Monetary Policy Strategies for the European Central Bank[*]

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Abstract

We develop a behavioral DSGE model which addresses the forward guidance puzzle. We then use the estimated model to assess if unconventional monetary policy tools such as negative interest rates, forward guidance, and asset purchases can provide effficient macroeconomic stabilization in a low nominal and real interest rate environment. While these tools boost output and inflation, the rebound from deep recession can still be painfully slow. "Makeup" strategies, including including average inflation and price level targeting, can further support recovery and reduce downside risks, though the benefits are quite modest under behavioral expectations.

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1. Introduction

The COVID crisis has induced many central banks to cut interest rates to historical lows as well as deploy a host of unconventional policy tools, including negative interest rates, forward guidance and large-scale asset purchases. Moreover, given that secular factors were viewed as depressing equilibrium real interest rates significantly even prior to COVID, central banks are giving prominent attention to how they might modify their **strategies** and tools to confront the challenges of a prolonged low interest rate environment.

While some options remain squarely within the dominant paradigm of flexible inflation targeting (see Svensson [115] for a comprehensive review) – such as raising the inflation target – other approaches involve more fundamental departures, including a shift to some form of price level targeting. But there are important questions about the conditions under which these alternative frameworks would yield beneficial effects, or if they would work at all. One crucial question is whether expectations would adjust to the new framework(s) in the manner implied by standard rational expectations models. Another key issue is whether a framework change should be adopted on a permanent basis, or only activated if the central bank is facing a liquidity trap (as in Bernanke's [13] proposal of temporary price-level targeting).

In this paper, we analyze alternative policy strategies for the ECB that may be appropriate in an environment with very low equilibrium real interest rates. Specifically, we estimate a DSGE model of the euro area that builds heavily on the workhorse model of Smets and Wouters [113] (SW07 henceforth). Our baseline allows for deviations from rational expectations (RE) by drawing on the behavioral approach in Gabaix [66] to address the forward guidance (FG henceforth) puzzle, though we also compare results to an estimated version with fully rational expectations. Intuitively, the large effects of changing policy rules often apparent under rational expectations should be damped if agents are myopic and focus on near-term developments, with our empirical estimates determining the quantitative departure from rational expectations. We use stochastic simulations to study both the conditional and unconditional probability distributions of key model variables, allowing for an assessment of which policies work well both in a liquidity trap and in normal times.

Within this setting, we begin by examining what policy changes might be desirable within the context of the current framework that focuses on stabilizing near-term inflation. Two issues stand out. First, we consider the potential costs of asymmetric reaction function – which puts a higher weight on a rise on inflation above target than a decline below target – relative to a symmetric formulation. Such an asymmetric response was arguably a key characteristic of ECB policy historically, and consistent with the ECB's preference to keep inflation "close to, but below 2 percent." While such a policy framework likely buttressed the ECB's credibility in the first decade or so of the ECB's existence, the ECB has been more concerned in recent years with low neutral interest rates and low inflation (Rostagno et al. [109]; Lagarde [91] and Langweiler and Orphanides [92]). Accordingly, ECB officials have emphasized the benefits of a symmetric target, and are aiming to further clarify their commitment to symmetry. Our framework is useful in assessing the potential benefits.

A second issue is whether it is desirable to react substantially to output growth, as the ECB appears to have done historically based on our estimated ECB reaction function. Such a policy may be appealing if policymakers are very uncertain about the level of potential output and are concerned about the inflationary effects of responding to a poorly measured output gap (Orphanides and Williams [105]). Such a policy may also make sense if there are significant "speed effects" in the Phillips Curve (as in Gali, forthcoming). However, it is less evident that such a reaction function would perform well in a deep recession, given that it could imply tightening soon after the economy starts to recover.

We also consider strategies that depart substantively from flexible inflation targeting, including "makeup" strategies that encompass price-level targeting and average inflation targeting. While much of our focus is on a permanent shift towards such a framework, we also consider temporary changes that would only apply when the economy is in a liquidity trap, as in Bernanke [13] or earlier research by Reifschneider and Williams [107].

Our estimated model captures several key features of the euro area economy which have important bearing both for the effectiveness of monetary policy tools as well as policy design. First, and most notably, we find strong support for the behavioral model relative to the rational expectations variant, with the posterior odds heavily tilted towards the former. Because households and firms substantially discount forward real interest rates at more distant horizons, forward guidance has far less traction to provide economic stimulus than under rational expectations. Second, in line with recent studies using US data and the ECBs NAWN II model by Coenen et al. [40], the sensitivity of inflation to marginal cost is estimated to be very low, i.e., the Phillips Curve is flat. As a consequence, inflation fluctuations are largely driven by price markup shocks, which create a quantitatively important trade-off between stabilizing economic activity and inflation (as recently shown by Debortoli et al. [45]). Third, consistent with the findings in Christiano, Motto and

Rostagno ([34], [35] and [36]), our estimated model implies that shocks originating in the financial sector are a key driver of business cycles in the Euro area.

Turning to policy design, our model simulations highlight the benefits of a symmetric inflation target. Notably, we find that an asymmetric response to inflation – consistent with a strong preference for keeping inflation slightly below 2 percent – significantly reduces the mean level of output, pushes average inflation persistently below target, and amplifies output volatility relative to the symmetric target. Intuitively, the flat Phillips Curve means that a policymaker favoring asymmetry must tighten more aggressively to keep inflation from rising above target after a positive markup shock, so that output falls more sharply.

In some contrast, a policy rule that responds aggressively to the change in the output gap has small effects on average, and even damps output volatility unconditionally. However, such a policy is quite problematic in a deep liquidity trap, as it implies relatively quick policy tightening that markedly slows the pace of recovery. Accordingly, there are clear benefits in responding substantially to inflation and output gaps in a deep recession, while foregoing any response to output growth.

We show that allowing somewhat more deeply negative interest rates and forward guidance based on the notational rate can help spur recovery, but the rebound from a deep recession can still be painfully slow, with inflation below target for many years. Make-up strategies including average inflation targeting (AIT) (see Vestin [116], Nessen and Vestin [104] and Svensson [114]) and price level targeting (PLT) (see e.g. Hunt and Laxton [82]) can spur somewhat faster improvement and limit downside risks. Even so, the benefits of a shift in strategy appear quite modest under the estimated behavioral model, and much smaller than under rational expectations. One feature evident from our simulations is that these strategies tend to perform less well unconditionally – generating considerably more output volatility than under strategies reacting to current inflation – suggesting the merits of the temporary deployment of these strategies (as in Bernanke [13]) rather than a more enduring commitment.

We also undertake a thorough robustness analysis aimed at addressing the sensitivity of the findings to some key properties in the model. These include allowing for a state-dependent slope of the Phillips curve (higher slope in booms and lower slope in recessions) and an asymmetric targeting regime in an environment that abstracts from markup shocks (and thus is most favorable to this sort of rule).

From a methodological perspective, our paper adds value to the existing literature, including the recent prominent papers by Bernanke, Kiley and Roberts [14], and Coenen, Galdon and Smets [41], by using an estimated dynamic stochastic general equilibrium (DSGE henceforth) that can help quantify departures from rational expectations in an environment with realistic frictions, and which allows for a steady state real rate substantially below the potential output growth rate. Our behavioral approach based on Gabaix is appealing insofar as it can easily be incorporated into a medium-sized DSGE model, and be flexibly parameterized to allow for different discounting in the price and aggregate demand equations. Even so, it is likely that a number of factors can help account for why expectations appear to adjust much less in practice than implied by models with fully rational expectations, including liquidity constraints as emphasized in McKay, Nakamura, and Steinsson [103], and information frictions in Angeletos and Lian [4].

Our paper is structured as follows. Section 2 presents the prototype model – the estimated model of SW07 amended to allow for behavioral expectations to mitigate the forward guidance puzzle (see Del Negro et al. [46] for further discussion). Section 3 discusses data and estimation, while Section 4 uses the estimated model to perform a posterior predictive analysis comparing the impulse responses to key shocks and to forward guidance. Section 5 considers unconditional and conditional simulations under variants of flexible inflation targeting, while Section 6 focuses on alternative policy strategies such as price level targeting. Following a discussion of robustness in Section 7, Section 8 summarizes our key findings and discusses some challenges for monetary policy and structural economic models in light of the pandemic. The appendices contain technical details on the model.

2. A Benchmark Macromodel

In this section, we present the model environment, which is the benchmark model of SW07, amended with the possibility that expectations are not fully rational. The SW07 model builds on the workhorse model by Christiano, Eichenbaum and Evans [30], but allows for a richer set of stochastic shocks. In Section 3, we describe how we estimate it using aggregate times series for the Euro Area.

2.1. Firms and Price Setting

Final Goods Production: The single final output good Y_t is produced using a continuum of differentiated intermediate goods $Y_t(f)$. Following Kimball [86], the technology for transforming these intermediate goods into the final output good is

$$\int_0^1 G_Y\left(\frac{Y_t(f)}{Y_t}\right)df = 1. \tag{2.1}$$

As in Dotsey and King [51], we assume that $G_Y(\cdot)$ is given by a strictly concave and increasing function:

$$G_Y\left(\frac{Y_t(f)}{Y_t}\right) = \frac{\phi_t^p}{1-(\phi_t^p-1)\epsilon_p}\left[\left(\frac{\phi_t^p+(1-\phi_t^p)\epsilon_p}{\phi_t^p}\right)\frac{Y_t(f)}{Y_t} + \frac{(\phi_t^p-1)\epsilon_p}{\phi_t^p}\right]^{\frac{1-(\phi_t^p-1)\epsilon_p}{\phi_t^p-(\phi_t^p-1)\epsilon_p}} + \left[1-\frac{\phi_t^p}{1-(\phi_t^p-1)\epsilon_p}\right], \tag{2.2}$$

where $\phi_t^p \geq 1$ denotes the gross markup of the intermediate firms. The parameter ϵ_p governs the degree of curvature of the intermediate firm's demand curve. When $\epsilon_p = 0$, the demand curve exhibits constant elasticity as with the standard Dixit-Stiglitz aggregator. When ϵ_p is positive the firms instead face a quasi-kinked demand curve, implying that a drop in the good's relative price only stimulates a small increase in demand. On the other hand, a rise in its relative price generates a large fall in demand. Relative to the standard Dixit-Stiglitz aggregator, this introduces more strategic complementary in price setting which causes intermediate firms to adjust prices less to a given change in marginal cost. Finally, notice that $G_Y(1) = 1$, implying constant returns to scale when all intermediate firms produce the same amount of the good.

Firms that produce the final output good are perfectly competitive in both product and factor markets. Thus, final goods producers minimize the cost of producing a given quantity of the output index Y_t, taking the price $P_t(f)$ of each intermediate good $Y_t(f)$ as given. Moreover, final goods producers sell the final output good at a price P_t, and hence solve the following problem:

$$\max_{\{Y_t, Y_t(f)\}} P_t Y_t - \int_0^1 P_t(f)\, Y_t(f)\, df, \tag{2.3}$$

subject to the constraint in (2.1). The first order conditions (FOCs) for this problem can be written

$$\begin{aligned}
\frac{Y_t(f)}{Y_t} &= \frac{\phi_t^p}{\phi_t^p-(\phi_t^p-1)\epsilon_p}\left(\left[\frac{P_t(f)}{P_t}\frac{1}{\Lambda_t^p}\right]^{-\frac{\phi_t^p-(\phi_p-1)\epsilon_p}{\phi_t^p-1}} + \frac{(1-\phi_t^p)\epsilon_p}{\phi_t^p}\right) \\
P_t\Lambda_t^p &= \left[\int P_t(f)^{-\frac{1-(\phi_t^p-1)\epsilon_p}{\phi_t^p-1}}\, df\right]^{-\frac{\phi_t^p-1}{1-(\phi_t^p-1)\epsilon_p}} \\
\Lambda_t^p &= 1 + \frac{(1-\phi_t^p)\epsilon_p}{\phi_p} - \frac{(1-\phi_t^p)\epsilon_p}{\phi_t^p}\int \frac{P_t(f)}{P_t}df,
\end{aligned} \tag{2.4}$$

where Λ_t^p denotes the Lagrangian multiplier on the aggregator constraint in (2.1). Note that when $\epsilon_p = 0$, it follows from the last of these conditions that $\Lambda_t^p = 1$ in each period t, and the demand and pricing equations collapse to the usual Dixit-Stiglitz expressions, i.e.

$$\frac{Y_t(f)}{Y_t} = \left[\frac{P_t(f)}{P_t}\right]^{-\frac{\phi_t^p}{\phi_t^p - 1}}, P_t = \left[\int P_t(f)^{\frac{1}{1-\phi_t^p}} df\right]^{1-\phi_t^p}.$$

Intermediate Goods Production: A continuum of intermediate goods $Y_t(f)$ for $f \in [0, 1]$ is produced by monopolistic competitive firms, each of which produces a single differentiated good. Each intermediate goods producer faces the demand schedule in equation (2.4) from the final goods firms through the solution to the problem in (2.3), which varies inversely with its output price $P_t(f)$ and directly with aggregate demand Y_t.

Each intermediate goods producer utilizes capital services $K_t(f)$ and a labor index $L_t(f)$ (defined below) to produce its respective output good. The form of the production function is Cobb-Douglas:

$$Y_t(f) = \varepsilon_t^a K_t(f)^\alpha \left[\gamma^t L_t(f)\right]^{1-\alpha} - \gamma^t \Phi,$$

where γ^t represents the labor-augmenting deterministic growth rate in the economy, Φ denotes the fixed cost (which is related to the gross markup ϕ_t^p so that profits are zero in the steady state), and ε_t^a is a total productivity factor which follows a Kydland-Prescott [89] style process:

$$\ln \varepsilon_t^a = \rho_a \ln \varepsilon_{t-1}^a + \eta_t^a, \eta_t^a \sim N(0, \sigma_a). \tag{2.5}$$

Firms face perfectly competitive factor markets for renting capital and hiring labor. Thus, each firm chooses $K_t(f)$ and $L_t(f)$, taking as given both the rental price of capital R_{Kt} and the aggregate wage index W_t (defined below). Firms can without costs adjust either factor of production, thus, the standard static first-order conditions for cost minimization implies that all firms have identical marginal costs per unit of output.

The prices of the intermediate goods are determined by nominal contracts in Calvo [24] and Yun [120] staggered style nominal contracts. In each period, each firm f faces a constant probability, $1-\xi_p$, of being able to re-optimize the price $P_t(f)$ of the good. The probability that any firm receives a signal to re-optimize the price is assumed to be independent of the time that it last reset its price. If a firm is not allowed to optimize its price in a given period, this is adjusted by a weighted combination of the lagged and steady-state rate of inflation, i.e., $P_t(f) = (1+\pi_{t-1})^{\iota_p}(1+\pi)^{1-\iota_p} P_{t-1}(f)$ where $0 \leq \iota_p \leq 1$ and π_{t-1} denotes net inflation in period $t-1$, and π the steady-state net inflation rate. A positive value of the indexation parameter ι_p introduces structural inertia into the inflation process. All told, this leads to the following optimization problem for the intermediate firms

$$\max_{\tilde{P}_t(f)} \mathrm{E}_t \sum_{j=0}^{\infty} (\beta\xi_p)^j \frac{\Xi_{t+j} P_t}{\Xi_t P_{t+j}} \left[\tilde{P}_t(f) \left(\Pi_{s=1}^j (1+\pi_{t+s-1})^{\iota_p} (1+\pi)^{1-\iota_p}\right) - MC_{t+j}\right] Y_{t+j}(f),$$

where $\tilde{P}_t(f)$ is the newly set price and $\beta^j \frac{\Xi_{t+j} P_t}{\Xi_t P_{t+j}}$ the stochastic discount factor. Notice that given our assumptions, all firms that re-optimize their prices actually set the same price.

As noted previously, we assume that the gross price-markup is time-varying and given by $\phi_t^p = \phi^p \varepsilon_t^p$, for which the exogenous component ε_t^p is given by an exogenous ARMA(1,1) process:

$$\ln \varepsilon_t^p = \rho_p \ln \varepsilon_{t-1}^p + \eta_t^p - \vartheta_p \eta_{t-1}^p, \eta_t^p \sim N(0, \sigma_p). \tag{2.6}$$

2.2. Households and Wage Setting

Following Erceg, Henderson and Levin [59], we assume a continuum of monopolistic competitive households (indexed on the unit interval), each of which supplies a differentiated labor service to the production sector; that is, goods-producing firms regard each household's labor services $L_t(h)$, $h \in [0,1]$, as imperfect substitutes for the labor services of other households. It is convenient to assume that a representative labor aggregator combines households' labor hours in the same proportions as firms would choose. Thus, the aggregator's demand for each household's labor is equal to the sum of firms' demands. The aggregated labor index L_t has the Kimball [86] form:

$$L_t = \int_0^1 G_L\left(\frac{L_t(h)}{L_t}\right) dh = 1, \tag{2.7}$$

where the function $G_L(\cdot)$ has the same functional form as does (2.2), but is characterized by the corresponding parameters ϵ_w (governing convexity of labor demand by the aggregator) and a time-varying gross wage markup ϕ_t^w. The aggregator minimizes the cost of producing a given amount of the aggregate labor index L_t, taking each household's wage rate $W_t(h)$ as given, and then sells units of the labor index to the intermediate goods sector at unit cost W_t, which can naturally be interpreted as the aggregate wage rate. From the FOCs, the aggregator's demand for the labor hours of household h – or equivalently, the total demand for this household's labor by all goods-producing firms – is given by

$$\frac{L_t(h)}{L_t} = G_L'^{-1}\left[\frac{W_t(h)}{W_t} \int_0^1 G_L'\left(\frac{L_t(h)}{L_t}\right) \frac{L_t(h)}{L_t} dh\right], \tag{2.8}$$

where $G_L'(\cdot)$ denotes the derivative of the $G_L(\cdot)$ function in equation (2.7).

The utility function of a typical member of household h is

$$\mathrm{E}_t \sum_{j=0}^{\infty} \beta^j \left[\frac{1}{1-\sigma_c}\left(C_{t+j}(h) - \varkappa C_{t+j-1}\right)\right]^{1-\sigma_c} \exp\left(\frac{\sigma_c - 1}{1+\sigma_l} L_{t+j}(h)^{1+\sigma_l}\right), \tag{2.9}$$

where the discount factor β satisfies $0 < \beta < 1$. The period utility function depends on household h's current consumption $C_t(h)$, as well as lagged aggregate consumption per capita, to allow for external habit persistence (captured by the parameter $\varkappa$). The period utility function also depends inversely on hours worked $L_t(h)$.

Household h's budget constraint in period t states that expenditure on goods and net purchases of financial assets must equal to the disposable income:

$$P_t C_t(h) + P_t I_t(h) + \frac{B_{t+1}(h)}{\varepsilon_t^b \tilde{R}_t} + \int_s \xi_{t,t+1} B_{D,t+1}(h) - B_{D,t}(h) \tag{2.10}$$
$$= B_t(h) + W_t(h) L_t(h) + R_t^k Z_t(h) K_t^p(h) - a(Z_t(h)) K_t^p(h) + \Gamma_t(h) - T_t(h).$$

Thus, the household purchases part of the final output good (at a price of P_t), which is chosen to be consumed $C_t(h)$ or invest $I_t(h)$ in physical capital. Following Christiano, Eichenbaum, and Evans [30], investment augments the household's (end-of-period) physical capital stock $K_{t+1}^p(h)$ according to

$$K_{t+1}^p(h) = (1-\delta) K_t^p(h) + \varepsilon_t^i \left[1 - S\left(\frac{I_t(h)}{I_{t-1}(h)}\right)\right] I_t(h). \tag{2.11}$$

The extent to which investment by each household turns into physical capital is assumed to depend on an exogenous shock ε_t^i and how rapidly the household changes its rate of investment according to the function $S\left(\frac{I_t(h)}{I_{t-1}(h)}\right)$, which we assume satisfies $S(\gamma) = 0$, $S'(\gamma) = 0$ and $S''(\gamma) = \Psi$ where γ is the steady state gross growth rate of the economy. The stationary investment-specific shock ε_t^i follows the process:

$$\ln \varepsilon_t^i = \rho_i \ln \varepsilon_{t-1}^i + \eta_t^i, \eta_t^i \sim N(0, \sigma_i).$$

In addition to accumulating physical capital, households may augment their financial assets through increasing their overall nominal bond holdings (B_{t+1}), from which they earn a gross nominal interest rate of R_t. Finally, the return on the bond portfolio is also subject to a risk-shock, ε_t^b, which follows an ARMA(1,1) process:

$$\ln \varepsilon_t^b = \rho_b \ln \varepsilon_{t-1}^b + \eta_t^b - \vartheta_b \eta_{t-1}^b, \eta_t^b \sim N(0, \sigma_b). \tag{2.12}$$

Fisher [64] shows that this shock can be given a structural interpretation.

