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RESEARCH PAPER 2023-004
MARCH 2023

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D/2023/1169/004

Optimal monetary policy and the vintage-dependent price and wage Phillips curves: An international comparison*

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Abstract. In this study, we compare the conduct of central banks across seven advanced economies by analyzing the relationship between observed and optimal monetary policies. We estimate the New Keynesian Phillips curves for prices and wages and use model-consistent welfare measures to conduct counterfactual analysis. What sets our approach apart is the focus on the impact of inertia on output gaps and price/wage dynamics, which we model using duration-dependent adjustments. Ignoring the effects of inertia on welfare and policies could result in a misleading and incomplete understanding of inflation dynamics. By incorporating this element into our analysis, we aim to identify common trends and specificities in central banks' monetary policy conduct across different countries.

JEL classification: E31, E32, C11.

Keywords: duration-dependent adjustments, intrinsic inflation persistence, DSGE models, hybrid Phillips curves, and optimal policy

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[*] The authors thank Elton Beqiraj, Paolo D'Imperio, Marco Di Pietro, Michel Juillard, and Willi Semmler for their helpful comments on preliminary versions. This paper is part of a research project investigating optimal policies and vintage-dependent price and wage adjustments in industrialized countries. The Sapienza University of Rome financed the project.

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1. Introduction

After at least three decades of moderate price and wage changes, inflation is back. This recent surge and persistence of inflation rates thus forcefully put forward the theme of price stability for monetary policy. This paper offers an international view of the issue. In a nutshell, we focus on the relationship between inertia and monetary policy and propose an international comparative analysis of the relationship between observed and optimal monetary policies in a context where inertial processes drive economic variables. By adopting a cross-country comparison, the idea is to broadly highlight common trends and specificities of different central banks in monetary policy conduct.

Economists have studied time-dependent price and wage adjustments in macroeconomic models.[1] It appears that these adjustments can significantly affect the nature of macroeconomic distortions. Furthermore, using vintage-dependent pricing models to introduce intrinsic inflation persistence has also become essential for understanding inflation dynamics in sticky price and wage models. Against this backdrop, our paper aims to investigate the effects of time-dependent price and wage adjustments on the nature of macroeconomic distortions in sticky price and wage models with intrinsic inflation persistence induced by vintage-dependent pricing models. We aim to comprehensively analyze the welfare costs generated by these adjustments and derive a model-consistent welfare measure to explain them. Moreover, the study will examine the impact of the slopes of price and wage hazard functions on the expectations of forward-looking agents and their decisions. Finally, we will investigate whether and how these effects impact monetary policy and highlight the implications for central bank policy in countries with different macroeconomic structures.

Overall, this paper aims to contribute to the existing literature by providing a detailed analysis of the effects of time-dependent price and wage adjustments on macroeconomic distortions and welfare costs. The study will also shed light on monetary policy's role in managing these adjustments' effects and offer insights for policymakers and researchers.

Our analysis focuses on intrinsic inflation persistence and its relationship with hazard functions, which measure the probability of changing a price and the duration of price stickiness. Sheedy (2007, 2010) introduced the general approach of considering intrinsic inflation persistence through time-dependent pricing mechanisms, which Di Bartolomeo and Di Pietro (2017) later

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[1] Among others, Cecchetti (1986), Coenen *et al*. (2007), Sheedy (2007, 2010), Woodford (2009), Midrigan (2011), Yao (2016), Di Bartolomeo and Di Pietro (2017, 2018). As noted by Woodford (2009), it should be stress that the forecast of a significant positive hazard rate the empirical findings of Eichenbaum *et al*. (2011). For wages, see Barattieri *et al*. (2014), Di Bartolomeo *et al*. (2020), Grigsby *et al*. (2021). A critical discussion on the evidence is provided in Di Bartolomeo and Di Pietro (2017).

generalized to wage dynamics. The hazard function is affected by whether it is upward or downward-sloping, which determines the probability of posting a new price for prices that have remained fixed for many periods. Di Bartolomeo *et al*. (2020) used a generalized model of Erceg *et al*. (2000) that accounts for price and wage hazard functions to analyze seven industrialized economies' price and wage structures. Building on their work, we extend the country comparison to an optimal monetary policy analysis.

We also build upon a second literature strand that examines optimal monetary policy by deriving a welfare criterion based on time-dependent models for both price and wage adjustments. This strand includes studies that have developed a general approach to approximating welfare around the steady state (such as Rotemberg and Woodford, 1997; Woodford, 2003; Benigno and Woodford, 2005, 2012). Our approach, based on Woodford's (2003) method, introduces a subsidy that counteracts distortions arising from market power so that a zero-inflation policy yields an efficient level of output in the steady state. Di Bartolomeo and Di Pietro (2018) previous work examined the link between time-dependent mechanisms and optimal monetary policy but focused only on prices, ignoring wage adjustments.

The remainder of the paper is organized as follows. Section 2 describes a simple New Keynesian model augmented with duration-dependent price adjustments and the model-consistent welfare function. Our research strategy and methodology are outlined in Section 3. Our results are presented in Section 4. Finally, Section 5 concludes.

2. The theoretical framework

2.1 The model[2]

We consider a small-scale New Keynesian DSGE model. The demand side of the economy is characterized by many identical households, each composed of a continuum of members that supply different labor services and consume goods. The supply side is populated by a continuum of firms that produce differentiated goods using household labor. The economy is characterized by monopolistic competition in the goods and labor markets. Firms and households are price and wage-setters and reset prices and wages periodically with a time-dependent probability. Nominal price and wage rigidities are modeled according to vintage-dependent mechanisms. The model is expressed as a deviation from its long-run level.

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[2] See Di Bartolomeo and Di Pietro (2017) for a detailed derivation of the model. A technical appendix is also available upon request.

The aggregate demand (1) is derived from the Euler equation. It inversely conveys the output gap (x_t) to the real interest rate (r_t). Formally,

$$x_t = \frac{1}{1+h} E_t x_{t+1} + \frac{h}{1+h} x_{t-1} - \frac{1-h}{\sigma(1+h)} (r_t + E_t z_{t+1} - z_t) \tag{1}$$

where h is the habit parameter; σ is the relative risk aversion coefficient; z_t is a preference shock that evolves according to $z_t = \rho_z z_{t-1} + \varepsilon_t^z$ with $\rho_z \in [0,1)$ and $\varepsilon_t^z \sim N(0, \sigma_z^2)$. The real interest rate is the difference between the nominal one (i_t) and the expected inflation rate ($E_t \pi_{t+1}^p$).

