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Asymmetric monetary policy rules for the euro area and the US

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Abstract

We analyse the implications of asymmetric monetary policy rules by estimating Markov-switching DSGE models for the euro area (EA) and the US. The estimations show that until mid-2014 the ECB's response to inflation was more forceful when inflation was above 2% than below 2%. Since then, the ECB's policy can be characterised as symmetric, and we quantify the macroeconomic implications of this policy change. We uncover asymmetries also in the Fed's policy, which has responded more strongly in times of crisis. We compute an optimal simple rule for the EA and the US in an environment with the effective lower bound and a low neutral real rate, and find that it prescribes a stronger response to inflation and the output gap when inflation is below target compared to when it is above target. We document its stabilisation properties had this optimal rule been implemented over the last two decades.

Keywords: Inflation targeting, Markov-switching DSGE, optimal monetary policy, effective lower bound, Bayesian Estimation.

JEL Classification: E52, E58, E31, E32.

Non-technical summary

The debate about asymmetric monetary policy frameworks has recently intensified. It has centred around two questions. *Have* central banks so far responded asymmetrically to macroeconomic conditions? And, *should* central bank respond asymmetrically?

In the euro area the debate on the degree of asymmetry of the ECB's price stability framework goes back to the early days of monetary union and has recently re-emerged.[1] For instance, Rostagno et al. (2019) estimate policy rules for the ECB over the period 1999-2008 and Paloviita et al. (2021) over the period 1999-2014. They find evidence of asymmetric policy responses, with more forceful reactions to inflation overshooting than undershooting. Rostagno et al. (2019) argue that this asymmetric response is the outcome of the ECB's framework as adopted in 1998 and clarified in 2003: it features a definition of price stability in terms of an inflation range between 0% and 2% as well as an inflation aim below but close to 2%. An inflation aim close to the upper edge of the price stability range may create an asymmetry, with the ECB responding (or perceived to respond) more strongly to inflation above the aim than below it. This type of asymmetric response may have been beneficial in keeping inflation in check in the face of the prevailing inflationary pressure hitting the euro area in the first ten years of the ECB's existence (1999-2008). But the environment has changed after the global financial crisis and the sovereign debt crisis due to persistently low inflation and declining natural real interest rate, r^*.

The ECB has officially communicated for the first time in July 2019 about whether its approach is symmetric. It has stated that it follows a symmetric approach around its inflation aim: "the Governing Council is determined to act, in line with its commitment to symmetry in the inflation aim" (ECB (2019)). In speeches, the ECB's then President Mario Draghi suggested that the symmetric approach may have been in place even earlier.

In the US, while the Fed's communication has emphasized a symmetric approach since 2012, in August 2020 the Fed adopted a makeup strategy with an asymmetric tilt. The new strategy aims to target average inflation and to counter shortfalls but not overshoots.

We contribute to the debate about whether over the last two decades the ECB's and the Fed's policy response has been symmetric or asymmetric. We estimate a general equilibrium

[1] This paper has been accepted for publication before the announcement of the ECB's new policy strategy on 8 July 2021, and therefore does not reflect it.

model allowing for asymmetric policy responses. For the ECB we find that up until mid-2014 the policy response can be characterised as asymmetric by responding more strongly to inflation above 1.9% than below it. Since mid-2014 there is evidence of a more symmetric response consistent with the change in the central bank's communication. We find that, had the ECB post-2014 kept following an asymmetric policy in line with the one estimated pre-2014, inflation over the period 2014-2019 would have been up to 20 basis points lower and the output gap up to 70 basis points lower than its actual realization.

For the Federal Reserve, we estimate the model over the last two decades and find evidence of asymmetry but of a different nature. We find that at times of financial distress, the Fed has responded more strongly to deteriorating macroeconomic conditions than in normal times.

Our second contribution is about whether the policy response *should* be asymmetric and in what way. Using our estimated general equilibrium model we show that when the natural real interest rate is low and there is a lower bound on interest rates, it is optimal to adopt an asymmetric response whereby the central bank reacts less forcefully to inflation above target than below target. The reason is that a low natural real interest rate and the lower bound on interest rates reduce the policy space available to the central bank to counteract recessionary shocks. This creates an asymmetry because the central bank is instead able to counteract inflationary shocks. As a result, an ex-ante symmetric inflation aim will over the longer term display below target averages. We find that, to counter the asymmetry introduced by the lower bound on nominal interest rates and the deflationary bias it produces, optimised rules call for stronger responses to low inflation than to high inflation.

Our final contribution is to run counterfactual simulations to assess how over the last two decades the euro area and US economies would have performed had the central bank in those countries followed the optimal asymmetric policy that we have derived. In both the euro area and the US, inflation and the output gap would have been better stabilised especially after the financial crisis. For the euro area, we find that inflation would have been about 30 basis points higher after the 2008 crisis, while the output gap would have closed more quickly. For the US, we find that inflation would have been around 30-40 basis points higher after the global financial crisis. The output gap would have been better stabilised, falling only to around -2% during the global financial crisis.

1 Introduction

There has recently been an intensification of the debate about positive and normative aspects of asymmetric monetary policy frameworks, both in an academic context as well as central banks' communication. Have central banks so far responded (a)symmetrically to macroeconomic conditions? And, should central banks respond (a)symmetrically to macroeconomic conditions?

In the euro area the debate on the degree of (a)symmetry of the ECB's price stability framework goes back to the early days of monetary union and has recently re-emerged. Early academic contributions are for instance Svensson (2002), who emphasizes that the ECB definition of price stability is "asymmetric", and Begg et al. (2002) stating that 2% inflation is a "ceiling" rather than a target for the ECB. More recently, Hartmann and Smets (2018) estimate policy rules for the ECB over the period 2000-2018, Rostagno et al. (2019) over the period 1999-2008 and Paloviita et al. (2021) over the period 1999-2014. They find evidence of asymmetric policy responses, but its specific form remains controversial. For instance, Hartmann and Smets (2018) find that the ECB tightened interest rates mainly in response to expected inflation above its inflation aim while it eased policy mainly in response to an expected slowdown in growth. Rostagno et al. (2019) and Paloviita et al. (2021) find more forceful reaction to inflation overshooting than undershooting of a 2% target. At the same time, the latter two papers show that this is difficult to distinguish from alternative specifications in which the policy response to inflation is symmetric around a lower inflation target.

Rostagno et al. (2019) argue that an asymmetric response to overshooting and undershooting of inflation from target may be the direct result of the ECB's quantitative approach to its price stability objective.[2] The reason is that the ECB framework featured a definition of price stability in terms of an inflation range between 0% and 2% as well as an inflation aim below but close to 2%. As the inflation aim was not in the middle of the inflation range but close to its upper edge, this may have created an asymmetry, with the ECB responding more strongly to inflation above the aim than below it.[3] They also argue that the estimated asymmetric response may have been

[2] The ECB has announced a new policy strategy on 8 July 2021.

[3] Specifically, the Treaty establishing the Economic and Monetary Union assigns to the ECB the primary objective of price stability. In 1998 the Governing Council of the ECB adopted a quantitative definition of price stability: "Price stability is defined as a year-on-year increase in the Harmonised Index of Consumer Prices (HICP) for the euro area of below 2%." In 2003 the Governing Council confirmed the definition of price stability and identified an inflation aim within the price stability range: the Governing Council "will aim to maintain inflation rates close to 2% over the medium term". In explaining this decision the ECB's Chief Economist of the time

beneficial in keeping inflation in check in the face of the prevailing inflationary pressure hitting the euro area in the first ten years of the ECB's existence (1999-2008). But they emphasize that it may have contributed to persistently low inflation when shocks turned disinflationary after the global financial crisis and the sovereign debt crisis in some euro area countries.

The ECB officially communicated for the first time in July 2019 about whether its approach is symmetric. It stated that it follows a symmetric approach around its inflation aim: "the Governing Council is determined to act, in line with its commitment to symmetry in the inflation aim" (ECB (2019)). Some statements by ECB's former President Draghi suggest that the symmetric approach may have been in place also earlier.[4] Besides the exact date in which the commitment to a symmetric approach may have started, it remains uncertain whether symmetry was intended to characterise a symmetric response to inflation above and below its aim or the desire to achieve symmetric inflation outcomes. The latter may not necessarily require a symmetric policy response to inflation.

Bianchi, Melosi and Rottner (2019) indeed point out that with a symmetric price stability objective, optimal policy in the presence of the lower bound on nominal interest rates and a low level of the natural real interest rate, r^*, calls for a specific type of asymmetric policy rule: one in which policy responds less forcefully to inflation above its target than below target.[5]

In the US, the 2012 FOMC's Statement on Longer-Run Goals and Monetary Policy Strategy referred to a "symmetric inflation goal", while the new policy framework announced in August 2020 consists of a makeup strategy defined by Vice Chair Clarida as temporary price-level targeting at the effective lower bound. He stated that "the new framework is asymmetric" (Clarida (2020a)), and explained that "In other words, the aim to achieve symmetric outcomes for inflation ... requires an asymmetric monetary policy reaction function in a low r^* world with binding ELB constraints in economic downturns" (Clarida (2020b)).

stated that: "this "close to 2%" is not a change, it is a clarification of what we have done so far, what we have achieved – namely inflation expectations remaining in a narrow range of between roughly 1.7% and 1.9% – and what we intend to do in our forward-looking monetary policy" (Issing (2003)). This continuity with past practice suggests that the period pre- and post-2003 may come from the same data generation process.

[4]In March 2016 Mario Draghi stated that "our mandate is defined as reaching an inflation rate which is close to 2% but below 2% in the medium term. [...] the Governing Council is symmetric in the definition of the objective of price stability over the medium term" (Draghi (2016b)). In June 2016 he stated that "our mandate is symmetric, and our commitment to our mandate is symmetric" (Draghi (2016a)).

[5]In contrast, in a non-linear model where the welfare problem is solved to third order, Benigno and Rossi (2021) show that a central bank should care more about high rather than low employment. The third order approximation creates a bias term in the loss function that the central bank minimises.

