to 0.166 for the pre-1980 period and 0.032 for the post-1980 period under the marginal-cost-

[30]See our discussion in introduction and references therein for more details.

Table 3: The Phillips curve slope: welfare cost of various policies

	Policy Parameters ϕ_π	ϕ_y	ϕ_R	μ_{π^*}	ρ_{π^*}	Conditional Welfare Cost $\lambda_c \times 100$	Unconditional Welfare Cost $\lambda_u \times 100$	$\sigma(\hat{\pi}_t)$	$\sigma(\hat{x}_t)$	$\sigma(\hat{R}_t)$
					(a) flat Philips curve: $\alpha = 0.85$					
(i) Taylor rule	1.50	0.50	0.80	—	—	0.503	0.537	3.458	2.464	3.136
(ii) Taylor-MRIT rule	1.50	0.50	0.80	-0.091	0.72	0.099	0.100	1.593	4.672	4.665
					(b) steep Phillips curve: $\alpha = 0.70$					
(i) Taylor rule	1.50	0.50	0.80	—	—	0.171	0.176	3.228	2.138	3.292
(ii) Taylor-MRIT rule	1.50	0.50	0.80	-0.076	0.72	0.123	0.127	2.397	2.392	3.259

Notes: (1) For each α case, the standard deviation of the innovation in the markup shock $\varepsilon_{\theta,t}$ is rescaled so that the variance of the reduced-form cost-push shock $\hat{u}_t$ in the NKPC remains the same as in the baseline case ($\alpha = 0.80$) — all other parameter values are set to those in Table 1. (2) In rule (ii) in each case we fix $\rho_{\pi^*} = 0.72$, i.e., the optimal value found in the baseline case in Table 2. (3) The conditional and unconditional welfare costs are in terms of percent consumption loss relative to the Ramsey allocation in each α case, i.e., we resolve the Ramsey allocation for each case. (4) The standard deviation $\sigma(\cdot)$ is expressed in percent (annualized for inflation and nominal interest rate).

based NKPC in (8). In addition, the slope κ in the output-gap-based NKPC in (9) is equal to 0.268 and 0.052 for the same two sub-periods. Thus, the slope of the NKPC appears to have flattened substantially, with the slope coefficient reduced to about a fifth of its pre-1980 period size.

Table 3 reports the welfare implications of the two different slopes of the NKPC under the Taylor rule (i) and the Taylor-MRIT rule (ii). In each case, we rescale the standard deviation of the innovation in the markup shock $\varepsilon_{\theta,t}$ so that the variance of the reduced-form cost-push shock $\hat{u}_t$ in the NKPC in (9) remains the same as in the baseline case of $\alpha = 0.8$. We do this to focus on the impact of the change in the slope of the NKPC on the effectiveness of monetary policy rules.

When the NKPC is flat ($\alpha = 0.85$), the standard Taylor rule implies a conditional and an unconditional welfare cost of 0.503% and 0.537%, respectively. The larger welfare costs than those under $\alpha = 0.70$ and $\alpha = 0.80$ in the baseline case are to be expected, since as mentioned above and discussed in Appendix D, a flatter NKPC makes it relatively harder for the monetary authority to stabilize inflation. However, the monetary authority can do better by adjusting the medium-run inflation target in the face of cost-push shocks when the Phillips curve becomes flatter. Here, the optimal μ_{π^*} value is more negative at -0.091 and the welfare gain is significantly larger compared to the baseline case reported in Table 2. The reverse occurs under a steep Phillips curve ($\alpha = 0.70$): the optimal μ_{π^*} value is less negative at -0.076 and the welfare gain appears to be lower. Using the unconditional welfare cost criterion, we can calculate the welfare gain by $(\lambda_{u,i} - \lambda_{u,ii})/\lambda_{u,i}$ where $\lambda_{u,i}$ and $\lambda_{u,ii}$ are the unconditional welfare costs for the Taylor rule (i) and the Taylor-MRIT rule (ii), respectively. We find that the welfare gain from adopting the Taylor-MRIT rule over the Taylor rule increases from 28% for $\alpha = 0.70$ to 81% for $\alpha = 0.85$. In the baseline case of $\alpha = 0.8$, reported in Table 2, the corresponding welfare gain is 65%.

The findings in Table 3 indicate that our proposed policy of properly adjusting the medium-run inflation target is even more appealing with the flattening of the Phillips curve. Considering the current economic environment of low inflation rates under a flat Phillips curve in many developed economies, the welfare benefit of such a policy is non-trivial and can even be substantial.

5.2 Aversion to interest-rate volatility

One potential cost of the MRIT policy is a higher nominal interest-rate volatility $\sigma(\hat{R}_t)$, as is evident from its standard deviations reported in Table 2 and from the impulse responses in Figure 1. In our cashless model, it is well-known that the utility-based welfare function does not depend on nominal interest rate fluctuations.[31] A high value of $\sigma(\hat{R}_t)$ therefore does not adversely affect welfare. Nonetheless, here, we perform a check on the possible welfare-reducing effect of nominal interest rate fluctuations. Instead of building a monetary model with an explicit consideration for $\sigma(\hat{R}_t)$, we perform an ad-hoc check using the following quadratic welfare loss function:

$$L = \sigma(\hat{\pi}_t)^2 + \lambda_x \sigma(\hat{x}_t)^2 + \lambda_R \sigma(\hat{R}_t)^2 \tag{19}$$

[31] See the derivations of the quadratic loss function in Benigno and Woodford (2005), Rotemberg and Woodford (1999), Steinsson (2003), and Woodford (2003).

Table 4: Welfare losses of various policies based on simple loss functions

	Model standard deviations			Woodford's (2003) loss function ($\lambda_x = 0.048$)			Williams's (1999) loss function ($\lambda_x = 1$)		
	$\sigma(\hat{\pi}_t)$	$\sigma(\hat{x}_t)$	$\sigma(\hat{R}_t)$	$\lambda_R = 0$	$\lambda_R = 0.077$	$\lambda_R = 0.154$	$\lambda_R = 0$	$\lambda_R = 0.02$	$\lambda_R = 0.04$
(i) Taylor rule	3.240	2.368	3.150	10.77	11.53	12.29	16.11	16.30	16.50
(ii) Taylor-MRIT	1.648	3.378	3.596	3.26	4.26	5.26	14.13	14.39	14.64
(iii) Optimized Taylor	2.317	3.028	3.239	5.81	6.62	7.42	14.54	14.75	14.96
(iv) Optimized Taylor-MRIT	1.242	2.920	5.846	1.95	4.58	7.21	10.07	10.75	11.44

Notes: The welfare loss function has a general form of $L = \sigma(\hat{\pi}_t)^2 + \lambda_x \sigma(\hat{x}_t)^2 + \lambda_R \sigma(\hat{R}_t)^2$. The standard deviation $\sigma(\cdot)$ is expressed in percent (annualized for inflation and nominal interest rate).

where λ_x and λ_R represent the relative weight on the output-gap and the nominal interest rate stabilization, respectively. We consider several different values of λ_x and λ_R, based on the values used in Williams (1999) and Woodford (2003): the former considers $\lambda_x = 1$ (hence, equal weights between inflation and output stabilization) and $\lambda_R = 0.02$, while the latter uses $\lambda_x = 0.048$ and $\lambda_R = 0.077$, based on reasonable calibrations of a micro-founded model. In addition, we consider a more conservative case in which the importance of nominal interest rate stabilization (λ_R) is doubled for both welfare loss functions.

Table 4 reports the findings. First, based on Woodford's loss function (with $\lambda_R = 0.077$), it turns out that the Taylor-MRIT rule (ii) yields the smallest welfare loss compared to the other three policies. Even though inflation is the least volatile in the optimized Taylor-MRIT rule (iv), the cost in terms of a higher $\sigma(\hat{R}_t)$ makes it less desirable than the Taylor-MRIT rule (ii). The welfare ranking across policies is the same as in Table 2, however, when we assume no direct welfare implication of nominal interest rate fluctuations ($\lambda_R = 0$). Here, for example, the optimized Taylor rule (iii) has three times the welfare loss than the optimized Taylor-MRIT rule (iv). In fact, across the different values of λ_R, the optimized Taylor rule (iii) has the largest welfare loss compared to the two policies with MRIT adjustments (policies (ii) and (iv)), despite of having the lowest $\sigma(\hat{R}_t)$. This remains true even when the importance of nominal interest rate stabilization is doubled ($\lambda_R = 0.154$).