We assume that agents can engage in friction-less trading of a complete set of contingent claims to diversify away idiosyncratic risk. The term $\int_s \xi_{t,t+1} B_{D,t+1}(h) - B_{D,t}(h)$ represents net purchases of these state-contingent domestic bonds, with $\xi_{t,t+1}$ denoting the state-dependent price, and $B_{D,t+1}(h)$ the quantity of such claims purchased at time t.

On the income side, each member of household h earns labor income $W_t(h) L_t(h)$, capital rental income of $R_t^k Z_t(h) K_t^p(h)$, and pays a utilization cost of the physical capital equal to $a(Z_t(h)) K_t^p(h)$

where $Z_t(h)$ is the capital utilization rate. The capital services provided by household h, $K_t(h)$ thereby equals $Z_t(h) K_t^p(h)$. The capital utilization adjustment function $a(Z_t(h))$ is assumed to satisfy $a(1) = 0$, $a'(1) = r^k$, and $a''(1) = \psi/(1-\psi) > 0$, where $\psi \in [0, 1)$ and a higher value of ψ implies a higher cost of changing the utilization rate. Finally, each member also receives an aliquot share $\Gamma_t(h)$ of the profits of all firms, and pays a lump-sum tax of $T_t(h)$ (regarded as taxes net of any transfers).

In every period t, each member of household h maximizes the utility function in (2.9) with respect to consumption, investment, (end-of-period) physical capital stock, capital utilization rate, bond holdings, and holdings of contingent claims, subject to the labor demand function (2.8), budget constraint (2.10), and transition equation for capital (2.11).

Households also set nominal wages in Calvo-style staggered contracts that are generally similar to the price contracts described previously. Thus, the probability that a household receives a signal to re-optimize its wage contract in a given period is denoted by $1 - \xi_w$. In addition, SW07 specify the following dynamic indexation scheme for the adjustment of wages for those households that do not get a signal to re-optimize: $W_t(h) = \gamma (1 + \pi_{t-1})^{\iota_w} (1 + \pi)^{1-\iota_w} W_{t-1}(h)$. All told, this leads to the following optimization problem for the households

$$\max_{\tilde{W}_t(h)} \mathrm{E}_t \sum_{j=0}^{\infty} (\beta \xi_w)^j \frac{\Xi_{t+j} P_t}{\Xi_t P_{t+j}} \left[\tilde{W}_t(h) \left(\Pi_{s=1}^{j} \gamma (1 + \pi_{t+s-1})^{\iota_w} (1 + \pi)^{1-\iota_w} \right) - W_{t+j} \right] L_{t+j}(h),$$

where $\tilde{W}_t(h)$ is the newly set wage and $L_{t+j}(h)$ is determined by equation (2.7). Notice that with our assumptions all households that re-optimize their wages will actually set the same wage.

Following the same approach as with the intermediate-goods firms, we introduce a shock ε_t^w to the time-varying gross markup, $\phi_t^w = \phi^w \varepsilon_t^w$, where ε_t^w is assumed being given by an exogenous ARMA(1,1) process:

$$\ln \varepsilon_t^w = \rho_w \ln \varepsilon_{t-1}^w + \eta_t^w - \vartheta_w \eta_{t-1}^w, \eta_t^w \sim N(0, \sigma_w). \tag{2.13}$$

2.3. Market Clearing Conditions and Monetary Policy

Government purchases G_t are exogenous, and the process for government spending relative to trend output in natural logs, i.e. $g_t = G_t / \left(\gamma^t Y\right)$, is given by the following exogenous AR(1) process:

$$\ln g_t = (1 - \rho_g) \ln g + \rho_g \left(\ln g_{t-1} - \rho_{ga} \ln \varepsilon_{t-1}^a \right) + \varepsilon_t^g, \varepsilon_t^g \sim N(0, \sigma_g). \tag{2.14}$$

Government purchases neither have any effects on the marginal utility of private consumption, nor do they serve as an input into goods production. The consolidated government sector budget constraint is

$$\frac{B_{t+1}}{\tilde{R}_t} = G_t - T_t + B_t,$$

where T_t are lump-sum taxes. By comparing the debt terms in the household budget constraint in equation (2.10) with the equation above, one can see that receipts from the risk shock are subject to iceberg costs, and hence do not add any income to the government.[1] We acknowledge that this is a simplistic modeling of the fiscal behavior of the government relative to typical policy models, and there might be important feedback effects between fiscal and monetary policies that our model does not allow for.[2] As discussed by Benigno and Nisticó [11] and Del Negro and Sims [50], the fiscal links between governments and central banks may be especially important today when central banks have employed unconventional tools in monetary policy. Nevertheless, we maintain our simplistic modeling of fiscal policy throughout the paper, as it allows us to examine the partial implications of amending the benchmark model with the ZLB constraint more directly.

The central bank's setting of the gross nominal policy rate R_t is assumed to be approximated by a Taylor-type policy rule (here stated in non-linearized form)

$$R_t = \max\left\{1, \left[R\ \left(\frac{\Pi_t}{\Pi}\right)^{r_\pi}\ \left(\frac{Y_t}{Y_t^{pot}}\right)^{r_y}\right]^{(1-\rho_R)} \left(\frac{Y_t}{Y_t^{pot}}/\frac{Y_{t-1}}{Y_{t-1}^{pot}}\right)^{r_{\Delta y}} R_{t-1}^{\rho_R}\varepsilon_t^r\right\}, \tag{2.15}$$

where Π_t denotes the is gross inflation rate, Y_t^{pot} is the level of output that would prevail if prices and wages were flexible, and variables without subscripts denote steady state values.[3] The policy shock ε_t^r is supposed to follow an AR(1) process in natural logs:

$$\ln \varepsilon_t^r = \rho_r \ln \varepsilon_{t-1}^r + \eta_t^r, \eta_t^r \sim N(0, \sigma_r). \tag{2.16}$$

Finally, total output of the final goods sector is used as follows:

$$Y_t = C_t + I_t + G_t + a(Z_t)\bar{K}_t,$$

where $a(Z_t)\bar{K}_t$ is the capital utilization adjustment cost.

2.4. Formation of Expectations

Following SW07, we first impose rational expectations, i.e. that $z_{t+1|t} = \mathrm{E}_t z_{t+1}$. We will henceforth refer to this as the RE model. However, we then allow for the possibility that households and

[1] But even if they did, it would not matter as the government is assumed to balance its expenditures each period through lump-sum taxes, $T_t = G_t + B_t - B_{t+1}/\tilde{R}_t$, so that government debt $B_t = 0$ in equilibrium. Furthermore, as Ricardian equivalence (see Barro, [10]) holds in the model, it does not matter for equilibrium allocations whether the government balances its debt or not in each period.

[2] See e.g., Leeper and Leith [94], and Leeper, Traum and Walker [95].

[3] We assume Y_t^{pot} is affected by four shocks: ε_t^a, ε_t^g, ε_t^b, and ε_t^i shocks. Hence, wage, price, monetary and term-premium shocks do not affect potential output.

firms form expectations in a non-rational fashion outside of steady state dynamics. Our modeling of behavioral expectations follows the spirit of Gabaix [66] by assuming that

$$z^{BR}_{t+1|t} = \varphi \mathrm{E}_t z_{t+1}$$

where the superscript BR abbreviates bounded rationality and cognitive discounted parameters φ_h (for households) and φ_f (for firms and labor unions) satisfies $0 < \varphi \leq 1$. Hence, wherever a forward-looking variable z_{t+1} appears in a linearized first-order conditions, it is replaced by φz_{t+1}. This approach is implemented by replacing each forward-looking variable z_{t+1} in the linearized first-order conditions of the rational expectations version of the model with φz_{t+1}. Relative to Gabaix [66], who uses these assumptions about expectations formation to rederive the first order conditions, our approach clearly involves some simplifications. However, it captures the spirit of both Gabaix and related work – including McKay, Nakamura, and Steinsson [103] – that a number of factors, including myopia and liquidity constraints, are likely to damp the role of expectations in shaping current outcomes.

The one exception to how we adjust expectations in the behavioral model is in the Fisher relationship, i.e. the determination of the real risk-free interest rate. Following Gabaix [66], we think about the real rate as a time t variable, and that arbitrage considerations suggest we should not allow for discounting of inflation expectations in this relationship, i.e. $r_t = rr_t - \pi_{t+1|t}$. While we found empirically that this decision is largely inconsequential for our estimations and simulations, one additional appealing feature with maintaining it is that it makes expectations formation in the flexible price-wage bloc of the model (used to keep track of potential output Y^{pot}_t in the policy rule, eq. 2.15) symmetric with expectations formation in the actual economy with sticky prices and sticky wages.[4]

Relative to the RE model, our formulation of the behavioral model introduces two additional parameters φ_h and φ_f which we estimate. By implication, the steady state of the model is unaffected in the behavioral version of the model, henceforth referred to as the BR model.

3. Estimation of Model

We now proceed to discuss how the model is estimated with and without imposing rational expectations. We also study the implications of deviating from RE with traditional posterior predictive analysis.

[4] In the flex price-wage equilibrium with constant (zero) inflation expectations, the real rate is a time t variable which is not directly affected by alternative assumptions about expectations formation.

3.1. Solving the Model

Before estimating the model, we log-linearize all the equations. The log-linearized representation is provided in A. To solve the system of log-linearized equations, we use the code package Dynare which provides an efficient and reliable implementation of the method proposed by Blanchard and Kahn [17]. In addition, Dynare allows us to simulate the model when imposing various nonlinear constraints on monetary policy conduct (for example, the zero lower bound) using the Fair-Taylor [62] method.

3.2. Data

We use seven key macro-economic quarterly Euro area time series as observable variables when estimating the SW model: the log difference of real GDP, real consumption, real investment and the real wage, log hours worked, the log difference of the GDP deflator, and the federal funds rate. These observables are identical to those used by Smets and Wouters ([112], [113]).[5]

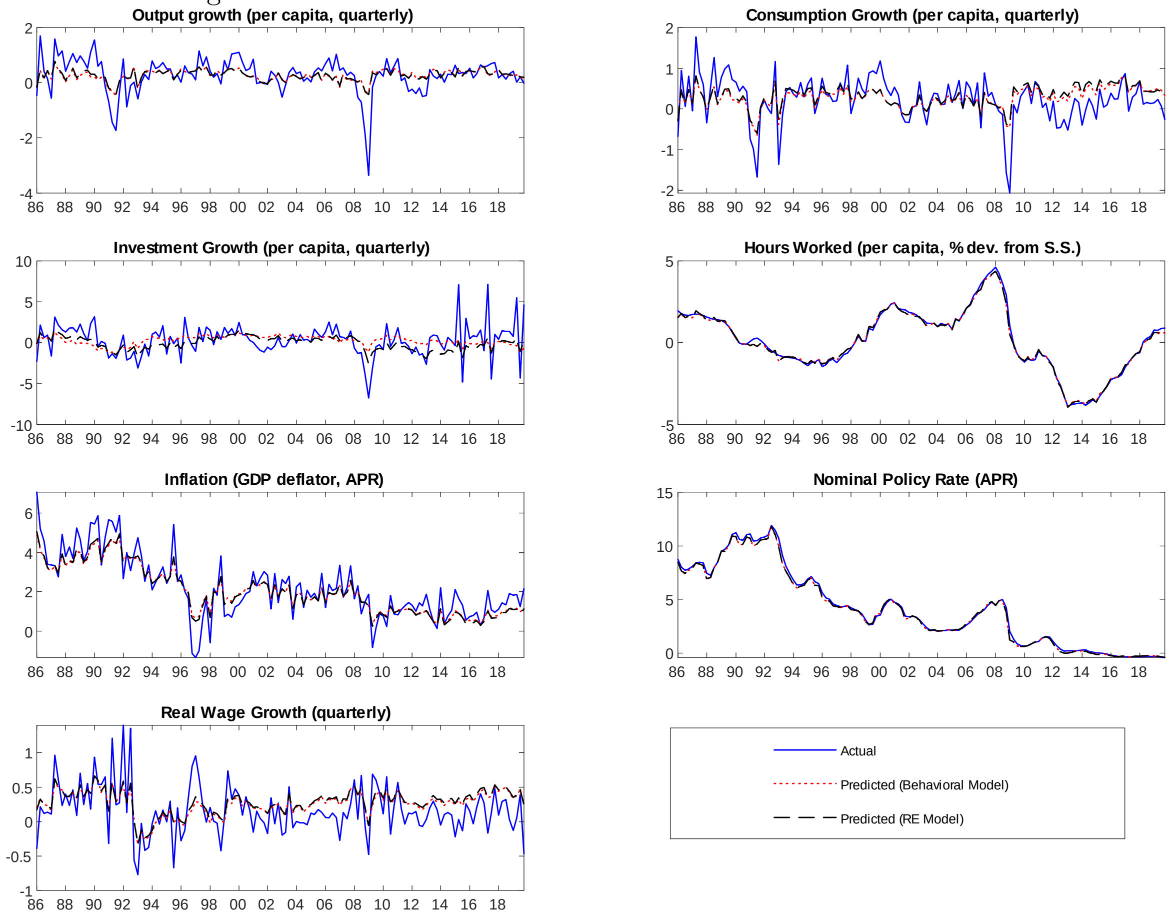
The solid blue line in Figure 3.1 shows the data for the period 1986Q1–2019Q4 which is used form the likelihood function.[6] From the figure, we see the extraordinary large fall in output during the recent global financial crisis, which exceeded the output contraction during the euro area debt crisis in 2012. The strains in the labor market are also evident, with hours worked per capita falling to a bottom low of -5 percent in 2012. Finally, we see that the ECB cut their policy rate (EONIA) below zero in early 2015 (the EONIA is measured as an average of daily observations in each quarter). Evidently, a EONIA just below zero appears to be perceived as an effective lower bound by the ECB governing council, as they have kept it as this level since 2015 and adopted alternative tools to make monetary policy more accommodating (see e.g. Rostagno et al. [109]). Meanwhile, inflation (measured by the GDP deflator) fell into deflationary territory by the end of 2009. Since then, inflation has slowly rebounded towards the ECB's target of "below but close to 2 percent".

The measurement equation, relating the variables in the model to the various variables we match

[5] A full description of the data used is provided in B.

[6] We start the estimation in 1985Q1 and use the first 4 quarters to form an initial estimate of the covariance matrix for the state vector. The figure also include red-dotted and black-dashed lines with one-sided filtered estimates from the BR and RE models, to be discussed in further detail in Section 3.4.

Figure 3.1: Actual and Predicted Data in the Behavioral Model



in the data, is given by:

$$Y_t^{obs} = \begin{bmatrix} \Delta \ln GDP_t \\ \Delta \ln CONS_t \\ \Delta \ln INVE_t \\ \Delta \ln W_t^{real} \\ \ln HOURS_t \\ 4\Delta \ln PGDP_t \\ FFR_t \end{bmatrix} = \begin{bmatrix} \ln Y_t - \ln Y_{t-1} \\ \ln C_t - \ln C_{t-1} \\ \ln I_t - \ln I_{t-1} \\ \ln (W/P)_t - \ln (W/P)_{t-1} \\ \ln L_t \\ 4 \ln \Pi_t \\ 4 \ln R_t \end{bmatrix} \approx \begin{bmatrix} \bar{\gamma} \\ \bar{\gamma} \\ \bar{\gamma} \\ \bar{\gamma} \\ 0 \\ 4\bar{\pi} \\ 4\bar{r} \end{bmatrix} + \begin{bmatrix} \hat{y}_t - \hat{y}_{t-1} \\ \hat{c}_t - \hat{c}_{t-1} \\ \hat{\imath}_t - \hat{\imath}_{t-1} \\ \hat{w}_t^{real} - \hat{w}_{t-1}^{real} \\ l_t \\ 4\pi_t \\ 4\hat{R}_t \end{bmatrix} \tag{3.1}$$

where ln and $\Delta \ln$ stand for log and log-difference respectively, $\bar{\gamma} = 100\,(\gamma - 1)$ is the common quarterly trend growth rate to real GDP, consumption, investment and wages, $\bar{\pi} = 100\pi$ is the quarterly steady-state inflation rate and $\bar{r} = 100\left(\beta^{-1}\gamma^{\sigma_c}\,(1+\pi) - 1\right)$ is the steady-state nominal interest rate. Notice that inflation and the EONIA are expressed in annualized rates. Given the estimates of the trend growth rate and the steady-state inflation rate, the latter will be determined by the estimated discount rate and the substitution elasticity σ_c. Our mapping between the model and the data is adapted from SW07, with the exception that we drop the average hours parameter constant $\bar{l}$ in the measurement equation for hours worked per capita.

3.3. Estimation Methodology

Following SW07, Bayesian techniques are adopted to estimate the parameters. Bayesian inference starts out from a prior distribution that describes the available information prior to observing the data used in the estimation. The observed data is subsequently used to update the prior, via Bayes' theorem, to the posterior distribution of the model's parameters which can be summarized in the usual measures of location (e.g. mode or mean) and spread (e.g. standard deviation and probability intervals).[7]

Table 3.1: Calibrated parameters.

Parameter	Description	Calibrated Value
δ	Depreciation rate	0.025
ϕ_w	Gross wage markup	1.50
g_y	Government G/Y ss-ratio	0.21
ϵ_p	Kimball elast. GM	10
ϵ_w	Kimball elast. LM	10
	Panel B: Parameters calibrated to hit SS Targets	
$\bar{\gamma}$	Quarterly growth in SS	0.3
$\overline{\pi}$	Quarterly inflation in SS	0.5
σ_c	Intertemp. cons. sub. elast.	0.5
β	Discount factor	0.99995

Note: Parameters above Panel B are adapted from SW07. The parameters listed in Panel B are set to hit 1.2 percent output growth (APR), 2 percent inflation (APR), 0.6 (2.6) percent steady state real (nominal) interest rate.

Some of the parameters in the model are kept fixed throughout the estimation procedure (i.e., are subject to infinitely strict priors). We choose to calibrate the parameters we think are weakly identified by the variables included in $\tilde{Y}_t^{obs}$ in equation (3.1). These are reported in Table 3.1, and are calibrated to the same values as in SW07. However, we deviate from SW07 by calibrating some additional parameters. These parameters, γ, σ_c, $\bar{\pi}$, and β, are set to impose certain values for steady state (i) output growth (ii) price inflation, and (iii) real and nominal policy rates which we want to condition the analysis on. If estimated, these parameters would instead reflect historical sample means for these variables which we do believe may be relevant going forward. Importantly, the King and Rebelo [85] utility function with non-separability between consumption and labor can be consistent with a balanced growth path even when the real rate is lower than the growth rate of the economy in steady state.

[7] We refer the reader to Smets and Wouters [112] for a more detailed description of the estimation procedure.

The remaining 31 (32 in the behavioral model) parameters, which mostly pertain to the nominal and real frictions, policy rule parameters as well as the exogenous shock processes, are estimated. The first three columns in Table 3.2 shows the assumptions for the prior distribution of the estimated parameters. The location of the prior distribution is identical to that of SW07, with the exception of ϑ_p and ϑ_w for which we lowered the prior standard deviation from 0.2 to 0.1 to ensure that the posterior for $\vartheta_p < \rho_p$ and that $\vartheta_w < \rho_w$.[8] We use the beta distribution for all parameters bounded between 0 and 1. For parameters assumed to be positive, we use the inverse gamma distribution, and for the unbounded parameters, we use the normal distribution. The exact location and uncertainty of the prior can be seen in Table 3.2. For a more comprehensive discussion of choices regarding the prior distributions we refer the reader to SW07. The only parameter for which a prior is not given from SW is the behavioral parameter φ_h. For this parameter we impose a conservative beta prior centered around 0.975 with standard error 0.0125 so that rational expectations can be obtained as a special case in the estimation allowing for behavioral expectations. To begin with we impose the behavioral parameter for firms equal to unity ($\varphi_f = 1$). In Section 7 we study the robustness of the results in the BR model when we allow $\varphi_f < 1$.

Given the calibrated parameters in Table 3.1, we obtain the joint posterior distribution mode for the remaining parameters in Table 3.2 in two steps. First, the posterior mode and an approximate covariance matrix, based on the inverse Hessian matrix evaluated at the mode, is obtained by numerical optimization on the log posterior density. Second, the posterior distribution is subsequently explored by generating draws using the Metropolis-Hastings algorithm. The proposed distribution is taken to be the multivariate normal density centered at the previous draw with a covariance matrix proportional to the inverse Hessian at the posterior mode; see Schorfheide [110] and Smets and Wouters [112] for further details. The results in Table 3.2 shows the posterior mode of all the parameters along with the approximate posterior standard deviation obtained from the inverse Hessian at the posterior mode. Finally, one column reports the posterior mode in the SW07 paper.