We contribute to the debate on the positive and normative aspects of asymmetric monetary policy by using a Markov-switching DSGE model. Our model builds on the DSGE model of Smets and Wouters (2007) but we extend it to allow for asymmetry in the policy response to macroeconomic conditions. We introduce also a second nonlinearity in order to account for the lower bound on nominal interest rates.

Our first contribution is to estimate the model on euro area and US data to assess whether over the last two decades there is evidence of nonlinearity in the ECB's and the Fed's policy response. For the ECB, we estimate the model allowing for endogenous switching of the coefficient on inflation in the policy rule depending on whether inflation is above or below target. We find that up until mid-2014 the policy response can be characterised as asymmetric by responding more strongly to inflation above 1.9% than below it. We show that such an asymmetric response to inflation can generate adverse interactions with the lower bound on nominal interest rates in a low r^* environment. When agents in the economy foresee the policy rate hitting the lower bound, they start saving in advance in order to smooth consumption through the lower bound period during which policy is not able to react. When monetary policy is asymmetric by responding less strongly to inflation below target than above target, the deflationary bias created by the lower bound is amplified. In our general equilibrium model agents are aware of the possibility of regime changes and they form expectations taking them into account. These effects on expectations arise even in a model with exogenous switching. In a general equilibrium model with endogenous switching there are two additional effects. First, symmetric shocks can produce asymmetric effects. The asymmetry arises from the differential response of the monetary authority rather than nonlinearities in the structure of the economy. Second, pre-emptive policy actions are effective, see Davig and Leeper (2006).

We also find that since mid-2014, when the ECB has started deploying a range of non-standard policy measures – which we capture by using a shadow interest rate – the ECB response is consistent with having become symmetric by responding to inflation below target as strongly as it responded to inflation above target prior to mid-2014. Our structural model allows us to provide a quantification of the macroeconomic relevance of this switch. We find that, had the ECB post-2014 kept following an asymmetric policy in line with the one estimated pre-2014, inflation over the period 2014-2019 would have been up to 20 basis points lower and the output gap up to 70 basis points lower than its actual realization.

For the Federal Reserve, we estimate the model over the last two decades allowing all policy parameters to switch and we assume that the regime switching probabilities are constant and therefore that the economy switches exogenously between two regimes. This is motivated by the observation that prior to August 2020 the Federal Reserve's monetary policy strategy and communication have not emphasized asymmetric elements in the policy reaction. Therefore, we take an agnostic approach, and we let the regime switches be constant and not dependent on any endogenous variables. We find evidence of asymmetric policy response, but of a different nature compared to the euro area. The response to inflation and output is higher in a regime that appears correlated with high financial stress. This suggests that the Fed has responded to deteriorating financial conditions over and above macroeconomic conditions.

Our second contribution is to quantify the optimal degree of policy asymmetry in response to macroeconomic conditions using the estimated model for the euro area and the one for the US. We assume a symmetric price stability objective and include the lower bound on nominal interest rates. Due to the lower bound, when the steady state level of the interest rate is low as in our exercise, monetary policy may not entirely counter disinflationary shocks with its policy rate. As a result, average inflation may be below the inflation target. We find that in such an environment the central bank should adopt an asymmetric response by responding less forcefully to inflation above target than below target. This type of inversely asymmetric policy rule is analysed also by Bianchi, Melosi and Rottner (2019), who arrive at similar conclusions in a calibrated model. We contribute to this literature by providing a quantification of the optimised response to inflation, the output gap and the policy-rule persistence parameter depending on whether inflation is above or below target using a fully estimated model.

Our final contribution is to run counterfactual simulations to assess how over the last two decades the euro area and US economies would have performed had the central bank in those countries followed the optimal asymmetric policy response that we have derived: In both the euro area and the US, inflation and the output gap would have been better stabilised. For the euro area, we find that inflation would have been about 30 basis points higher after the 2008 crisis, while the output gap would have closed more quickly. For the US, we find that inflation would have been slightly higher after the burst of the dot-com bubble, and around 30-40 basis points higher after the global financial crisis. The output gap would have been better stabilised, falling only to around -2% during the global financial crisis.

The paper is organised as follows. In Section 2, we present the model and the regime switching monetary policy. In Sections 3, we present the estimation method and the data. In Section 4, we present the estimation results for the euro area and assess the macroeconomic implications of the estimated asymmetric policy response. We also derive optimal policy for the euro area. In Section 5, we present the estimation results for the US and we derive optimal policy for the US. In the last section we offer conclusions.

2 Model

The model builds on Smets and Wouters (2007) and follows their notation where applicable (abbreviated as SW07 in the remainder). We make three main modifications to the original SW07. First, we add a permanent technology shock. Second, we modify the modelling of monetary policy. Third, we make some modifications in the estimation. We describe these in turn. We include a permanent technology shock in order to construct the policy-relevant output gap as the difference between output and its stochastic trend. We regard this as a better description of actual monetary policy compared to the SW07 formulation in terms of flexible-price output gap.[6] Adding a unit root technology shock, Z_t, the production function becomes:

$$Y_t = A_t(K_t^s(i))^{\alpha}(Z_t L_t(i))^{1-\alpha} - Z_t \Phi \tag{1}$$

The labour augmenting technology follows the process below:

$$log(Z_t/Z_{t-1}) = g_{z,t} = \rho_{g_z} g_{z,t-1} + \eta_t^{g_z} \tag{2}$$

with $g_{z,t}$ being the growth rate of permanent technology.

The economy grows at the growth rate of permanent technology in steady state. In order to ensure a balanced growth path, we detrend all real variables in the model by the technology trend, Z_t. Potential output in the model grows at the rate of technological growth. Therefore, the measure of potential output in the model is Z_t. The detrended output is then the measure of the output gap $Y_t/Z_t = y_t$

[6] A flexible-price output gap tends to be more volatile than output gaps estimated by central banks. Since the central bank's response in the model depends on the output gap, it is important to measure it in a way that is consistent with central bank's view. For a longer discussion about different types of output gaps, see Adolfson et al. (2011). In the estimation we consider the output gap as an observable variable.

The full model equations are described in Appendix A.

2.1 Monetary policy

Monetary policy is set according to an otherwise standard policy rule but we deviate from SW07 by allowing some of the coefficients to switch between two regimes, as explained below. Formally, the policy rule in its general form is:

$$r_t = \rho^m(S)(r_{t-1}) + (1 - \rho^m(S)) \left[\phi_\pi(S)(\pi_t - \bar{\pi}) + \phi_y(S)(y_t)\right] + \sigma^m(S)\varepsilon_t^i. \tag{3}$$

where y_t is the trend output gap and S denotes the regime.

In some of the policy simulations we carry out with our estimated model we add a neutral rate and the lower bound on nominal interest rates to study their interactions with asymmetric inflation targeting. The nominal neutral rate is implemented as an intercept, r_t^*, in the policy rule, and it is shown in Equation 4.[7] This ensures that the policy rate on average equals the neutral rate. The neutral rate process itself if written as in Holston, Laubach and Williams (2016) to depend on the trend growth rate and an idiosyncratic shock. Given that the structural equations of the model are written as deviations from the steady state, we simply replace any appearances of the policy rate by the gap between the policy rate and the neutral rate. In the simulations that are done for a specific level of the neutral rate, we shock the neutral rate process such that it falls to the assumed level, then set $\rho^{m*} = 1$ and $\gamma_{ga} = 0$ such that the neutral rate stays at this level through the simulation.[8] In the simulations in which we include a lower bound, the policy rate equation will be drawn for a shadow rate indicated below as r_t^{rule}. The actual policy rate will be equal to the shadow rate until it reaches the effective lower bound (indicated with elb in Equation 4).

$$\begin{aligned}
r_t^{rule} - r_t^* &= \rho^m(S)(r_{t-1}^{rule} - r_{t-1}^*) + (1 - \rho^m(S)) \left[\phi_\pi(S)(\pi_t - \bar{\pi}) + \phi_y(S)(y_t)\right] + \sigma^m(S)\varepsilon_t^m \\
r_t &= max(elb, r_t^{rule}) \\
r_t^* &= \rho^{m^*} r_{t-1}^* + \gamma_{ga} * g_{z,t} + \sigma^{m*}\varepsilon_t^{m*}
\end{aligned} \tag{4}$$

[7] Corbo and Strid (2020) model the nominal neutral rate as a time-varying intercept in the policy rule.
[8] Otherwise the simulation results would be affected by the fluctuating neutral rate.

2.2 Measurement equations

The measurement equations are similar to SW07 with the exception that they now reflect the presence of the permanent technology shock. Additionally, we consider the trend output gap as an observable in order to capture as closely as possible the measure of the output gap that policymakers may consider relevant for their policy decisions. In order to be able to add this additional observed variable and avoid stochastic singularity, we add a measurement error to the measurement equation of the output gap. Nominal variables are not affected by the trend growth. All measurement equations are listed below.

$$\begin{aligned}
dc_t^{obs} &= c_t - c_{t-1} + g_{z,t} + g_z^* \\
di_t^{obs} &= i_t - i_{t-1} + g_{z,t} + g_z^* \\
dy_t^{obs} &= y_t - y_{t-1} + g_{z,t} + g_z^* \\
dw_t^{obs} &= w_t - w_{t-1} + g_{z,t} + g_z^* \\
y_t^{obs} &= y + \sigma^y \varepsilon_t^y \\
pi_t^{obs} &= \pi_t + \bar{\pi} \\
l_t^{obs} &= l_t + \bar{l} \\
r_t^{obs} &= r_t + \bar{r}
\end{aligned}$$

2.3 Regime switching

We assume that there are two regimes in which the policy parameters are allowed to differ. We consider two types of processes for the switching parameters: constant probabilities where the switching between the regimes is exogenous, and time-varying probabilities where the probability of switching is endogenous to the level of inflation.

In the constant probability model the economy switches to another regime with probabilities that are exogenous and whose value is estimated.

In the time-varying probability model we define the two regimes by high (above target) and low (below target) inflation. The central bank's response to the deviation of inflation from target is stronger in the high inflation regime than in the low inflation regime. This is implemented by restricting the coefficient on inflation in the policy rule in the high inflation regime to be larger than in the low inflation regime. This assumption is not very restrictive because the difference in the response coefficients in the two regimes can be arbitrarily small. Switching between the two regimes is endogenous in that it depends on the deviation of annual inflation from the inflation target, with inflation itself being an endogenous variable in the model. When the annual rate of inflation is high relative to the target, the probability of switching to the high inflation regime increases. Vice versa, when the annual inflation rate is below the aim, the probability of switching to the low inflation regime increases.