Under Williams' loss function we find that for all three values of λ_R we consider ($\lambda_R = 0$, 0.02, and 0.04), the optimized Taylor-MRIT rule (iv) yields the smallest welfare loss. It is still the case that compared to MRIT policies (ii) and (iv), the optimized Taylor rule (iii) has the largest welfare loss. Thus, while the welfare gains from MRIT adjustments are reduced

Table 5: Welfare cost of various policies under different Taylor-rule specifications

	Policy Parameters				Conditional Welfare Cost	Unconditional Welfare Cost	$\sigma(\hat{\pi}_t)$	$\sigma(\hat{x}_t)$	$\sigma(\hat{R}_t)$
	ϕ_π	ϕ_y	ϕ_{g_y}	μ_{π^*}	$\lambda_c \times 100$	$\lambda_u \times 100$			
(a) $\log(R_t/\bar{R}) = \phi_R \log(R_{t-1}/\bar{R}) + (1-\phi_R)[\phi_\pi \log(\Pi_t/\bar{\Pi}) + \phi_{g_y}\{\log(Y_t/Y_t^*) - \log(Y_{t-1}/Y_{t-1}^*)\}]$									
(i) Taylor rule	1.50	—	0.50	—	0.351	0.363	3.085	3.441	2.856
(ii) Taylor-MRIT	1.50	—	0.50	-0.021	0.299	0.308	2.638	3.840	2.875
(iii) Optimized Taylor	3.00	—	0.25	—	0.190	0.193	2.220	3.316	3.080
(iv) Optimized Taylor-MRIT	3.00	—	0.00	-0.014	0.167	0.168	1.782	3.786	3.243
(b) $\log(R_t/\bar{R}) = \phi_R \log(R_{t-1}/\bar{R}) + (1-\phi_R)[\phi_\pi \log(\Pi_t/\bar{\Pi}) + \phi_y \log(Y_t/Y_t^*) + \phi_{g_y}\{\log(Y_t/Y_t^*) - \log(Y_{t-1}/Y_{t-1}^*)\}]$									
(i) Taylor rule	1.50	0.25	0.25	—	0.296	0.309	3.099	2.741	2.936
(ii) Taylor-MRIT	1.50	0.25	0.25	-0.052	0.158	0.163	1.959	3.503	3.135
(iii) Optimized Taylor	3.00	0.16	0.92	—	0.178	0.183	2.371	2.814	3.791
(iv) Optimized Taylor-MRIT	3.00	2.54	2.74	-0.150	0.025	0.025	1.340	2.575	6.265

Notes: In all cases, we fix $\phi_R = 0.80$ — furthermore, for the MRIT policies (ii) and (iv), we fix $\rho_{\pi^*} = 0.72$, equal to its optimal value in the baseline case reported in Table 2. All other aspects are identical as in Table 2, including the parameter values and the standard deviations of the exogenous shocks.

when the welfare function depends on nominal interest rate fluctuations in addition to those of inflation and the output gap, it does not nullify them altogether.

5.3 Alternative Taylor-rule specifications

We next investigate whether the welfare gains from the MRIT policy are sensitive to assuming different Taylor-rule specifications.[32] In particular, instead of responding to the output-gap, we consider alternative scenarios where the monetary authority responds to a different measure of real economic activity in the Taylor rule (10) or (11). The findings for various policy rules (i)-(iv) are reported in Table 5, where in all cases, we fix $\phi_R = 0.8$. Furthermore, for the MRIT policies (ii) and (iv), we fix $\rho_{\pi^*} = 0.72$, equal to its optimal value in the baseline case reported in Table 2.

[32] We thank an anonymous referee for suggesting this analysis.

5.3.1 Responding to output gap growth

We first consider a case where the measure of real activity is the growth rate of the output gap, $\log(Y_t/Y_t^*) - \log(Y_{t-1}/Y_{t-1}^*)$, so the Taylor-rule specification is given by

$$\begin{aligned}\log(R_t/\bar{R}) &= \phi_R \log(R_{t-1}/\bar{R}) \\ &\quad + (1-\phi_R)\left[\phi_\pi \log(\Pi_t/\Pi_t^*) + \phi_{g_y}\left\{\log(Y_t/Y_t^*) - \log(Y_{t-1}/Y_{t-1}^*)\right\}\right]\end{aligned} \tag{20}$$

We assume $\phi_\pi = 1.50$ and $\phi_{g_y} = 0.50$ for the standard Taylor rule (i). As reported in panel (a) of Table 5, both conditional and unconditional welfare costs of the Taylor rule (i) are larger compared to the corresponding rule in Table 2. Although the rule specification (20) yields a slightly lower $\sigma(\hat{\pi}_t)$, the standard deviation of the output gap $\sigma(\hat{x}_t)$ is appreciably higher.

Why are the welfare costs larger when the monetary authority responds to output gap growth than when responding to the output-gap *level*? Consider a persistent inflationary cost-push shock, which reduces the output gap on impact. When the economy was initially at the steady state, this shock implies negative output gap *growth* on impact — but assuming no other shock after the impact period, the growth rates become positive in subsequent periods. All else equal, this means that responding to the output gap growth ($\phi_{g_y} > 0$) leads to a smaller increase in R_t on impact, but a larger increase in R_t after that. The former leads to a higher $\sigma(\hat{\pi}_t)$ and lower $\sigma(\hat{x}_t)$, while the latter implies a lower $\sigma(\hat{\pi}_t)$ and higher $\sigma(\hat{x}_t)$. These conflicting effects in turn imply that the welfare costs may be largely insensitive to the value of ϕ_{g_y} and reacting too strongly to the fluctuations in output gap growth could be welfare-reducing.[33] In fact, we find that setting $\phi_{g_y} = 0$—while leaving other parameters unchanged—yields a smaller unconditional welfare cost of 0.342% in comparison to 0.363% when $\phi_{g_y} = 0.5$.[34] Simply put, the growth rate of the output gap is not a welfare-relevant measure of real activity in the Taylor-type rule. Since in the model it is the output gap *level*, not its growth rate, that matters for welfare, the monetary authority should respond to the

[33] A similar logic applies for the other two shocks. Under a positive productivity shock (or a negative government purchase shock) starting at the steady state, for example, output gap growth is negative on impact, while it's always positive in subsequent periods.

[34] When $\phi_{g_y} = 0$, $\sigma(\hat{\pi}_t) = 2.982$ and $\sigma(\hat{x}_t) = 3.470$.

fluctuations of the former. This point is important when assessing the extent of the welfare gain under the MRIT policies (ii) and (iv) below.

Under the Taylor-MRIT rule (ii) (where we still fix $\phi_\pi = 1.50$ and $\phi_{g_y} = 0.50$), while there still exists a welfare improvement from the MRIT adjustment, the extent of the improvement is considerably smaller than under the baseline Taylor-rule specification discussed in Section 4. Here, the optimal μ_{π^*} value is less negative at -0.021 and the unconditional welfare cost is still 0.308%, which implies a welfare gain is only 15% compared to the Taylor rule (i).

The optimized Taylor rule (iii) is able to produce lower welfare costs than rule (ii). Here, the optimal ϕ_π is 3 and the optimal ϕ_{g_y} is 0.25. The larger reduction in the welfare costs under this policy stems mostly from the higher value of ϕ_π, which reduces inflation variation arising from cost-push shocks and both inflation and output gap variations arising from productivity and government purchase shocks. It is possible, however, to lower the welfare costs further by additionally adjusting the medium-run inflation target under the optimized Taylor-MRIT rule (iv), though to a smaller extent compared to in the baseline Taylor-rule specification (11). Recall that under the baseline specification, the optimal policy combination in the face of cost-push shocks is to aggressively adjust the inflation target ($\mu_{\pi^*} = -0.15$) *and* to strongly respond to output gap fluctuations ($\phi_y = 2.48$). This policy combination is infeasible under the specification (20).

5.3.2 Responding to the output gap level and growth rate

What happens when we assume the following Taylor-rule specification,

$$\log(R_t/\bar{R}) = \phi_R \log(R_{t-1}/\bar{R}) + (1-\phi_R)\left[\begin{array}{c} \phi_\pi \log(\Pi_t/\Pi_t^*) + \phi_y \log(Y_t/Y_t^*) \\ +\phi_{g_y}\left\{\log(Y_t/Y_t^*) - \log(Y_{t-1}/Y_{t-1}^*)\right\} \end{array}\right], \quad (21)$$

where the monetary authority responds to the fluctuations in both the level and the growth rate of the output gap. This specification is used in the estimated model for the U.S. economy in Smets and Wouters (2007). Panel (b) in Table 5 reports the findings, assuming $\phi_\pi = 1.50$ and the equal weight of $\phi_y = \phi_{g_y} = 0.25$ in rules (i) and (ii).