The supply side is described by the Phillips curve (2) that relates inflation (π_t^p) positively to the real marginal cost (mc_t). Formally,

$$\pi_t^p = \psi_p \pi_{t-1}^p + \beta\left[1 + (1-\beta)\psi_p\right] E_t \pi_{t+1}^p - \beta^2 \psi_p E_t \pi_{t+2}^p + \frac{k_p(mc_t + \zeta_t)}{1 + \varepsilon_p \phi/(1-\phi)} \tag{2}$$

where β is the discount factor; ϕ is labor weight in the Cobb-Douglas-production function; ε_p is the elasticity of substitution between goods; and ζ_t is a supply (or additive price markup) shock that evolves according to $\zeta_t = \rho_\zeta \zeta_{t-1} + \varepsilon_t^\zeta$ with $\rho_\zeta \in [0,1)$ and $\varepsilon_t^\zeta \sim N\left(0, \sigma_\zeta^2\right)$. The two parameters ψ_p and k_p in (2) defines the slope and the intercept of the Phillips curve and derives from the slope (φ_p) and intercept (α_p) of the (price) hazard function. They are as follows:

$$\begin{cases} \psi_p = \dfrac{\varphi_p}{(1-\alpha_p) - \varphi_p\left[1 - \beta(1-\alpha_p)\right]} \\ k_p = \dfrac{(\alpha_p + \varphi_p)\left[1 - \beta(1-\alpha_p) + \beta^2 \varphi_p\right]}{(1-\alpha_p) - \varphi_p\left[1 - \beta(1-\alpha_p)\right]} \end{cases} \tag{3}$$

It is worth noting that α_p is the probability of resetting the price at time *t* of a firm that has set its price at *t*–1, while φ_p is the slope of the hazard, which can be flat as in Calvo (1983) pricing (when $\varphi_p = 0$), upward-sloping (when $\varphi_p > 0$), or downward-sloping (when $\varphi_p < 0$). The parameters also define the unconditional probability of a price reset, i.e., $\alpha_p + \varphi_p$, and the unconditional expected duration of price stickiness, i.e., $\left(1-\varphi_p\right)/\left(\alpha_p + \varphi_p\right)$.[3]

The marginal cost (mc_t) and the production function (y_t) are:

$$mc_t = \omega_t + n_t - y_t \tag{4}$$

$$y_t = a_t + (1-\phi) n_t \tag{5}$$

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[3] See Sheedy (2007).

where n_t are the hours worked; a_t is a production disturbance that evolves as $a_t = \rho_a a_{t-1} + \varepsilon_t^a$ with $\rho_a \in [0,1)$ and $\varepsilon_t^a \sim N(0, \sigma_a^2)$.

The equilibrium of the labor market is defined by the wage Phillips curve (6) that conveys wage inflation (π_t^w) negatively to the gap between the real wage (ω_t) and the marginal substitution rate between labor and consumption (mrs_t). Formally, we can write:

$$\pi_t^w = \psi_w \pi_{t-1}^w + \beta[1 + (1-\beta)\psi_w] E_t \pi_{t+1}^w - \beta^2 \psi_w E_t \pi_{t+2}^w - \frac{k_w(\omega_t - mrs_t)}{1 + \varepsilon_w \gamma} \tag{6}$$

where γ is the inverse of Frisch elasticity; ε_w is the elasticity of substitution between workers' services. Note that we can define: $\omega_t - \omega_{t-1} = \pi_t^w - \pi_t^p$. Again, parameters ψ_w and k_w derive from the slope (α_w) and intercept (φ_w) of the (wage) hazard function:

$$\begin{cases} \psi_w = \dfrac{\varphi_w}{(1-\alpha_w) - \varphi_w[1 - \beta(1-\alpha_w)]} \\ k_w = \dfrac{(\alpha_w + \varphi_w)[1 - \beta(1-\alpha_w) + \beta^2 \varphi_w]}{(1-\alpha_w) - \varphi_w[1 - \beta(1-\alpha_w)]} \end{cases} \tag{7}$$

The interpretation of α_w and φ_w is like that of (3). Therefore, the unconditional probability of a wage reset is $\alpha_w + \varphi_w$ and the unconditional expected duration of price stickiness is $(1-\varphi_w)/(\alpha_w + \varphi_w)$. It is easy to verify that for $\varphi_w = 0$, equation (7) collapses to a flat Calvo's wage-adjustment mechanism (cf. Erceg *et al.*, 2000).

The marginal rate of substitution between labor and consumption is derived from the household's utility function and can be written as follows:

$$mrs_t = \frac{\sigma}{1-h}(y_t - h y_{t-1}) + \gamma n_t - z_t \tag{8}$$

The model is closed by the specification of monetary policy that is set according to a simple Taylor rule (Taylor, 1999):

$$i_t = \rho_i i_{t-1} + (1-\rho_i)\left(\delta_\pi \pi_t^p + \delta_y y_t\right) + \varepsilon_t^i \tag{9}$$

where $\delta_\pi > 0$ is the feedback coefficient of the monetary policy; $\delta_y > 0$ is the feedback coefficient on output gap; $\rho_i \in [0,1)$ is a smoothing parameter that captures policy inertia; $\varepsilon_t^i \sim N(0, \sigma_i^2)$ is a white noise (i.e., policy innovation.)

2.2 The welfare loss function

To evaluate the monetary policy across countries, we derive a model-consistent welfare-loss function by second-order Taylor approximating the expected value of the intertemporal utility function.

The period utility is:[4]

$$U_t(C_t, C_{t-1}, N_t(j)) = \frac{(C_t - hC_{t-1})^{1-\sigma}}{1-\sigma} - \frac{N_t(j)^{1+\gamma}}{1+\gamma} \tag{10}$$

By a second-order approximation, once we account for the aggregate resource constraint, i.e., $c_t = y_t$, (10) can be written as:

$$u_t \simeq U_c Y \left[\frac{1-h\beta}{1-h}\left(y_t + \frac{y_t^2}{2}\right) - \frac{\sigma}{2}\left(\frac{y_t - hy_{t-1}}{1-h}\right)^2\right] + U_n N \left[\int_0^1 n_t\,(j)dj + \frac{1+\gamma}{2}\int_0^1 n_t^2\,(j)dj\right]$$

(11)

where the symbol $\simeq$ indicates that an approximation is accurate up to the second order and steady state values are denoted by upper case letters.