Endogenous switching is characterized by:

$$\begin{aligned} P(S_1, S_2) &= 1 - \frac{1}{1 + e^{c_{1,2}(\pi_t^4 - \bar{\pi} - a_1)}} \\ P(S_2, S_1) &= \frac{1}{1 + e^{c_{2,1}(\pi_t^4 - \bar{\pi} - a_2)}} \end{aligned} \tag{5}$$

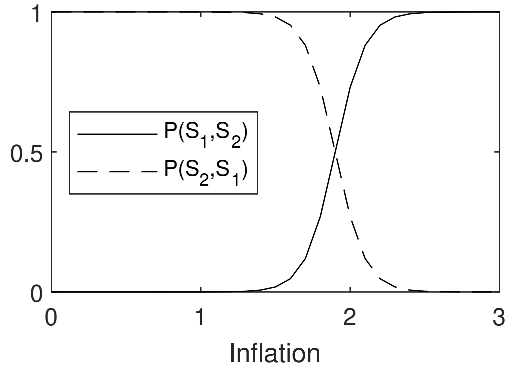
where $\pi_t^4 = \pi_t - \pi_{t-4}$, and $P(S_1, S_2)$ is the probability of switching from the low to the high inflation regime, and $P(S_2, S_1)$ is the probability of switching from the high to the low inflation regime. The adjustment factors c_1, c_2 govern the strength of the relationship between the probability and observed inflation relative to the threshold, while the parameters a_1, a_2 set the exact threshold at which the switch occurs. The probability of staying in each regime is the probability of not switching and can be calculated as the residual from the above equations.

The probabilities of switching are illustrated in Figure 1 below. The probability of switching from low response state to the high response state $P(S_1, S_2)$ is low when inflation is below the target. As inflation increases closer to the target of 1.9% in this example, the probability increases and reaches close to 1 when inflation is above the target. The probability of switching from high response state to the low response state $P(S_2, S_1)$ declines as inflation rises above the target.

In Section 4.3 we add a third regime, the ELB regime.[9] In that case, the switching proba-

[9]There are alternative ways to model the ELB regime in the literature. Guerrieri and Iacoviello (2015) for example propose a piece-wise linear method for implementing the ELB. Given the linearity of each state of the interest rate, there are no precautionary effects arising from the ELB. Instead, when the ELB is modelled as a

Figure 1: Probabilities of endogenous switching



bilities related to the asymmetric response to inflation are defined in the set of Equations 6.[10] The probabilities of moving from regime 1, which is defined by inflation below target, to regime 2, which is defined by inflation above target, remain as above except that additionally the probability of being at the lower bound is low. The probability of being at a lower bound depends on the deviation of the shadow interest rate, r_t^{rule}, from the lower bound, *elb*.

$$
\begin{aligned}
P(S_1, S_2) &= \frac{1}{exp(c_3(elb - r_t^{rule}))}\left[1 - \frac{1}{1 + exp(c_1(\pi_t^4 - \bar{\pi}))}\right] \\
P(S_2, S_1) &= \frac{1}{exp(c_3(elb - r_t^{rule}))}\left[\frac{1}{1 + exp(c_2(\pi_t^4 - \bar{\pi}))}\right] \\
P(S_1, S_3) &= 1 - \frac{1}{exp(c_3(elb - r_t^{rule}))} \\
P(S_2, S_3) &= 1 - \frac{1}{exp(c_3(elb - r_t^{rule}))} \\
P(S_3, S_2) &= \frac{1}{exp(c_3(elb - r_t^{rule}))}\left[1 - \frac{1}{1 + exp(c_1(\pi_t^4 - \bar{\pi}))}\right] \\
P(S_3, S_1) &= \frac{1}{exp(c_3(elb - r_t^{rule}))}\left[\frac{1}{1 + exp(c_2(\pi_t^4 - \bar{\pi}))}\right]
\end{aligned} \tag{6}
$$

3 Markov-switching estimation

The Markov-switching structure of the model makes the solution methods typically used for constant parameter DSGEs unsuitable. This is due to agents in our model having to take into

separate regime, the probability of hitting the ELB in the future is taken into account in the solution.

[10] In simulation exercises carried out in Section 4.3 we set for simplicity parameters a_1, a_2 to zero and hence do not show them in the equations here.

consideration the expectations of all states of the world in all regimes and not just the current one. The model is solved with a Newton algorithm, developed by Maih (2015). It is a more stable and more general algorithm than for example the method developed for linearised models by Farmer, Waggoner and Zha (2011).

The Markov-switching structure implies also that in the estimation we cannot use the standard Kalman filter. Due to the non-linearity of the solution, we use an approximate filter combining steps of the Kalman filter, the Hamilton filter, and the collapsing of regimes so as to keep the filtering and the computation of the likelihood tractable. This likelihood is then combined with the priors to form the posterior kernel, which we optimise to find the mode. Such filtering procedures were brought to the economics literature by Kim and Nelson (1999), but have long been used in the engineering literature, see for instance Bar-Shalom et al. (2002).

In order to optimise the posterior kernel, we start by running an "Artificial Bee Colony" algorithm developed by Karaboga and Basturk (2007). The Artificial Bee Colony (ABC) approach is an efficient constrained optimisation procedure that is able to swarm large areas with a lower probability of being stuck at local minima. For standard optimisers it is difficult to optimise a surface with multiple local peaks. The ABC algorithm, which is a derivative-free optimisation approach that mimics the behaviour of bee colonies, helps circumvent this problem.

After running the ABC optimisation, we use the optimised parameters as initial values in a more standard fmincon routine to get an estimate of a posterior mode. The ABC routine is thorough, but also time consuming and we run it for approximately 24 hours before turning to the fmincon routine. With the optimised starting values from the ABC routine, the fmincon runs smoothly without evidence of local minima.

3.1 Data

We estimate the euro area model using data from 1999Q1 to 2014Q2. The choice of the end of the sample is motivated by the fact that in June 2014 the ECB started adopting negative rates and other unconventional policy tools, as well as emphasising concerns about low inflation, which may suggest a shift towards a more symmetric behaviour. We will test whether there is evidence of such a shift. All variables except for the output gap and population growth come from the Area Wide Model (AWM) database (Fagan et al., 2001). The output gap is computed using the European Commission's estimate (AMECO) of potential output. The series is annual. In order to produce a quarterly series, we first derive potential output from the AMECO output gap by using the AWM output. The series for potential output we have derived is then interpolated to quarterly frequency using a cubic spline method. We then recompute the quarterly output gap series using the quarterly output and quarterly interpolated potential output series. Data referring to the real variables in the aggregate economy (GDP, consumption, and investment) are adjusted by population growth. Population growth is the share of those over 15 years of age and comes from Eurostat.

The US estimation uses the Smets and Wouters (2007) dataset extended by the authors. The sample runs from 1990Q1 to 2019Q2. From the time the Fed reached the lower bound on the policy rate in 2008, we use the shadow rate of De Rezende and Ristiniemi (2018) in place of the policy rate in the estimation. The shadow rate is equal to the Fed Funds Rate in the pre-2008 periods as there were no unconventional monetary policy measures in place before that. The other data are from Smets and Wouters (2007) extended to 2019Q2. The output gap is computed as a difference between BEA output and US Congressional Budget Office potential GDP.[11]

3.2 Parameters

The calibrated parameters are shown in Table 1. The inflation aim is set at 1.9% for the EA and 2.0% for the US annually. The measurement error on the output gap is calibrated to 10% of the standard deviation of the series for both US and EA. For the EA, the discount rate is set at 0.16 implying a discount factor of 0.998. For the US we estimate the discount rate. The remaining calibrated parameters that are in common with Smets and Wouters (2007) are taken from there. We have set slope parameters of the switching probabilities to fairly standard values that allow switching around the inflation level of 1.9%.

The priors are mostly standard, see Table 5 in Appendix 3.2. However, we use lower and upper ranges for the regime switching inflation and output gap responses, as well as for the monetary policy shock volatility in the Taylor rule. Given a probability of the estimated values being in that range, which we set at 90%, the prior distributions can be computed.

[11] FRED code GDPC1_GDPPOT.

Table 1: Calibrated parameters

Parameter description	Calibration value EA	US
Steady state inflation rate (quarterly)	0.475	0.5
Capital depreciation rate	0.025	0.025
Gross mark-up on wages	1.3	1.3
Share of government spending in output	0.18	0.18
Curvature of Kimball aggregator for wages	10	10
Curvature of Kimball aggregator for prices	10	10
Discount rate	0.16	
Measurement error of standard deviation of the output gap	0.164	0.207
c_1	1	
c_2	1	

4 Asymmetric monetary policy in the euro area

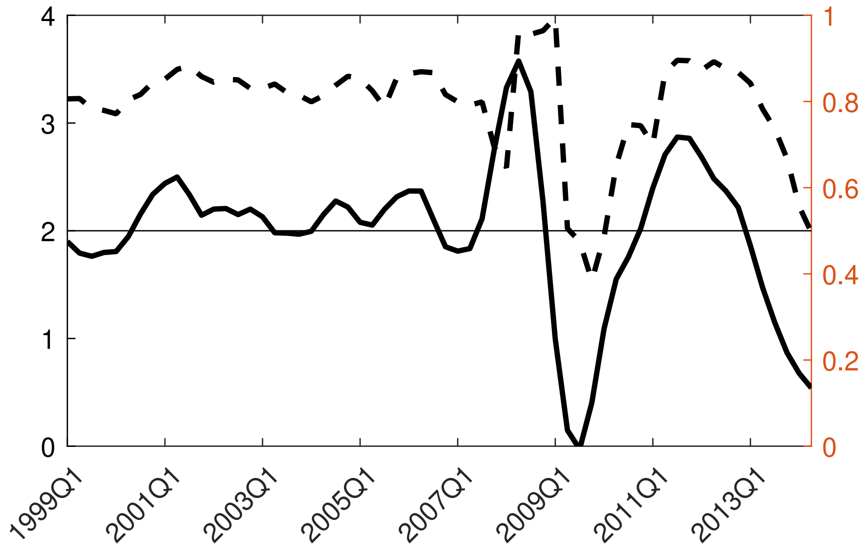
As described above, for the euro area we aim to assess whether the policy response to inflation has been lower when inflation has been below the target than when inflation has been above the target. For this reason we estimate an endogenously switching model where only the coefficient on inflation in the policy rule is allowed to switch between the two regimes.