Looking at the result under the Taylor-MRIT rule (ii), it is apparent that the optimal μ_{π^*}

is found to be between the optimal value based on the baseline specification of responding to the output gap only (11) reported in Table 2 and the specification of responding to output gap growth only (20) reported in panel (a) of Table 5. The unconditional welfare gain from the MRIT adjustment is $(0.309 - 0.163)/0.309 = 47\%$, which is smaller than under the baseline specification (65%) but larger than in the case where the monetary authority responds to output gap growth only (15%). The Taylor-MRIT policy (ii) also yields slightly lower welfare costs compared to the optimized Taylor-rule policy (iii), where we fix $\mu_{\pi^*} = 0$ but search for the optimal set of $\{\phi_\pi, \phi_y, \phi_{g_y}\}$ values.

Importantly, with specification (21) in which the monetary authority can respond to the variation in the welfare-relevant output gap *level*, the optimized Taylor-MRIT policy (iv) is now able to replicate the Ramsey allocation: the welfare costs are trivial at 0.025% of consumption per capita. Once again, the optimal policy combination involves a strong response to inflation fluctuations ($\phi_\pi = 3$), a strong response to output gap fluctuations ($\phi_y = 2.54$), and an aggressive adjustment of the medium-run inflation target ($\mu_{\pi^*} = -0.15$). The value of ϕ_{g_y} hardly matters for welfare. When we set $\phi_{g_y} = 0$ instead of $\phi_{g_y} = 2.74$ in policy (iv) for example, the unconditional welfare cost is now 0.034%.

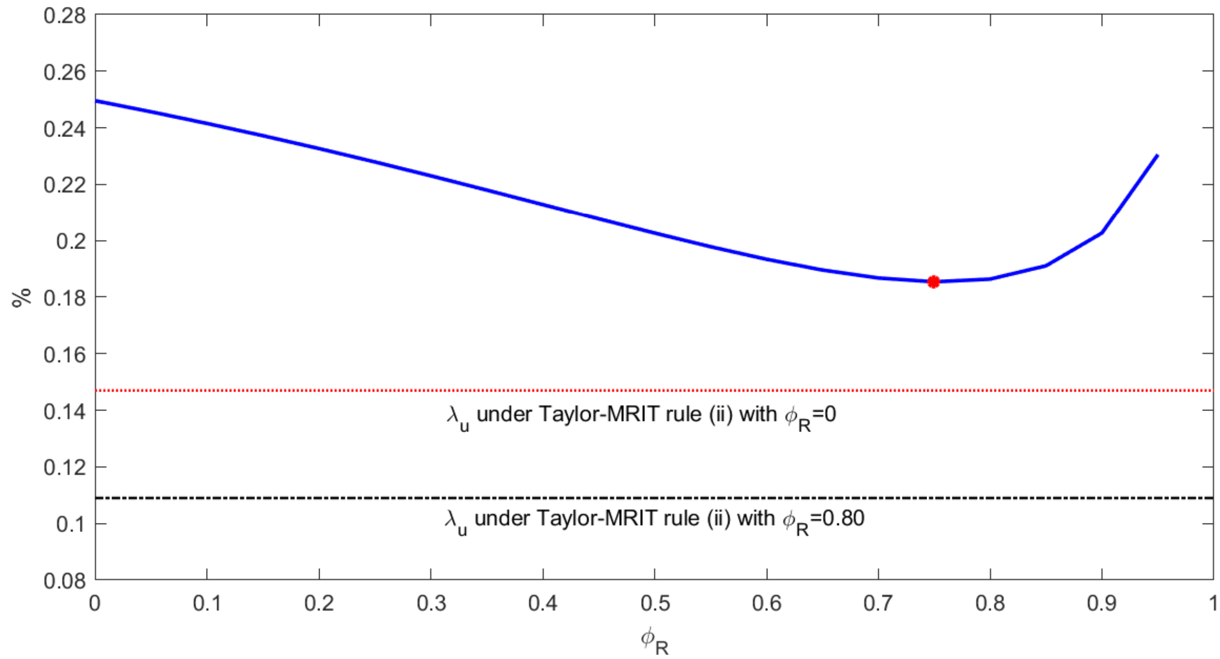
To sum up, with either alternative rule specification, we still find that adopting the MRIT policy is welfare-improving. But the extent of the improvement does depend on the Taylor-type rule specification.

5.4 Interest-rate smoothing

Next, we assess the importance of interest-rate smoothing in the Taylor-type rule for our results. Figure 4 plots the unconditional welfare costs under the optimized Taylor rule (iii) for different values of the smoothing parameter ϕ_R. For each $\phi_R \in [0, 1)$ we compute the optimal $\{\phi_\pi, \phi_y\}$ coefficients and the associated welfare cost. Also plotted in the figure are the unconditional welfare costs under the Taylor-MRIT rule (ii), fixing $\phi_R = 0.8$ (the benchmark value) and $\phi_R = 0$ (no interest-rate smoothing).

In line with the discussions in Levin, Wieland and Williams (1999), Williams (1999), and Woodford (1999), we find that a high degree of interest rate inertia improves welfare. Here, the welfare cost is at its minimum when $\phi_R = 0.76$, with $\phi_\pi = 3$ and $\phi_y = 0.15$, resulting

Figure 4: Unconditional welfare costs under the optimized Taylor rule (iii) for different degrees of interest-rate smoothing



Notes: (1) We plot the unconditional welfare cost for the optimized Taylor rule (iii) given each value of ϕ_R (solid line). The asterisk mark indicates the lowest welfare cost with $\lambda_u = 0.185\%$, achieved when $\phi_\pi = 3$, $\phi_y = 0.15$, and $\phi_R = 0.76$. We restrict $1 \leq \phi_\pi \leq 3$ and $0 \leq \phi_y \leq 3$ when searching for the optimal coefficients as in the baseline case. (2) Under the Taylor-MRIT rule (ii) when $\phi_R = 0$ (dotted line), the unconditional welfare cost is $\lambda_u = 0.147\%$ and the optimal MRIT coefficients are $\mu_{\pi^*} = -0.072$ and $\rho_{\pi^*} = 0.79$. (3) Under the Taylor-MRIT rule (ii) when $\phi_R = 0.8$ (dashed line), the unconditional welfare cost is $\lambda_u = 0.109\%$ and the optimal MRIT coefficients are $\mu_{\pi^*} = -0.084$ and $\rho_{\pi^*} = 0.72$.

in an unconditional welfare cost of 0.185%.[35] These policy coefficients and the associated welfare cost are very similar to those under rule (iii) in Table 2 when we fix $\phi_R = 0.8$. More importantly, we find that irrespective of the degree of interest-rate smoothing, the welfare costs under the optimized Taylor rule (iii) are higher than the cost under the Taylor-MRIT rule (ii). Not only this is true when $\phi_R = 0.8$ in the benchmark case presented in Table 2, but also when there is no smoothing ($\phi_R = 0$) where the welfare cost is higher. Thus, our results do not appear to be sensitive to the degree of interest-rate smoothing in the policy rule.

[35]Note that the optimal $\{\phi_\pi, \phi_y, \phi_R\}$ values under rule (iii) would be exactly $\{3, 0.15, 0.76\}$ if we search for all three parameter values that minimize the unconditional welfare cost.

5.5 Extensions with capital accumulation and sticky wages

We also examine the robustness of our results when we extend the model to include capital accumulation or nominal wage rigidity. As shown in Appendices B and C, although each feature affects the extent of the welfare improvement, our policy prescription of MRIT adjustment still yields a non-trivial welfare gain that is not attainable within a standard Taylor-type rule with a constant inflation target. There is evidence that capital accumulation makes the policy prescription even more potent. That is, a given decrease in the medium-run inflation target following an inflationary cost-push shock leads to a higher welfare gain than in the baseline model without capital accumulation. With sticky wages, there is an additional implication involving the trade-off between the stabilization of the output-gap, price inflation, and wage inflation. This additional friction changes the way the stabilization trade-off is improved. There is an indication that the MRIT policy leads to an improved trade-off between wage inflation stabilization and the other two stabilization goals (price inflation and the output gap).

6 Conclusion

In this paper we show that there is an important role for inflation target adjustment in a central bank's stabilization policy. Our findings demonstrate that it is welfare-improving to adjust the medium-run inflation target in the opposite direction to a realization of a cost-push shock. That is, the target needs to be increased when negative cost-push shocks contribute to a low-inflation environment. This additional policy tool, as a makeup strategy, improves the policy stabilization trade-off and leads to significant welfare improvement that is not attainable in a conventional interest-feedback rule with a constant long-run inflation target. Moreover, the welfare implications are more pronounced under a flatter Phillips curve. Our results are robust to various extensions and changes to the model such as capital accumulation, nominal wage rigidity, and different interest-rate rules.