3.4. Posterior Distributions

To understand how allowing for deviations from rational expectations affects the estimation outcome, Table 3.2 reports results of the benchmark rational expectations model, referred to as "RE

[8] Notice that this ensures that positive innovations to both price and wage markups cause their respective shock processes to decay back to steady state from positive values.

Model", as well as the model allowing for behavioral expectations.

There are three important features to notice with regards to the posterior and log marginal likelihoods in Table 3.2. First, the log marginal likelihood (LML henceforth) is substantially higher for the behavioral model compared to the RE model. If both models are considered equally probable ex ante, the estimation results strongly favors the behavioral model according to its posterior odds ratio, although Figure 3.1 displays no visible large differences between the two models one-sided predicted values. Even so, it should be noted that the strong evidence in favor of the behavioral model is contingent on the calibration of σ_c to 0.5 (allowing the model to account for steady state annualized real interest rate equal to 0.6 percent and an annualized steady state output growth rate of 1.2 percent).

Table 3.2: Prior and Posterior Distributions.

Parameter		Prior distribution			original SW07	Posterior distribution			
					Posterior	RE Model		Behavioral Model	
		type	mean	std.dev.	mode	mode	std.dev.	mode	std.dev.
Households Cogn. Discount.	φ_h	beta	0.975	0.0125	-	-	-	0.952	0.01
Calvo prob. prices	ξ_p	beta	0.667	0.05	0.65	0.864	0.02	0.867	0.02
Calvo prob. wages	ξ_w	beta	0.667	0.05	0.73	0.747	0.04	0.761	0.04
Indexation prices	ι_p	beta	0.5	0.15	0.22	0.176	0.08	0.174	0.08
Indexation wages	ι_w	beta	0.5	0.15	0.59	0.240	0.08	0.248	0.08
Gross price markup	ϕ_p	normal	1.25	0.125	1.61	1.709	0.09	1.755	0.09
Capital production share	α	normal	0.3	0.1	0.19	0.082	0.01	0.089	0.01
Capital utilization cost	ψ	beta	0.5	0.15	0.54	0.772	0.10	0.517	0.15
Investment adj. cost	Ψ	normal	4	1.5	5.48	8.923	1.08	7.826	1.00
Habit formation	$\varkappa$	beta	0.7	0.1	0.71	0.640	0.04	0.641	0.04
Labor supply elast.	σ_l	normal	2	0.75	1.92	1.146	0.57	0.913	0.50
Stationary tech. shk. pers.	ρ_a	beta	0.5	0.2	0.95	0.940	0.02	0.934	0.02
Risk premium shk. pers.	ρ_b	beta	0.5	0.1	0.18	0.952	0.01	0.949	0.01
Invest. spec. tech. shk. pers.	ρ_i	beta	0.5	0.2	0.71	0.203	0.10	0.158	0.08
Gov't cons. shk. pers.	ρ_g	beta	0.5	0.2	0.97	0.968	0.02	0.967	0.02
Price markup shk. pers.	ρ_p	beta	0.5	0.2	0.9	0.650	0.08	0.640	0.08
MA(1) price markup shock	ϑ_p	beta	0.5	0.1	0.74	0.527	0.10	0.531	0.10
Wage markup shk. pers.	ρ_w	beta	0.5	0.2	0.97	0.910	0.02	0.913	0.02
MA(1) wage markup shock	ϑ_w	beta	0.5	0.1	0.88	0.727	0.06	0.754	0.06
Response of $g_t$to ε_t^a	ρ_{ga}	beta	0.5	0.25	0.52	0.421	0.08	0.413	0.08
Stationary tech. shk. std.	σ_a	invgamma	0.1	2	0.45	0.333	0.02	0.328	0.02
Risk premium shk. std.	σ_b	invgamma	0.1	2	0.24	0.146	0.02	0.206	0.03
Invest. spec. tech. shk. std.	σ_i	invgamma	0.1	2	0.45	0.871	0.09	0.960	0.08
Gov't cons. shk. std.	σ_g	invgamma	0.1	2	0.52	0.314	0.02	0.313	0.02
Price markup shk. std.	σ_p	invgamma	0.1	2	0.14	0.157	0.02	0.162	0.02
Wage markup shk. std.	σ_w	invgamma	0.1	2	0.24	0.094	0.01	0.095	0.01
Inflation response	r_π	normal	1.5	0.25	2.03	1.729	0.22	1.620	0.22
Output gap response	r_y	normal	0.125	0.05	0.08	0.162	0.03	0.157	0.03
Diff. output gap response	$r_{\Delta y}$	normal	0.125	0.05	0.22	0.216	0.03	0.186	0.03
Mon. pol. shock std.	σ_r	invgamma	0.1	2	0.24	0.105	0.01	0.098	0.01
Mon. pol. shock pers.	ρ_r	beta	0.5	0.2	0.12	0.296	0.06	0.323	0.07
Interest rate smoothing	ρ_R	beta	0.75	0.1	0.81	0.908	0.01	0.918	0.01
Log posterior						-418.40		-402.86	
Log marginal likelihood		Laplace				-492.75		-481.00	
		MCMC-MHM				-492.82		-481.15	

Note: Euro area data for 1985Q1–Q4 are used as pre-sample and the log-likelihood is evaluated for the period 1986Q1–2019Q2. A posterior sample of 100,000 post burn-in draws was generated in the Metropolis-Hastings chain. Convergence was checked using standard diagnostics such as CUSUM plots and the potential scale reduction factor on parallel simulation sequences. The Markov chain Monte Carlo modified harmonic mean (MCMC-MHM) marginal likelihood was numerically computed from the posterior draws using the estimator of Geweke [75].

The fact that the LML is higher for the BR model might be surprising, given that the unconditional variance of some of the key exogenous innovations are notably larger in this variant of the model. However, this can be understood by recognizing that a given-sized exogenous impetus typically propagates less in the BR model relative to the RE model. One good example is the risk shock $\hat{\varepsilon}_t^b$. In simplifed variant of the model without habit and separability between consumption and labor ($\sigma_c = 1$), the discounted consumption euler equation can be written

$$\widehat{c}_t = -\mathrm{E}_t \Sigma_{s=0}^{\infty} \left(\varphi_h\right)^s \left[(\hat{R}_{t+s} - \widehat{\pi}_{t+1+s} + \hat{\varepsilon}_{t+s}^b) \right],$$

and it is evident from this equation that a given sized change impetus to $\left\{\hat{\varepsilon}_t^b\right\}_{s=0}^{\infty}$ will affect $\widehat{c}_t$ notably more in the RE model with $\varphi_h = 1$ compared to the BR model in which φ_h is estimated to be about 0.95.

If we include σ_c in the estimation with the SW07 prior, LML for the RE model increases to -487.12 (MCMC-MHM) so the difference in LML between the BR and RE models shrinks from 11.7 to 5. So while the BR model still has higher LML, the difference is notably smaller. Also, for the RE model, the estimate of σ_c equals 1.24 which implies a notably higher annualized steady state real rate of 1.5 percent.

Second, the policy and deep parameters are generally similar to those estimated by SW07, but there are some notable exceptions. First, in line with several recent papers,the estimated degree of price stickiness is somewhat more pronounced compared to SW07. We have a posterior mode for ξ_p in the range $0.85 - 0.90$ whereas SW07 obtained 0.65. The tendency of an increased degree of price stickiness in the extended sample is supported by Del Negro, Giannoni and Schorfheide [47], who argue on US data that a New Keynesian model similar to ours augmented with financial frictions points towards slow adjustment in prices to fit the behavior of inflation during the Great Recession. We also have a somewhat higher degree of wage stickiness than estimated previously on US data, the SW posterior mode for ξ_w is about 0.73 in SW07, and on EA data we get a posterior mode for ξ_w around 0.75. This estimate is very close to the estimate in the ECBs NAWM II model (see [40]). These estimates imply that the response of price inflation is very sluggish and muted for key shocks in the model, reflecting an estimated high degree of price and wage stickiness. We also do a robustness experiment when imposing a higher degree of wage stickiness in Section 7.

Third and finally, in terms of stochastic shock processes, we see in Table 3.2 that while the estimates for most of the shocks processes are similar, a notable difference is that the process for the risk premium shock changes considerably in our sample which includes the financial crisis. While the risk premium shock has a high standard error (0.24) and low persistence (0.18) in the original SW07 model, the process becomes much more persistent (0.95) in our EA sample for the behavioral model. As a consequence, the unconditional variance of the risk shock is around three times as high in our estimated model compared to SW07 (0.18 compared to 0.06). As we will see next, this finding implies that the risk shock is a key driver of business cycles in the Euro area, consistent with the earlier findings in Christiano et al. ([34], [35] and [36]) and the more recent evidence by Kollmann et al. [88].

4. Posterior Predictive Analysis

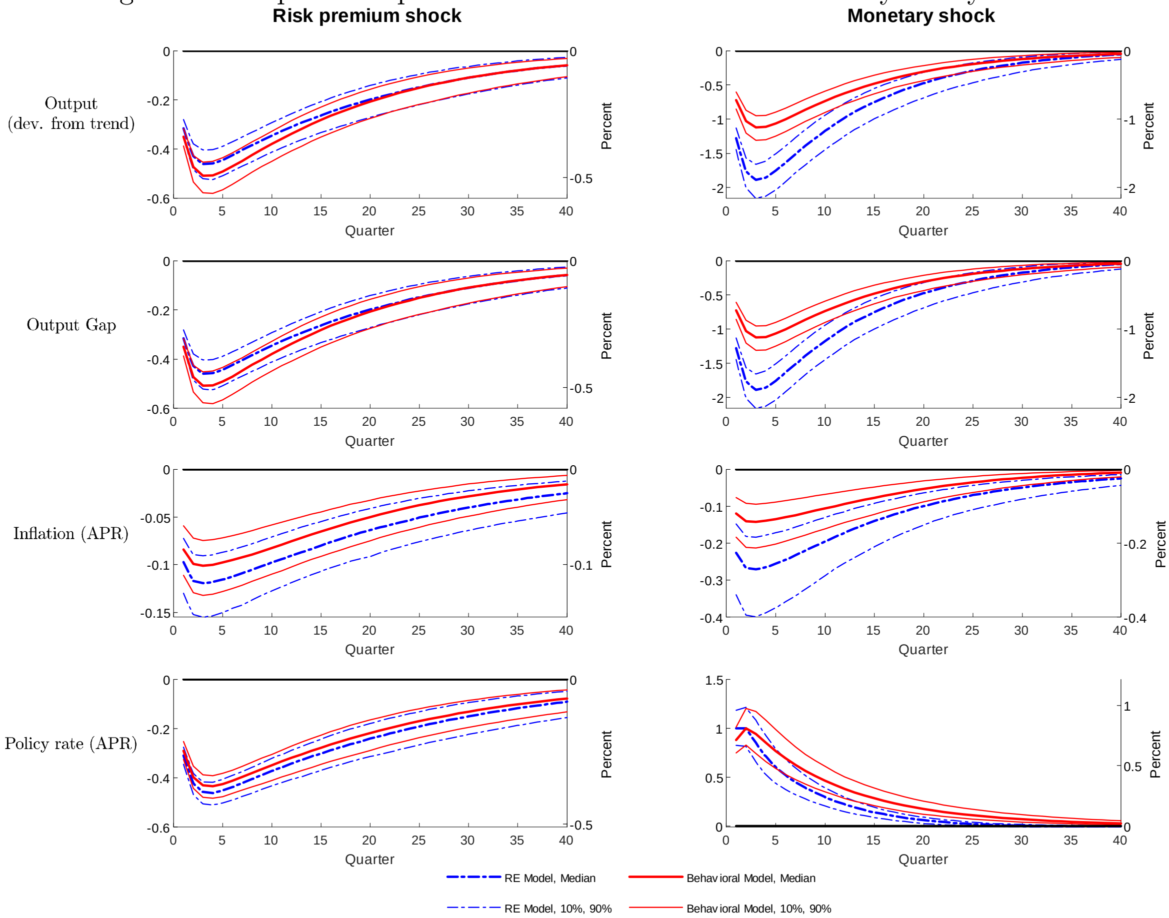
We now move on to a posterior predictive analysis with the estimated RE and BR models. Specifically, we study the differences in impulse response functions for some key shocks, with the aim to garner key lessons of the transmission of monetary policy, and to learn about the role of various shocks for accounting for output and inflation dynamics in the estimated model. Second, we study the effects of forward guidance at different horizons, to learn the extent to which the behavioral model mutes the forward guidance puzzle (see e.g. Del Negro et al. [46]). It is also interesting to learn about the extent to which the RE model indeed features a forward guidance (FG henceforth) puzzle for the euro area as previous analyses on the FG puzzle focuses on models estimated for the US with a notably higher steady state real rate ($\sigma_c > 1$).

4.1. Transmission of Shocks

Figures 4.1 and 4.2 show the effects of four key shocks in the model: Risk shocks (financial stress), monetary policy, technology and price markup shocks. Together, these four shocks account for 99 (96) percent of output gap fluctuations and 83 (86) percent of price inflation fluctuations in the behavioral (RE) model. The figures show the median, and 10- and 90-percent percentiles of impulse response functions based on the posterior obtained through the Metropolis Hastings chain. Apart from the monetary policy shock, which is normalized to imply a peak one percentage point increase in the policy rate, the figures show the effects of one standard deviation innovation and it is therefore possible to read off the relative importance of risk, technology and markup shock for the reported variables.

Turning first to the risk shock in Figure 4.1, we see that risk shocks affect output more in the behavioral model relative to the RE model. At first glance, this may be surprising given that the risk shock enters the model isomorphically to a policy rate shock and the discounting should therefore mute the effects of the shock in the behavioral model. The answer to this puzzling finding is simple, and the larger impact on output in the behavioral model is driven by the higher estimated

Figure 4.1: Impulse Responses of Risk Premium and Monetary Policy Shocks

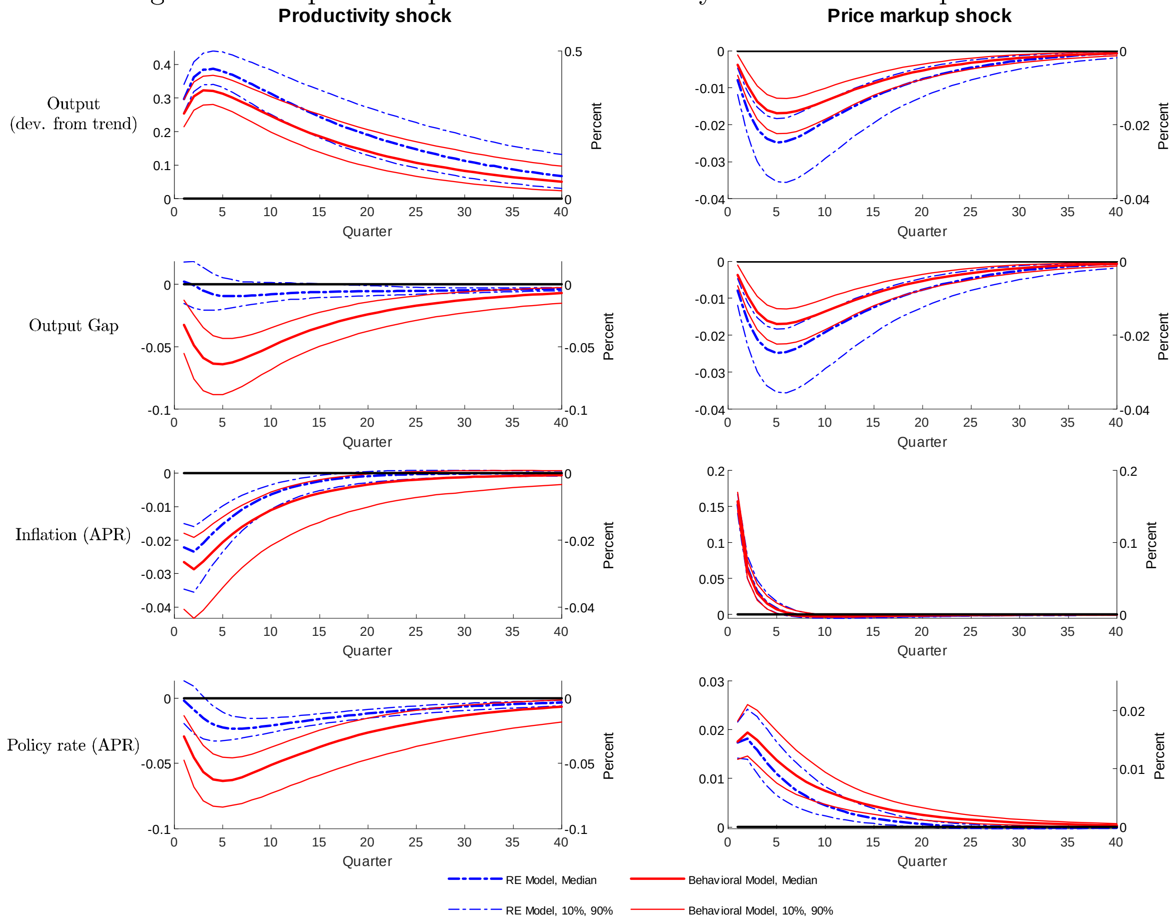


standard deviation for the risk shock (0.21 compared to 0.14 in the RE model).[9] For the monetary policy shock, we see that output and the output gap responds less. Inflation also responds less in the behavioral model, reflecting a smaller impact on the marginal cost path. A striking observation is how little inflation is affected by monetary policy shocks in the behavioral model. According to our estimated behavioral model, an interest rate hike of 100 basis points only lowers annualized inflation by a little more than 0.1 percentage points and output by about 1 percent (median estimates). In the RE model, the corresponding elasticities are considerably larger: the same-sized policy shock lowers annualized inflation and output by -0.25 percentage points and -1.8 percent, respectively. Recent VAR evidence for EA (see e.g. Andrade and Ferroni [6]) suggest effects that more in line with the behavioral than the RE model.

Figure 4.2 shows the effects of technology and price markup shocks. By comparing with the risk shocks in Figure 4.1 we see that while technology shocks have slightly larger effects on output

[9] Notice while that the risk-shock affect some flex price variables like the potential real interest rate, it does not affect potential output, so output and the output gap responsds equally following a risk shock.

Figure 4.2: Impulse Responses of Productivity and Price Markup Shocks



compared to the risk shock, the risk shock has a larger impact on the output gap. For inflation, we see that price markup shocks is dominant source of fluctuations in price inflation, which quite limited effects on output and the output gap.

Taken together, these observations imply that fluctuations in the output gap (and output growth) and inflation are not driven by the same shocks in the model; fluctuations in the output gap are primarily driven by the risk shock, while inflation is primarily driven by price markup shocks. Hence, our estimated model implies that there is an important trade-offs involved between stabilizing inflation and the output gap. Priority to price stability, as is implied by the ECB's current mandate, may consequently come at the cost of higher volatility in economic activity. A key driver behind this finding is the estimated low slope of the Phillips curve (i.e. sensitivity of current inflation to current marginal costs), which implies that inflation fluctuations are largely driven by cost-push/price markup shocks.

4.2. Effects of Forward Guidance

We now turn to study the effects of forward guidance in the estimated model. Linearized around the deterministic steady state, the simple instrument rule in eq. (2.15) is given by

$$\widehat{R}_t^* \;=\; (1-\rho_R)\left[r_\pi \widehat{\pi}_t \;+\; r_y \widehat{x}_t\right] + r_{\Delta y}\Delta\widehat{x}_t \;+\rho_R \widehat{R}_{t-1}^* \;+\varepsilon_t^r, \tag{4.1}$$

where $\widehat{x}_t$ denotes the output gap, i.e. $\widehat{x}_t = \hat{y}_t - \hat{y}_t^{pot}$.