The estimation finds support for a different inflation response in the two regimes. The posterior mode estimates are shown in Table 5 in the Appendix. The inflation coefficient in regime 1 (low inflation) is 1.28 compared to 1.75 in regime 2 (high inflation). This suggests that over the estimation sample 1999Q1-2014Q2 the ECB has responded less strongly to inflation deviations when inflation has been below the target.

The values of the other parameters are broadly in line with estimates found in analyses for the euro area available in the literature.

Filtering the model through the estimation period allows us to compute the smoothed probabilities of residing in each regime. Figure 2 displays the probability of regime 2 (high inflation regime) along with annual inflation. Since the probability of switching depends on annual inflation, we expect to see a strong relationship between the probability of residing in a regime and the level of inflation, which is indeed the case. When inflation is high, the probability of being in the high inflation regime is also high. Before the Global Financial Crisis the probability of regime 2 has been high. Since the crisis, inflation has fluctuated more strongly and we see periods where the probability has fallen significantly.

Figure 2: Inflation and regime 2 probability



Note: Annual inflation (solid, LHS), smoothed probability of regime 2 (dashed, RHS). The regime switching is endogenous and depends on the level of inflation.

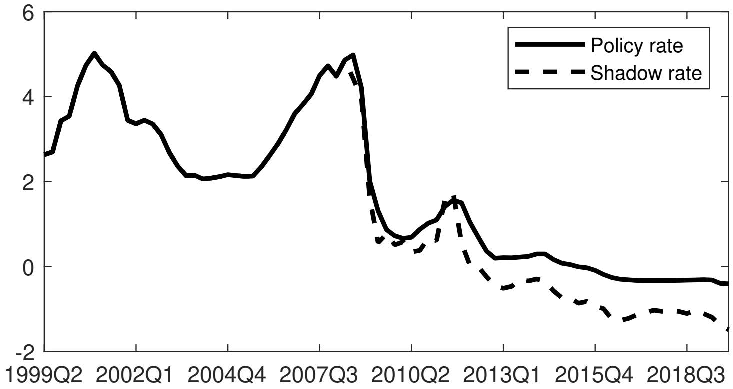
4.1 Implications of symmetric reaction post-2014

Our estimation sample for the euro area ends in 2014Q2. We test whether it is more likely that the ECB policy has continued to behave asymmetrically since then or whether it has changed to a more symmetric strategy. We compare the asymmetric model to a symmetric model that we construct by taking the estimated asymmetric model and changing the inflation response in the low inflation state to be the same as in the high inflation state. As inflation has been below target after 2014, historical regularities would suggest that we should find that the ECB response to inflation has been weak. But if the ECB has changed its approach and become more symmetric by responding more strongly to low inflation (as some statements by ECB's former President Draghi may suggest) we should find support for the strong inflation response.

One challenge in this assessment is that from mid-2014 onward the ECB's response has mainly taken the form of non-standard measures. To account for this we replace the policy rate with the shadow rate, displayed in Figure 3. We use the measure of the shadow rate constructed by De Rezende and Ristiniemi (2018)[12].

[12] The reason for using this measure is that it does not require specifying a lower bound. The ECB has reduced short-term rates throughout this period and it is therefore difficult to set a lower bound as other shadow rate

Figure 3: Euro area shadow rate and policy rate



Note: Shadow rate (dashed), policy rate (solid). Both are annualised.

We filter the two linear models, one with the low inflation response when inflation is low and one with the high inflation response when inflation is low, and compare the log-likelihood of each model to judge which model is more likely. The log-likelihood of the high inflation-response model is higher at 234.2 compared to the log-likelihood of the low inflation-response model at 231.6. This suggests that the ECB has responded more strongly to disinflationary shocks over this period compared to what would have been suggested by historical regularities. It also suggests that the ECB policy has become symmetric since mid-2014. Paloviita et al. (2021), using a single-equation approach based on estimating a policy rule, similarly finds evidence of a more symmetric response since 2014.

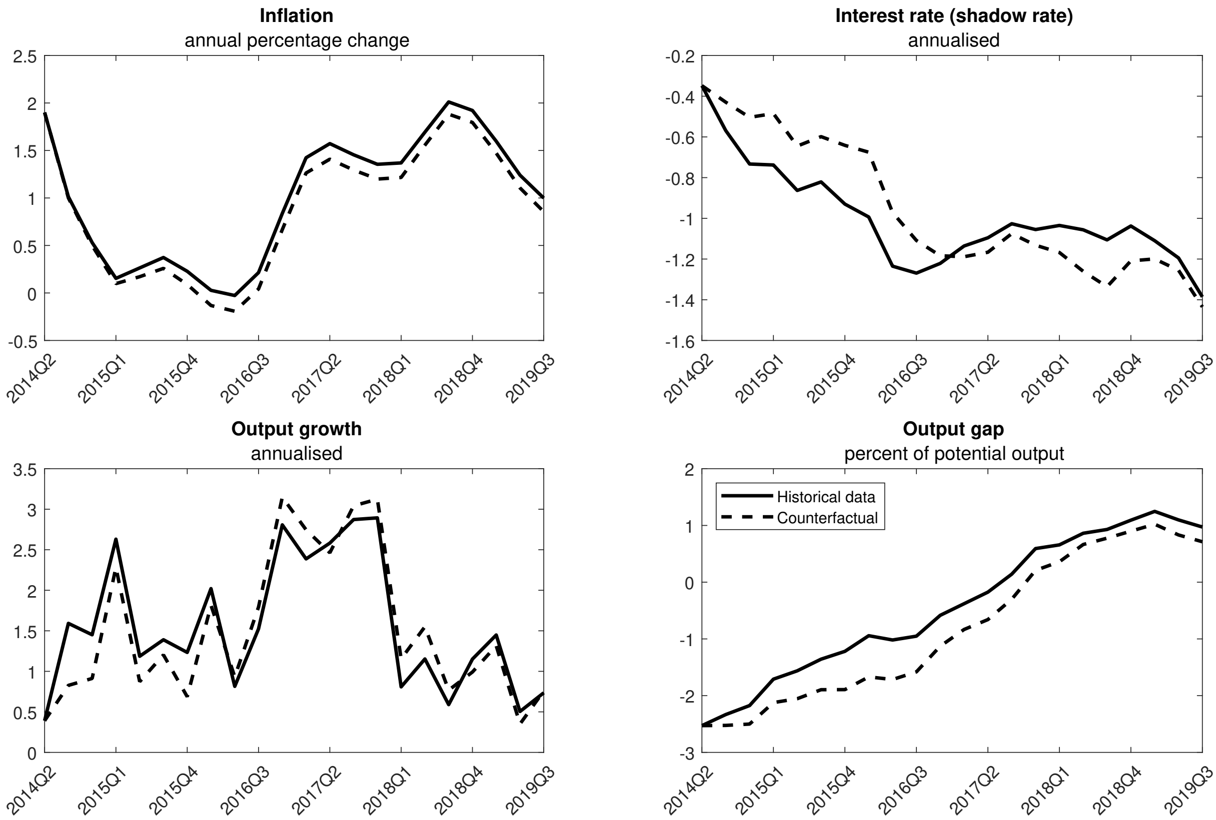
To assess the macroeconomic implications of having adopted a symmetric response, we construct a counterfactual in which we assume that the ECB kept following the asymmetric policy rule estimated over the pre-2014 period. Figure 4 shows the results. The solid line is the smoothed variable based on the high inflation response regime. We then recover the underlying structural shocks and run a counterfactual using the same shocks and imposing the low inflation response coefficient estimated pre-2014 for the low inflation regime. The counterfactual is the dashed line in the figure.

The counterfactual simulation provides evidence that the adoption of a symmetric response since 2014 has resulted in a lower policy rate (up to 32bps, see top right panel), and less sluggish output growth especially at the beginning of the period (bottom left). Had the ECB not adopted

models require

a symmetric approach, the output gap would have been up to 72bps more negative and inflation would have been even lower than it was in reality, with a difference by up to 17 basis points (top left).

Figure 4: Counterfactual exercise



Note: Counterfactual is a simulation of the low inflation model, conditional on shocks filtered from the high inflation model.

4.2 Asymmetric inflation targeting and lower bound on nominal interest rates

The macroeconomic implications of the estimated asymmetric response over the pre-2014 period whereby the reaction to inflation is lower when it is below the target than when is above the target should be expected to become especially consequential in the presence of the lower bound on nominal interest rates. The reason is that the lower bound creates in itself an asymmetry even in the presence of an otherwise symmetric response coefficient to inflation. In the presence of the lower bound the central bank cannot respond freely to negative shocks, hence inflation remains below target. Once inflation recovers, a central bank that follows an inflation targeting approach responds by lifting the interest rate. In face of inflationary shocks instead the central bank can effectively stabilise inflation. Therefore, over the longer term, and even in the presence of symmetric shocks, average inflation will display a negative bias (see for instance Kiley and Roberts (2017)). An asymmetric policy rule should be expected to aggravate this problem. The reason is that, when inflation is below its target, the central bank responds less forcefully, leading to more frequent and more protracted lower bound episodes, and thus to lower inflation outcomes. Hence, the switch to stronger policy response to inflation once inflation is above target should lead to a larger deflationary bias when the lower bound is coupled with the asymmetric policy response estimated pre-2014.