Our proposed scenario is relevant to the current U.S. low-inflation environment since the recovery from the Great Recession. Inflation has been persistently below the Fed's 2% target since the target was introduced in 2012 and the economy appears to have approached the long-run unemployment rate in 2017. In addition, the Phillips curve appears to be flatter than in the past as pointed out by Blanchard (2016). If inflation continues to undershoot the 2% target while job growth remains strong and the unemployment rate is below the long-run unemployment rate, low inflation and low unemployment can be largely attributable to negative "cost-push" or similar types of shocks such as changes in price and wage markups and oil price shocks. If this is the case, our findings suggest that it may be prudent for the Federal Reserve to increase its inflation target, at least in the medium run.

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Appendices

A Model

This appendix describes additional details of the model and computational issues.

Our model consists of a representative household, a continuum of monopolistically-competitive firms producing differentiated varieties, and a monetary policy authority. The model is close to the model used in Schmitt-Grohé and Uribe (2007), although we abstract from monetary distortions, capital accumulation, and fiscal policy.

A.1 Households

Households choose the state-contingent consumption, C_t, labor service, N_t, and one-period discount bond, B_t, to maximize the lifetime utility,

$$E_t \sum_{s=0}^{\infty} \beta^s \frac{[C_{t+s}(1-N_{t+s})^{\gamma}]^{1-\sigma}-1}{1-\sigma},$$

subject to the per-period nominal budget constraint

$$P_t C_t + B_t \leq R_{t-1} B_{t-1} + W_t N_t + \Pi_t^{prof} + T_t,$$

or, in real terms,

$$C_t + b_t \leq R_{t-1} \frac{b_{t-1}}{\Pi_t} + w_t N_t + \frac{\Pi_t^{prof}}{P_t} + \tau_t.$$

$b_t \equiv B_t/P_t$ is real bond, R_t is the nominal interest rate, w_t is the real wage, $\frac{\Pi_t^{prof}}{P_t}$ is the proceed of real profits from intermediate-goods firms (owned by households), and τ_t is the real tax or transfer. The consumption index C_t is a Dixit-Stiglitz CES aggregator of differentiated consumption goods or varieties, given by

$$C_t = \left[\int_0^1 C_t(i)^{1/(1+\theta_t)} di\right]^{1+\theta_t} \tag{A.1}$$

where

$$\theta_t = 1/(\eta_t - 1) \tag{A.2}$$

is the firms' stochastic average markup at time t and η_t is the elasticity of substitution across varieties.

The resulting households' efficiency conditions:

$$0 = C_t^{-\sigma} (1 - N_t)^{\gamma(1-\sigma)} - \lambda_t \tag{A.3}$$

$$0 = -\gamma C_t^{1-\sigma} (1 - N_t)^{\gamma(1-\sigma)-1} + \lambda_t w_t \tag{A.4}$$

$$0 = \lambda_t - \beta R_t E_t \frac{\lambda_{t+1}}{\Pi_{t+1}} \tag{A.5}$$

Here, λ_t is the Lagrange multiplier (the shadow cost of consumption).

A.2 Firms

Firms produce the differentiated varieties using the production function

$$Y_t(i) = z_t N_t(i).$$

The labor market is global. Firms face infrequent opportunities to adjust their prices optimally in a Calvo (1983) manner, with probability $1 - \alpha$ every period. When a firm i is not allowed to adjust optimally, with probability α, it simply indexes its current prices to the constant long-run (steady-state) inflation target:

$$P_t(i) = P_{t-1}(i)\overline{\Pi}.$$

Given the CES aggregation and the above structure, the demand for each variety i at time $t + j$ for firms that last adjusted its price optimally at time t is

$$Y_{t+j}(i) = \left[\frac{\tilde{P}_t \Psi_{jt}}{P_{t+j}}\right]^{-\eta_t} Y_{t+j},$$

where, given the indexation scheme,

$$\Psi_{jt} = \overline{\Pi}^j$$

Y_t is the aggregate output and $\tilde{P}_t$ is the common optimal price at t chosen by all optimizing firms, satisfying

$$0 = E_t \sum_{j=0}^{\infty} \alpha^j Q_{t,t+j} Y_{t+j} P_{t+j}^{\eta_t} \Psi_{jt}^{1-\eta_t} \left[\tilde{P}_t - \frac{\eta_t}{\eta_t - 1} MC_{t+j} \Psi_{jt}^{-1} \right].$$

$Q_{t,t+j} \equiv \beta^j E_t \frac{\lambda_{t+j}/P_{t+j}}{\lambda_t/P_t}$, MC_t, and P_t denoting the nominal stochastic discount factor (between time t and $t+j$), nominal marginal cost, and the aggregate price level, respectively.

The aggregate price level is given by

$$P_t^{1-\eta_t} = (1-\alpha)(\tilde{P}_t)^{1-\eta_t} + \alpha \left(\overline{\Pi} P_{t-1} \right)^{1-\eta_t}$$

Equating aggregate demand with aggregate supply, we obtain (after some rearranging)

$$z_t N_t = Y_t \Delta_t, \tag{A.6}$$

$$Y_t = C_t + G_t, \tag{A.7}$$

where $\Delta_t = \int_0^1 (P_t(i)/P_t)^{-\eta_t} \, di$ is a measure of price dispersion, i.e., the relative-price distortion. G_t is the aggregate government spending, aggregated the same way as in (A.1).

A.3 Recursive representations

The optimal price equation (A.2) and the aggregate price equation (A.2) can be expressed recursively as

$$\tilde{p}_t \equiv \frac{\tilde{P}_t}{P_t} = \frac{\eta_t}{\eta_t - 1} \frac{K_{1t}}{K_{2t}} \tag{A.8}$$

$$K_{1t} = \lambda_t Y_t mc_t + E_t \left[\alpha\beta \overline{\Pi}^{-\eta_t} \Pi_{t+1}^{\eta_t} K_{1,t+1} \right] \tag{A.9}$$

$$K_{2t} = \lambda_t Y_t + E_t \left[\alpha\beta \overline{\Pi}^{1-\eta_t} \Pi_{t+1}^{\eta_t - 1} K_{2,t+1} \right] \tag{A.10}$$

$$1 = (1-\alpha)(\tilde{p}_t)^{1-\eta_t} + \alpha \left(\overline{\Pi} \Pi_t^{-1} \right)^{1-\eta_t}. \tag{A.11}$$

$mc_t \equiv MC_t/P_t$ is the average real marginal cost — given the production function,

$$mc_t = w_t/z_t. \tag{A.12}$$

We can also recursively write the relative-price distortion as

$$\Delta_t = (1-\alpha)(\tilde{p}_t)^{-\eta_t} + \alpha \left(\overline{\Pi}\Pi_t^{-1}\right)^{-\eta_t} \Delta_{t-1} \tag{A.13}$$

A.4 The monetary policy rule and the adjustment of the medium-run inflation target

In the baseline model without the adjustment of the medium-run inflation target (MRIT), the monetary policy authority is assumed to follow a Taylor-type rule,

$$\log(R_t/\bar{R}) = \phi_R \log(R_{t-1}/\bar{R}) + (1-\phi_R)\left[\phi_\pi \log(\Pi_t/\bar{\Pi}) + \phi_y \log(Y_t/Y_t^*)\right], \tag{A.14}$$

where Y_t^* is the potential or natural level of output, defined as the level of output in the flexible-price equilibrium with constant markup, satisfying

$$Y_t^* = \frac{\frac{(\bar{\eta}-1)}{\bar{\eta}} z_t + \gamma G_t}{\gamma + \frac{(\bar{\eta}-1)}{\bar{\eta}}}. \tag{A.15}$$

In an alternative model with our proposed policy, the monetary authority employs the modified Taylor-type rule and adjusts the MRIT in response to the markup shock:

$$\begin{aligned}
\log(R_t/\bar{R}) &= \phi_R \log(R_{t-1}/\bar{R}) + (1-\phi_R)\left[\phi_\pi \log(\Pi_t/\Pi_t^*) + \phi_y \log(Y_t/Y_t^*)\right] && \text{(A.16)}\\
\log(\Pi_t^*) &= \log(\bar{\Pi}) + \mu_{\pi^*} \upsilon_{\pi^*,t} && \text{(A.17)}\\
\upsilon_{\pi^*,t} &= \rho_{\upsilon_{\pi^*}} \upsilon_{\pi^*,t-1} + \varepsilon_{\theta,t} && \text{(A.18)}
\end{aligned}$$

Here, we assume that the adjustment of the MRIT is endogenous, i.e., it evolves due to the monetary authority's action, rather than exogenously. Setting $\mu_\theta = 0$ yields the standard assumption that the medium-run inflation target is equal to its constant long-run inflation target.