The second-order approximation of the aggregate employment, $N_t \equiv \int_0^1 N_t\,(j)dj$, is

$$n_t + \frac{1}{2}n_t^2 \simeq \int_0^1 n_t\,(j)dj + \frac{1}{2}\int_0^1 n_t^2\,(j)dj \tag{12}$$

Using the approximation of the labor-demand equation, we obtain

$$\int_0^1 n_t^2\,(j)dj \simeq n_t^2 + \varepsilon_w^2 var_j w_t(j) \tag{13}$$

Manipulating together (12) and (13), we rewrite (11), as

$$u_t \simeq U_c Y \left[\frac{1-h\beta}{1-h}\left(y_t + \frac{y_t^2}{2}\right) - \frac{\sigma}{2}\left(\frac{y_t - hy_{t-1}}{1-h}\right)^2\right] + U_n N \left[n_t + \frac{1+\gamma}{2}n_t^2 + \frac{\varepsilon_w^2 \gamma}{2} var_j w_t(j)\right] \tag{14}$$

Now we derive a relation between aggregate employment and output:[5]

$$N_t = \int_0^1 \int_0^1 N_t\,(i,j)djdi = \Delta_{w,t}\Delta_{p,t}\left(\frac{Y_t}{A_t}\right)^{\frac{1}{1-\delta}} \tag{15}$$

where $\Delta_{w,t} \equiv \int_0^1 \left(\frac{W_t(j)}{W_t}\right)^{-\varepsilon_w} dj$ and $\Delta_{p,t} \equiv \int_0^1 \left(\frac{P_t(i)}{P_t}\right)^{\frac{-\varepsilon_p}{1-\delta}} di$ measure the degree of wage and price dispersion, respectively.

Log-linearizing (15), under the normalization $A = 1$, we get:

$$(1-\delta)n_t = y_t - a_t + \frac{\varepsilon_p}{2\Theta_p} var_i\{p_t(i)\} + \frac{(1-\delta)\varepsilon_w}{2} var_j\{w_t(j)\} \tag{16}$$

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[4] We used the fact that $C_t = \int_0^1 C_t\,(j)dj$. Since the same is not true for $N_t(j)$, we keep the index j for the labor supply.

[5] See Galì (2008, p. 142).

where $var_i\{p_t(i)\}$ and $var_j\{w_t(j)\}$ indicate the cross-sectional variance of prices and wages, respectively; $\Theta_p = \frac{1-\delta}{1-\delta+\delta\varepsilon_p}$.

Substituting (16) into (14), we obtain

$$\begin{aligned} u_t \simeq U_c Y \left[\frac{1-h\beta}{1-h}\left(y_t + \frac{y_t^2}{2}\right) - \frac{\sigma}{2}\left(\frac{y_t - hy_{t-1}}{1-h}\right)^2\right] + \\ + \frac{U_n N}{1-\delta}\left[y_t + \frac{\varepsilon_p var_i\{p_t(i)\}}{2\Theta_p} + \frac{\varepsilon_w var_j\{w_t(j)\}}{2\Theta_w} + \frac{(1+\gamma)y_t^2}{2(1-\delta)}\right] \end{aligned} \tag{17}$$

where $\Theta_w = (1-\delta)(1+\varepsilon_w\gamma)$.

Accounting for an efficient steady state,[6] i.e., $-U_n/U_c = MPN = (1-\delta)Y/N$, and using (17), after some algebra, we get:

$$\begin{aligned} w_t \simeq -\frac{1}{2}N^{1+\gamma}E_0 \Bigg\{\sum_{t=0}^{\infty}\beta^t\left[\left(\frac{\sigma}{\lambda} + \frac{\gamma+\delta}{1-\delta}\right)y_t^2 + \frac{\sigma h}{\lambda}(hy_{t-1}^2 - 2y_t y_{t-1})\right] + \\ + \frac{\varepsilon_p}{\Theta_p}\sum_{t=0}^{\infty}\beta^t\left[var_i\{p_t(i)\}\right] + + \frac{\varepsilon_w}{\Theta_w}\sum_{t=0}^{\infty}\beta^t\left[var_j\{w_t(j)\}\right]\Bigg\} \end{aligned} \tag{18}$$

where $\lambda = (1-h\beta)(1-h)$.

To obtain an expression for $var_j\{w_t(j)\}$ and $var_i\{p_t(i)\}$, we exploit that the log-aggregate-wage level evolves as $\log W_t = \sum_{h=0}^{\infty}\theta_{w,h}\log W_{t-h}^*$, where W_t^* is the reset wage and $\theta_{w,h}$ the share of workers posting a wage which last change was h periods ago. Thus, the wage level is a weighted average of past reset wages and the share of workers using such wages at time t and the same holds for the log-aggregate-price level.

Exploiting the above log adjustments and the properties of the variance, we approximate the discounted sum of price or wage dispersion Δ_t^i for $i \in \{p, w\}$ as:

$$\sum_{t=0}^{\infty}\beta^t\Delta_t^i \simeq \frac{1}{d_i}\sum_{t=0}^{\infty}\beta^t\left[\left(\pi_t^i - \varphi_i\pi_{t-1}^i\right)^2 - (\alpha_i + \varphi_i)(\pi_t^i)^2\right] \tag{19}$$

where $d_i = [1-\beta(1-\alpha_i-\varphi_i)](\alpha_i+\varphi_i) \in (0,1)$.

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[6] We assume an output or employment subsidy that offsets the distortions due to the market powers so that the steady state under a zero-inflation policy involves an efficient output level. The approach can be generalized to the case of a distorted steady state. However, this introduces further complications (see Benigno and Woodford, 2005a, 2005b, 2012).