To analyse the interaction between the asymmetry coming from the lower bound and the one from the asymmetric response to inflation, we make three modifications to our estimated model, and we draw generalised impulse response functions to a sequence of adverse risk premium shocks. The first modification is to introduce the lower bound as described in section 2. We set the lower bound on the policy rate at -1%, the level at which Darracq Pariès et al. (2020) estimate the reversal rate to be. The second modification is to lower the level of the neutral interest rate to 0.25, which is consistent with the current level of neutral rate according to recent estimates for the euro area by Brand and Mazelis (2019) and brings the frequency of hitting the lower bound into alignment with the literature on the lower bound.

We assume that adverse risk premium shocks of 1.5 times their standard deviation hit the economy for four periods. Given that we draw only one illustrative IRF per model specification, we set the parameters in the switching probabilities in a way that it ensures that the switching happens very close to the inflation target. This ensures that the effects of the lower bound and of the asymmetric inflation response can be easily distinguished.[13]

The generalised impulse response functions are shown in Figure 5. We implement the lower bound on interest rates by applying positive monetary policy shocks of the size needed to bring the interest rate back to the lower bound. We consider two cases: one in which agents in the economy are aware that the policy rate might hit the lower bound, and another where agents are unaware of the lower bound. The first case is implemented via anticipated monetary policy shocks, and the second via unanticipated monetary policy shocks. Following the adverse risk premium shocks, the interest rate in the case where the lower bound is not anticipated (red line) falls initially at the same rate as in the case without the lower bound (blue line). In this case there is no anticipation effect arising from the possibility that the central bank will have to keep the interest higher than the policy rule would prescribe. However, the interest rate falls faster in the case where agents anticipate the lower bound and start saving in order to smooth consumption through the lower bound episode (yellow and purple lines).

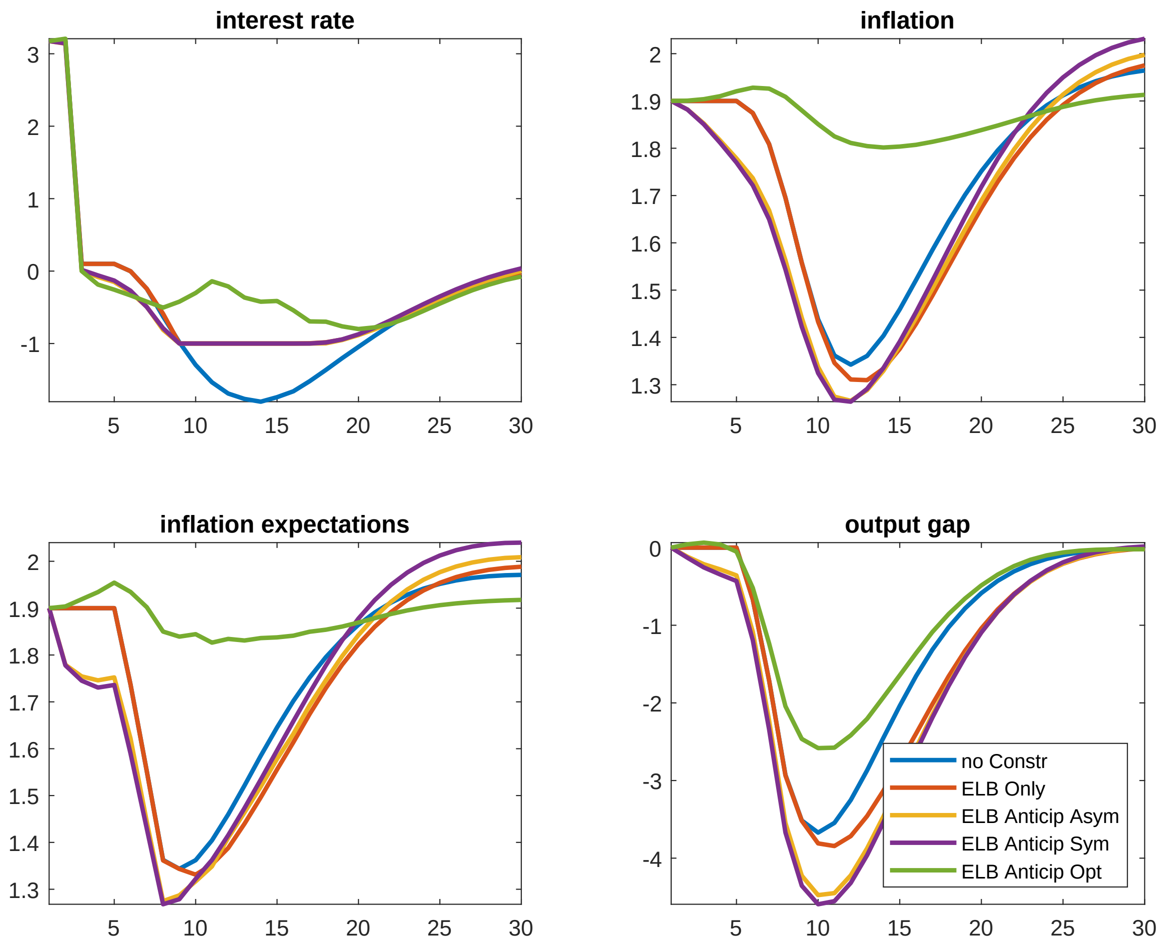
The top right panel and the bottom left panel of Figure 5 show annual inflation at time t and four quarters ahead, respectively. It shows that inflation falls more strongly (yellow and purple lines) when agents anticipate the lower bound because they start reducing consumption even before the lower bound episode begins. The different response between the anticipated and unanticipated lower bound persists also once the interest rate hits the lower bound even if at that point also the agents who did not anticipate the lower bound are confronted with it and start reducing consumption. When agents do not anticipate the lower bound, inflation falls by less even at the trough (red line).

Assuming an asymmetric response to inflation, the destabilising effect of the lower bound becomes stronger, as shown by comparing the asymmetry case (yellow line) to the symmetric case (purple line). In the asymmetric case, the response to inflation is weak when inflation is low, while it becomes stronger as inflation reaches the target.[14] The green line represents optimal policy and it is discussed in the next section.

[13] We set $c_1 = 55, c_2 = 57, a_1 = -0.05, a_2 = 0.05$.

[14] Erceg et al. (2021) simulate a DSGE Model estimated for Euro Area with a calibrated asymmetric policy function to show that when the response to inflation is higher for inflation above the target, inflation and output gap are 30bp and 1.5pp lower on average respectively compared to a symmetric rule.

Figure 5: GIRFs to a risk shock



Note: Blue - no ELB constraint, no asymmetry. Orange - ELB, no asymmetry. Yellow - ELB is anticipated, asymmetry. Purple - ELB is anticipated, symmetry. Green - ELB is anticipated, optimised policy rule parameters. Inflation and inflation expectations annual percentage change, interest rate annualised, output gap level.

4.3 Optimising monetary policy parameters in the two regimes

Given the model and the regime switching probabilities that depend on inflation, we compute the optimal policy response in each of the two regimes. To abstract from negative rates, which may trigger side effects that are not captured in our analysis of optimal monetary policy, we set the lower bound at 0%. We set the neutral nominal rate at 3%.[15]

In order to find the optimal parameters, we simulate 5000 quarters of data for different policy rule parameter values. For each of the simulation results we discard the first 50 quarters

[15]The parameters determining the switching probabilities are set to $c_1 = 10, c_2 = 10, c_3 = 30$. These values are chosen to ensure that the lower bound binds.

Table 2: Prior distributions and posterior estimates for the optimised simple rule

	Lower quartile	Upper quartile	Distribution	Optimal
$^{\pi}(S_1)$	2	10	Gamma	6.34
$^{\pi}(S_2)$	1	7	Gamma	2.38
$^{y}(S_1)$	0.1	4	Gamma	0.95
$^{y}(S_2)$	0.1	4	Gamma	0.19
$\rho^m(S_1)$	0.6	0.95	Beta	0.72
$\rho^m(S_2)$	0.6	0.95	Beta	0.86

Note: Quartiles show a 90% probability range.

as burn-in and then compute root mean squared deviations of annual inflation, π_t^4 and output gap, y_t from their targets, as well as squared differences in the annualised policy rate, $r_t - r_{t-1}$. These values are used to minimise the standard quadratic loss function with smoothing below.[16]

$$Loss_t = RMSD(\pi_t^4)^2 + 0.25RMSD(y_t)^2 + (r_t - r_{t-1})^2 \tag{7}$$

The optimisation algorithm we use is the ABC algorithm. In order to discipline the optimisation, we set priors that penalise the log of the loss. Specifically, we set upper and lower bounds and the probability at which the parameters should be found within the bounds. We set the probability at 90%. The priors are shown in Table 2. The 90% ranges for the priors are fairly wide and have the same values in the two regimes except for inflation, where however the bounds overlap for almost all of the range. We set a gamma distribution on all but the persistence parameters as the inflation and output gap responses should be positive while we use a beta distribution for the interest rate smoothing so that the parameters is restricted to lie within (0,1).

The last column of Table 2 shows the optimised coefficients. In regime 1, which is characterised by below-target inflation, the optimal response prescribes a larger response to both inflation and output gap compared to regime 2, which is characterised by above-target inflation. The optimised interest rate smoothing parameter is lower in the regime associated with low inflation. This somewhat counters the larger inflation and output gap responses but only

[16]The loss function weights are standard and equivalent to equal weights on inflation, unemployment rate through Okun's law, and on the smoothing term. With a weight of 1 on the unemployment rate, by Okun's law the weight on the output gap becomes 0.5. Squaring the term results in a weight of 0.25 on the output gap. See Kiley and Roberts (2017).

marginally, as the smoothing parameter is fairly similar across the two regimes.

The implications of adopting the asymmetric policy rule with the optimised coefficients is shown with the green line in Figure 5. We use the same sequence of adverse risk premium shocks implemented in Section 4.2.[17] Inflation now barely falls below the target. The output gap, although it turns negative, falls by less than in the case in which the central bank follows the estimated rule. Interestingly, the interest rate does not hit the lower bound, as expectations of a strong policy response to negative shocks to inflation and output gap help alleviate the effect of the shocks.