A.5 Evolution of exogenous variables

The model has three exogenous variables: productivity, z_t, government spending, G_t, and average markup, θ_t. Their evolutions follow

$$\log(z_t) = \rho_z \log(z_{t-1}) + \varepsilon_{z,t}, \tag{A.19}$$

$$\log(G_t/\bar{G}) = \rho_g \log(G_{t-1}/\bar{G}) + \varepsilon_{g,t}, \tag{A.20}$$

$$\log(\theta_t) = (1-\rho_\theta)\log(\bar{\theta}) + \rho_\theta \log(\theta_{t-1}) + \varepsilon_{\theta,t}. \tag{A.21}$$

Aggregate fluctuations are driven by three exogenous shocks: $\varepsilon_{z,t} \sim i.i.d.\ N(0,\sigma_z^2)$, $\varepsilon_{g,t} \sim i.i.d.\ N(0,\sigma_g^2)$, and $\varepsilon_{\theta,t} \sim i.i.d.\ N(0,\sigma_\theta^2)$.

A.6 Complete equilibrium equations (competitive equilibrium)

In the standard model without MRIT, the complete equilibrium conditions (under competitive equilibrium) are given by equations (A.2), (A.3), (A.4), (A.5), (A.6), (A.7), (A.8), (A.9), (A.10), (A.11), (A.12), (A.13), (A.14), (A.15), and the evolution equations of exogenous variables (A.19)- (A.21). The corresponding endogenous variables are C_t, Y_t, N_t, λ_t, w_t, R_t, Π_t, $\tilde{p}_t$, K_{1t}, K_{2t}, Δ_t, mc_t, Y_t^*, and η_t.

In the model with the MRIT adjustment, the policy rule (A.14) is replaced with (A.16)-(A.18). The medium-run inflation target, Π_t^*, is now an endogenous variable. We solve for the equilibrium using a perturbation method, up to a second-order approximation — see Johnston, King and Lie (2014) for the detail of the solution method.

A.7 Ramsey policy

We derive the Ramsey equilibrium by formulating a recursive Lagrangian as in Marcet and Marimon (2019). The objective function is the households' welfare as the Ramsey policy authority is benevolent. The Ramsey authority conducts policy in a decentralized setting.

This means that all the private-sector efficiency conditions described above have to be respected, and becomes the constraint set in the optimal policy problem (the Lagrangian). As is standard in the literature, we do not take a stand on the form of the optimal policy rule and search instead for the equilibrium allocation under the Ramsey policy — in technical term, this means that policy rule (A.14) is not part of the Ramsey authority's constraint set. The Ramsey policy is solved under the assumption of a constant long-run inflation target, $\Pi_t^* = \bar{\Pi}$.

B Further robustness: Adding capital accumulation

In this appendix, we examine whether our results are robust to including capital accumulation into the model. In this extended model, we assume that households accumulate physical capital K_t with the evolution of the capital stock:

$$K_{t+1} = (1-\delta)K_t + I_t \tag{B.1}$$

where I_t is investment and δ is the depreciation rate. The period budget constraint in real terms becomes

$$C_t + I_t + \frac{B_t}{P_t} \leq R_{t-1}\frac{B_{t-1}}{P_{t-1}\Pi_t} + \frac{W_t}{P_t}N_t + \frac{R_t^k}{P_t}K_t + \frac{\Pi_t^{prof}}{P_t} + \frac{T_t}{P_t},$$

where R_t^k is the rental rate of capital. On the production side, each intermediate-goods firm now produces a differentiated variety i using capital and labor with a production technology

$$Y_t(i) = z_t K_t(i)^{\chi} N_t(i)^{1-\chi}, \tag{B.2}$$

where χ is the share of capital. Other aspects of the model are identical to those of the baseline model in Appendix A.

We calibrate $\delta = 0.024$ and $\chi = 0.3$ as in Schmitt-Grohé and Uribe (2007). All other parameter values are the same as in the baseline model (see Table 2 in the main text), except for the standard deviation of the average markup shock, σ_θ. We re-calibrate σ_θ so that the

Table B.1: Model with capital accumulation: welfare cost of various policies

	Policy Parameters ϕ_π	ϕ_Y	ϕ_R	μ_{π^*}	ρ_{π^*}	Conditional Welfare Cost $\lambda_c \times 100$	Unconditional Welfare Cost $\lambda_u \times 100$	$\sigma(\hat{\pi}_t)$	$\sigma(\hat{x}_t)$	$\sigma(\hat{R}_t)$
(i) Taylor rule	1.50	0.50	0.80	—	—	0.286	0.303	3.240	1.646	1.854
(ii) Taylor-MRIT	1.50	0.50	0.80	-0.018	0.93	0.031	0.038	1.765	2.714	1.496
(iii) Optimized Taylor	3.00	0.35	0.80	—	—	0.107	0.125	1.918	3.177	1.162
(iv) Optimized Taylor-MRIT	3.00	1.01	0.80	-0.020	0.93	0.027	0.027	1.750	2.588	1.233

Notes: The conditional and unconditional welfare costs are in terms of consumption loss relative to the Ramsey allocation with capital. The standard deviation $\sigma(\cdot)$ is expressed in percent (annualized for inflation and nominal interest rate).

model matches the standard deviation of inflation in the data for the post-war U.S. economy (3.24% per annum), under the Taylor-rule coefficients $\phi_\pi = 1.5$, $\phi_y = 0.5$, and $\phi_R = 0.8$. This requires $\sigma_\theta = 0.123$, versus 0.115 in the baseline case. Given the calibration, we obtain $\bar{C}/\bar{Y} = 0.66$, $\bar{I}/\bar{Y} = 0.17$, and $\bar{G}/\bar{Y} = 0.17$ in the steady state. We re-solve the model's equilibrium, including the Ramsey allocation. Note that the optimal steady-state inflation rate under the Ramsey policy is still zero in this extended model with capital — see Faia (2008) for more details.

Table B.1 presents the welfare costs of rules (i)-(iv) based on this extended model. Under the Taylor rule (i), the unconditional welfare cost is 0.303%, with $\sigma(\hat{\pi}_t) = 3.24$ and $\sigma(\hat{x}_t) = 1.65$. As in the baseline model, the welfare cost is quite high under rule (i); these costs are not directly comparable to those in the baseline model, however, as the Ramsey allocations are not the same in the two models. The output gap is less volatile in the model with capital.

Under the Taylor-MRIT rule (ii), the reductions in both welfare cost measures compared to rule (i) are sizeable. Here, for example, the unconditional welfare cost is merely 0.038%, indicating that the Taylor-MRIT can closely replicate the Ramsey allocation. Looking at the standard deviations, it appears this much lower welfare cost arises due to a much lower $\sigma(\hat{\pi}_t)$.[36] This much lower inflation variation is achieved with a relatively small value of $\mu_{\pi^*}{=}-0.018$, somewhat surprisingly. Thus, with capital accumulation, the monetary author-

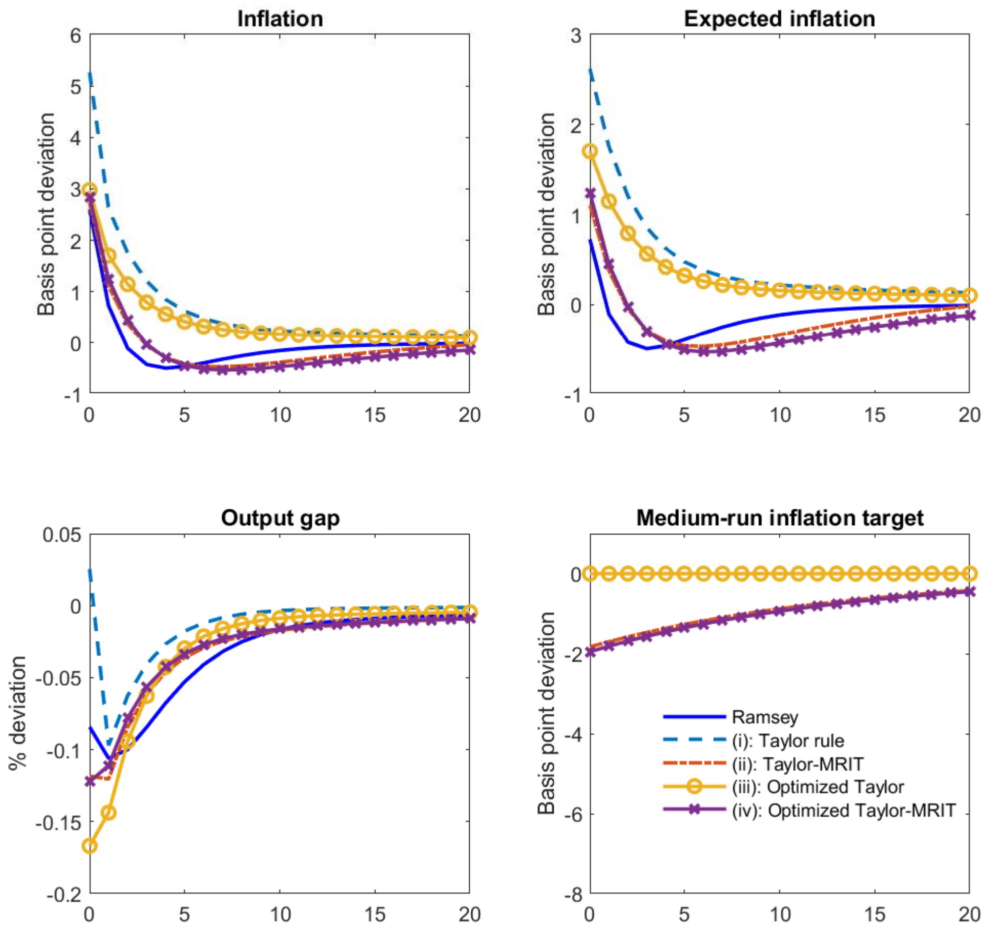
[36] As shown by Edge (2003), in a sticky-price model with capital accumulation, the utility-based welfare criterion—based on a second-order approximation to the utility function—is a complicated function of other variables (e.g. the squared deviations of investment and capital from their flexible-price levels) in addition to inflation and output-gap variations. Inflation variation, however, is still the most important determinant of welfare.