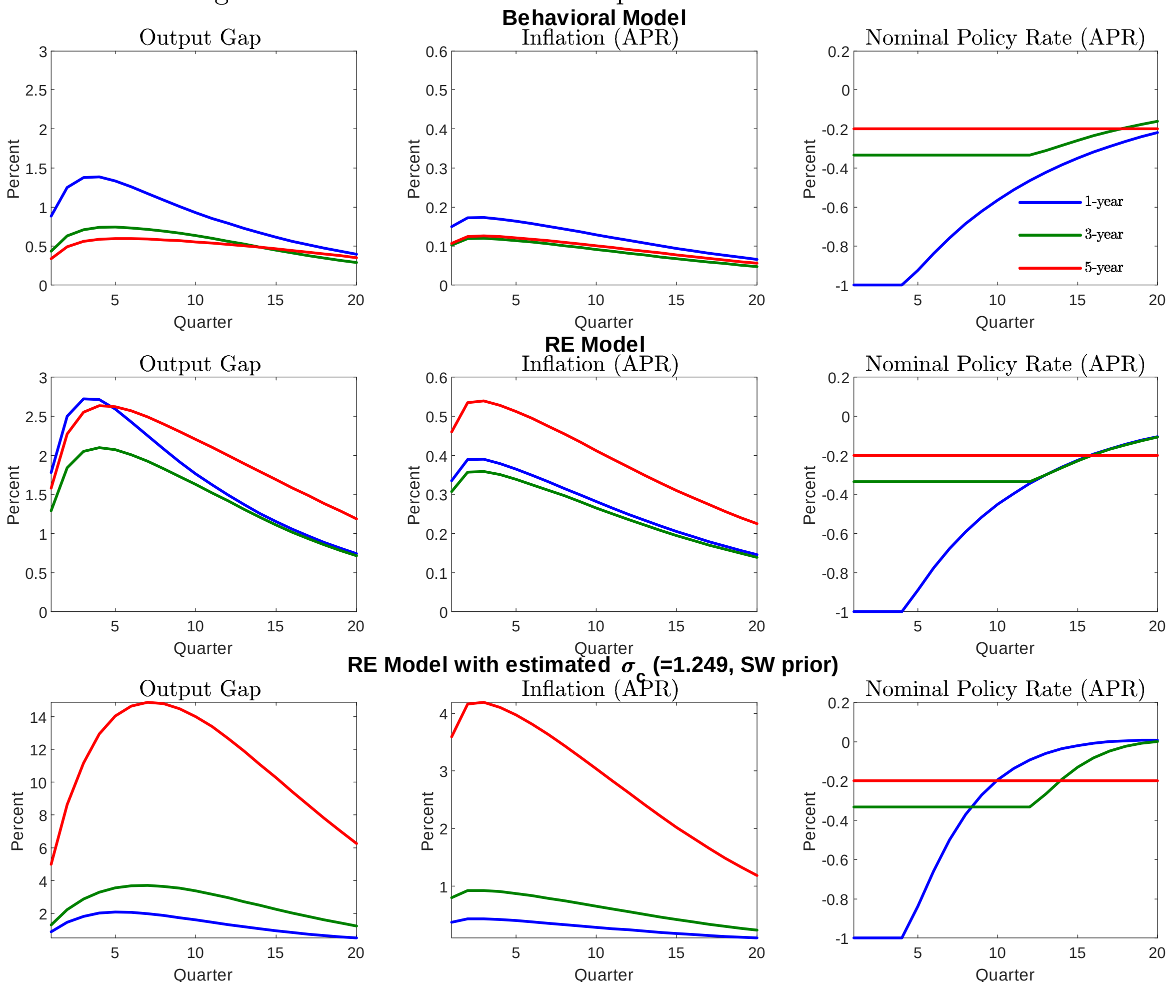
We introduce FG by assuming that the CB announces in period t a path of current and future policy innovations $\varepsilon_{t+h|t}^r$ such that the policy rate $\widehat{R}_{t+h|t}^*$ is kept below its baseline path with 1 percent for 1-year ($h_1 = 0,\ldots,3$ quarters), 3-years ($h_3 = 0,\ldots,11$ quarters), and 5-years ($h_5 =0,\ldots,19$ quarters). Notice that we make the FG simulations for the different horizons h_i comparable by sizing the lower nominal interest path so that the alternative paths sum to 4 percent in present value terms. Recalling that $\beta \approx 1$, we will thus have that the policy rate equals -0.33 percent for the 3-year and $-.20$ percent for the 5-year FG horizons, respectively. A whole sequence of (negative) shocks $\varepsilon_{t+h|t}^r$ are needed because the anticipation of future lower rates than suggested by the systematic part of rule causes output and prices to go up today and thus put upward pressure on policy rates today. This feature reinforces the stimulative effect of the commitment to keep interest rates "lower for longer" (i.e. lower than prescribed by the rule). The simulations are done for the posterior mode in Table 3.2.

The results are shown in Figure 4.3. The upper row reports the behavioral model, the second the RE model conditional on $\sigma_c = 0.5$, while the third row the effects when in line with the estimates in SW07 calibrate σ_c to be above unity (1.1) This latter calibration implies that the steady state real interest rate equals 1.3 instead of 0.6 percent.

As expected, the first row shows that the behavioral model with discounting implies that short-term policy announcements are more potent than announcements about stimulative policy far into the future. The reason is that both households and firms discount the future real interest rate path in the consumption Euler and Tobins-q first order conditions.

For the RE model with $\sigma_c = 0.5$, we find that a same-sized FG announcement has considerably larger effects on inflation and the output gap at the one-year horizon, and that the impact increases rather than decrease at the 5-year horizon. For the 3-year horizon, the effects are also somewhat smaller compared to the 1-year horizon. However, it is interesting to note that even the effects of a 5-year guidance are not found to be outsized, as in Del Negro et al. [46] and Carlstrom et al. [27]. The reason is the specification of the utility function and the calibration of σ_c well below

Figure 4.3: Forward Guidance Experiment in Different Models



unity which enables both the BR and RE models to match a low steady state real interest rate. To see this, the last row reports the same simulation when σ_c is estimated in the RE model using the SW prior instead of calibrated to 0.5 (resulting in a posterior mode of 1.249).[10] Conditional on this higher σ_c value, we see from the last row that the model generates outsized and unrealistically large effects on output and inflation for the 5-year horizon experiment, i.e. the FG puzzle.

5. Economic Fluctuations Under Current Monetary Policy Regime

We now proceed by using the behavioral model estimated in Section 3 to assess the implications of monetary constraints and the ECB's target formulation on unconditional simulated distributions and conditional forecast distributions. We begin by comparing unconditional distributions in a symmetric case – in which the ECB follows the estimated Taylor rule – with an asymmetric specifi-

[10] SW07 use a normal prior centered around 1.5 with standard error of 0.375 for this parameter.

cation in which the ECB responds more aggressively to inflation when expected inflation exceeds 2 percent. The latter regime attempts to capture a key feature of ECB's historical approach that has focused heavily on containing upside inflationary pressures, and has been reflected in the ECB's objective of keeping inflation "close to, but less than, 2% over the medium term."[11] We then use the model to assess how changes to the ECB's reaction function and the use of UMP tools can affect the conditional distributions of key variables in the recovery from a deep recession. In these experiments, we report results for the behavioral and rational expectations models both to provide intuition into how the behavioral model works and to highlight the role of expectations in shaping outcomes.

5.1. Unconditional Fluctuations

Under the symmetric regime, the ECB simply follows the estimated policy rule in eq. (4.1) though subject to an ELB constraint. To model the asymmetric regime, we modify the rule by adding a term $\bar{r}_\pi \max(\widehat{\bar{\pi}}^e_t, 0)$ that calls for the ECB to tighten in response to a rise in expected inflation $\widehat{\bar{\pi}}^e_t$ above the non-stochastic target. Specifically, these considerations are captured in a rule of the form:

$$\begin{aligned} \widehat{R}^*_t \;&=\; \rho_R \widehat{R}_{t-1} \;+\; (1-\rho_R)\left[r_\pi \widehat{\pi}_t \;+\; r_y \hat{x}_t\right] + r_{\Delta y}\Delta \hat{x}_t + \bar{r}_\pi \max(\widehat{\bar{\pi}}^e_t, 0) + \hat{\varepsilon}^r_t \;, \\ \widehat{R}_t &= \max\left\{-\left(\bar{r} - ELB\right), \widehat{R}^*_t\right\}. \end{aligned} \tag{5.1}$$

Here expected inflation is defined as $\widehat{\bar{\pi}}^e_t = (\hat{\pi}_{t+4|t} + \hat{\pi}_{t+3|t} + \hat{\pi}_{t+2|t} + \hat{\pi}_{t+1|t})/4$, and $\bar{r}_\pi$ is set to zero in the symmetric case and to $\bar{r}_\pi = r_\pi$ in the asymmetric case. We do not attempt to estimate $\bar{r}_\pi$ since $\bar{\pi}^e_t$ has only exceeded π^* in 6 quarters since the inception of the ECB January 1, 1999.

The policy rule in eq. (5.1) assumes that the central bank will keep $\widehat{R}_t$ – if constrained by the ZLB (so the $ELB = 0$) – at its lower bound $(-\bar{r})$ as long as the shadow rate, $\widehat{R}^*_t$, is below the lower bound.[12] We initially set $ELB = 0$, implying that the actual nominal policy rate $\widehat{R}_t + \bar{r}$ cannot be below zero. We will later allow for negative policy rates. i.e., $ELB < 0$. In setting the policy rate, we initially assume that the central bank smooths over the actual lagged interest rate $\widehat{R}_{t-1}$, but subsequently allow for smoothing over the notional rate.

[11] As noted in the introduction, the ECB has progressively emphasized a more symmetric approach in recent years (see, for instance, the July 25th 2019 monetary policy statement). Even so, further clarification – including to the specific language describing the ECB's inflation objective – could help solidify the public's perception that the ECB is following a symmetric approach.

[12] Note that $\widehat{R}_t$ in the policy rule (5.1) is measured as percentage point deviation from its non-stochastic quarterly steady state level $(\bar{r})$, so restricting $\widehat{R}_t$ not to fall below $-\bar{r}$ is equivalent to imposing the ZLB.See (3.1) for the definition of $\bar{r}$.

Our specification of asymmetry captures in a simple way the ECB's longstanding priority to fight high inflation and be more vigilant to upside inflation risks. While stylized, it provides a constructive benchmark to assess the implications of an asymmetric target formulation and the trade-offs it implies between inflation and output gap stabilization.

For these two monetary policy regimes, we simulate a long sample of 25,000 observations in the estimated model. Notably, the simulated sample is generated by sampling stochastic i.i.d. shocks rather than bootstrapping from the estimated model as in Bernanke, Kiley and Roberts [14].[13] Because there is some the correlation among the smoothed shocks in the estimated model – which explains the ELB episodes with below-target inflation and subdued economic activity in the sample – our procedure means that we present conservative estimates of the costs of the ELB.

Figure 5.1 reports the simulation results for the model with behavioral expectations with the left column showing the results under the symmetric rule and the right column the asymmetric rule. The asymmetric regime is associated with inflation and output gap distributions which are notably more left-skewed (i.e., have long left tails). The left-skewed distributions imply that the output gap is negative on average, and that the mean inflation rate falls short of the inflation target of 2 percent.

Table 5.1 helps quantify how the nature of the rule – symmetric or asymmetric – affects the distribution of key variables, with Panel A reporting results for the behavioral model, and Panel B under rational expectations. the corresponding simulations with rational expectations.

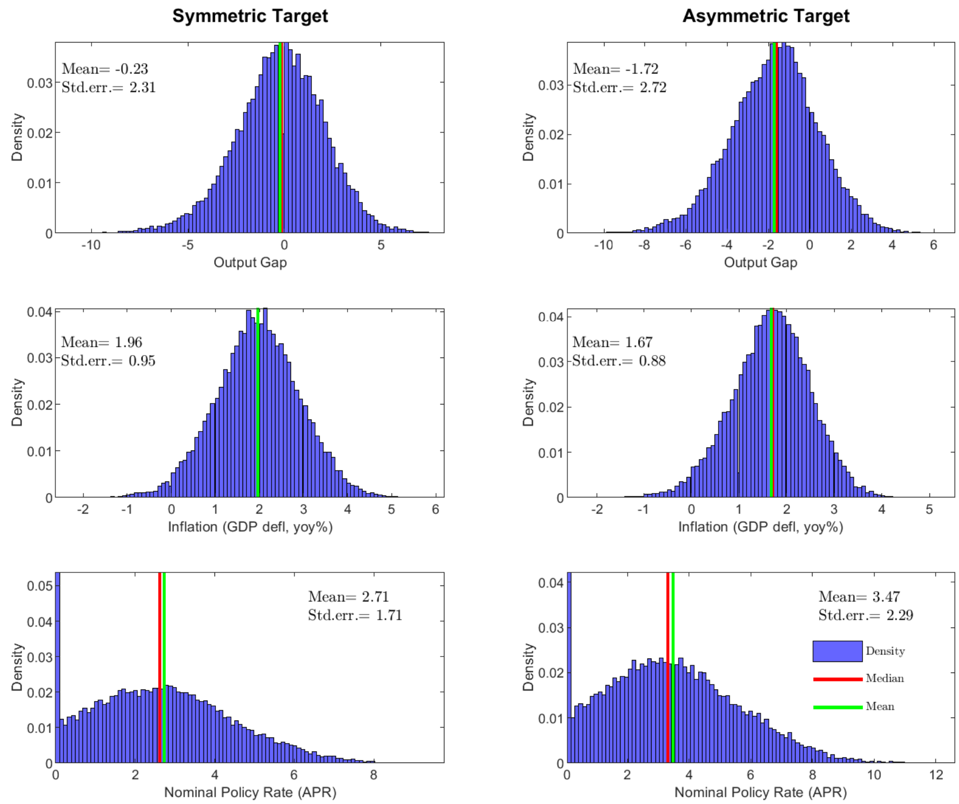
The symmetric rule in the behavioral model implies an average inflation rate only a tad below 2 percent, and a slightly negative mean output gap of -0.2. The small downward bias in average inflation and in the output gap reflect the nonlinearity posed by the ELB constraint. Because the ELB occurs slightly more often and implies more contractionary effects under rational expectations, the negative inflation and output gap bias is a bit more pronounced, but still fairly modest.

Under the asymmetric policy rule, the downward bias in both inflation and the output gap is much more pronounced. The average inflation rate runs well below 2 percent ($1\frac{3}{4}$ percent), and the mean output gap is -1.7 percent in the behavioral and -1.9 percent in the RE model. The only favorable aspect of the asymmetric policy rule is that it generates slightly lower inflation volatility, reflecting that the probability of inflation exceeding 2 percent is notably lower under the asymmetric rule.

The large average output cost under the asymmetric policy response largely reflects an impor-

[13] Specifically, by setting the seed of the random number generator to draw exactly the same exogenous shocks in all simulations we ensure that any differences are driven by the alternative monetary policy regimes.

Figure 5.1: Histogram of Unconditional Simulations under the Current Policy Regime



tant role for cost-push shocks (price and wage markup) and a low sensitivity of inflation to aggregate demand (i.e., flat Phillips curve) in the estimated model. To be concrete, the policymaker's preference for offsetting a positive cost-push (to keep inflation from rising much above 2 percent) requires engineering a sharp output contraction given the flat slope the Phillips Curve. Since cost-push shocks that boost inflation expectations about 2 percent occur frequently, the asymmetric policy rule pushes the output gap zero on average. While it is assumed in these simulations that the sensitivity of inflation to the output gap is state independent (i.e. the same regardless of the economy is operating above or below its potential), allowing the sensitivity to be more somewhat more (less) sensitive to demand when output is above (below) potential does not change this conclusion as shown subsequently in the robustness analysis in Section 7.[14]

[14] While the asymmetric rule pushes down the mean inflation rate and causes the output gap to run signficantly negative on average, it has a neglible effect on the likelihood that the ELB will bind. However, it seems plausible that the asymmetric rule could noticeably amplify ELB risks in the plausible case that low realized inflation were allowed to feed through to long-run inflation expectations (so that long-run inflation expectations were not well anchored, rather than closely tethered to the inflation target as in our simulations).

Table 5.1: Unconditional Distributions for Current Policy Regime.

Model	Inflation					Output Gap			Output Growth		Policy Rate		
Variant	Mean	Std	P($\pi \leq 0$)	P($\pi > 2$)	P($\pi > 3$)	Mean	Std	M($x \vert x \leq x^{5th}$)	Mean	Std	Mean	Std	P($R = 0$)
Panel A: Baseline Behavioral Model													
Symmetric	1.96	0.95	2.09	48.53	13.71	-0.23	2.31	-5.46	1.2	1.46	2.71	1.71	4.47
Asymmetric	1.67	0.88	2.52	35.09	4.74	-1.72	2.72	-6.37	1.2	1.5	3.47	2.29	3.40
Panel B: RE Model													
Symmetric	1.91	1.04	3.66	47.50	14.12	-0.44	2.76	-7.74	1.20	1.60	2.67	1.72	4.99
Asymmetric.	1.56	0.99	4.47	31.82	4.00	-1.94	3.17	-8.31	1.20	1.69	2.88	1.83	4.68

Note: All variables in the table are in annualized rates. Std is the standard deviation of the series computed based in the simulated sample with $25,000$ observations. M($x|x \leq x^{5th}$) is mean of the output gap series counting only observations below or equal its 5^{th} percentile (which is contingent on each policy). Symmetric regime results in based on the estimated rule (5.1) with $\bar{r}_\pi = 0$ whereas the asymmetric rule sets $\bar{r}_\pi = r_\pi$.

5.2. Conditional Forecast Distributions

After having studied how deployment of UMP tools can affect the unconditional densities, we now turn to analyzing how monetary policy can influence the recovery from a deep recession. To do so, we derive conditional forecast distributions for key macroeconomic variables under different assumptions about monetary policy that condition on outcomes through 2020Q3.[15] Given that output decline through that period was driven by the highly unusual circumstances of the pandemic, allowing the model to generate forecast paths implies a very slow path to recovery that is likely too pessimistic (as we show below). The model simply can't take account of the special circumstances driving much of the output decline, e.g., lockdowns, that can be expected to have more transient effects on output than implied by the shocks in the model. Even so, the analysis is very useful for considering monetary options in a severe downside scenario, as well as in considering monetary options in a deep recession more generally.

Turning to specifics, we compute conditional forecast distributions over the 2020Q4-2025Q3 period under four alternative formulations of policy.[16] First, we assume monetary policy is subject to the ZLB and follows the rule in (5.1) – we refer to this case as the "Estimated Rule".[17] Importantly, this policy implies that the central bank smooths over the actual rate and that it responds

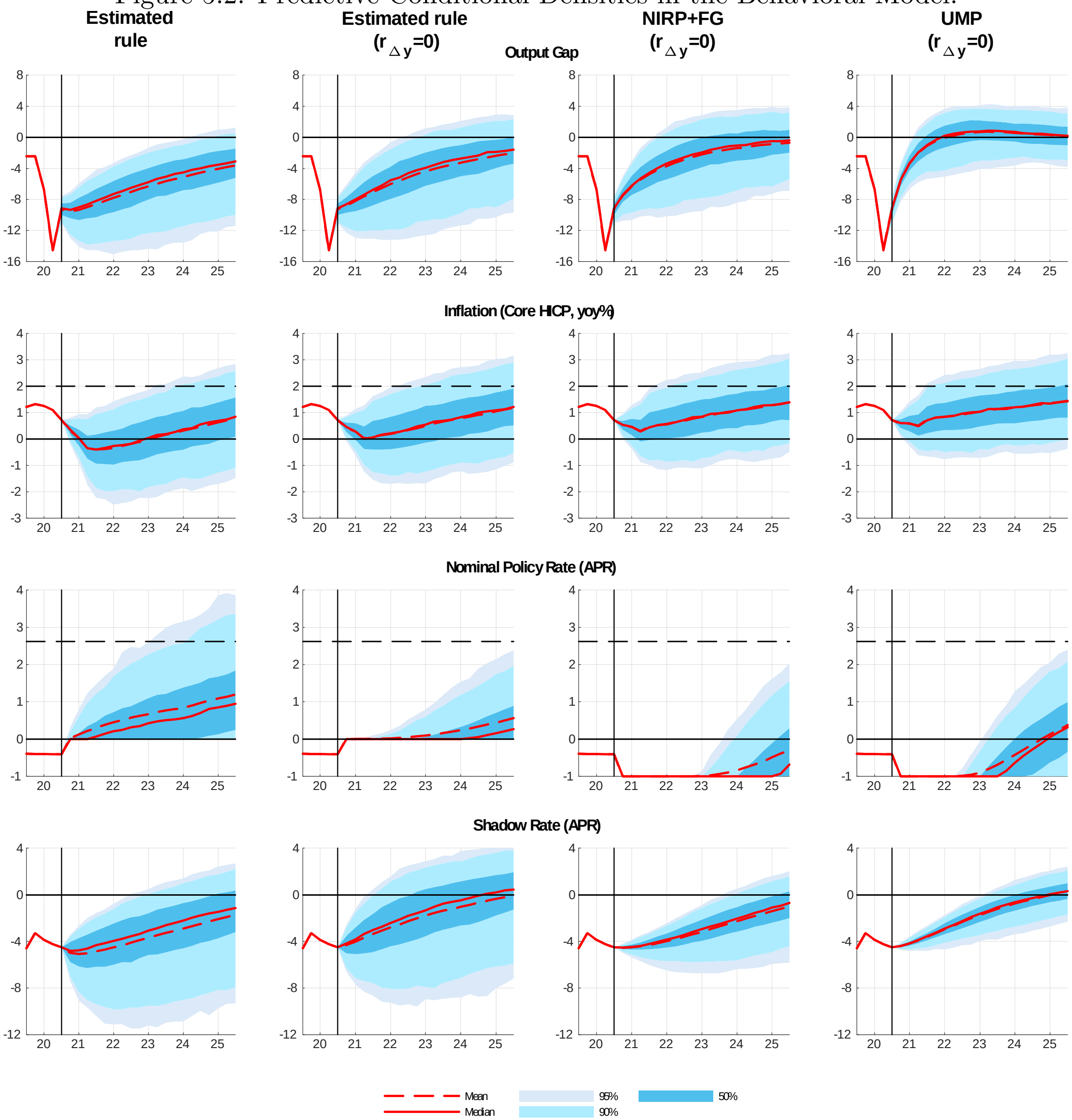
[15] Specifically, to our baseline sample (which ends 2019Q4) we add observations on output, consumption, investment, hours worked per capita, inflation, and the policy rate for 2020Q1 and 2020Q2. We do not provide the model with real wage growth, since this series fluctuate sharply during 2020Q1-Q3. For 2020Q3, which is based on the 2020 fall WEO forecasts, we only provide the model wih 5 observables (output, consumption, investment, policy rate and inflation). Finally, since core HICP is more commonly referred to as intermediate target variable for ECB monetary policy than inflation measured with the GDP deflator, we use the former when obtaining the smoothed state in 2020Q3 (although the model is estimated on inflation measured with the GDP deflator following SW07).