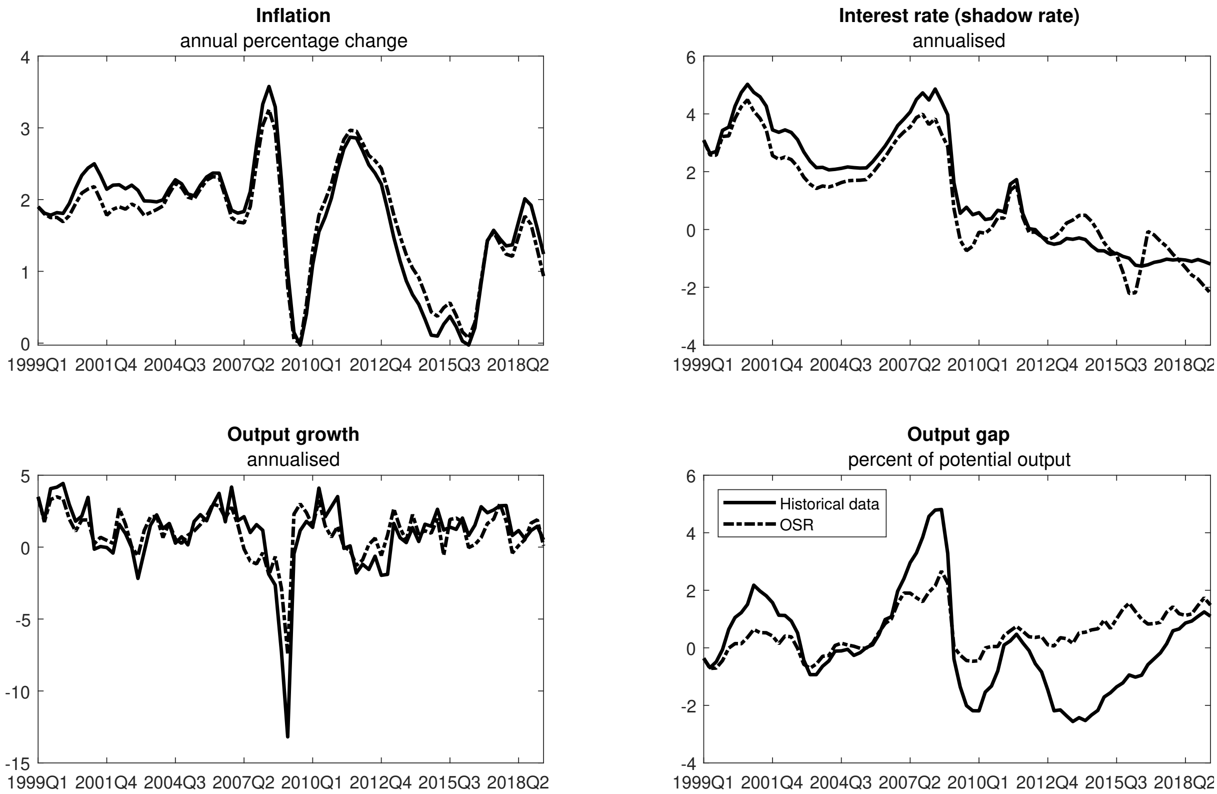
Given the optimised coefficients, we run a counterfactual where we quantify the macroeconomic implications had the ECB's policy rule been calibrated to the optimised coefficients. We use data from 1999Q1 to 2019Q2. In a first step, we filter the estimated model and save the shock series. In a second step we run the model using the optimal policy rule coefficients conditional on the shocks derived in the first step.[18]

The counterfactual is shown in Figure 6. In 2000-2002, when inflation was above the 2% target, the counterfactual shows that inflation would have been instead closer to target. After 2012, when inflation started moving significantly below 2%, the counterfactual shows that inflation would have been around 30 basis points higher, while the output gap would have become mostly positive. It should be noted that inflation post-2012 remains significantly below 2% also in the counterfactual. This is largely explained by the shocks prevailing at the time, as filtered by the model in the first step described above, and the flatness of the Phillips curve, which implies that in the counterfactual the policy accommodation exerts strong impact on the output gap but relatively little effect on inflation. Therefore, additional accommodation to bring inflation higher so as to be closer to its target would have implied even larger and more positive output gap, which is penalised by the optimised policy rule.

[17] In this case because the shadow interest rate is close to the lower bound, and we do not condition on the regime, there is some uncertainty about which regime takes place at each point in time across the different draws. For this reason, we simulate the adverse shock series 100 times and display the mean of the outcomes.

[18] Due to uncertainty in the regime switching series, we run the second step a hundred times and take the mean of the outcomes.

Figure 6: Counterfactual with optimised policy coefficients, EA



Note: The OSR counterfactual for the euro area is constructed by simulating the model with optimised coefficients given the true shocks filtered in the estimated model.

5 Uncovering regime switches in US monetary policy

The Federal Reserve's monetary policy strategy and communication over the last thirty years (up until August 2020) have not emphasized asymmetric elements in the policy reaction. Therefore, differently from the EA model, we take an agnostic approach rather than focusing on a possible switch in the policy response to inflation. We allow all policy parameters to switch and assume that the regime switching probabilities are constant and the economy switches exogenously between two regimes. Regime 1 is characterised by lower inflation and lower output response compared to regime 2 by assumption. But we leave the estimation free to decide how large the difference is across the two regimes and what explains it. Therefore, this assumption is not very restrictive as the estimation could deliver that the difference in the response coefficients across the two regimes is arbitrarily small. We do not place any restriction on the policy persistence and the monetary policy shock volatility across the two regimes, but they are allowed to switch.

We set an uninformative prior centered at 0.5 for the probability of switching from regime 1 to 2 as well as for the probability of switching from regime 2 to 1. The other priors are fairly similar to the ones for the EA model, except that we estimate the discount rate and set the priors of trend growth and hours closer to their means. The priors and posterior estimates are shown in Table 5 in the Appendix.

The estimation uncovers some differences in the monetary policy response across the two regimes. Looking at the last column of Table 5, which displays the posterior mode estimates of the US model, we see that the inflation response is lower in regime 1, while the output response is similar across the two regimes. The persistence of the monetary policy shock is higher in regime 1, compensating somewhat for the fact that the inflation response in that regime is lower. The policy shock volatility in regime 1 is lower than in regime 2.[19]

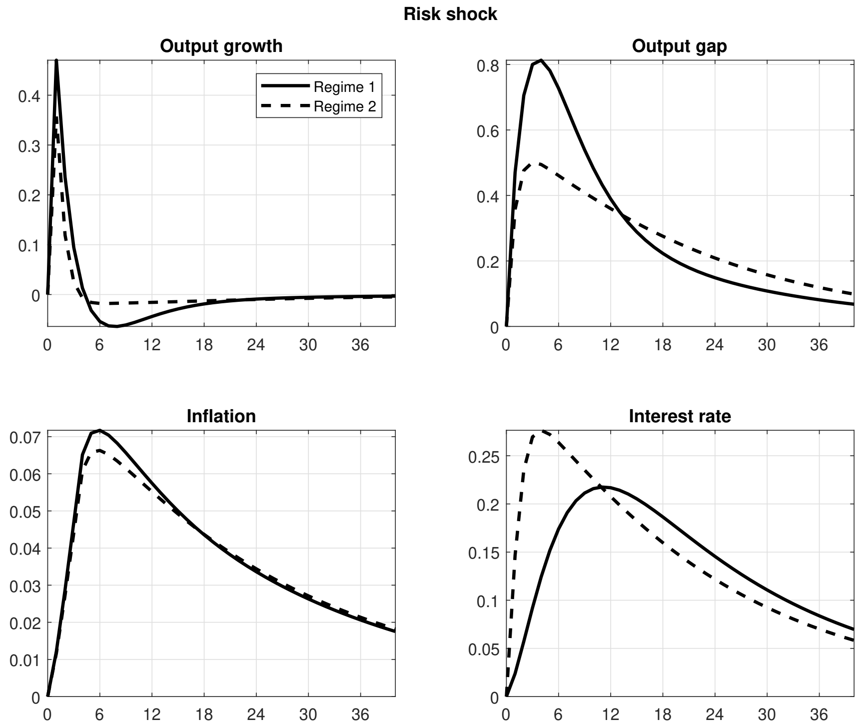
Figure 7 shows impulse response functions to an adverse risk premium shock. Monetary policy responds less strongly to inflation in regime 1 than in regime 2. Although the response is more persistent, this is not sufficient to compensate for the lower response to inflation, and as a result inflation and the output gap rise by more in regime 1. Table 5 shows also the estimated switching probabilities. The probability of switching from regime 1 to 2, $P(S_1, S_2)$ is low at 0.16, while the probability of switching from regime 2 to 1, $P(S_2, S_1)$ is high at 0.81. Therefore, the economy spends more time in regime 1, which is the low response regime. There are only some rare periods in which there is a switch to regime 2 with stronger monetary policy response.

To shed light on the possible drivers of the policy switches, we plot in Figure 8 the probability of the high response regime (regime 2, dashed line) and inflation (solid line). It shows that the probability of the high response regime (regime 2) has been low at around 5% throughout most of the sample. However, there are times when the probability rises to close to 100%. Looking at the dates at which the switches occurred we can see that those are times of financial distress. The specific events are the burst of the dot.com bubble, the 2008 crisis, and the Taper Tantrum episode.

In order to further understand the drivers of the switching episodes, in Table 3 we show the correlations of the regime 2 (high response) probability with the shocks in the model. We find

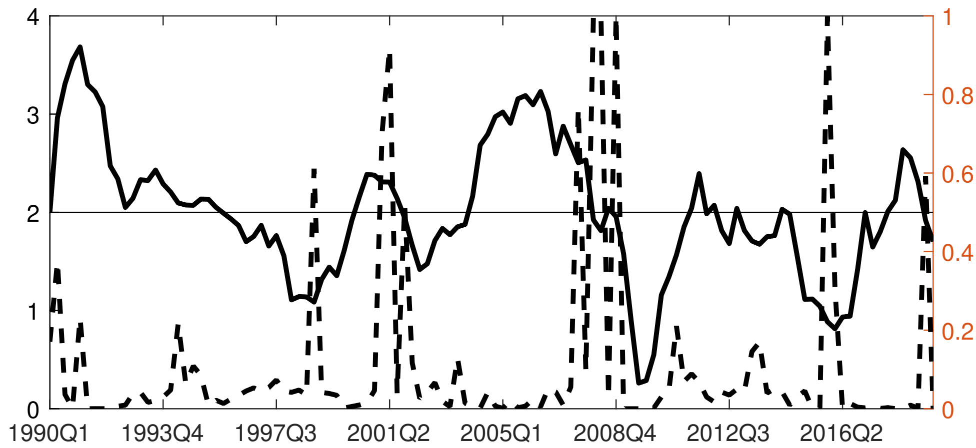
[19] Sims and Zha (2006) estimate structural VARs for the US for 1951Q1 to 2003Q3 and find that in this period, the best fitting model is the one that allows for switching only in the volatility of the policy shock, rather than any of the structural parameters.