ity does not have to decrease the medium-run inflation target by much to stabilize inflation following an inflationary cost-push shock — our proposed MRIT policy appears to be more effective with the additional propagation mechanism arising from capital accumulation. The target adjustment, however, needs to be more persistent than in the baseline model without capital accumulation, since it endogenously induces a more persistent effect of a cost-push shock.

While the optimized Taylor rule (iii) also results in lower welfare costs, the extent of the welfare improvement is smaller. In fact, we find that when considering $\{\phi_\pi, \phi_y\} > 0$ without an upper bound, the optimal values of ϕ_π and ϕ_y are 4.55 and 0.54, respectively, with the conditional and unconditional welfare cost given by $\lambda_c = 0.105\%$ and $\lambda_u = 0.122\%$, respectively. The extent of the welfare improvement from the inflation-target adjustment under rule (ii) is thus not achievable in a conventional Taylor-type rule with a constant inflation target. Under the optimized Taylor-MRIT rule (iv), the welfare costs are even lower as expected, though not by much. The optimal value of μ_{π^*} is also very similar to that in rule (ii) and hence, the adjustment of the inflation target following a cost-push shock is of a smaller magnitude compared to that in the baseline model without capital. As in the baseline model, however, policy (iv) also entails a strong response to output-gap fluctuations, i.e., a relatively high value of ϕ_y.

Figure B.1 plots the impulse responses to a 1% cost-push shock based on the extended model. The addition of capital accumulation induces more-protracted responses in all variables, as expected. Importantly, we find that it remains the case that the MRIT policies (ii) and (iv) produce more-subdued inflation movements following the inflationary cost-push shock, compared to the rules (i) and (iii) with a constant inflation target. Similarly to the baseline model without capital, we also observe that the reductions in the medium-run inflation target under rules (ii) and (iv) induce a period of the inflation rates below its long-run target) and yield lower inflation expectations comparable to that under the Ramsey policy. The improvement in the inflation-output trade-off from the MRIT adjustments is clearly visible from the responses of inflation and the output gap on impact. Comparing the Taylor-MRIT rule (ii) and the optimized Taylor rule (iii), for example, the latter rule incurs a larger output-gap loss and a (slightly) larger increase in inflation on impact. Thus, our results are

Figure B.1: Model with capital accumulation: impulse responses to a 1% cost-push shock



Note: The policy coefficients for rules (i)-(iv) are given in Table B.1.

robust to adding capital accumulation into the model.

C Further robustness: Adding sticky wages

In the model in the main text, the labor market is assumed to be perfectly competitive and nominal wages are flexible. In this appendix, we examine the robustness of our results when we augment the model to include nominal wage rigidity. We follow the set-up in Erceg, Henderson and Levin (2000) and introduce wage rigidity via the Calvo (1983) staggered contract — see also Rabanal and Rubio-Ramírez (2005) and Smets and Wouters (2007) for a similar approach. This augmented model thus has an additional friction arising from sticky nominal wages. In the set-up, households supply differentiated labor services, which gives them some monopoly power in setting their own wages. These differentiated labor services are combined by a labor union into a composite labor, which is used by the intermediate-goods firms as an input into production. For a more detailed exposition of the set-up, we refer the interested readers to the aforementioned papers.

To allow for a straightforward aggregation of the welfare function we assume, as in Erceg, Henderson and Levin (2000), that the period utility function of household $l \in [0,1]$ is separable in consumption and labor, given by

$$U(c_t, N_t(l)) = \frac{C_t^{1-\sigma}}{1-\sigma} - \Psi \frac{N_t(l)^{1+\gamma}}{1+\gamma} \tag{C.1}$$

The aggregate welfare function is then

$$V_t = \int_0^1 \tilde{\mathcal{W}}_t(l) dl \tag{C.2}$$

where

$$\tilde{\mathcal{W}}_t(l) = U(c_t, N_t(l)) + \beta E_t \mathcal{W}_{t+1}(l)$$

The function (C.2) can be recursively written as

$$V_t = \left[\frac{C_t^{1-\sigma}}{1-\sigma} - \frac{\Psi}{1+\gamma} \upsilon_t^w {N_t}^{1+\gamma} \right] + \beta E_t V_{t+1} \tag{C.3}$$

where N_t is the aggregate labor and

$$\upsilon_t^w \equiv \int_0^1 \left(\frac{W_t(l)}{W_t} \right)^{-\phi(1+\gamma)} dl$$

is a measure of wage dispersion. This is recursively given by

$$\upsilon_t^w = (1-\alpha_w) \left(w_t^* \right)^{-\phi(1+\gamma)} + \alpha_w \left(\pi_t^w \right)^{\phi(1+\gamma)} \upsilon_{t-1}^w \tag{C.4}$$

where w_t^* is the optimal real wage chosen by households that are able to change their wage (with probability $1-\alpha_w$), $\pi_t^w \equiv W_t/W_{t-1}$ is the wage inflation, which is linked to price inflation π_t via the relationship

$$\pi_t^w = \frac{w_t}{w_{t-1}}\pi_t, \tag{C.5}$$

and W_t and w_t are aggregate nominal wage and real wage, respectively. Other elements of the augmented model are the same as in baseline model, e.g., labor is the only input into production and there is no capital accumulation. The cost-push shocks are also assumed to arise from shocks to firms' average price markup. Note that with sticky wages, technology and government spending shocks also create a trade-off between various stabilization goals. We still consider, however, that the monetary authority adjusts the medium-run inflation target in the face of cost-push shocks only.

Parametrization The inverse elasticity of intertemporal substitution is set to $\sigma = 2$ as in the baseline model. We calibrate the inverse Frisch labor supply elasticity γ so that the augmented model and the baseline model have the same elasticity under the steady-state labor of $\bar{N} = 0.2$ — this requires $\gamma = 0.73$. The scaling parameter Ψ in (C.1) is set so that $\bar{N} = 0.2$ in the Ramsey steady state. The Calvo wage-rigidity parameter α_w is set to 0.8, equal to the value of the corresponding price-rigidity parameter α. The elasticity of substitution across labor types is set to $\phi = 6$, as in Rabanal and Rubio-Ramírez (2005). All other parameter values are the same as in the baseline model (see Table 2 in the main text), except for the standard deviation of the average markup shock, σ_θ. We re-calibrate σ_θ so that the augmented model matches the standard deviation of inflation in the data for the post-war U.S. economy (3.24% per annum), under the Taylor-rule coefficients $\phi_\pi = 1.5$, $\phi_y = 0.5$, and $\phi_R = 0.8$. This requires $\sigma_\theta = 0.161$, versus 0.115 in the baseline case.

Given the parametrization above, we re-solve the model's equilibrium, including the Ramsey allocation, up to a second-order approximation. We use V_t in (C.3) as our aggregate welfare measure — this measure is also the objective function of the benevolent Ramsey planner. Based on this welfare function, we can calculate the second-order approximation to the welfare cost measures—λ_c and λ_u—for any alternative policy rule, in a similar manner as described in the main text. Note that in our cashless model, the Ramsey steady-state price inflation rate and wage inflation rate are both zero.