[16] Our model-based conditional forecast distributions do aim to account for the quantitative easing that the ECB has done thus far under all of the monetary policy options considered. In this vein, we assume that the UMP tools deployed by the ECB has reduced the risk premium by 400 basis points (in annualized terms) and adjust the filtered risk premium shock $\hat{\varepsilon}_t^b$ in eq. (2.12) up accordingly.

[17] In all the conditional simulations below, we drop the term $r_\pi \max(\widehat{\overline{\pi}}_t^e, 0)$ in the policy rule (5.1) and assume that the ECB behaves symmetrically rather than potentially create rather than pursue an especially tight policy when inflation expectations exceed 2 percent. In contrast to the unconditional simulations, we also set the variance of the exogenous monetary policy shock $\hat{\varepsilon}_t^r$ in the policy rule to zero. We think it is reasonable to allow for policy shocks in the previous unconditional setting, reflecting some shifting policy preferences over time, but abstract from them in a conditional setup with a very challenging outlook.

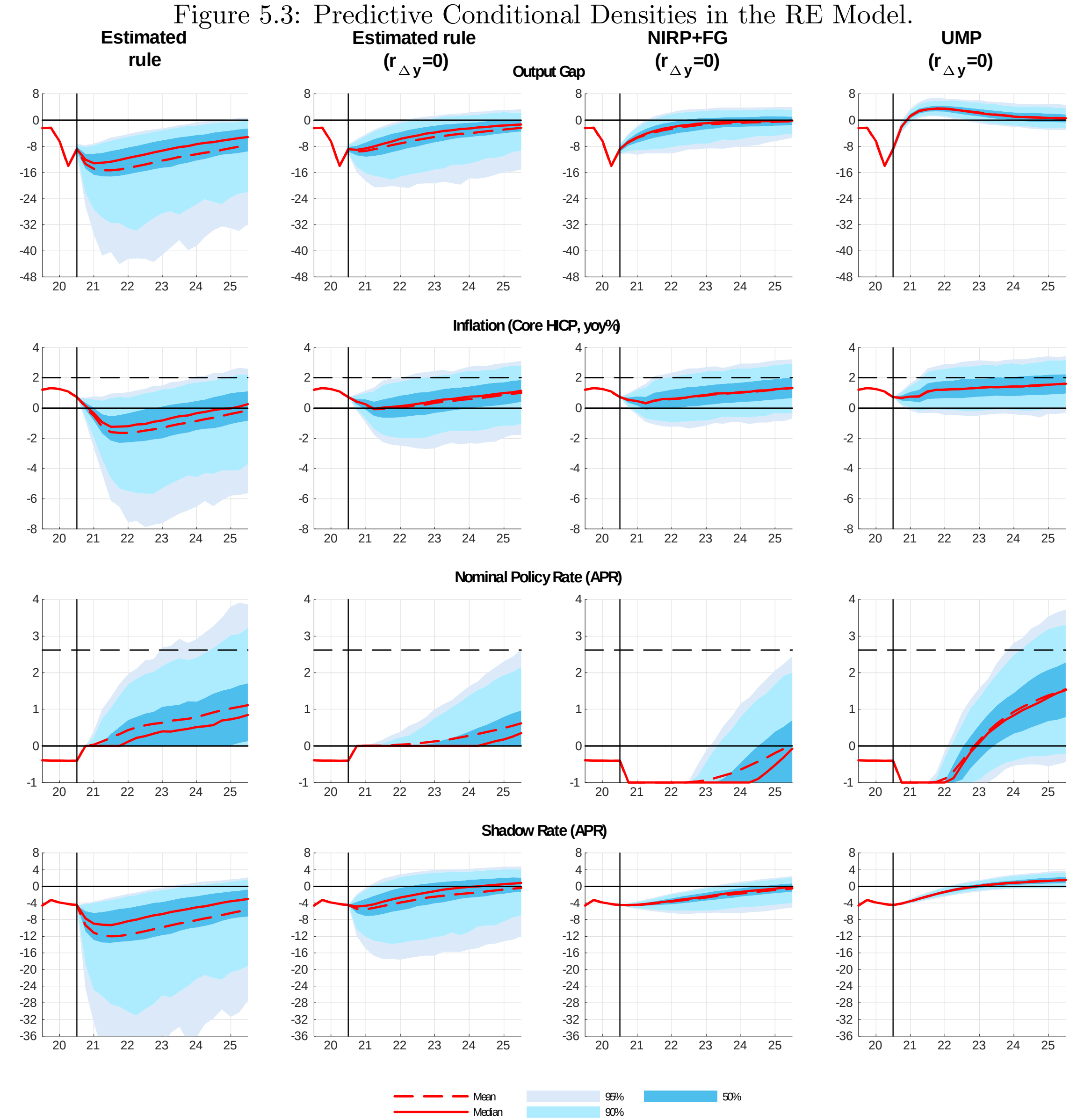
vigorously to output growth. Second, we present results when not responding to output growth "Estimated Rule ($r_{\Delta y} = 0$)" to highlight the important role of output growth in the formulation of policy in a recovery from a severe recession. This shift in policy happens unexpectedly and is fully credible. However, the central bank still responds to the output gap (i.e. $r_y > 0$).

Figure 5.2: Predictive Conditional Densities in the Behavioral Model.



Third, we assume ECB can deploy some UMP tools by setting $ELB = -1/4$ (-1 percent annualized) and adopt a lower for longer policy by smoothing over the shadow rate $\widehat{R}^*_{t-1}$ instead of $\widehat{R}_{t-1}$ in (5.1)– we refer to this case as "NIRP+FG ($r_{\Delta y} = 0$)" in the figure. This corresponds to a deposit rate cut of 50 basis points relative to the level that prevailed in 2021:Q1. While it is possible that the reversal rate (see Brunnermeier and Koby [22])is somewhat lower still, no central bank had pushed rates below -75 basis points as of early 2021, so this would break new ground. Our modeling of state-dependent forward guidance (replacing $\rho_R \widehat{R}_{t-1}$ with $\rho_R \widehat{R}^*_{t-1}$ in 5.1) is in the spirit of the"lower for longer policy" considered by Reifschneider and Williams [107] given that ρ_R is estimated to be quite high (about .91).[18]

Figure 5.3: Predictive Conditional Densities in the RE Model.



The fourth case builds on the previous one – by assuming the ECB pursues more deeply negative rates and forward guidance through the shadow rate – but also assumes that it undertakes additional

[18] To form an initial value of R^*_t – i.e. what the ECB policy rate would be if unconstrained by an ELB – we use the techniques in Wu and Xia [118] to come up with −4.51 percent in 2020Q3.

large scale asset purchases to offset elevated private bond spreads $\hat{\varepsilon}_t^b$ – we refer to this case as "UMP ($r_{\Delta y} = 0$)".[19] Since the filtered value for the risk premium shock $\hat{\varepsilon}_t^b$ allows for a larger scope of asset purchases than current levels of BBB-AAA spreads, we limit the effects the asset purchase component ϱ_t can have on the effective interest rate in eq. (C.1) to the equivalence of about 150 basis points on a ten-year yield the first two years.

The conditional densities are constructed allowing for both parameter and shock uncertainty. Specifically, we draw 100 parameter vectors from the 100,000 draws in the Metropolis chain and for each of these 100 posterior draws we simulate the economy forward 10 times allowing for shock uncertainty (i.e. unexpected shocks hitting the economy in each period). All shocks are drawn without replacement. Thus, they are different for each of the 100 parameter draws from the posterior, but they are the same for each policy formulation, so that the different outcomes are driven purely by policy and not by luck. From the 1,000 projections, we form the conditional densities reported in Figure 5.2.

There are several interesting features apparent in Figure 5.2. First, while the output gap is massive and persistent under the estimated rule (first column), inflation only dips transiently into deflationary territory (in 2021-2022). Hence, the behavioral model provides a way of accounting for the "missing deflation" puzzle emphasized by Linde and Trabandt [98] without relying on large positive markup shocks (see Fratto and Uhlig [65]). Second, the uncertainty bands for core inflation are close to symmetric even without unconventional policy tools (again, this is apparent from the first column, but also for the other policy options considered). Thus, the ZLB does not trigger any sizable downside inflation risk according to the behavioral model (see previous discussion of monetary policy shocks and FG in section 4).

A third feature of the simulations is that reacting to output growth – as under the estimated rule – markedly slows the recovery in output and inflation. In particular, because the central bank responds vigorously to output growth through $r_{\Delta y}$, it tends to hike rates quickly when growth rebounds (recall that the growth rate term $r_{\Delta y}\Delta\widehat{x}_t$ is not multiplied by $1-\rho_R$ in the policy rule 5.1), as is apparent from the mean and median interest rate interest rate projections. Accordingly, there are sizeable benefits from adopting an alterative reaction which does not react to output growth in spurring a faster recovery, as seen in the second column. Some what generally, these results highlight the drawback of a strong output growth coefficient in a severe recession when inflation is well below target, even while acknowledging that there may be some benefits of such a

[19] Appendix C provides a detailed description of modeling of asset purchases.

reaction function under more historically normal conditions for reasons emphasized by Orphanides.

The fourth feature is the apparent benefits of UMP tools in spurring faster recover. When allowing for negative rates and forward guidance that takes account of the lagged shadow rate (column three), the drop in inflation is moderated further and the output gap is more quickly brought back towards target. In this case, given that the shadow rate remains well below the ELB for an extended period, a policy rate hike before 2023 is basically a zero probability event. When also allowing for asset purchases (column four), the outlook improves further and the output gap closes at the end of 2021. Inflation, on the other hand, still remains persistently below the 2 percent target during the forecast horizon although the deflation probability is now significantly smaller.

Figure 5.3) presents results for the model with rational expectations. As in the behavioral model, it is clear that the pace of recovery improves markedly under the reaction function not responding to output growth (comparing the second to the estimated rule in the first column), and that UMP tools are strongly beneficial. However, a striking feature of the RE model is that downside risks to output and inflation are clearly more dire, especially under the estimated rule (column one). Moreover, the benefits to the modal outlook – and in reducing downside risks – of making a credible commitment not to respond to output growth and to deploy UMP tools are much stronger than in the behavioral model. This reflects that such tools are notably more potent under RE given that the central bank has much more power to influence expectations.

All told, the modal outlook and associated uncertainty bands appear reasonably similar in the two models under the more aggressive policy responses in UMP tools (columns three and four). However, it is important to underscore the different reasons underlying this end result. In particular, while monetary policy constraints have less adverse effects in the behavioral model than under rational expectations, the more aggressive policy options (including UMP tools) are also less effective and hence do not improve outcomes as much as in the RE model.

6. Economic Fluctuations Under Alternative Monetary Policy Strategies

In this section, we use the estimated model to assess the merits of alternative monetary policy strategies, including price level targeting and average inflation targeting. Given that these strategies pledge to take account of past inflation performance, they may differ substantially from flexible inflation targeting (which focuses on recent inflation outcomes, typically within the last year). We consider both a permanent shift toward these types of strategies, as well as a more temporary shift that would only take effect when policy rates reached their effective lower bound. Our simulations continue to assume that the ECB follows a symmetric rule when not constrained by the ELB, and hence abstract from the term $r_\pi \max(\widehat{\pi}^e_t, 0)$ in the policy rule (5.1). [20]

6.1. Alternative Policy Regimes

6.1.1. Permanent Average Inflation and Price Level Targeting Regimes

Following Vestin [116] and Nessen and Vestin [104], we characterize average inflation targeting (AIT) by the policy rule:

$$\widehat{R}_t = \max\left\{-\bar{r}, \rho_R \widehat{R}_{t-1} \ + \ (1-\rho_R) \ \left[r_\pi \bar{\pi}_t + r_y \hat{x}_t\right] \ + r_{\Delta y}\Delta\hat{x}_t + \hat{\varepsilon}^r_t \right\}. \tag{6.1}$$

where $\bar{\pi}_t = \frac{1}{T^*}\Sigma_{s=0}^{T^*-1}\hat{\pi}_{t-s}$. The rule thus implies that the central bank takes account of past deviations of inflation from target stretching back T^*periods. The longer the target horizon T^*, the more closely the regime resembles price level targeting.

For AIT, we set $T^* = 19$ (which is the optimal horizon in Vestin [116]), and hence consider a five year target horizon. For price level targeting (PLT), we set $T^* = \infty$ so that the central bank in effect targets the price level (as a deviation from the linear inflation target price trend), but maintains the inflation response coefficient r_π unchanged at its estimated posterior value. In the AIT case, we also consider an alternative variant in which r_π is multiplied by 5, and thus implicitly consider the following inflation terms in the policy rule

$$r_\pi \hat{\pi}^{yoy}_t + r_\pi \hat{\pi}^{yoy}_{t-4} + r_\pi \hat{\pi}^{yoy}_{t-8} + r_\pi \hat{\pi}^{yoy}_{t-12} + r_\pi \hat{\pi}^{yoy}_{t-16} = 5 r_\pi \Sigma_{s=0}^{19} \hat{\pi}_{t-s} = r_\pi^{AIT} \bar{\pi}_t \tag{6.2}$$

where $\hat{\pi}^{yoy}_t$ denotes four-quarter moving average of inflation (deviation from its non-stochastic target). This latter specification follows Arias et al. [5] who consider a larger weight for the average inflation gap in their AIT rule. By presenting results for a unchanged coefficient and a coefficient 5 times larger, we can parse out the partial effects of the AIT gap and a larger coefficient on this gap.

6.1.2. Temporary Average Inflation and Price Level Targeting Regimes

Following Bernanke [13], Bernanke et al. [14], and Clarida's [39] interpretation of the Federal Reserve's new monetary policy framework, we complement the analysis of permanent AIT and

[20] In Appendix E we additionally study the merits of changes to the inflation target (1.5 and 2.5 percent) and a target band regime where the central bank only reacts forcefully if expected inflation is below (above) 1.5 (2.5) percent.

PLT frameworks with an analysis of a temporary shift to AIT or PLT that only takes hold when the economy is constrained by the ELB.

The temporary AIT regime builds on the rule (6.1),

$$\widehat{R}_t = \max\left\{-\bar{r}, \rho_R \widehat{R}_{t-1} \;+\; (1-\rho_R)\;\left[I_t^{ZLB} r_\pi^{AIT} \bar{\pi}_t + (1-I_t^{ZLB}) r_\pi \pi_t + r_y \hat{x}_t\right] \;+ r_{\Delta y} \Delta \hat{x}_t + \hat{\varepsilon}_t^r\;\right\} \tag{6.3}$$

where the ZLB indicator function is given by the logistic function

$$I_t^{ZLB} = \frac{1}{1 + e^{k\left(\widehat{R}_t^* + \bar{r}\right)}}, \tag{6.4}$$

where $k = 25$ and

$$\widehat{R}_t^* \;=\; \rho_R \widehat{R}_{t-1}^* \;+\; (1-\rho_R)\;\left[I_t^{ZLB} r_\pi^{AIT} \bar{\pi}_t + (1-I_t^{ZLB}) r_\pi \pi_t + r_y \hat{x}_t\right] \;+ r_{\Delta y} \Delta \hat{x}_t + \hat{\varepsilon}_t^r\;. \tag{6.5}$$

The rule (6.3) implies a temporary switch from current to average inflation when the unconstrained shadow policy rate, $\widehat{R}_t^* + \bar{r}$, is below or at the ZLB since $I_t^{ZLB} \approx 1$ as long as $\widehat{R}_t^* + \bar{r} \leq 0$ (noting that $ELB = 0$ in these simulations). When the policy rate is sufficiently above the ZLB then $I_t^{ZLB} = 0$ and the central bank follows the standard flexible inflation targeting rule (5.1) (without the asymmetric term, so $\bar{r}_\pi = 0$).

For the temporary price level targeting regime, we assume that

$$\widehat{R}_t = \max\left\{-\bar{r}, \rho_R \widehat{R}_{t-1} \;+\; (1-\rho_R)\;\left[I_t^{ZLB} r_\pi p_t^{ZLB} + (1-I_t^{ZLB}) r_\pi \pi_t + r_y \hat{x}_t\right] \;+ r_{\Delta y} \Delta \hat{x}_t + \hat{\varepsilon}_t^r\;\right\} \tag{6.6}$$

where the price level gap is calculated as

$$p_t^{ZLB} = I_t^{ZLB}\left(\pi_t + p_{t-1}^{ZLB}\right). \tag{6.7}$$

Equation (6.7) implies that the central bank only attempts to close a price level gap p_t^{ZLB} (i.e. a price path running below the central bank's target path) when the central bank is constrained by the ZLB and $I_t^{ZLB} = 1$. This means that the central bank does not attempt to make up for any shortfall of the price level relative to its target path emerging prior to hitting the ZLB (when $I_t^{ZLB} = 0$). I_t^{ZLB} is determined by eq. (6.4) where $\widehat{R}_t^*$ in the temporary PLT case is given by (6.5) with $r_\pi^{AIT} \bar{\pi}_t$ replaced by $r_\pi p_t^{ZLB}$.

6.2. Unconditional Distributions for Alternative Regimes

In Table 6.1 we report the implications of the alternative AIT and PLT regimes with the results under the estimated (symmetric) rule based on equation (5.1) serving as a benchmark.

Table 6.1: Unconditional Distributions for Alternative Policy Regimes.

Policy Regime	Inflation Mean	Std	$P(\pi \leq 0)$	$P(\pi > 2)$	$P(\pi > 3)$	Output Gap Mean	Std	$M(x \mid x \leq x^{5th})$	Output Growth Mean	Std	Policy Rate Mean	Std	$P(R \leq 0)$
Panel A: Behavioral Model													
Symmetric Target	1.96	0.95	2.09	48.53	13.71	-0.23	2.31	-5.46	1.2	1.46	2.71	1.71	4.47
AIT	1.97	0.91	1.57	48.74	12.96	-0.18	2.38	-5.43	1.2	1.5	2.69	1.63	3.93
AIT - $r_\pi^{AIT} = 5r_\pi$	1.98	0.71	0.28	48.53	7.82	-0.16	2.45	-5.33	1.2	1.54	2.70	1.72	5.16
PLT	2.00	0.63	0.05	49.84	5.91	-0.16	3.57	-7.91	1.2	1.91	2.75	2.03	9.50
Temp. AIT	1.96	0.95	1.98	48.05	13.74	-0.22	2.30	-5.41	1.2	1.46	2.71	1.71	4.29
Temp. AIT - $r_\pi^{AIT} = 5r_\pi$	2.02	0.89	0.92	50.54	14.10	0.02	2.13	-4.47	1.2	1.45	2.66	1.74	5.54
Temp. PLT	2.05	0.89	0.92	52.00	14.60	0.13	2.12	-4.09	1.2	1.45	2.60	1.78	10.30
Panel B: RE Model													
Symmetric Target	1.91	1.04	3.66	47.50	14.12	-0.44	2.76	-7.74	1.2	1.6	2.67	1.72	4.99
AIT	1.94	0.94	2.29	48.09	13.00	-0.30	2.72	-6.93	1.2	1.65	2.67	1.63	4.14
AIT - $r_\pi^{AIT} = 5r_\pi$	1.98	0.7	0.21	48.57	7.57	-0.11	2.8	-6.17	1.2	1.69	2.64	1.53	3.65
PLT	2.00	0.63	0.04	50.02	5.58	-0.05	4.43	-9.65	1.2	2.38	2.66	1.64	5.12
Temp. AIT	1.92	1.01	3.28	47.66	14.17	-0.39	2.63	-7.16	1.2	1.60	2.68	1.71	4.60
Temp. AIT - $r_\pi^{AIT} = 5r_\pi$	2.02	0.93	1.22	50.41	14.81	0.05	2.14	-4.57	1.2	1.52	2.66	1.72	3.72
Temp. PLT	2.03	0.93	1.25	51.05	15.04	0,.12	2.07	-4.07	1.2	1.50	2.63	1.76	8.48

Note: All variables in the table are in annualized rates. Std is the standard deviation of the series computed based in the simulated sample with $25,000$ observations. $M(x|x \leq x^{5th})$ is mean of the output gap series counting only observations below or equal its 5^{th} percentile (which is contingent on each policy regime). "Symmetric Target" drops the term $r_\pi \max(\widehat{\overline{\pi}}^e_t, 0)$ from the policy rule (5.1). "AIT" is average inflation targeting given by the rule in eq. (6.1) with $T^* = 19$, whereas "PLT" is price level targeting with policy given by same rule but $T^* = \infty$. "Temporary AIT" policy follows the rule (6.3) with the indicator function defined by eq. (6.4). "Temp AIT - $r_\pi^{AIT} = 5r_\pi$" is the same as "Temporary AIT" except that r_π^{AIT} is 5 times larger ($5r_\pi$). "Temporary PLT" policy follows the rule (6.6) with the ZLB price level gap given by equation (6.7) and indicator function defined by eq. (6.4).