Figure 7: IRFs to a risk premium shock in the US



Note: Output growth and interest rate are annualised, inflation is in annual percentage change while the output gap is a percentage of potential output.

Figure 8: Inflation and probability of regime 2



Note: Inflation is annual (solid) and probability of regime 2 is the smoothed probability (dashed).

a large negative correlation of the regime 2 probability with the risk premium shock and with the investment technology shock. These are shocks that typically play a large role in explaining financial distress. The estimated stronger monetary policy response during these episodes

Table 3: Correlations of regime 2 probability and shocks, US

	Stationary technology	Risk premium	Government spending	Permanent technology	Investment technology	Price mark-up	Wage mark-up
Corr	-0.07	-0.36	0.15	-0.08	-0.10	-0.24	0.04

suggests that the Fed has responded to deteriorated financial conditions in crisis times, as documented by Christiano et al. (2014) for example. In those episodes macroeconomic variables may not have deteriorated strongly on impact. Hence, the policy response to macroeconomic indicators may appear as having become stronger. Also Bernanke and Boivin (2003) find that in 1992-1993 and 1998 the Fed eased more than predicted by their model, presumably due to financial problems in the economy. These episodes are also captured in Figure 8 by a rising high-response regime (regime 2) probability.

For example, during both 1992–1993 and 1998 the Fed eased significantly more than predicted by our model, presumably due to financial problems in the economy (the "financial headwinds" in 1992–93, the Russian crisis in 1998). One interpretation is that, in these episodes, the Fed felt that financial conditions had changed the impact of a given change in the funds rate, and adjusted accordingly. In any event, the Fed's actions in 1992–1993 seem to have been particularly successful, as they achieved lower unemployment in 1993–1996 than implied by the simulations, without lasting effects on inflation.

5.1 Optimal monetary policy response with endogenously switching regimes in the US

To compute the optimised policy response for the US, we use a setting similar to the one we adopted for the EA. Specifically, we assume that the regime switching happens endogenously depending on the level of inflation. We assume that the structural parameters that we have estimated are independent of the monetary policy regime in place. Given the structural parameters and the model for the endogenous switching, we optimise the monetary rule parameters. The optimisation routine is the same as when optimising the parameters for the EA, but we set slightly different priors compared to the EA to account for the dual mandate of the Fed. For instance, the prior interval for the output gap coefficients is wider. Persistence parameter distributions are also slightly wider as the sample is longer and contains periods with high interest rates.

As for the euro area, it is found that the response to inflation and the output gap is higher in the regime 1, which has a higher probability of taking place when inflation is below the target. Persistence is lower in the low inflation regime, somewhat countering the higher inflation and output gap responses. Earlier studies present a range of optimised responses depending on an estimated model and time period. Schmitt-Grohe and Uribe (2007) and Williams (1999) find the optimised values for the coefficients in the rule to be $1.56 - 3$ on inflation, $0.01 - 1.87$ on output growth, and $0.77 - 1.10$ on smoothing. The highest value on inflation is found in an optimisation where the inflation coefficient cannot exceed 3. [20]

Table 4: Prior distributions and posterior estimates for the optimised simple rule

	Lower quartile	Upper quartile	Distribution	Optimal
$^{\pi}(S_1)$	2	10	Gamma	5.26
$^{\pi}(S_2)$	1	8	Gamma	2.48
$^{y}(S_1)$	0.2	6	Gamma	1.83
$^{y}(S_2)$	0.2	6	Gamma	0.51
$\rho^m(S_1)$	0.5	0.95	Beta	0.69
$\rho^m(S_2)$	0.5	0.95	Beta	0.84

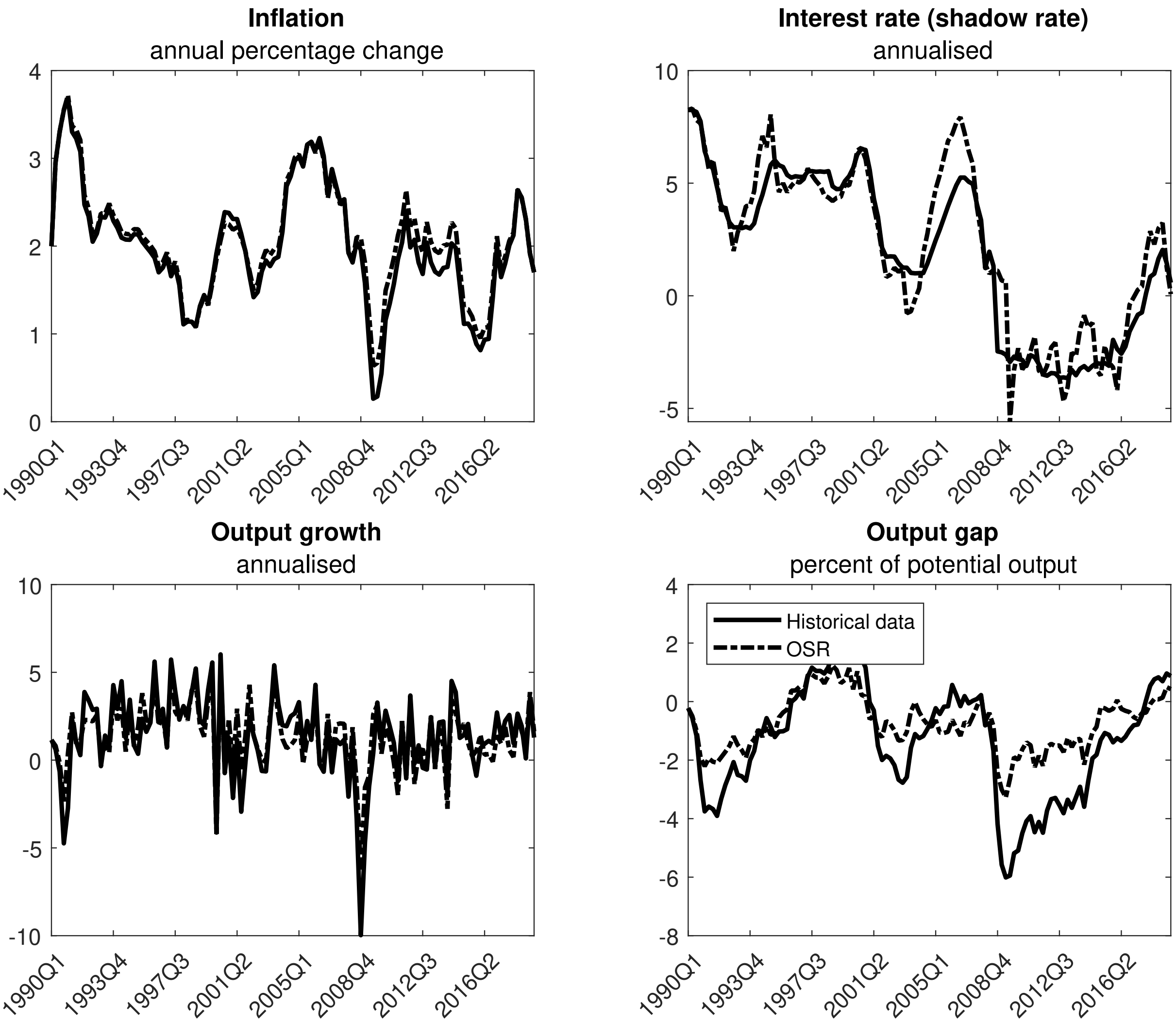
Note: Quartiles show a 90% probability range.

Using these optimised parameters, we run a counterfactual to assess how the US economy would have performed, had the Fed responded with the optimised parameters throughout the estimation sample. To compute this counterfactual, we follow a procedure similar to the one we have used for the euro area. In a first step we filter the data with the estimated model, which for the US included constant switching parameters. In a second step, we use the endogenously switching model where the monetary policy rule parameters are changed to the optimised coefficients, and simulate a time-series from the model conditional on the shocks from the first step. Throughout the exercise, we continue to use the shadow rate in place of the policy rate.

Figure 9 shows the results of the counterfactual exercise. Inflation is slightly higher after the burst of the dot-com bubble, and around 30-40 basis points higher after the financial crisis. The output gap is better stabilised and falls only to around -2% during the Global Financial Crisis. The interest rate is more volatile.

[20] Nakov (2008) in a simple model with a ZLB, but without smoothing in the policy rule, or cost-push shocks in the model finds that the optimal coefficient on inflation is 100, and between 0.75 and 1.5 on the output gap.

Figure 9: Annual inflation (solid) and probability of regime 2 (dashed)



Note: The counterfactual is a simulation of the endogenously switching model with optimised policy rule parameters, conditional on true shocks derived from filtering data from the estimated model where the regime probabilities switch exogenously.

Conclusion

This paper estimates Markov-switching DSGE models for the euro area and the US over the last few decades and uncovers differences in monetary policy across regimes.

We find that monetary policy in the euro area until mid-2014 was asymmetric, with stronger response to inflation when it is above target than when it is below target. Thereafter, the policy response can be characterised as symmetric. We illustrate how the estimated asymmetric response pre-2014 would aggravate the negative effects of the lower bound on interest rates due to the presence of the lower bound and a low r* environment.

We find that monetary policy in the US has been asymmetric but in a different way compared to the euro area. The policy response to inflation and economic slack has been stronger in times of financial distress. We suggest that this may be explained by the Fed responding during those times to other indicators, such as proxies of financial tensions, over and above inflation and slack.