Table C.1: Model with sticky prices and sticky wages: welfare cost of various policies

	Policy Parameters					Conditional Welfare Cost	Unconditional Welfare Cost	$\sigma(\hat{\pi}_t)$	$\sigma(\hat{x}_t)$	$\sigma(\hat{\pi}^w_t)$
	ϕ_π	ϕ_Y	ϕ_R	μ_{π^*}	ρ_{π^*}	$\lambda_c \times 100$	$\lambda_u \times 100$			
(i) Taylor rule	1.50	0.50	0.80	—	—	0.220	0.230	3.240	2.772	0.952
(ii) Taylor-MRIT	1.50	0.50	0.80	-0.008	0.91	0.156	0.162	3.121	2.898	0.769
(iii) Optimized Taylor	1.22	0.13	0.80	—	—	0.117	0.117	3.207	3.478	0.602
(iv) Optimized Taylor-MRIT	1.38	0.14	0.80	-0.005	0.91	0.054	0.052	3.086	3.575	0.282

Notes: The conditional and unconditional welfare costs are in terms of consumption loss relative to the Ramsey allocation with both nominal price and wage rigidities. The standard deviation $\sigma(\cdot)$ is expressed in percent (annualized for price inflation $\sigma(\hat{\pi}_t)$ and wage inflation $\sigma(\hat{\pi}^w_t)$).

Results Table C.1 reports the welfare costs of policies (i)-(iv) based on this extended model. We also report the standard deviation of wage inflation, $\sigma(\hat{\pi}^w_t)$, since with sticky wages the welfare-theoretic loss function depends on the variation in wage inflation, in addition to output-gap and inflation variations (see Erceg, Henderson and Levin (2000)). Under the Taylor rule (i) the unconditional welfare cost is 0.230%, with $\sigma(\hat{\pi}_t) = 3.24$, $\sigma(\hat{x}_t) = 2.77$, and $\sigma(\hat{\pi}^w_t) = 0.95$. The welfare cost is not directly comparable to that in the baseline model with flexible wages, in part because the Ramsey allocations are different in the two models. Notwithstanding, the welfare cost of adopting the Taylor rule is non-trivial.

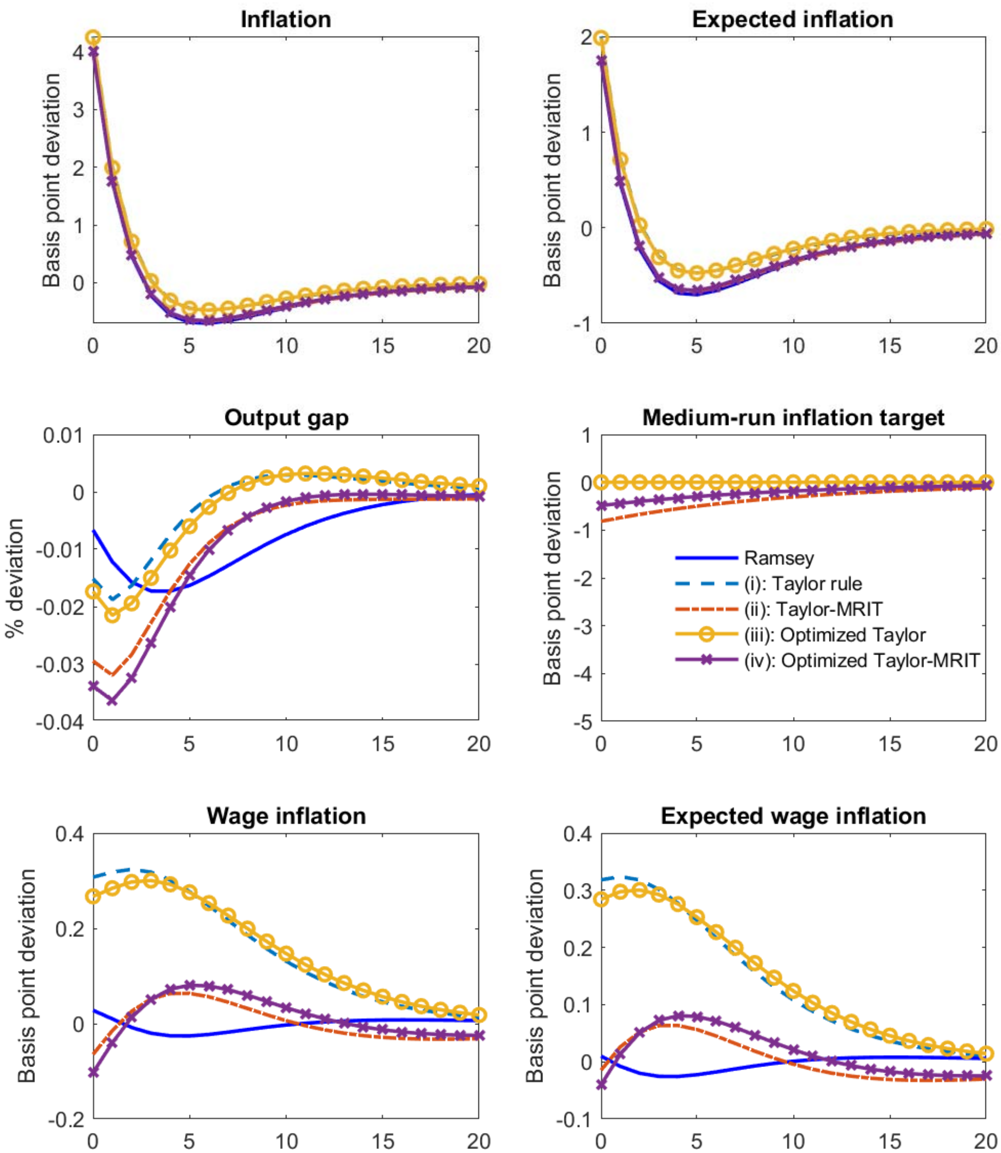
The Taylor-MRIT rule (ii) is associated with optimal MRIT coefficients of μ_{π^*}=-0.008 and ρ_{π^*}=0.91. The additional friction due to sticky wages calls for a much less negative contemporaneous response with more persistent inflation target adjustment than in the baseline model with flexible wages. The different values of the optimal coefficients reflect the fact that with nominal wage rigidity. the monetary authority faces an additional trade-off involving the stabilization of wage inflation. We find that the reduction in the welfare cost over the Taylor rule (i) is substantial. The unconditional welfare cost is now 0.162%, versus 0.230% in rule (i). Here, it has to take into account that the MRIT adjustment also affects the welfare-relevant variation in wage inflation. Looking at the standard deviations, it appears that the welfare gain is mostly due to the reduction in wage-inflation variation ($\sigma(\hat{\pi}^w_t)$), notwithstanding a slightly lower price-inflation variation, $\sigma(\hat{\pi}_t)$.

Under the optimized Taylor rule (iii), the optimal inflation-feedback and output-feedback coefficients are $\phi_\pi = 1.22$ and $\phi_y = 0.13$. The additional policy trade-off involving wage-inflation stabilization is responsible for the relatively-low optimal value of the inflation-feedback coefficient ϕ_π (< 3). What's the role of other shocks than a cost-push shock in the stabilization trade-off? When shutting down the cost-push shock, we find that the optimal policy coefficient values are given by $\phi_\pi = 2.02$ and $\phi_y = 0.16$, which are smaller than those in the baseline model with flexible wages in which the optimized Taylor rule calls for the maximum allowable value of $\phi_\pi = \phi_y = 3$ when there is no cost-push shock. Hence, our finding suggests that even without the cost-push shock, there is a non-negligible trade-off between wage inflation and price inflation/output stabilization. Consistent with this interpretation, we observe that the lower unconditional welfare cost under rule (iii) (0.117%) versus rule (ii) (0.162%) stems from a lower $\sigma(\hat{\pi}^w_t)$ — both $\sigma(\hat{\pi}_t)$ and $\sigma(\hat{x}_t)$ are actually higher under rule (iii) despite the lower welfare cost. The importance of wage-inflation stabilization under nominal wage rigidity is consistent with the finding in Erceg, Henderson and Levin (2000) who show that price-inflation targeting leads to a very large welfare loss compared to wage-inflation targeting, although as discussed in Chugh (2006), the inclusion of fiscal policy and fiscal shocks may alter this conclusion.

Under the optimized Taylor-MRIT rule (iv), we find an even lower welfare cost: the unconditional welfare cost is now only 0.05% of consumption relative to the Ramsey allocation. The optimal value of μ_{π^*} is -0.005, with $\phi_\pi = 1.38$ and $\phi_y = 0.14$, which are very similar to the optimal $\{\phi_\pi, \phi_y\}$ in rule (iii). We again observe that the reduction in $\sigma(\hat{\pi}^w_t)$ is largely responsible for the much-lower welfare cost — here, $\sigma(\hat{\pi}_t)$ is only slightly lower compared to that in rule (iii), with $\sigma(\hat{x}_t)$ slightly higher. There is a sense that the target adjustment in the face of a cost-push shock leads to an improved trade-off between wage-inflation stabilization and the other two stabilization goals (price inflation and output gap).