Finally, noting that up to a second-order approximation $\frac{\varepsilon_p}{2\Theta_p} var_i\{p_t(i)\} \simeq (1-\delta)^2 log\Delta_t^p$ and $\frac{1-\varepsilon_w}{2} var_j\{w_t(j)\} \simeq (1-\delta)^2 log\Delta_t^w$, we substitute (19) into (18) to get our welfare measure with internal habit and duration-dependent-price and wage adjustments:

$$w_t \simeq -\frac{1}{2} E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{\left(\pi_t^p - \varphi_p \pi_{t-1}^p\right)^2 - \left(\alpha_p + \varphi_p\right)\left(\pi_t^p\right)^2}{d_p \Theta_p \varepsilon_p^{-1}} + \frac{\sigma(y_t - hy_t)^2}{\lambda} + \right. \\ \left. + \frac{(\gamma+\delta) y_t^2}{1-\delta} + \frac{(\pi_w^w - \varphi_w \pi_{t-1}^w)^2 - (\alpha_w + \varphi_w)(\pi_t^w)^2}{d_w \Theta_w \varepsilon_w^{-1}} \right\} \tag{20}$$

Equation (20) shows that welfare is a quadratic expression of the output gap, price, and wage inflation.

3. Methodology

3.1 Monetary policy counterfactuals

Optimal policies are evaluated within a "what if" exercise. After estimations based on the observed dynamics, we perform a counterfactual policy analysis that concerns what the Central Banks would have done if, ceteris paribus, they had maximized a model-based welfare function facing the identified historical shocks.

Our exercise is thus implemented in a two-step procedure.

1. We estimated the model (1)-(9) for seven countries: Australia, Canada, France, Germany, Italy, the United Kingdom, and the United States. Specifically, we estimate a) the deep parameters characterizing the slopes and initial values of price and wage Phillips curves; b) the historical-shock innovation series.[7] Note that estimations include the monetary policy rule (9), which captures the observed behavior of the central bank.
2. We simulate the model (1)-(8) by assuming that the central bank minimizes the welfare loss (20) and faces the historically estimated shock dynamics. We consider both commitment and discretion. To this extent, we developed an algorithm based on Soderlind (1999), which accounts for 1) multiple shocks, 2) changes in the current state of the economy, and 3) past promises for the case of commitment.[8] It is worth noting that we assume that the monetary authorities react to the estimated shock dynamics. The assumption is equivalent to considering

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[7] See the following subsection for details.

[8] Details are available in Appendix A.

that the central banker only knows what he would have known at every moment the policy was implemented.

Commitment and discretion are two extreme cases of monetary conduct. By assessing the results of simulations conducted under commitment and discretion regimes, we can establish a metric for determining the central bankers' relative attitude. This involves comparing the forecast error generated by the commitment simulation to that of the discretion simulation, and determining whether the central bank's conduct aligns more closely with commitment or discretion based on which simulation yields a relatively smaller (or greater) error. To evaluate performance in our multivariate context, we utilize a summary measure that considers the joint forecasting performance of commitment and discretion, which involves computing a multivariate statistic by dividing the inverse of the log determinant of the variance-covariance matrix of forecast errors by 2 to convert from variance to standard error and by the number of variables to obtain an average figure (Del Negro *et al*., 2007). Additionally, we evaluate differences in performance for relevant single variables using the root-mean-square error (RMSE).

3.2 Phillips curve estimations and historical shock determination

We estimated the model for seven countries: Australia, Canada, France, Germany, Italy, the United Kingdom, and the United States. We consider four macroeconomic variables for each country: real GDP, price inflation, real wage, and nominal interest rate.

The "Gross Domestic Product by Expenditure in Constant Prices," is used as a proxy for the real GDP and has been collected from the US Bureau of Economic Analysis, retrieved from the FRED Database, and Organization for Economic Cooperation and Development (OECD) database for the US and the remaining countries, respectively. The price inflation is the log difference of the "GDP Implicit Price Deflator" and is collected by the US Bureau of Economic Analysis and the OECD for the US and the other countries, respectively, except for Italy, for which the log difference of the "Consumer Price Index of All Items" has been employed. The real wage is obtained by dividing the nominal wage, measured by the "Compensation per hour in the nonfarm business sector" (from the US Bureau of Labor Statistics) and "Hourly wage rate for all activities" (from the OECD) for the US and the other countries respectively by the corresponding price inflation as above described. Finally, the "Effective Federal Funds Rate" provided by the Board of Governors of the Federal Reserve System is employed for the nominal interest rates. We used the "Interest rates on short-term securities" from the International Monetary Fund for the remaining countries. Output and real wage are detrended, whereas inflation and interest rate are demeaned. Four orthogonal shocks drive the dynamics of our model. As the number of observable variables equals the number of exogenous shocks, the estimation does not present problems deriving from stochastic singularities. We consider a sample ranging from the 1980s to the beginning of the recent crisis. A more extended sample is considered for the US starting from the 1960s.

We use Bayesian techniques to estimate the structural macro model. Any model can be written in a general compact form as:

$$f(y_t, y_{t-1}, \exp(\varepsilon_t), \theta) = 0 \tag{21}$$

where $y_t \in \mathbb{R}^n$ is the vector of endogenous variables; $\varepsilon_t \in \mathbb{R}^q$ is the vector of structural innovations, which are driven by $\varepsilon_t \backsim N(0, \Sigma)$; $\theta \in \mathbb{R}^m$ is the vector of model parameters.

By solving $f(y, \theta) = 0$, we get the steady state that is indicated as $\bar{y}(\theta)$. The linear approximation of (21) can be written as

$$\hat{y}_t = T(\theta)\hat{y}_{t-1} + R(\theta)\varepsilon_t \tag{22}$$

where $\hat{y}_t = y_t - \bar{y}(\theta)$. Equation (22) is the reduced form of the DSGE model (state equation). It is worth noting that (22) maps our model (1)-(9).

We do not observe all the endogenous variables. Let $Y_T^* = \{\hat{y}_1^*, \hat{y}_2^*, \dots \hat{y}_T^*\}$ be the sample of the $p < n$ observed variables for each country between 1 and T. To bring the model to the data, we augmented the state equation (22) with an additional set of equations linking the data for the subset of observed variables to the endogenous ones:

$$\hat{y}_t^* = Zy_t + \xi_t \tag{23}$$

where Z is an appropriate $p \times n$ matrix filled with zeros and ones and $\xi_t \in \mathbb{R}^p$ is a vector of potential measurement errors (we assume ξ_t=0). Note that $y_t = \hat{y}_t + \bar{y}(\theta)$ in equation (23).