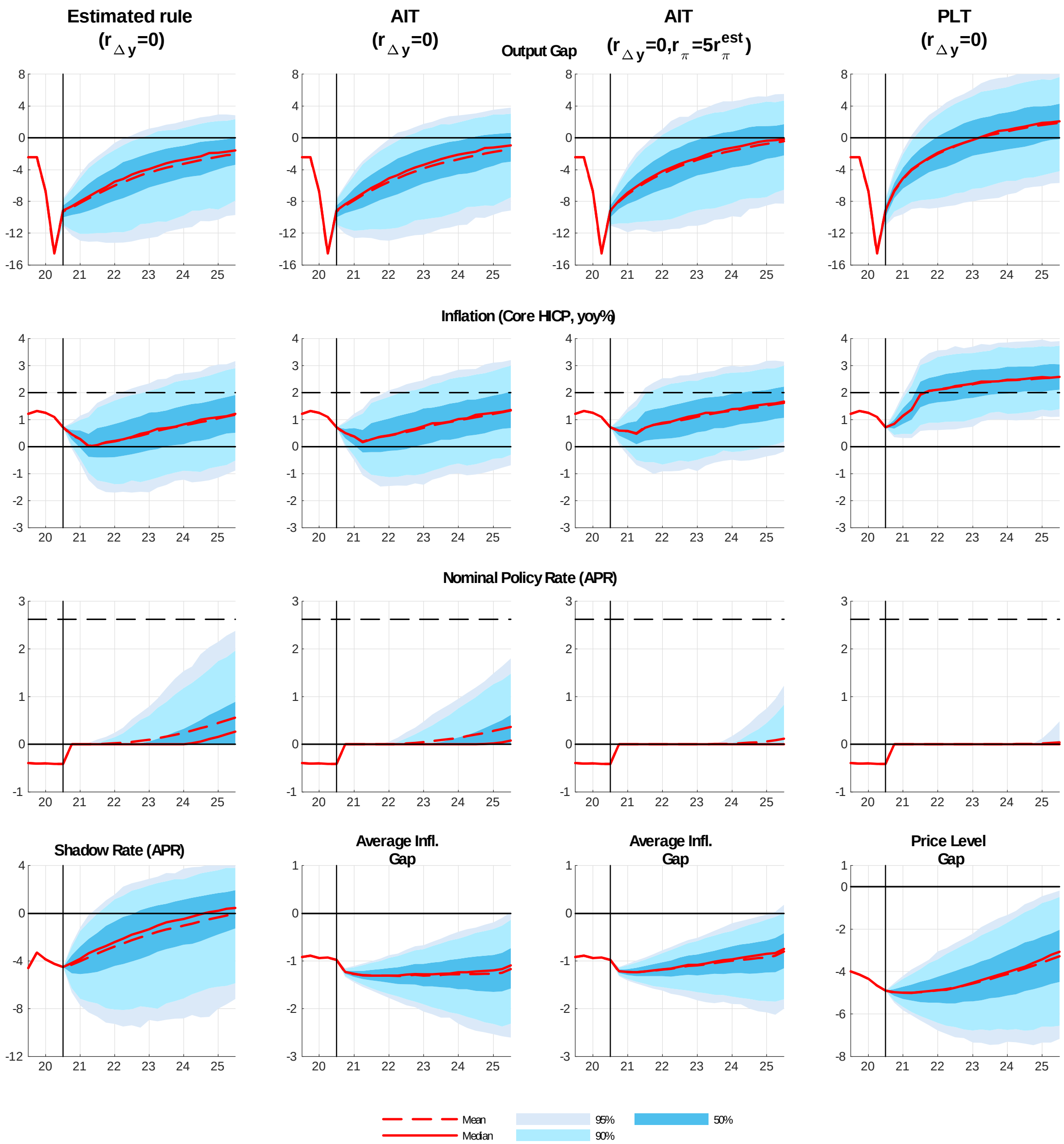
Table 6.1 shows that adopting PLT permanently can result in significantly higher output gap volatility and generate deeper recessions. Intuitively, committing to reverse a runup in inflation—say arising from a markup shock—entails sharp monetary tightening that has costly implications for output relative to allowing "bygones to be bygones." This hypothesis – that wage and price markup shocks drive higher output gap volatility under PLT – can be corroborated by shutting down these shocks: in this case, we find that PLT reduces the output gap substantially (by over 30 percent) while also reducing inflation volatility. The more aggressive AIT strategy has some of the qualitative implications insofar as it reduces inflation volatility at the cost of amplifying output gap volatility, but the effects are much less apparent than under PLT.

The table also indicates that the higher output gap volatility associated with permanent PLT and some forms of AIT is no longer apparent if PLT or AIT is deployed on a temporary basis when the ELB is binding. Under these circumstances, output gap volatility even declines somewhat, which is suggestive of the benefits of these strategies in a deep liquidity trap.

6.3. Conditional Distributions for Alternative Regimes

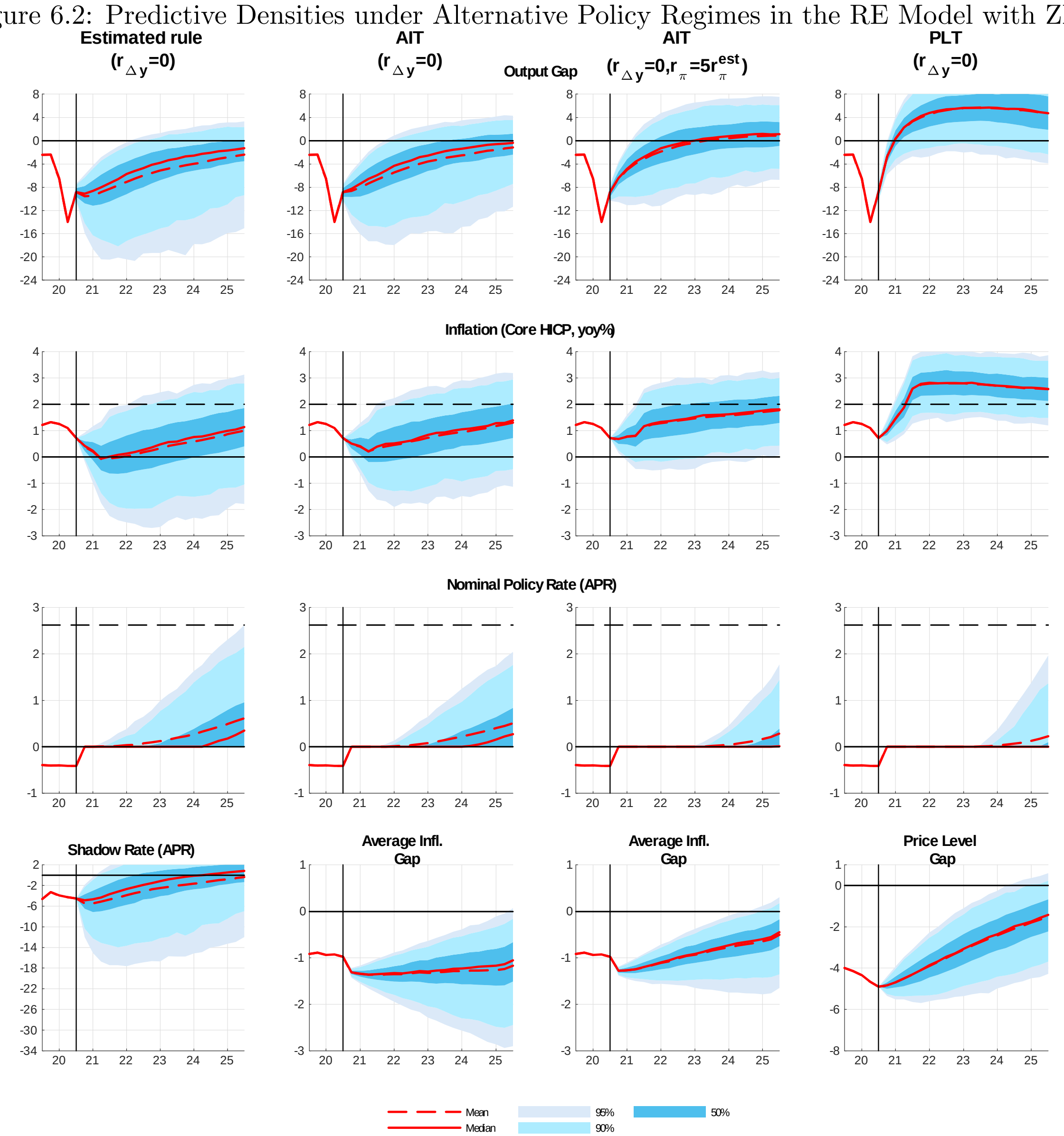
We next compute conditional distributions under the alternative monetary policy regimes over the 2020Q4-2025Q3 period following the same approach as in 5. In particular, the policy regime is assumed to change unexpectedly and the public believes the change will be permanent. Sampling is without replacement so that differences across regimes are due to the alternative conduct of policy rather than to chance. To highlight the "pure" effects of a shift in regime, we assume that no UMP tools are deployed, and use the results under the estimated historical rule as a reference point to gauge the effects. In all of the rules, we set the coefficient $r_{\Delta y} = 0$, reflecting our findings in Section 5.2 that responding to output growth is undesirable in a deep recession.

Figure 6.1: Predictive Densities under Alternative Policy Regimes in the Behavioral Model with ZLB.



We consider two variants of the temporary AIT regime; one in which the AIT gap coefficient r_π in the rule (6.1) equals its historical posterior estimate in Table 3.2 and another in which the effective AIT gap coefficient is five times larger (see 6.2). The initial value of the average inflation gap and price level gap are calculated based on the preceding 5-years of data for core HICP inflation, implying a negative initial 5-year annualized AIT gap of -1 percent, and a -5 percent price level gap.

Figure 6.2: Predictive Densities under Alternative Policy Regimes in the RE Model with ZLB.



The results for the behavioral model are presented in Figure 6.1. Relative to the estimated historical rule without any UMP tools, AIT results in improved conditional forecasts for inflation and the output gap, especially in the case in which the coefficient on the AIT is amplified (column 3). Interestingly, while AIT is often referred to as a "makeup" strategy for inflation, it turns out that inflation converges monotonically towards target even under the more aggressive variant. Temporary price level targeting is noticeably more successful in boosting output and inflation, and in spurring a faster recovery. Inflation does persistently overshoot the long-run target, though pressures remain contained with the (median) inflation rate never much exceeding 2-1/2 percent. In all of these variants, the path of policy rates is considerably more accommodative than under the estimated rule.

As seen in Figure 6.2, the benefits of changing strategy is larger under rational expectations. The more aggressive AIT results in some overshooting of the output gap, and inflation converge to baseline by the end of the forecast period (though still without overshooting). The output gap turns positive even more quickly under temporary PLT, and remains persistently large and positive, which fuels a sizeable inflation overshoot. As expected, under rational expectations the central bank can engineer a better outlook under the alternative regimes with a smaller dose of monetary accommodation (in nominal terms); comparing the nominal policy rate distributions in the behavior and rational expectations model versions, the mean nominal rate is higher in the latter.

7. Robustness Analysis

We next consider the robustness of our results along some key dimensions. These include assessing the role of markup shocks; allowing for behavioral expectations in the pricing equations; and considering a variant of the model that allows for state-dependencies in the slope of the Phillips curve. We also study a variant of the RE model with a higher inter-temporal substitution elasticity σ_c. All of the experiments impose the ELB, but do not involve any deployment of UMP tools. We begin by outlining the setup of the four robustness experiments, and then discuss the results.

7.1. Robustness Experiments

7.1.1. No Markup Shocks

In our first experiment, the standard deviations of the price and wage markup shocks (σ_p and σ_w) are set to zero so that the trade-off between stabilizing output and inflation is notably smaller.

7.1.2. Behavioral Expectations for Firms and Labor Unions

Our second experiment allows for behavioral expectations in wage and price formation. We do so by reestimating the model assuming that φ_f follows the same prior as φ_h in Table 3.2. We obtain a posterior mode for φ_f of about 0.95 (similar to the posterior for φ_h). In Appendix D we report more results (posterior mode, log marginal likelihood, impulses to various shocks and conditional distributions) for the model with behavioral expectations in both the demand and pricing block. As noted in the appendix, while allowing for behavioral expectations in the pricing block is associated with a substantive improvement in log marginal likelihood, the posterior impact of an interest change on inflation becomes very small relative to standard point estimates in the empirical literature on identified monetary policy shocks (see e.g. Christiano, Eichenbaum and Evans [30] and Angeloni et al. [9]). While the interest rate-inflation elasticity in our estimated DSGE model is still within uncertainty bands in empirical studies, the small posterior estimate of the elasticity made us opt to use the variant without behavioral expectations as our baseline model. But as discussed below and in the appendix, our main conclusions continue to hold up well under this alternative specification (and, in fact, even appear strengthened).

7.1.3. State Dependent Pricing

Our third robustness experiment examines the possibility that the slope of the NKPC becomes notably higher when the economy is booming, and conversely somewhat lower in recessions. As noted earlier, empirical evidence suggests that the slope of the Phillips curve has become flatter since the outbreak of the global financial crisis. Linde and Trabandt [98] shows that a nonlinear formulation of a standard New Keynesian model in which consumer preferences are specified with a Kimball Aggregator can generate a "banana-shape" Phillips curve. Since it is beyond the scope of the paper to consider a fully nonlinear formulation of the model, we capture the basic features of their framework by assuming that the slope coefficient π_2 in the linearized Phillips curve (see A)

$$\widehat{\pi}_t - \iota_p \widehat{\pi}_{t-1} = \pi_1 \left(\mathrm{E}_t \widehat{\pi}_{t+1} - \iota_p \widehat{\pi}_t \right) + \pi_2 \left(x_t \right) \widehat{mc}_t + \hat{\varepsilon}_t^p,$$

is a function of the output gap x_t. In particular, we assume the following functional form

$$\pi_2 \left(x_t \right) = \frac{5\pi_2}{1 + e^{-\Xi(x_t - \bar{x})}},$$

where Ξ is set so that the effective slope coefficient ranges from close to zero when the output gap is below -6 percent to 5 times the posterior mode for π_2 when the output gap exceeds 6 percent. This implies setting $\Xi = 1.33$. Finally, $\bar{x}$ is a constant which ensures that $\pi_2 (0) = \pi_2$.

7.1.4. Rational Expectations with Higher σ_c

Our fourth robustness experiment studies an alternative RE version of the model in which σ_c is calibrated to $= 1.249$ (i.e. the value obtained if σ_c is estimated using the SW07 prior and hence features an equilibrium real rate of 1.4 percent). While the ELB constraint is much more damaging to the economy for this calibration, an offsetting effect is that the ZLB will tend not to bind as often because the equilibrium real interest rate is considerably higher. Hence, the net effect is uncertain a priori.

7.1.5. Bootstrapped innovations

We have thus far maintained the assumption that the sampled innovations are normally distributed, and independent of each other contemporaneously and across time. As a final experiment, we examine the robustness of the results when we follow Bernanke, Kiley and Roberts [14] and bootstrap from the smoothed innovations obtained in the estimation of the model instead of sampling i.i.d. normally distributed innovations from a random number generator. Specifically, we bootstrap blocks of innovations of stochastic length 1-20 quarters (uniform distribution). Although we do not change the sign of any the innovations we draw (i.e. the η_t^j's in the shock processes $\ln \varepsilon_t^j = \rho_j \ln \varepsilon_{t-1}^j + \eta_t^j$), they have a zero mean by construction from the Kalman filter and the unconditional standard error of the bootstrapped innovations is very similar to the standard errors reported in Table 3.2. However, the statistical properties of the bootstrapped innovations differ from the random number generated innovations in that they are non-normal, and correlated contemporaneously and across time. As we will see below, this has a noticeable impact on the findings for both the benchmark behavioral and RE models.

7.2. Results

In Table 7.1 we report the results of the robustness analysis. We present results for both symmetric and asymmetric regimes analyzed in Section 5.1.

The results in Table 7.1 shows that price and wage markup shocks are a key driver of the average output costs under an asymmetric formulation of the target. However, even without markup shocks there is a negative inflation bias and the economy operates below potential on average. This reflects that other supply side shocks (here, technology shocks) also drive a wedge between inflation and output gap stabilization, and that even an asymmetric reaction to demand shocks translates into negative output and inflation bias. An even flatter slope of the Phillips curve – which is implied by allowing for behavioral expectations of firms and labor unions in deciding on wages and prices in the pricing block of the model – almost doubles the average output cost under an asymmetric inflation target. As monetary policy affects inflation through aggregate demand in the model, a flatter Phillips curve means that the output gap becomes notably more volatile to keep inflation volatility unchanged.

Table 7.1: Robustness Analysis.

Model	Inflation					Output Gap			Output Growth		Policy Rate		
Variant	Mean	Std	P($\pi \leq 0$)	P($\pi > 2$)	P($\pi > 3$)	Mean	Std	M($x \mid x \leq x^{5th}$)	Mean	Std	Mean	Std	P($R \leq 0$)
Baseline BR Model													
Sym. Target	1.96	0.95	2.09	48.53	13.71	-0.23	2.31	-5.46	1.2	1.46	2.71	1.71	4.47
Asym. Targ.	1.67	0.88	2.52	35.09	4.74	-1.72	2.72	-6.37	1.2	1.5	3.47	2.29	3.40
BR Model Without Markup Shocks													
Sym. Target	1.98	0.45	0.04	50.69	0.73	-0.12	2.31	-5.62	1.2	1.47	2.78	1.69	4.11
Asym. Targ.	1.83	0.35	0.04	39.58	0.00	-0.64	1.96	-5.63	1.2	1.39	2.90	1.78	3.95
Behavioral Expectations also in Pricing Bloc													
Sym. Target	1.99	0.99	2.22	50.05	15.67	-0.33	2.89	-6.75	1.2	1.45	2.79	1.84	5.07
Asym. Targ.	1.80	0.89	2.33	41.84	8.14	-3.22	4.69	-10.65	1.2	1.62	4.46	3.34	3/07
BR Model with State Dep. Slope of Price Phillips Curve													
Asym. Targ.	1.81	0.81	1.21	40.75	6.89	-2.12	3.23	-7.54	1.2	1.54	3.89	2.41	1.50
RE model with estimated σ_c (=1.249)													
Sym. Target	1.92	1.48	9.51	49.02	22.68	-0.54	4.08	-10.85	1.2	2.68	3.67	2.35	6.05
Asym. Targ.	1.38	1.36	12.17	31.75	7.71	-2.49	4.62	-12.03	1.2	2.68	3.97	2.60	5.81
BR Model with Bootstrapped Shocks													
Sym. Target	1.71	1.15	6.02	38.07	11.73	-0.30	3.53	-8.68	1.2	2.07	2.88	2.44	8.57
Asym. Targ.	1.47	1.07	6.53	28.22	3.52	-1.41	3.70	-8.89	1.2	2.11	3.41	3.11	8.02
RE Model with Bootstrapped Shocks													
Sym. Target	1.52	1.42	11.30	35.72	11.32	-1.01	4.92	-15.13	1.2	2.55	2.84	2.43	10.63
Asym. Targ.	1.23	1.37	12.02	23.82	2.00	-2.02	5.05	-15.16	1.2	2.60	2.91	2.49	10.53

Note: All variables in the table are in annualized rates. Std is the standard deviation of the series computed based in the simulated sample with 25,000 observations. M($x \mid x \leq x^{5th}$) is mean of the output gap series counting only observations below or equal its 5^{th} percentile (which is contingent on each model variant). Benchmark is the asymmetric policy rule (5.1) without any UMP\ tools (i.e. first row in Table 5.1). BR denotes the model with behavioral expectations.