We compute optimised policy rules in which coefficients are allowed to switch across regimes of inflation above target and below target in the presence of the lower bound on nominal interest rates and a low r*. The response to inflation has to be less forceful when inflation is above target than when it is below target. We run counterfactuals for the euro area and the US to assess what would have happened, had the central bank adopted over the last two decades the optimised asymmetric policy response that we have computed on the basis of the estimated model parameters and shocks.

The regime switching models we have estimated can be used to study alternative monetary policy frameworks. A case in point is the Fed's new framework announced in August 2020, which envisages an asymmetric response to inflation as well as to employment.

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Appendix A Model

Resource constraint:

$$\hat{y}_t = \hat{g}_t + c_y\hat{c}_t + i_y\hat{i}_t + z_y\hat{u}_t \tag{8}$$

Consumption Euler equation:

$$\begin{aligned}\hat{c}_t = & \frac{1}{1+he^{-g_z^*}}E_t[\hat{c}_{t+1}] + \frac{he^{-g_z^*}}{1+he^{-g_z^*}}\hat{c}_{t-1} - \frac{(1-he^{-g_z^*})}{\sigma_c(1+he_{-g_z^*})}(\hat{r}_t - \hat{r}_t^n - E_t[\hat{\pi}_{t+1}]) + \hat{\hat{b}} \\ & - \frac{1}{1+he^{-g_z^*}}(he^{-\hat{g}_z^*}g_{z,t} - E_t\hat{g}_{z,t+1}) \\ & + \frac{(\sigma_c - 1)}{\sigma_c(1+he^{-g_z^*})}\frac{\omega^{*h}L^*}{c^*}(\hat{L}_t - E_t[\hat{L}_{t+1})]\end{aligned} \tag{9}$$

Investment Euler equation:

$$\hat{i}_t = \frac{1}{S''e^{2g_z^*}(1+\beta e^{(1-\sigma_c)g_z^*})}\hat{q}_t^k + \frac{1}{1+\beta e^{(1-\sigma_c)g_z^*}}(\hat{i}_{t-1} - \hat{g}_{z,t}) + \frac{\beta e^{(1-\sigma_c)g_z^*}}{1+\beta e^{(1-\sigma_c)g_z^*}}E_t[\hat{i}_{t+1} + \hat{g}_{z,t+1}] + \mu_t \tag{10}$$

Arbitrage equation value of capital:

$$\hat{q}_t^k = -\hat{R}_t^D + E_t[\hat{\pi}_{t+1}] + \frac{1}{\frac{1-he^{-g_z^*}}{\sigma_c(1+he^{-g_z^*})}}\hat{\hat{b}}_t + \frac{r^{*k}}{r^{*k}+(1-\delta)}E_t[r_{t+1}^k] + \frac{(1-\delta)}{r^{*k}+(1-\delta)}E_t q_{t+1}^k \tag{11}$$

Aggregate production function:

$$\hat{y}_t = \Phi(\hat{A}_t + \alpha\hat{k}_t + (1-\alpha)\hat{L}_t) \tag{12}$$

Definition of capital services:

$$ln(k_t) - ln(k^*) = \hat{k}_t = \hat{u}_t - \hat{g}_{z,t} + \hat{\bar{k}}_{t-1} \tag{13}$$

First order condition, capacity utilisation:

$$u_t = \frac{1-\psi}{\psi}\hat{r}_t^k \tag{14}$$

Law of motion of capital:

$$\hat{\bar{k}}_t = (1 - \frac{r^*}{\bar{k}^*})(\hat{\bar{k}}_{t-1} - \hat{g}_{z,t}) + \frac{r^*}{\bar{k}^*}\hat{i}_t + \frac{r^*}{\bar{k}^*}S'' e^{2g_z^*}(1 + \beta e^{(1-\sigma_c)g_z^*})\hat{\mu}_t \tag{15}$$

First order condition, labour:

$$\hat{mc}_t = (1-\alpha)\hat{\omega}_t + \alpha \hat{r}_t^k - \hat{A}_t \tag{16}$$

Price Phillips curve:

$$\begin{aligned}\hat{\pi}_t = &\left(\frac{1}{1+\iota_p \bar{\beta} e^{g_z^*}}\right)(\bar{\beta} e^{g_z^*} E_t(\hat{\pi}_{t+1}) + \iota_p \hat{\pi}_{t-1} + (1-\iota_p)\hat{\bar{\pi}}_t - \bar{\beta} e^{g_z^*}(1-\iota_p)E_t[\hat{\bar{\pi}}_{t+1}] \\ &+ \frac{1}{((\phi_p - 1)\varepsilon_p + 1)}\left(\frac{(1-\zeta_p)(1-\zeta_p \bar{\beta} e^{g_z^*})}{\zeta_p}\right)\hat{mc}_t) + \hat{\lambda}_{p,t}\end{aligned} \tag{17}$$

Firm first order condition, capital:

$$\hat{r}_t^k = \hat{\omega}_t + \hat{L}_t - \hat{k}_t \tag{18}$$

Wage Phillips curve:

$$\begin{aligned}\hat{\omega}_t = &\left(\frac{1}{1+\bar{\beta} e^{g_z^*}}\right)(\hat{\omega}_{t-1} - \hat{g}_{z,t} + \bar{\beta} e^{g_z^*}(E_t[\hat{\omega}_{t+1}] + \hat{g}_{z,t+1} + E_t[\hat{\pi}_{t+1}]) - (1 + \bar{\beta} e^{g_z^*}\iota_\omega)\hat{\pi}_t + \iota_\omega \hat{\pi}_{t-1} \\ &+ (1-\iota_\omega)\hat{\bar{\pi}}_t - \bar{\beta} e^{g_z^*}(1-\iota_\omega)E_t[\hat{\bar{\pi}}_{t+1}] \\ &+ \frac{(1-\zeta_\omega \bar{\beta} e^{g_z^*})(1-\zeta_\omega)}{\zeta_\omega((\phi_\omega - 1)\varepsilon_\omega + 1)}\left[-\hat{\omega}_t + \sigma_l \hat{L}_t + \frac{1}{1-he^{-g_z^*}}(\hat{c}_t - he^{-g_z^*}\hat{c}_{t-1} + he^{-g_z^*}\hat{g}_{z,t}\right]) + \hat{\lambda}_{\omega,t}\end{aligned} \tag{19}$$

Table 5: Prior and posterior parameters

		EA			US		
Parameter	distribution	Prior mean (lq)	std (uq)	Posterior mode	Prior mean (lq)	std (uq)	Posterior mode
σ^a	inv. gamma	0.1	2	0.28	0.1	2	0.43
σ^b	inv. gamma	0.1	2	0.05	0.1	2	0.08
σ^g	inv. gamma	0.1	2	0.24	0.1	2	0.35
σ^I	inv. gamma	0.1	2	0.36	0.1	2	0.30
σ^p	inv. gamma	0.1	2	0.04	0.1	2	0.13
σ^w	inv. gamma	0.1	2	0.15	0.1	2	0.44
σ^{gz}	inv. gamma	0.1	2	0.19	0.1	2	0.08
α	normal	0.3	0.05	0.26	0.3	0.05	0.17
σ_c	normal	1.5	0.375	0.98	1.5	0.375	0.93
Φ	normal	1.25	0.125	1.44	1.25	0.125	1.55
ρ_{ga}	normal	0.5	0.2	0.81	0.5	0.2	0.49
φ	normal	4	1.5	5.40	4	1.5	4.55
h	beta	0.7	0.1	0.80	0.7	0.1	0.66
ξ_w	beta	0.5	0.1	0.81	0.5	0.1	0.68
ξ_p	beta	0.65	0.05	0.84	0.75	0.05	0.92
σ_l	normal	2	0.75	1.68	2	0.75	0.88
ι_w	beta	0.5	0.15	0.52	0.5	0.15	0.43
ι_p	beta	0.5	0.15	0.63	0.5	0.15	0.37
ψ	beta	0.5	0.1	0.65	0.5	0.1	0.63
ρ_a	beta	0.5	0.1	0.88	0.5	0.2	0.96
ρ_b	beta	0.5	0.2	0.85	0.5	0.2	0.96
ρ_g	beta	0.5	0.2	0.96	0.5	0.2	0.99
ρ_I	beta	0.5	0.2	0.45	0.5	0.2	0.69
ρ_{ms}	beta	0.3	0.1	0.49	0.3	0.1	0.53
ρ_p	beta	0.3	0.1	0.58	0.3	0.1	0.31
ρ_w	beta	0.5	0.1	0.67	0.5	0.2	0.98
μ_p	beta	0.5	0.2	0.11	0.5	0.2	0.33
μ_w	beta	0.5	0.2	0.97	0.5	0.2	0.93
$\bar{\gamma}$	normal	0.25	0.05	0.16	0.34	0.05	0.34
$100(\beta^{-1}-1)$					0.3	0.6	0.42
$\bar{l}$	normal	0	0.2	0.10	-1.24	0.2	-1.29
ρ_{g_z}	beta	0.5	0.1	0.61	0.5	0.1	0.83
ϕ^y	normal	0.1	0.05	0.14			
ρ^m	beta	0.75	0.1	0.81			
σ^m	inv. gamma	0.1	2	0.08			
$\phi^\pi(S_1)$	inv. gamma	(1	2)	1.28	(1	2)	1.11
$\phi^\pi(S_2)$	inv. gamma	(1.5	2.5)	1.75	(1.5	2.5)	1.83
$\phi^y(S_1)$	inv. gamma				(0.01	0.4)	0.50
$\phi^y(S_2)$	inv. gamma				(0.01	0.4)	0.50
$\rho^m(S_1)$	beta				(0.06	.95)	0.90
$\rho^m(S_2)$	beta				(0.06	.95)	0.27
$\sigma^m(S_1)$	inv. gamma				(0.0001	0.5)	0.07
$\sigma^m(S_2)$	inv. gamma				(0.0001	0.5)	0.30
$P(S_1, S_2)$	beta				0.5	0.2	0.16
$P(S_2, S_1)$	beta				0.5	0.2	0.81
log-post:				-78.2549			-437.59
log-MDD(Laplace)				-180.234			-539.209

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