The model (22)-(23) defines a joint probability distribution parametrized function over a sample of variables $p(Y_T^* | \phi)$, where ϕ is the vector of parameters to be estimated (θ, and Σ). A joint probability density function can summarize our prior information about parameters. Let the prior density be $p_0(\phi)$, the posterior distribution, $p_1(\phi | Y_T^*)$, is given by (Bayes theorem):

$$p_1(\phi | Y_T^*) = \frac{p_0(\phi) p(Y_T^* | \phi)}{p(Y_T^*)} \tag{24}$$

The denominator of (24) is the marginal density of the sample, which is defined by a weighted mean of the sample conditional densities over all the possible values for the parameters.

As long as $p(Y_T^*)$ does not involve ϕ, we can ignore it in the estimation, then the posterior density is proportional to the product of the prior density and the density of the sample conditional on the parameters of the model (likelihood function):

$$p(\phi | Y_T^*) \propto p_0(\phi) p(Y_T^* | \phi) \tag{25}$$

The prior density deforms the shape of the likelihood. From equation (25), we can make any inference about ϕ.

To evaluate the likelihood, $L(\phi, Y_T^*)$, we need to specify the marginal density, $p(y_0^*|\phi)$, and the conditional density, $p(y_t^*, Y_{t-1}^*, \phi)$, i.e.,

$$L(\phi, Y_T^*) = p(Y_T^*|\phi) = p(y_0^*|\phi)_{t=1}^{T} p(y_t^*|Y_{t-1}^*, \phi) \tag{26}$$

The distribution of the initial condition, y_0, is set equal to the ergodic distribution of the stochastic difference equation, which is Gaussian since the disturbances of (22) are assumed to be Gaussian. The density of $y_t^*|Y_{t-1}^*$ is obtained from the mean of the density of $y_t^*|y_t$ weighted by the density of $y_t|Y_{t-1}^*$.[9] The former comes from the measurement equation (23). The latter is obtained by a Kalman filter, which is used to evaluate the density of the latent variables (y_t) conditional on the sample up to time $t - 1$ (Y_{t-1}^*).

After writing the model in state-space form, the likelihood function is evaluated according to the Kalman filter, whereas prior distributions are used to introduce additional non-sample information into the parameter's estimation. Once a prior distribution is elicited, the posterior density for the structural parameters is obtained by re-weighting the likelihood by a prior. Finally, the posterior is computed using numerical integration by applying the Metropolis-Hastings (MH) algorithm for Monte Carlo integration.[10]

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[9] As far as y_t^* depends on unobserved endogenous variables, evaluation of the density of $y_t^*|Y_{t-1}^*$ is not trivial.

[10] For an exhaustive analysis of Bayesian estimation methods, see, e.g., Herbst and Schorfheide (2015).

4. Results

4.1 Estimated Phillips Curves

Our estimations are reported in Table 1, which also reports the assumed priors.[11] We show the posterior estimation of the structural parameters obtained by the Metropolis-Hastings algorithm.[12]

Table 1 – Countries' priors and estimated posteriors

	Prior		Posterior Distribution						
	Density	Mean	Australia	Canada	UK	France	Germany	Italy	US
α_p	Beta	0.20	0.028	0.018	0.026	0.026	0.022	0.014	0.025
φ_p	Uniform	0.00	0.200	0.305	0.201	0.126	0.244	0.256	0.174
α_w	Beta	0.20	0.068	0.109	0.154	0.088	0.091	0.079	0.235
φ_w	Uniform	0.00	0.291	0.315	0.172	0.112	0.250	0.333	0.171
h	Beta	0.60	0.905	0.893	0.924	0.964	0.936	0.947	0.852
σ	Gamma	1.00	1.590	1.314	1.416	1.280	1.312	1.438	2.261
γ	Gamma	2.00	3.044	2.623	2.918	2.733	2.661	2.456	2.587
δ_π	Normal	1.70	1.455	1.420	1.280	1.113	1.467	1.570	1.179
δ_y	Normal	0.15	0.157	0.186	0.093	0.175	0.128	0.151	0.207
ρ_i	Beta	0.50	0.899	0.796	0.839	0.860	0.898	0.842	0.805
σ_ζ	Inv. G	0.01	0.026	0.015	0.033	0.035	0.013	0.017	0.019
σ_a	Inv. G	0.01	0.129	0.037	0.193	0.028	0.080	0.026	0.035
σ_z	Inv. G	0.01	0.062	0.050	0.055	0.086	0.069	0.087	0.065
σ_v	Inv. G	0.01	0.002	0.002	0.002	0.002	0.001	0.002	0.002
ρ_ζ	Beta	0.50	0.776	0.781	0.757	0.809	0.838	0.797	0.827
ρ_a	Beta	0.50	0.336	0.471	0.332	0.910	0.402	0.569	0.729
ρ_z	Beta	0.50	0.768	0.735	0.805	0.799	0.812	0.751	0.763

The results for all the countries under analysis confirm that the vintage-dependent mechanism accounts for the intrinsic inflation persistence in prices and wages. Accordingly, we get empirical evidence of a positive slope, as indicated by the parameter φ_i, with $i = \{p, w\}$, for both the hazard function in prices and wages. The other parameter estimates are for all countries in line with the literature. The response of the monetary authority to inflation and the output gap is consistent with the Taylor principle, and the estimated coefficients of the monetary rule are standard. The estimated degree of interest rate smoothing ρ_i highlights a high degree of autocorrelation of the monetary policy. Concerning the utility function parameters, we find a substantial degree of habit in consumption, considering the structural factors generating output inertia in the sample. The relative risk aversion and inverse of Frisch elasticity estimates are similar among countries. All the shocks are characterized by high degrees of autocorrelation.

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[11] Details are provided in Appendix B.

[12] Estimations have been performed using Dynare (see Adjemian *et al.*, 2011).

The estimated Phillips Curves are reported in Table 2. The table highlights the differences across countries in the backward components of the curves and the sacrifice ratios. Both are relevant for policy decisions. On the one hand, persistence in the inflation process means excessive price increases can persist in the economic system without further external shocks once inflation picks up. On the other hand, flat Phillips Curves imply that the sacrifice ratio is high, i.e., bringing down excessive inflation by contracting aggregate demand is costly for the central bank. High sacrifice ratios and persistence imply that the central bank becomes less powerful once inflation is entrenched in the economy.