As a further check, Figure C.1 plots the impulse responses to a 1% cost-push shock. We observe that the responses of price-inflation (top left panel) are roughly the same under all four policy rules — in fact, they replicate the Ramsey dynamics quite well. It is still the case that decreasing the inflation target following the inflationary cost-push shock in rule (ii) and rule (iv) leads to lower expected inflation compared to either rule (i) or rule (iii), where the inflation target remains constant. But this effect is small, especially compared to the effect on the dynamics of wage inflation. We observe that under rules (ii) and (iv) with

Figure C.1: Model with sticky prices and sticky wages: impulse responses to a 1% cost-push shock



Note: The policy coefficients for rules (i)-(iv) are given in Table C.1.

inflation-target adjustments, wage-inflation (bottom left panel) is much more stabilized. The same holds true for expected wage-inflation (bottom right panel). Hence, consistent with the findings in Table C.1, the welfare improvement from the inflation-target adjustment is due to this policy yielding lower wage-inflation volatility. This is true in spite of relatively higher output-gap volatility (middle left panel).

We conclude that our proposed MRIT policy still leads to a welfare improvement, even with nominal wage rigidity. The improvement is not attainable with a standard Taylor-type rule with a constant inflation target. The additional friction, however, affects the extent of the welfare gain, and changes the way that the stabilization trade-off is altered and improved.

D Illustration of the monetary-policy implications of a flat NKPC in the face of cost-push shocks

To illustrate the implications of a flatter (or steeper) NKPC for monetary policy in the presence of cost-push shocks, we consider a prototypical three-equation New Keynesian model. The log-linearized version of the prototype New Keynesian model yields the following representation for the New Keynesian Phillips curve, the IS curve, and the monetary policy rule:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa y_t + \mu_t \tag{D.1}$$

$$y_t = E_t y_{t+1} - (\hat{R}_t - E_t \pi_{t+1}) \tag{D.2}$$

$$\hat{R}_t = \phi_\pi (\pi_t - \pi^*) + \phi_y y_t \tag{D.3}$$

where π_t is inflation, y_t is the output gap, $\hat{R}_t$ is the short-term nominal interest rate, π^* is the (long-run) inflation target, and μ_t is a cost-push shock.

Now, we consider the policy response to cost-push shocks in this model. A positive realization of these shocks creates an upsurge in inflation and a negative output gap. Iterating the NKPC in (D.1) forward indicates that inflation is a function of the expected discounted sum of the future output gap y_t and cost-push shock μ_t:

$$\pi_t = E_t \sum_{s=0}^{\infty} \beta^s \left(\kappa y_{t+s} + \mu_{t+s}\right). \tag{D.4}$$

The strength of the link between inflation and the output gap is directly governed by the slope parameter κ in (D.4). When κ is small (i.e., the NKPC is flat), the output gap hardly drives inflation dynamics and the variation in inflation would be mostly explained by the cost-push shocks, μ_t. In addition, the IS curve in (D.2) shows that the output gap is a function of the sum of expected future real interest rates by iterating the IS curve forward:

$$y_t = -E_t \sum_{s=0}^{\infty} (R_{t+s} - \pi_{t+s+1}). \tag{D.5}$$

Thus, the monetary authority can influence the output gap by manipulating the real rate indirectly through adjustments of the short-term nominal interest rate given sticky prices using the Taylor-type policy rule in (D.3). In response to the increase in inflation, the monetary authority raises the nominal interest rate by amounts greater than increases in inflation so that the real interest rate goes up.[37] The IS curve in (D.5) implies that the increase in the real interest rate lowers the output gap further and in turn, inflation is reduced through the NKPC relationship.

However, as pointed out in the cost-push channel for inflation, a flat NKPC implies that the effect of output gap on inflation fluctuations is limited so that monetary policy is less effective in controlling inflation in the face of cost-push shocks. Thus, the effect of cost-push shocks on inflation would last longer. It is also notable that the decrease of the output gap arising from the positive cost-push shocks lowers the nominal interest rate in the opposite direction compared to the effect of inflation gap on the adjustment of the nominal interest rates, as noted in the monetary policy rule (D.3). In the presence of the trade-off between inflation stabilization and output-gap stabilization, e.g., due to the existence of the cost-push shock, this offsetting effect weakens the monetary authority's reaction to inflation fluctuations and presents an additional difficulty in conducting monetary policy

A flat NKPC has also an important welfare implication that the inflation variation becomes enormously more important than the output gap fluctuation. Following Rotemberg and Woodford (1997, 1999), Woodford (2003), and Steinsson (2003), the utility-based welfare loss function in period t can be represented by

$$L_t = -\frac{1}{2}\left[\pi_t^2 + \frac{\kappa}{\eta} y_t^2\right] \tag{D.6}$$

[37] The increase in the nominal interest rate is due to $\phi_\pi > 1$. More precisely, we consider the determinate regions of the parameter space for ϕ_y, ϕ_π, and κ. For more details, see Bullard and Mitra (2002).

where η is the steady-state elasticity of substitutions between intermediate-good varieties. Woodford (2003) shows that the weight on the output gap κ/η in the loss function (D.6) is small using the conventional calibrated parameters so that inflation plays a primary role in determining household welfare. In addition, we can see that as the NKPC becomes flatter (i.e., $\kappa \to 0$), the inflation variation becomes even more important because the weight on the output gap in the loss function gets smaller.

In short, the flattening of the NKPC complicates the conduct of monetary policy and results in a difficulty of improving household welfare through monetary policy from three perspectives: (i) the fraction of inflation variation due to cost-push shocks becomes increasingly substantial; (ii) controlling inflation through monetary policy becomes much harder in the face of cost-push shocks; and (iii) inflation becomes completely dominant over the output gap in determining household welfare.

E Responding to the natural rate of interest

Here, we consider a modified version of Taylor-type rule in which the nominal interest rate responds to the natural rate of interest in addition to inflation and the output gap as follows:

$$\log(R_t/\bar{R}) = \phi_R \log(R_{t-1}/\bar{R}) + (1-\phi_R)\left[\phi_\pi \log(\Pi_t/\Pi_t^*) + \phi_Y \log(Y_t/Y_t^*) + \phi_{r^n} \log(r_t^n \overline{\Pi}/\overline{R})\right]$$

where r_t^n is the natural rate of interest, defined as the interest rate under the flexible-price equilibrium with no mark-up shock.

We first set the natural rate reaction coefficient ϕ_{r^n} to 1, which is the prescribed optimal value with productivity and spending shocks (see e.g., Galí (2015)). All other structural parameter values are set to those for the baseline model presented in Table 1. As shown in Table E.1 (a), we find that reacting one-to-one to the natural interest rate in the Taylor-type rule (the Taylor-natural rate rule, hereafter) improves welfare upon the Taylor rule, but it is not large enough to outperform our proposed Taylor-MRIT rule. In addition, we also search for the optimized value of ϕ_{r^n} that minimizes the unconditional welfare measure, and it is found to be $\phi_{r^n} = 0.62$. But the improvement is marginal and the welfare cost is still greater

Table E.1: Reacting to the natural rate of interest under the Taylor rule and the welfare cost

	Policy Parameters						Conditional Welfare Cost	Unconditional Welfare Cost	$\sigma(\hat{\pi}_t)$	$\sigma(\hat{x}_t)$	$\sigma(\hat{R}_t)$
	ϕ_π	ϕ_Y	ρ_R	ϕ_{r^n}	μ_{π^*}	ρ_{π^*}	$\lambda_c \times 100$	$\lambda_u \times 100$			
(a) All three shocks											
Taylor rule, $\phi_{r^n} = 0$	1.50	0.50	0.80	0	—	—	0.298	0.312	3.240	2.368	3.150
Taylor rule, $\phi_{r^n} = 1$	1.50	0.50	0.80	1	—	—	0.259	0.274	3.275	1.395	4.368
Taylor rule, optimized ϕ_{r^n}	1.50	0.50	0.80	0.62	—	—	0.238	0.252	3.126	1.606	3.852
(b) Technology and gov't spending shocks only (No markup shock)											
Taylor rule, $\phi_{r^n} = 0$	1.50	0.50	0.80	0	—	—	0.105	0.109	1.164	2.260	2.710
Taylor rule, $\phi_{r^n} = 1$	1.50	0.50	0.80	1	—	—	0.066	0.071	1.258	1.202	4.062
Taylor rule, optimized ϕ_{r^n}	1.50	0.50	0.80	0.62	—	—	0.045	0.048	0.793	1.443	3.501

than that under the Taylor-MRIT rule.

In Table E.1 (b), we shut down the mark-up (cost-push) shock and perform the same analysis. We find that the Taylor-natural rate rule can reach the unconditional welfare cost of 0.071% with $\phi_{r^n} = 1$ and 0.048% with the optimized coefficient $\phi_{r^n} = 0.62$. Thus, we conclude that additionally responding to the natural rate of interest cannot achieve the welfare level associated with our proposed policy rule when cost-push shocks are present. The MRIT policy works through a different channel than the Taylor-natural rate rule.