State-dependencies in the Phillips Curve elevate the output costs relative the benchmark model with a constant slope. Again, this finding is driven by trade-off shocks. This is because the output gap is not necessarily elevated when inflation is high. Moreover, the output costs in the rational expectations model are higher than in the benchmark model, so the greater severity of ELB episodes outweigh a higher steady state real interest rate.

The final experiment with bootstrapped innovations reveals even larger gains from adopting a symmetric target. Even with a symmetric target, the bootstrapped shocks results in significant average downward inflation bias, reflecting some large negative disinflationary shocks during the estimation period. Again, it should be stressed that the bootstrapped innovations have zero mean and same standard deviation when the innovations are i.i.d., so the fact that the inflation bias is notably more negative reflects that the shocks are non-normal and correlated across time and contemporaneously with other innovations. However, despite the quantitative differences, bootstrapping the shocks does not change our findings from a qualitative perspective. A symmetric target generates large gains in terms of a smaller inflation bias and less volatile inflation and output gaps in both the behavioral and rational expectations models.

8. Concluding Remarks

We have assessed the effects of UMP in a workhorse macroeconomic model. Our estimated model suggest that UMP have some scope for providing better stabilization, but cannot fully offset negative output effects of an asymmetric target. Results show sizeable output gains moving away from an asymmetric to a symmetric target. Asymmetric target associated with substantially lower mean output level; this result is driven by shock structure and flat Phillips curve.

We adopted a simplistic reduced form approach to study large scale asset purchases. While we believe this is a useful starting point, a more serious treatment of unconventional monetary policy is warranted. Doing so in policy models seems to imply that we have to tackle one old key-challenge in macro modeling, namely the failure of the expectations hypothesis (see e.g. Campbell and Shiller [26]), in favor of environments where the expectations hypothesis does not necessarily hold.

There are several additional issues to address in future work: First, it would be valuable to examine the robustness of results for alternative ways to address the FG puzzle. Secondly, it would be valuable to assess the robustness and impact of behavioral expectations when assuming the central bank minimizes a loss function following an operational loss function as in Locarno and Locarno [99] and Svensson ([115], [114]). A third important extension, following Coenen, Galdon and Smets [41], would be to study how active fiscal policy can provide support when monetary policy is constrained.

Finally, while our paper have taken some steps in assessing the role of the ZLB in workhorse macromodels, several important extensions are warranted. An obvious extension would be to assess how our results hold up in a nonlinear framework. However, before such an exercise can be done in model environments with many shocks, endogenous state variables and observables, we need better numerical and estimation techniques to handle nonlinear models.

Appendices

A. Linearized Model Representation

In this appendix, we summarize the log-linear equations of the basic SW-model stated in Section 2. The complete model also includes the seven exogenous shocks $\varepsilon_t^a, \varepsilon_t^b, \varepsilon_t^i, \varepsilon_t^p, \varepsilon_t^w, \varepsilon_t^r$ and g_t, but their processes are not stated here as they were already shown in the main text. Consistent with the notation of the log-linearized *endogenous* variables $\hat{x}_t = dx_t/x$, the exogenous shocks are denoted with a 'hat', i.e. $\hat{\varepsilon}_t = \ln \varepsilon_t$.

First, we have the consumption Euler equation:

$$\widehat{c}_t = \tfrac{1}{(1+\varkappa/\gamma)}\mathrm{E}_t\widehat{c}_{t+1} + \tfrac{\varkappa/\gamma}{(1+\varkappa/\gamma)}\widehat{c}_{t-1} - \tfrac{1-\varkappa/\gamma}{\sigma_c(1+\varkappa/\gamma)}(\hat{R}_t - \mathrm{E}_t\widehat{\pi}_{t+1} + \hat{\varepsilon}_t^b) - \tfrac{(\sigma_c-1)(w_*^h L/c_*)}{\sigma_c(1+\varkappa/\gamma)}(\mathrm{E}_t\widehat{L}_{t+1} - \widehat{L}_t), \quad (A.1)$$

where $\varkappa$ is the external habit parameter, σ_c the reciprocal of the inter-temporal substitution elasticity, $w_*^h L/c_*$ the steady state nominal labor earnings to consumption ratio.

Next, we have the investment Euler equation:

$$\widehat{i}_t = \tfrac{1}{(1+\overline{\beta}\gamma)}\left(\widehat{i}_{t-1} + \overline{\beta}\gamma\mathrm{E}_t\widehat{i}_{t+1} + \tfrac{1}{\gamma^2\Psi}\widehat{Q}_t^k\right) + \widehat{\varepsilon}_t^q, \quad (A.2)$$

where $\bar{\beta} = \beta\gamma^{-\sigma_c}$, Ψ is the investment adjustment cost, and the investment specific technology shock $\widehat{\varepsilon}_t^q$ has been re-scaled so that it enters linearly with a unit coefficient. Additionally $i_1 = 1/(1+\beta)$ and $i_2 = i_1/\psi$, where β is the discount factor and ψ is the elasticity of the capital adjustment cost function.

The price of capital is determined by:

$$\widehat{Q}_t^k = -(\hat{R}_t - \mathrm{E}_t\widehat{\pi}_{t+1} + \widehat{\varepsilon}_t^b) + q_1\mathrm{E}_t r_{t+1}^k + (1-q_1)\mathrm{E}_t Q_{t+1}^k, \quad (A.3)$$

where $q_1 \equiv r_*^k/(r_*^k + (1-\delta))$ in which r_*^k is the steady state rental rate to capital, δ the depreciation rate.

Fourth, we have the optimal condition for the capital utilization rate $\widehat{u}_t$:

$$\widehat{u}_t = (1-\psi)/\psi\widehat{r}_t^k, \quad (A.4)$$

where ψ is the elasticity of the capital utilization cost function and capital services used in production $(\widehat{k}_t)$ is defined as:

$$\widehat{k}_t = \widehat{u}_t + \widehat{\bar{k}}_{t-1}, \quad (A.5)$$

where $\widehat{\bar{k}}_{t-1}$ is the physical capital stock which evolves according to the capital accumulation equation:

$$\widehat{\bar{k}}_t = \kappa_1 \, \widehat{\bar{k}}_{t-1} + (1-\kappa_1)\widehat{i}_t + \kappa_2 \widehat{\varepsilon}_t^q \tag{A.6}$$

with $\kappa_1 = (1 - (i_*/\bar{k}_*)$ and $\kappa_2 = (i_*/\bar{k}_*)\gamma^2 \Psi$.

The following optimal capital/labor input condition also holds:

$$\widehat{k}_t = \widehat{w}_t - \widehat{r}_t^k + \widehat{L}_t, \tag{A.7}$$

where $\widehat{w}_t$ is the real wage.

The log-linearized production function is given by:

$$\widehat{y}_t = \phi_p \left(\alpha \widehat{k}_t + (1-\alpha)\widehat{L}_t + \widehat{\varepsilon}_t^a \right), \tag{A.8}$$

in which ϕ_p is the fixed costs of production corresponding to the gross price markup in the steady state, and $\widehat{\varepsilon}_t^a$ is the exogenous TFP process.

Aggregate demand must equal aggregate supply:

$$\widehat{y}_t = \frac{c_*}{y_*}\widehat{c}_t + \frac{i_*}{y_*}\widehat{i}_t + g_t + \frac{r_*^k k_*}{y_*}\widehat{u}_t, \tag{A.9}$$

where g_t represents the exogenous demand component.

Next, we have the following log-linearized price-setting equation with dynamic indexation ι_p:

$$\widehat{\pi}_t - \iota_p \widehat{\pi}_{t-1} = \pi_1 \left(\mathrm{E}_t \widehat{\pi}_{t+1} - \iota_p \widehat{\pi}_t \right) - \pi_2 \widehat{\mu}_t^p + \widehat{\varepsilon}_t^p, \tag{A.10}$$

where $\pi_1 = \beta$, $\pi_2 = (1-\xi_p\beta)(1-\xi_p)/[\xi_p(1+(\phi_p-1)\epsilon_p)]$, $1-\xi_p$ is the probability of each firm being able to re-optimize the price each period, ϵ_p is the curvature of the aggregator function (eq. (2.2)), and the markup shock $\widehat{\varepsilon}_t^p$ has been re-scaled to enter with a unit coefficient. The price markup $\widehat{\mu}_t^p$ equals the inverse of the real marginal cost, $\widehat{\mu}_t^p = - \widehat{mc}_t$, which in turn is given by:

$$\widehat{mc}_t = (1-\alpha) \, \widehat{w}_t^{real} + \alpha \, \widehat{r}_t^k - \widehat{\varepsilon}_t^a. \tag{A.11}$$

We also have the following wage-setting equation allowing for dynamic indexation of wages for non-optimizing households:

$$(1+\bar{\beta}\gamma)\widehat{w}_t^{real} - \widehat{w}_{t-1}^{real} - \bar{\beta}\gamma \mathrm{E}_t \widehat{w}_{t+1}^{real} = \tag{A.12}$$

$$\frac{(1-\xi_w\bar{\beta}\gamma)(1-\xi_w)}{[\xi_w(1+(\phi_w-1)\epsilon_w)]} \left(\frac{1}{1-\varkappa/\gamma}\widehat{c}_t - \frac{\varkappa/\gamma}{1-\varkappa/\gamma}\widehat{c}_{t-1} + \sigma_l \widehat{L}_t - \widehat{w}_t \right) - (1+\bar{\beta}\gamma\iota_w)\widehat{\pi}_t + \iota_w \widehat{\pi}_{t-1} + \bar{\beta}\gamma \mathrm{E}_t \widehat{\pi}_{t+1} + \widehat{\varepsilon}_t^w,$$

where ϕ_w the gross wage markup, $1-\xi_p$ is the probability of each household being able to re-optimize its wage each period, ϵ_w is the curvature of the aggregator function (eq, 2.7), and σ_l determines the elasticity of labor supply given σ_c (see equation (2.9)). The exogenous wage markup shock $\hat{\varepsilon}_t^w$ has been re-scaled to enter linearly with a unit coefficient.

Finally, we have the monetary policy rule:

$$\widehat{R}_t \; = \; \rho_R \widehat{R}_{t-1} \; + \; (1-\rho_R)\,(r_\pi \widehat{\pi}_t \; + \; r_y \hat{y}_t^{gap}) + r_{\Delta y} \Delta \hat{y}_t^{gap} \; + \hat{\varepsilon}_t^r, \tag{A.13}$$

where $\hat{y}_t^{gap} = \widehat{y}_t - \widehat{y}_t^{pot}$, or in words: the difference between actual output and the output prevailing in the flexible price and wage economy in absence of the inefficient price and wage markup shocks. We solve for $\widehat{y}_t^{pot}$ by setting $\xi_p = \xi_w = 0$ and removing $\hat{\varepsilon}_t^w$ and $\hat{\varepsilon}_t^p$ from the system of equations given by (A.1) – (A.13). Note that when we impose the ZLB on the model, equation (A.13) is replaced by equation (5.1) whenever the ZLB binds.

B. Data

In this appendix, we provide the sources on the data we use in the analysis.

The benchmark model is estimated using seven key macro-economic time series: real GDP, consumption, investment, hours worked, real wages, prices, and a short-term interest rate. The Bayesian estimation methodology is extensively discussed by [113]. GDP, consumption and investment were taken from the EUROSTAT since 1995, prior to 1995 the changes were used from the New Area-Wide Model (NAWM) database (Haver Analytics, accessed on 12th of August, 2020). Real gross domestic product is expressed in billions of seasonally and working day adjusted chained 2015 euros for the data since 1995, prior to 1995 the seasonally and working day adjusted chained 1995 euros data were used to backcast the data. Household and NPISH final consumption expenditures and gross fixed private domestic investment are deflated with the GDP-deflator. Inflation is the first difference of the log of the implicit price deflator of GDP. Core inflation is defined as HICP excluding Energy and Unprocessed Food (Haver code P023SHXU@EUDATA). Total hours worked since 1995 was defined as total hours divided by population (Haver code J025OETE@EUDATA). For the period before 1995 we used annual hours data for the four major economies of the Euro area (Germany, France, Italy and Spain) and made it quarterly by the Litterman algorithm in Eviews (vesion 10+) using the quarterly profile of the employment to population ratio. Wages are calculated from the wage rate in the NAWM database and then updated by compensation per employee from Eurostat (Haver code: L025CESI@EUDATA) and divided by the GDP price deflator in order to get the real wage variable.

The aggregate real variables are expressed per capita by dividing with population aged 15 or older. All series are seasonally and working day adjusted. The interest rate is the EONIA overnight deposit rate since 1994, prior to 1994 we used the New Area-Wide Model database data (Haver code Q023STN@EUDATA). Consumption, investment, GDP, wages, and hours are expressed in 100 times log. The interest rate and inflation rate are expressed on a quarterly basis during the estimation (corresponding with their appearance in the model), but in the figures the series are reported on an annualized (400 times first log difference) or yearly (100 times the four-quarter log difference) basis.

C. Modeling of Large Scale Asset Purchases

We consider a simple reduced form approach by assuming that the central bank's purchases of government and corporate assets provides the central bank with a wedge ϱ_t through which it can affect the effective nominal interest rate facing households and firms in the linearized model.[C.1] Accordingly, the effective interest rate is given by

$$\widehat{R}_t^{eff} = \widehat{R}_t + \varepsilon_t^b + \varrho_t, \tag{C.1}$$

where the exogenous risk shock ε_t^b follows eq. (2.12) and the policy rate follows eq. (5.1). The asset purchase component ϱ_t is state-contingent and follows

$$\varrho_t = \rho_\varrho \varrho_{t-1} - (1-\rho_\varrho)\, \sigma_{\varrho,t} \left(\Sigma_{s=0}^{19} \varepsilon_{\varrho,t-s}\right), \tag{C.2}$$

$$\varepsilon_{\varrho,t} = \frac{1}{1+e^{k\left(\widehat{R}_t^{*}+\bar{r}-ELB\right)}}, \tag{C.3}$$

$$\sigma_{\varrho,t} = \varpi \max\left\{\varepsilon_t^{b,5y} + \varrho_t^{5y}, 0\right\} \varepsilon_{\varrho,t}, \tag{C.4}$$

where $\varepsilon_t^{b,5y}$+ ϱ_t^{5y} is the 5-year ahead effective risk-premium, i.e.

$$tp_t^{5y} = \varepsilon_t^{b,5y} + \varrho_t^{5y} = \Sigma_{s=0}^{19}\left(\varepsilon_{t+s|t}^{b} + \varrho_{t+s|t}\right), \tag{C.5}$$

The idea behind the specification in eqs. (C.2)-(C.5) is that when monetary policy is unconstrained by the ELB, the CB does not undertake any asset purchases. But when the policy rate approaches

[C.1] We recognize that large scale asset purchases which flattens the yield curve may impede banks profitability as in Karadi and Nakov [84]. But we believe this effect should be of second order relative to the stimulative effects LSAPs have.

its ELB, then the central bank start asset purchases if interest rate spreads are elevated. If the logistic parameter k is set large enough eqs. (C.3)-(C.4) implies that

$$\varepsilon_{\varrho,t} = 0 \text{ when } \widehat{R}_t^* + \bar{r} >> ELB,$$
$$\varepsilon_{\varrho,t} = 1 \text{ when } \widehat{R}_t^* + \bar{r} << ELB,$$

and when $\varepsilon_{\varrho,t} = 1$ then $\sigma_{\varrho,t} > 0$ if the effective risk premium $\varepsilon_t^{b,5y} + \varrho_t^{5y} > 0$. This setup implies that we can control how quickly the CB will enter and exit asset purchases through the logistic parameter k and the smoothing coefficient ρ_ϱ. The size of asset purchases can be controlled with $0 < \varpi \leq 1$. Since the risk-premium shock ε_t^b is a key driver of business cycles in our estimated model, offsetting its adverse effects on the economy will normally be very effective and provide substantial economic stimulus when the policy rate is at the ELB. An exception to this is if a recession occurs when risk-premiums are compressed: in such a scenario, asset purchases will not be an effective instrument for providing monetary stimulus in our setup. As a starting point, we set $\rho_\varrho = 0.8$, $k = 15$ and $\varpi = 1$ in the simulations below.

D. Model With Behavioral Expectations in Pricing Bloc

In this appendix, we provide additional results for the behavioral model when allowing for non-rational expectations in the pricing bloc of the model, i.e. in the wage and pricing equations. This formulation of the model features non-rational expectations in all equations except for the real rate, which we retain to be determined by rational expectations (for arbitrage reasons).

Following the ideas in Gabaix [66], we estimate different discounting parameters for household and firms, imposing the same prior. The estimation results are reported in Table D.1. As can be seen, the behavioral parameters are quite similar, and the log marginal likelihood is further improved when allowing for behavioral expectations in the pricing bloc of the model.

In Figure D.1 we report impulses in the fully behavioral model, benchmarking towards the RE model as in the main text. Relative to the behavioral model in the main text, we see that allowing for behavioral expectations in the pricing bloc further mutes the inflation response to monetary policy shocks. Behavioral expectations in the pricing bloc lowers the sensitivity of inflation to aggregate demand and thereby effectively flattens the Phillips curve further. Figure D.2 shows similar effects for technology and price markup shocks. The our posterior median estimate for the policy rate - inflation elasticity is notably smaller than estimates in empirical studies on identified monetary policy shocks in VAR models, which may reflect problems with model misspecification.

As discussed in the main text, this is main reason why we omitted behavioral expectations in the pricing bloc in the baseline model.

Table C.1: Prior and Posterior Distributions With Behavioral Expectations in Pricing Bloc.

Parameter		Prior distribution			original SW07	Posterior distribution			
					Posterior	RE Model		Behavioral Model	
		type	mean	std.dev.	mode			mode	std.dev.
Cognitive discounting	φ_h	beta	0.975	0.0125	-	-	-	0.944	0.01
Cognitive discounting in PC	φ_f	beta	0.975	0.0125	-	-	-	0.946	0.02
Calvo prob. prices	ξ_p	beta	0.667	0.05	0.65	0.864	0.02	0.834	0.02
Calvo prob. wages	ξ_w	beta	0.667	0.05	0.73	0.747	0.04	0.709	0.04
Indexation prices	ι_p	beta	0.5	0.15	0.22	0.176	0.08	0.239	0.12
Indexation wages	ι_w	beta	0.5	0.15	0.59	0.240	0.08	0.247	0.09
Gross price markup	ϕ_p	normal	1.25	0.125	1.61	1.709	0.09	1.751	0.09
Capital production share	α	normal	0.3	0.1	0.19	0.082	0.01	0.090	0.01
Capital utilization cost	ψ	beta	0.5	0.15	0.54	0.772	0.10	0.434	0.15
Investment adj. cost	Ψ	normal	4	1.5	5.48	8.923	1.08	7.814	1.01
Habit formation	$\varkappa$	beta	0.7	0.1	0.71	0.640	0.04	0.636	0.04
Labor supply elast.	σ_l	normal	2	0.75	1.92	1.146	0.57	1.282	0.56
Stationary tech. shk. pers.	ρ_a	beta	0.5	0.2	0.95	0.940	0.02	0.931	0.02
Risk premium shk. pers.	ρ_b	beta	0.5	0.1	0.18	0.952	0.01	0.965	0.01
Invest. spec. tech. shk. pers.	ρ_i	beta	0.5	0.2	0.71	0.203	0.10	0.171	0.08
Gov't cons. shk. pers.	ρ_g	beta	0.5	0.2	0.97	0.968	0.02	0.968	0.02
Price markup shk. pers.	ρ_p	beta	0.5	0.2	0.9	0.650	0.08	0.635	0.09
MA(1) price markup shock	ϑ_p	beta	0.5	0.1	0.74	0.527	0.10	0.540	0.10
Wage markup shk. pers.	ρ_w	beta	0.5	0.2	0.97	0.910	0.02	0.971	0.01
MA(1) wage markup shock	ϑ_w	beta	0.5	0.1	0.88	0.727	0.06	0.684	0.07
Response of g_t to ε_t^a	ρ_{ga}	beta	0.5	0.25	0.52	0.421	0.08	0.414	0.08
Stationary tech. shk. std.	σ_a	invgamma	0.1	2	0.45	0.333	0.02	0.328	0.02
Risk premium shk. std.	σ_b	invgamma	0.1	2	0.24	0.146	0.02	0.204	0.03
Invest. spec. tech. shk. std.	σ_i	invgamma	0.1	2	0.45	0.871	0.09	0.967	0.08
Gov't cons. shk. std.	σ_g	invgamma	0.1	2	0.52	0.314	0.02	0.313	0.02
Price markup shk. std.	σ_p	invgamma	0.1	2	0.14	0.157	0.02	0.166	0.02
Wage markup shk. std.	σ_w	invgamma	0.1	2	0.24	0.094	0.01	0.108	0.01
Inflation response	r_π	normal	1.5	0.25	2.03	1.729	0.22	1.593	0.22
Output gap response	r_y	normal	0.125	0.05	0.08	0.162	0.03	0.145	0.03
Diff. output gap response	$r_{\Delta y}$	normal	0.125	0.05	0.22	0.216	0.03	0.188	0.03
Mon. pol. shock std.	σ_r	invgamma	0.1	2	0.24	0.105	0.01	0.097	0.01
Mon. pol. shock pers.	ρ_r	beta	0.5	0.2	0.12	0.296	0.06	0.323	0.07
Interest rate smoothing	ρ_R	beta	0.75	0.1	0.81	0.908	0.01	0.926	0.02
Log posterior						-418.40		-392.485	
Log marginal likelihood	Laplace					-492.75		-472.880	
	MCMC-MHM					-492.82		-472.585	

Note: Euro area data for 1985Q1–Q4 are used as pre-sample and the log-likelihood is evaluated for the period 1986Q1–2019Q2. A posterior sample of 100,000 post burn-in draws was generated in the Metropolis-Hastings chain. Convergence was checked using standard diagnostics such as CUSUM plots and the potential scale reduction factor on parallel simulation sequences. The Markov chain Monte Carlo modified harmonic mean (MCMC-MHM) marginal likelihood was numerically computed from the posterior draws using the estimator of Geweke [75].