Table 2 – Estimated Phillips Curves

Country	Prices			Wages		
	forward	backward	sacrifice ratio	forward	backward	sacrifice ratio
Australia	0.992	0.207	4.23	0.993	0.319	2.53
Canada	0.993	0.313	3.10	0.993	0.368	2.10
France	0.991	0.129	6.37	0.991	0.124	4.50
Germany	0.992	0.251	3.64	0.992	0.282	2.59
Italy	0.992	0.261	3.62	0.993	0.373	2.16
UK	0.992	0.207	4.25	0.992	0.210	2.50
US	0.991	0.179	4.86	0.992	0.236	1.79

Note: The backward component of the Phillips curve is that associated with t–1 (the component associated with t–2 is obtained by multiplying by $-\beta^2$.) See equations (2) and (6). The sacrifice ratios are the inverse of the slope of the Phillips curves.

Price and wage inflation are relatively persistent in Canada. Conversely, these are relatively not persistent in France. The two countries represent two extreme cases. Price inflation is also not very persistent in the United States, where wage variations are moderately persistent. In addition to Canada, wage variations are relatively persistent in Australia and Italy. Price trends are moderately persistent in Italy and Germany and, to a lesser extent, in Australia and the UK. The sacrifice ratios for France are relatively high for both prices and wages. The other countries show minor differences. The sacrifice ratio of price (wage) inflation in the United States is relatively high (low.)

Drawing from the estimated Phillips Curves, Table 3 reports the unconditional probability of a price reset which is expressed by $\alpha + \varphi$ and the unconditional expected duration of price stickiness which is $(1 - \varphi)/(\alpha + \varphi)$. Except for France, countries in the sample exhibit similar duration for both prices and wages. The outcomes are in line with the micro evidence. Despite some degree of variability,[13] micro evidence finds a duration between 2 and 4 quarters for both prices and wages.[14] As mentioned, France behaves as an outlier since both prices and wages duration are longer than one year, i.e., 6.3 and 4.7 quarters for prices and wages, respectively. Opposite cases are Italy and Canada, performing with a lower duration for both prices and wages.

Table 3 – Countries' Phillips Curves: Estimated unconditional probability and duration

Country	Prices		Wages	
	prob.	duration	prob.	duration
Australia	0.22	3.64	0.35	2.03
Canada	0.31	2.26	0.41	1.68
UK	0.22	3.64	0.32	2.59
France	0.14	6.29	0.19	4.68
Germany	0.26	2.92	0.34	2.21
Italy	0.35	2.14	0.40	1.68
US	0.19	4.37	0.40	2.08

4.2 Optimal policy design across countries

Now, we investigate which alternative history we would have observed if monetary policy had been conducted according to an optimizing welfare-based criterion. To this extent, we extrapolate the historical values of the relevant shocks from our estimates and compute the optimal response of the monetary authority to them. Practically, by using an optimization algorithm,[15] we run two simulations (one for commitment and another for discretion) and obtain the counterfactual path of the economy.

Our results are reported in Figure 1 and Table 4. The figure plots the path for the welfare-relevant variables (output, price, and wage inflation) obtained from discretion and commitment simulation and their observed values. The table summarizes their standard deviations. It also reports the standard deviations observed in the data.

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[13] Depending on the sample and period used for the analysis.

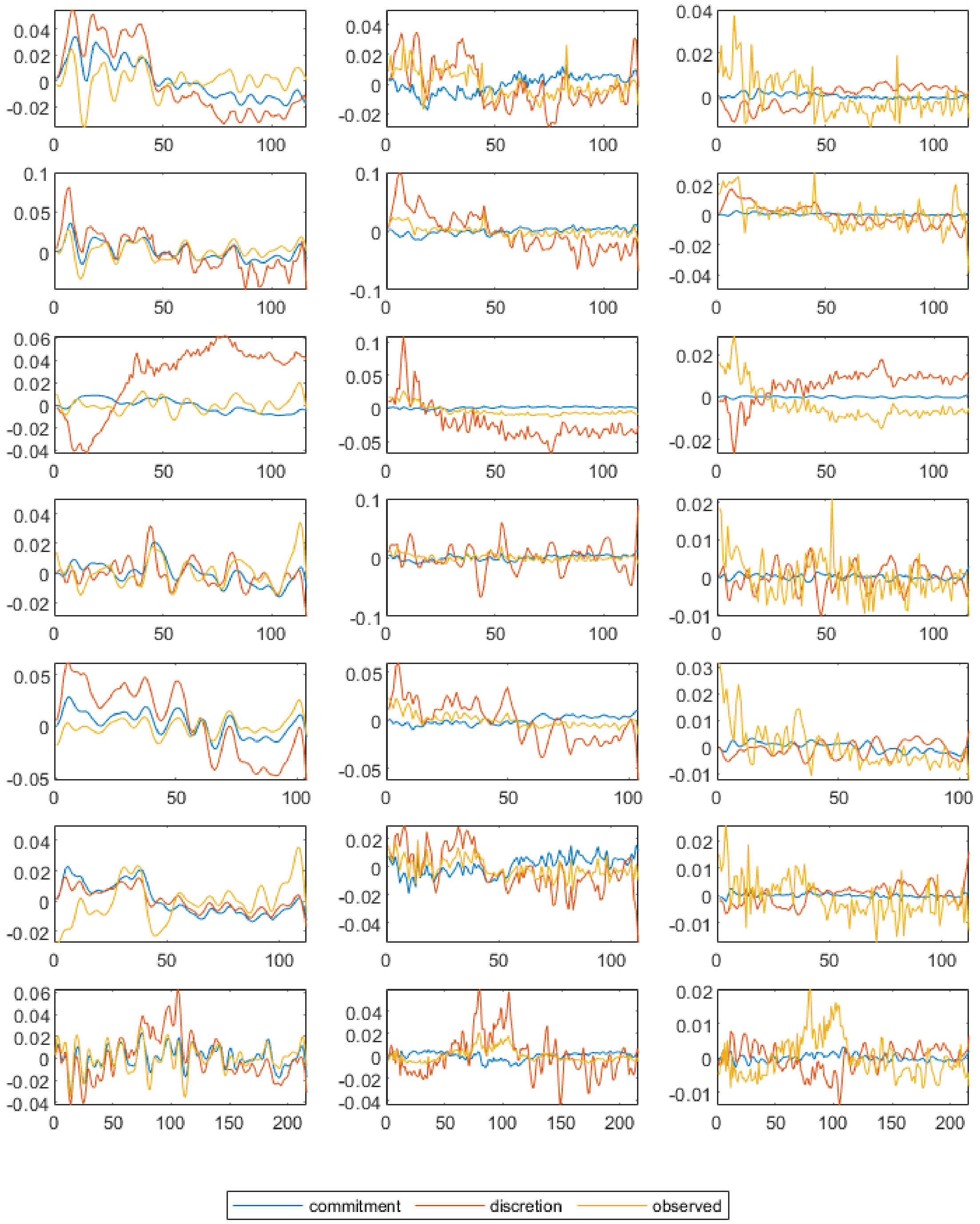
[14] Among others, for the United States, Christiano *et al.* (2005) found, e.g., 2.5 and 2.8 for price and wage durations; Rabanal and Rubio-Ramirez (2005) found 4.2 and 2.3; Galì *et al.* (2011) found 2.3 and 1.8; Di Bartolomeo and Di Pietro (2017) found 3.7 and 2.0.

[15] As described in Section 3.1 and further detailed in Appendix A.

Table 4 – Observed and simulated standard deviations for the welfare-relevant variables

	Australia	Canada	France	Germany	Italy	UK	US
Observed in the data							
Output gap	0.0102	0.0111	0.0066	0.0095	0.0083	0.0132	0.0119
Price inflation	0.0093	0.0090	0.0082	0.0056	0.0071	0.0072	0.0058
Wage inflation	0.0096	0.0101	0.0082	0.0056	0.0081	0.0072	0.0060
Simulated under discretion							
Output gap	0.0310	0.0244	0.0309	0.0501	0.0305	0.0072	0.0197
Price inflation	0.0193	0.0333	0.0291	0.0393	0.0185	0.0160	0.0181
Wage inflation	0.0055	0.0068	0.0076	0.0294	0.0119	0.0038	0.0038
Simulated under commitment							
Output gap	0.0147	0.0112	0.0057	0.0076	0.0118	0.0104	0.0098
Price inflation	0.0063	0.0056	0.0016	0.0046	0.0042	0.0069	0.0034
Wage inflation	0.0011	0.0007	0.0004	0.0007	0.0017	0.0008	0.0001

Figure 1 – Observed and simulated dynamics of the welfare-relevant variables



Note: The figure shows a) by column output gap, price inflation, and wage inflation; b) by row Australia, Canada, France, Germany, Italy, the UK, and the US.

Compared to the observed behavior of macroeconomic variables, a regime of discretion leads to lower variability of wage inflation in most countries in the sample, except Germany and Italy. In contrast, due to its credibility, the central banker has more power to influence expectations in a commitment regime, resulting in a more overall stabilization of inflation and inflation expectations over extended periods. This behavior leads to low price and wage inflation variability in all countries in the sample under commitment. However, the optimal variability of the output gap for some countries (Australia, Canada, and Italy) is slightly larger than the observed variability. As a result, the observed variability of price inflation is higher than that consistent with the commitment policy regime but much lower than that associated with discretion in all countries. Similarly, observed wage inflation variability is higher than simulated under commitment, except for Italy. However, optimal variabilities of the output gap in the commitment regime are slightly larger than those observed in the data for all countries except Italy.

The impact on welfare is described in Table 5. Following, e.g., Ravenna and Walsh (2011), the table reports the welfare losses expressed as a percent of steady-state consumption.[16] The table reports the estimated losses (column (1)) and welfare losses obtained in the alternative polity scenarios (column (2)-(4).) It also reports the welfare gap between the observed loss and the counterfactual one both for commitment and discretion (column (3)-(5).)

Table 5 – Observed and simulated welfare losses (in percent of steady-state consumption)

Country	Observed	Discretion		Commitment	
	(1)	(2)	(3)	(4)	(5)
Australia	6.42	2.55	3.87	0.33	6.09
Canada	3.11	2.80	0.31	0.18	2.93
France	4.84	7.93	-3.09	0.02	4.82
Germany	1.59	0.61	0.98	0.07	1.52
Italy	0.65	0.66	-0.01	0.08	0.57
UK	4.59	1.54	3.05	0.27	4.32
US	2.82	5.03	-2.21	0.34	2.48

The estimated welfare losses show that Italy and Germany got lower estimated welfare losses over the period under analysis, unlike Australia, France, and the UK, where the observed monetary policy experienced more considerable welfare costs. Counterfactual exercises show that optimal monetary policy under commitment is always less costly regarding welfare losses, expressed in terms of their welfare equivalent permanent consumption reduction. The gain of commitment over discretion and the observed policy becomes large in France, Australia, and the US. The case of Italy is interesting as the welfare losses obtained under the observed monetary regime are almost equivalent to those that would have been observed if the central bank had acted under discretion. Moreover,

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[16] It is worth noting that welfare loss in the last column does not depend on the estimations of the Taylor rule parameters, but it only depends on the observed dynamics of the relevant macro variables (cf. Table 3.).

discretionary policies outperform in terms of welfare losses the observed Taylor-based rule in four out of seven countries in the sample, namely Australia, Canada, Germany, and the UK.

Table 5 shows a comparison between the different regimes in terms of welfare loss. However, this comparison can be misleading, as differences between different countries depend on different historical shocks, so relative comparisons are only partially indicative of the behavior of central bankers. In the following subsection, we focus on the latter.

4.3 Central bankers' attitudes

Central bank theory emphasizes the relationship between policy regimes and expectations, as the latter is crucial in transmitting monetary policies to the economy. There are two opposing policy regimes; commitment and discretion. They differ in the central bank's ability to constrain itself contingently to observed shocks. A central banker who operates under commitment creates persistence in policy decisions to influence the actions of forward-looking agents.[17] However, in a model with intrinsic price persistence through the Phillips Curves, any central bank's actions, regardless of the regime, will tend to persist and influence expectations. Identifying the effects of different policy regimes in a Phillips Curve model with forward and backward components is, therefore, challenging.