Finally, in Figure D.3 we report the conditional distributions for alternative monetary policy regimes with behavioral expectations for both households and firms. Relative to the results in Figure 6.1, we see that the gains of the alternative regimes are notably smaller. This finding is driven by the fact that behavioral expectations in the pricing bloc further discounts the expectational gains of changes in the policy regime.

Figure D.1: Impulse Responses of Risk Premium and Monetary Policy Shocks With Behavioral Expectations for Both Households and Firms.

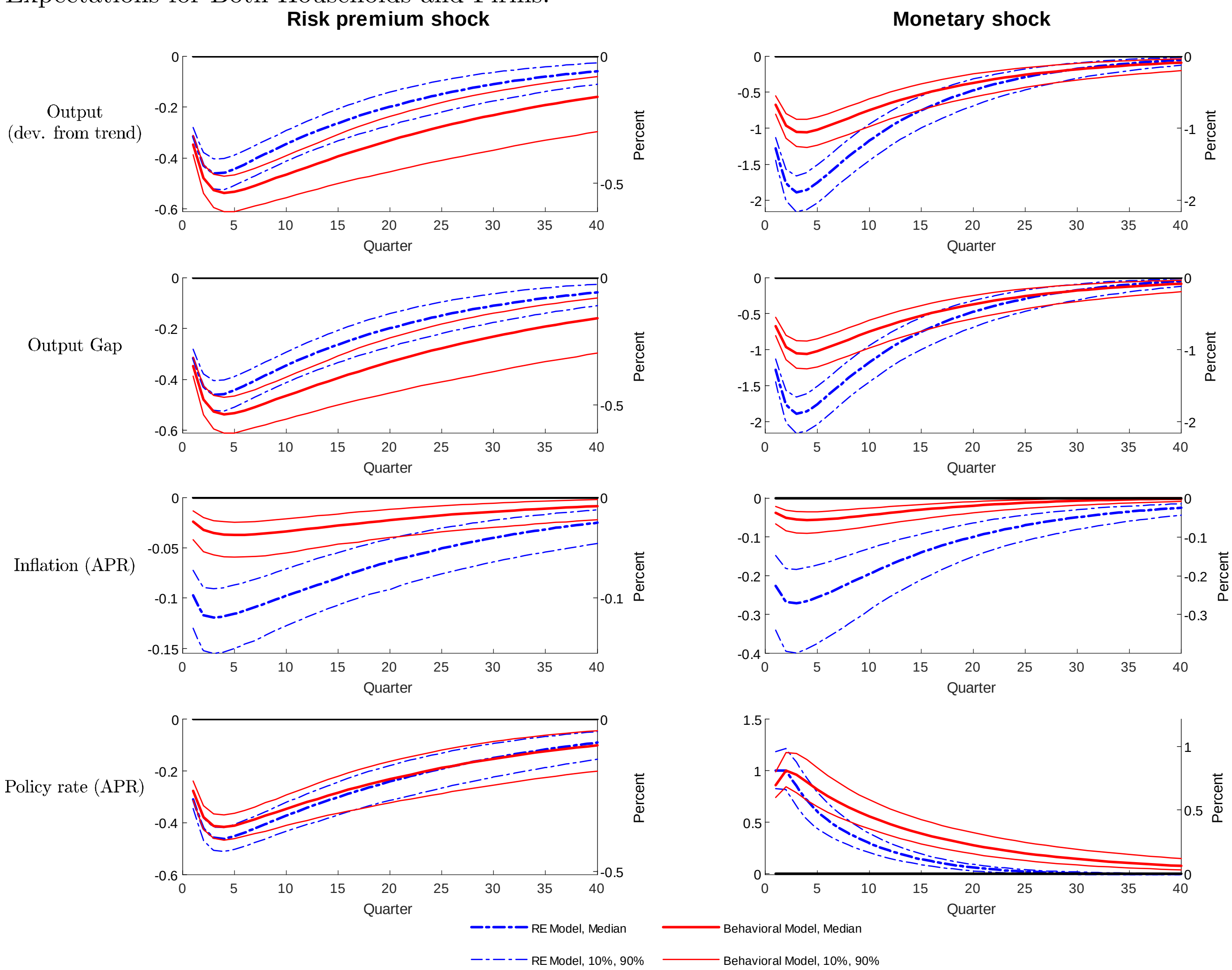


Figure D.2: Impulse Responses of Productivity and Price Markup Shocks With Behavioral Expectations for Both Households and Firms.

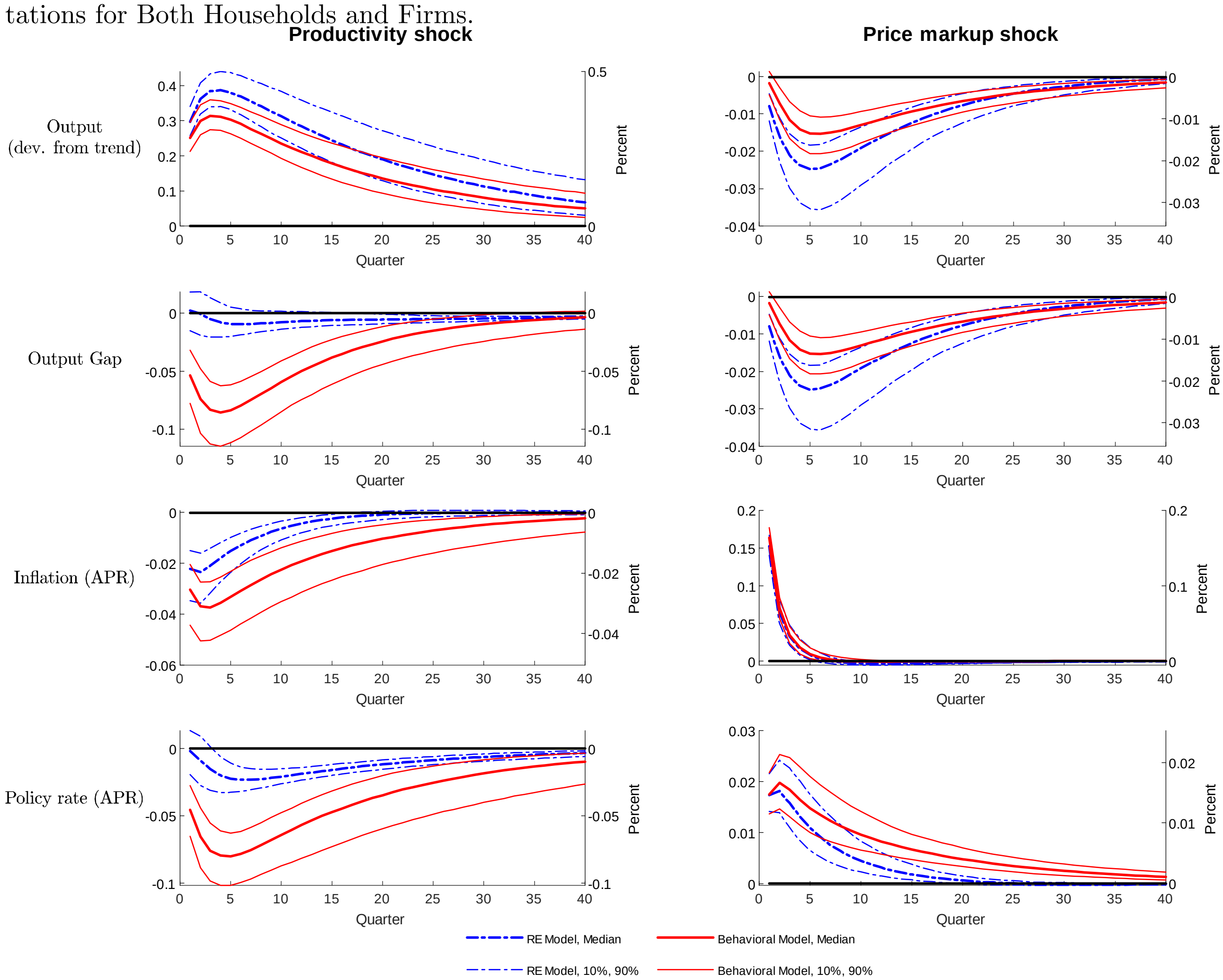
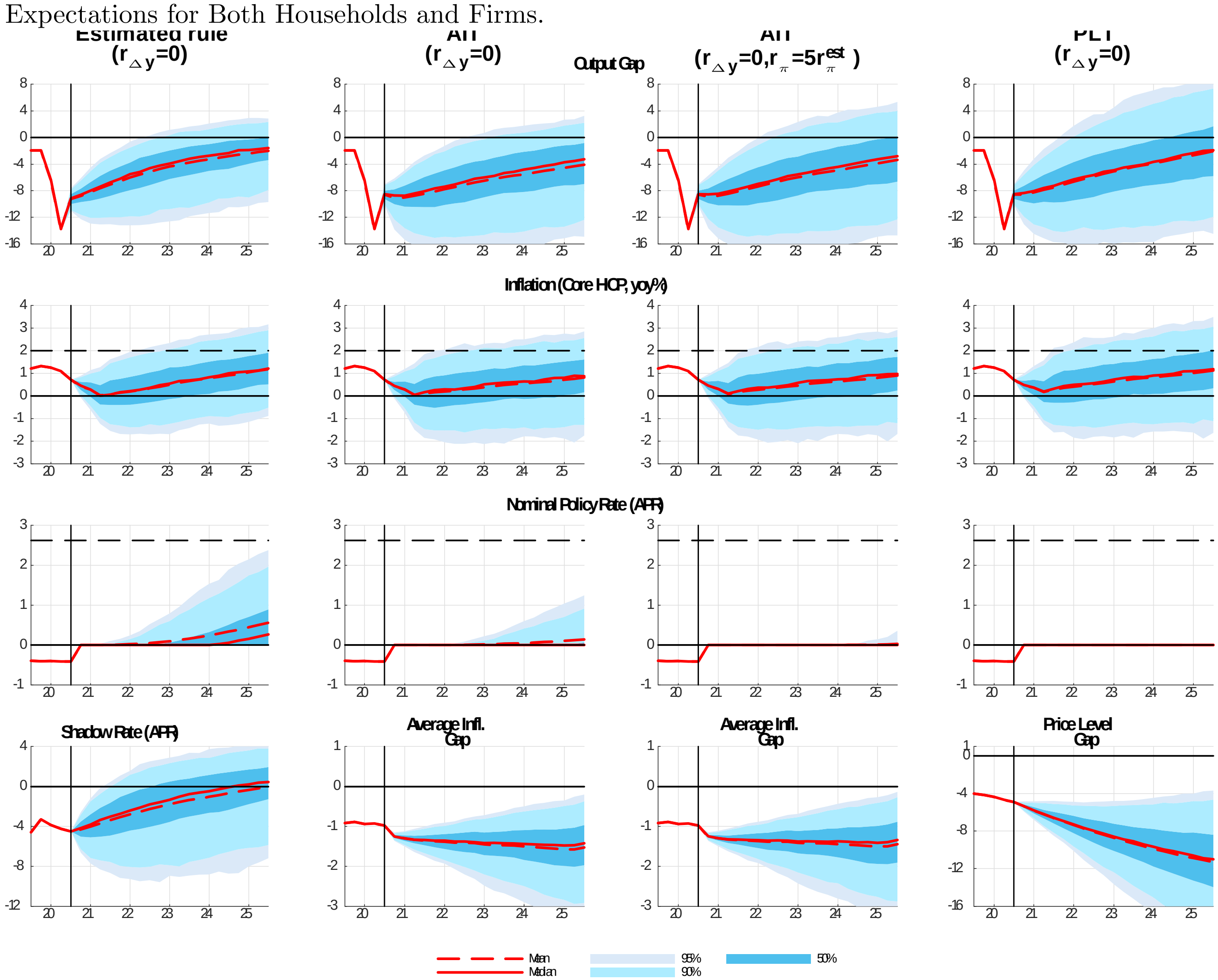


Figure D.3: Predictive Conditional Densities Under Alternative Policy Regimes with Behavioral Expectations for Both Households and Firms.



E. Merits of Changes in Inflation Target and Target Band Regimes

In this appendix, we present some additional experiments with alternative levels for the inflation target as well as a target-band regime. We first present details about the modelling of each alternative policy experiment, and thereafter present unconditional results. We do not present conditional forecasts for these alternative regimes as they would not differ much from the baseline projections in Figures 5.2 and 5.3 since inflation projection is subdued (only a small portion of the projects inflation rates exceed 1.5 percent).

E.1. Lower (Higher) Inflation Target

In this case, we lower the steady state inflation target from 2 to 1.5 percent. A lower symmetric point target has been advocated by some as a route forward to have a clearer target while retaining a similar probability of inflation exceeding, say, 3 percent. Since prominent scholars have also advocated that the central banks in general (Blanchard, Dell'Ariccia and Mauro [18]) and the ECB in particular (Andrade et al. [7]) should raise the inflation target in a low equilibrium rate environment, we also entertain a increase in the symmetric target from 2 to 2.5 percent.

E.2. Inflation Target Band

For this regime we assume that monetary policy is largely passive when inflation is inside a target band of $1-3$ percent, but active according to the estimated rule outside this band. Let us denote the systematic part of the policy rule in eq. (5.1) – excluding the asymmetric term $r_\pi \max(\widehat{\overline{\pi}}_t^e, 0)$ – as $\widehat{R}_t^* = f(S_t)$. We can then write the target band rule as

$$\begin{aligned} \widehat{R}_t^* &= (1-\Omega_t)\,1.01\hat{\pi}_t^{yoy} + \Omega_t f(S_t), \\ \widehat{R}_t &= \max\left\{-(\bar{r}-ELB), \widehat{R}_t^*\right\}, \end{aligned} \tag{E.1}$$

where the state-dependent coefficient $0 \le \Omega_t \le 1$ is defined as

$$\Omega_t = \frac{1}{1+e^{k\left(\widehat{\overline{\pi}}_t^e - \pi^{lb}\right)}} + \frac{1}{1+e^{-k\left(\widehat{\overline{\pi}}_t^e - \pi^{ub}\right)}},$$

where $\widehat{\overline{\pi}}_t^e$ is the one-year ahead expected inflation rate (i.e. $\widehat{\overline{\pi}}_t^e = (\hat{\pi}_{t+4|t} + \hat{\pi}_{t+3|t} + \hat{\pi}_{t+2|t} + \hat{\pi}_{t+1|t})/4$), the logistic parameter $k = 15$, $\pi^{lb} = -0.5/4$ and $\pi^{ub} = 0.5/4$.[E.2] The rule in eq. (E.1) implies that if inflation is expected to remain inside the target band, and no further shocks hit the economy,

[E.2] Notiice that $\widehat{\overline{\pi}}_t^e$ is the expected yearly percent deviation from target expressed at a quarterly rate, so if $\widehat{\overline{\pi}}_t^e = -1/4$ then the yearly inflation is expected to be $2-1=1$ percent.

then the real policy rate will be adjusted very slowly to bring inflation towards the mid-point (π^*) of the target band through the coefficient $1.01\,(\pi_t^{yoy} - \pi^*)$.[E.3]

E.3. Results

Table E.1 indicates that modest variations of the inflation target around 2 percent are likely to carry implication for the macroeconomy. A regime with a lower (symmetric) inflation target equal to 1.5 percent causes deflation risks to increase notably and output to operate further below potential on average. Since the steady state real rate may be even lower than what we assume (0.65 percent), a lower inflation target may be even more costly than suggested by our simulations. A higher inflation target, on the other hand, reduces the deflation probability but increases the probability that inflation exceeds 3 percent notably. A plus with a higher credible inflation target is that it allows the economy to operate closer to potential on average in a low real rate environment. Finally, the table report results of a "target band" for inflation. This is when monetary policy is much less responsive to economic activity and inflation developments when inflation is between 1.5 and 2.5 percent. Such a band will trigger larger fluctuations in inflation and the output gap relative to a point-target regime without reducing interest volatility much in the BR model, although inflation will be close to 2 percent on average.

Table E.1: Unconditional Distributions for Alternative Inflation Target Regimes.

Policy	Inflation					Output Gap			Output Growth		Policy Rate		
Regime	Mean	Std	P($\pi \leq 0$)	P($\pi > 2$)	P($\pi > 3$)	Mean	Std	M($x \mid x \leq x^{5th}$)	Mean	Std	Mean	Std	P($R \leq 0$)
Panel A: Behavioral Model													
Sym 2% Target	1.96	0.95	2.09	48.53	13.71	-0.23	2.31	-5.46	1.2	1.46	2.71	1.71	4.47
Sym 1.5%. Target	1.44	0.96	6.91	27.92	5.22	-0.37	2.45	-6.08	1.2	1.48	2.3	1.64	7.23
Sym 2.5% Target	2.47	0.94	0.57	69.97	28.53	-0.15	2.22	-4.99	1.20	1.44	3.16	1.77	2.82
Target Band	1.96	1.22	5.55	49.14	20.54	-0.23	3.1	-6.67	1.2	1.72	2.73	1.68	5.07
Panel B: RE Model													
Sym 2% Target	1.91	1.04	3.66	47.50	14.12	-0.44	2.76	-7.74	1.2	1.6	2.67	1.72	4.99
Sym 1.5% Target	1.34	1.12	10.27	27.32	5.55	-0.78	3.35	-10.25	1.2	1.74	2.25	1.64	8.15
Sym 2.5% Target	2.44	1.01	1.12	68.37	28.73	-0.26	2.44	-6.19	1.20	1.54	3.13	1.78	3.04
Target Band	1.81	1.72	14.96	47.72	27.49	-0.96	4.07	-12.36	1.2	2.05	2.8	2.24	11.25

Note: All variables in the table are in annualized rates. Std is the standard deviation of the series computed based in the simulated sample with 25,000 observations. M($x \mid x \leq x^{5th}$) is mean of the output gap series counting only observations below or equal its 5^{th} percentile. "Sym 2% Target" drops $r_\pi \max(\widehat{\bar{\pi}}^e_t, 0)$ from the policy rule (5.1). "Sym 1.5% Target" lowers inflation target to 1.5 percent, whereas "Sym 2.5% Target" increases inflation target to 2.5 percent. "Target Band" is when the ECB follows the rule in eq. (E.1).

In the RE model, the costs of a lower inflation target is somewhat higher because ZLB episodes become more frequent and are more costly. Conversely, the benefits of a higher target are somewhat more pronounced. Moreover, a inflation target band regime is even less tempting in the RE model as it causes the ZLB to become a more binding constraint.

[E.3] I.e. Ω_t is close to nil when $-\pi^{lb} < \widehat{\bar{\pi}}^e_t < \pi^{ub}$ and approaches unity when $\widehat{\bar{\pi}}^e_t$ deviates sufficiently from the target band.

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