Our strategy involves assessing the consistency between the simulated and observed data. While expecting either policy regime to predict the data ideally is unrealistic, we aim to gauge how the observed policy can be attributed to one of the central banker's two policy regimes by measuring relative deviations. To accomplish this, we evaluate the joint forecasting performance of each policy regime's simulation and compare it to the observed outcomes. To do so, we use the inverse log determinant of the variance-covariance matrix of forecast errors, divided by two to convert from variance to standard error and by the number of variables to obtain an average figure (Del Negro *et al*., 2007).

Our results are reported in Table 6. In the first row, we display our multivariate statistic in the case of the commitment regime. This statistic is always higher than the one associated with discretion, as shown in row (2), which reports the percent improvement of forecasting of commitment compared to discretion. Similarly, rows (3)-(5) present the change for the differences in performance for the specific single variables relevant to welfare (output gap and price and wage inflation.) For such a comparison, we use the change in the root-mean-square error (RMSE.) The percentage improvements are computed by taking the relative difference multiplied by 100.

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[17] The central banker's constraint will affect current variables to the extent that the agents' action is forward-looking.

Table 6 – Commitment vs. discretion (RMSE)

	Australia	Canada	France	Germany	Italy	UK	US
Commitment	-0.0059	-0.0057	-0.0052	-0.0055	-0.0055	-0.0058	-0.0053
Change (%)*							
Multivariate	8.6	7.9	14.5	12.9	13.1	4.5	10.8
Output gap	43.9	59.2	77.3	19.6	67.4	-14.5	63.3
Price inflation	-8.0	58.0	64.3	69.8	40.8	15.7	39.9
Wage inflation	30.1	-11.7	49.3	16.8	11.7	24.0	37.8

Note (*). For each cell, we (successfully) tested that the change implied by the commitment to discretion was statistically different from zero.

The impact of the ECB's action has been similar across France, Italy, and Germany. Indeed, in all euro area countries, the conduct of the central banker can be cataloged as a commitment, which has greater explanatory power over the data (more than 10%) for all the three variables relevant to welfare than discretion. For instance, commitment outperforms discretion in explaining the observed data by 12.9% in Germany. Regarding RMSE, the commitment outperforms the forecasted output gap, price inflation, and wage inflation in Germany and the US. However, in the US, the commitment is more oriented towards output stabilization than inflation, while the ECB's policy can be defined as strongly inflation-oriented. A rough measure of this difference is the gap between the improvement in the output gap and inflation in RMSEs, which is 24.3 p.p. for the US and -50.2 p.p. for Germany. Therefore, we can conclude that the ECB's policy has effectively reduced inflation and stabilized the economy, while the Fed's policies are weakly inflation-oriented.

4. Conclusions

Our paper reported the estimated Phillips Curves for several countries and highlighted the relevance of persistence in the inflation process and sacrifice ratios for policy decisions. The paper investigates the alternative history that would have been observed if monetary policy had been conducted according to an optimizing welfare-based criterion. The paper showed that optimal monetary policy under commitment is always less costly regarding welfare losses, expressed in terms of their welfare equivalent permanent consumption reduction. The gain of commitment over discretion and the observed policy becomes enormous in France, Australia, and the US. The paper also discussed central bankers' *attitudes* towards commitment and discretion by evaluating the joint forecasting performance of each policy regime's simulation and compared it to the observed outcomes to gauge how the observed policy can be attributed to one of the central banker's two policy regimes.

Appendix A

The algorithm is a three-step optimization procedure to find the optimal policy for a theoretical macro model. The algorithm is based on Soderlind (1999) and requires the estimation results from the model as inputs.

1. The first step of the algorithm is to calibrate the deep parameters of the model to the estimated values, which involves adjusting the model parameters to match the estimated time series. This step is solved by Bayesian estimation of the model.
2. The second step is to extract the historical-shock series from the estimation results, which involves identifying the patterns of shocks that have occurred in the past and using this information to inform the model.
3. The third step of the algorithm is to run the Soderlind (1999) algorithm to compute the optimal policy in response to the dynamics of the observed shocks and the subsequent economic reaction. Note that the algorithm considers the monetary authority's past promises when commitment is simulated.

Overall, the algorithm is a way to optimize the policy response of a theoretical macro model based on the estimation results from the data. The algorithm seeks to find the optimal policy given the historical patterns of shocks.

Appendix B

The parameters that are essential for our analysis are the ones that define the Phillips curves, specifically the slopes and initial values. We have incorporated relatively wide priors in our estimations to enable the possibility of positive or negative hazards. For the slopes, φ_p and φ_w, since they can take on either positive or negative values, we have utilized a uniform distribution with a mean centered around zero and a diffuse support range of -0.5 to 0.5. As the initial values of the price and wage, we assign a Beta distribution to α_p and α_w (note that the initial range is between 0 and 1), which is centered on 0.2 and with a standard deviation equal to 0.15.

The other priors are established in the following manner. The coefficient for relative risk aversion (σ) is assumed to have a Gamma distribution with a mean of 1 and a standard deviation of 0.375. The inverse of Frisch elasticity (γ) is Gamma distributed with a mean of 2 and a standard deviation of 0.375. The habit parameter (h) is distributed according to a Beta distribution with a mean of 0.6 and a standard deviation of 0.2. The monetary policy's feedback coefficient (δ_π) is Normally distributed, with a mean of 1.7 and a standard deviation of 0.25. Meanwhile, the feedback coefficient on the output gap (δ_y) is Normally distributed with a mean of 0.15 and a standard deviation of 0.05.

Finally, the smoothing parameter (ρ_i) is distributed using a Beta distribution, with a center at 0.5 and a standard deviation of 0.2. The four shocks are distributed with an Inverse Gamma distribution, having a mean of 0.01 and 2 degrees of freedom. The autoregressive coefficients for the shocks are distributed according to a Beta distribution with a mean of 0.5 and a standard deviation of 0.2.

The remaining parameters are calibrated in a conventional way [18] To match the observed long-run interest rate, the discount factor (β) is set at 0.99. The parameter ϕ, from the production function, is calibrated to 0.33, the long-run labor share. The elasticity of substitution between goods (ε_p) and workers (ε_w) is calibrated to 6, resulting in an average markup of 20%.

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[18] This is standard procedure to avoid identification problems (Canova and Sala, 2009). The identification procedure has been performed using the identification condition developed by Iskrev (2010a, 2010b), implemented in the Dynare identification toolbox.

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