Macroeconomic Dynamics, **20**, 2016, 1504–1526. Printed in the United States of America.
doi:10.1017/S136510051400100X

ROBUST MONETARY POLICY IN A NEW KEYNESIAN MODEL WITH IMPERFECT INTEREST RATE PASS-THROUGH

RAFAEL GERKE AND FELIX HAMMERMANN
Deutsche Bundesbank

We use robust control to study how a central bank in an economy with imperfect interest rate pass-through conducts monetary policy if it fears that its model could be misspecified. We find that, first, whether robust optimal monetary policy under commitment responds more cautiously or more aggressively depends crucially on the source of shock. Imperfect pass-through amplifies the robust policy. Second, if the central bank is concerned about uncertainty, it dampens volatility in the inflation rate preemptively but accepts higher volatility in the output gap and loan rate. However, for highly sticky loan rates, insurance against model misspecification becomes particularly pricy. Third, if the central bank fears uncertainty only in the IS equation or the loan rate equation, the robust policy shifts its concern for stabilization away from inflation.

Keywords: Optimal Monetary Policy, Commitment, Model Uncertainty

1. INTRODUCTION

Seemingly similar models produce different predictions of how monetary policy affects the dynamics of policy-relevant variables. Cateau (2006), for example, illustrates that even New Keynesian models differ in their monetary transmission dynamics. It is not obvious how monetary policy should cope with such differences. The difficulty in setting the policy rate lies obviously in the fact that the policy maker does not know the true model or is not able to fully capture it. In general, the central bank must acknowledge that every model is a simplification, necessarily incomplete, and therefore a misspecified description of reality. Consequently, it seeks to design a policy that is robust against model misspecification.

The views expressed in this paper are those of the authors and do not necessarily reflect the views of the Deutsche Bundesbank or the Eurosystem. We appreciate the helpful comments and suggestions made by two anonymous referees, Heinz Herrmann, Teruyoshi Kobayashi, Jörn Tenhofen, Peter Tillmann, Andreas Worms, and participants at the Society of Computational Economics Conference in London, 2010 and the Dynare Conference in Atlanta, 2011. We are indebted to Paolo Giordani, Paul Söderlind, and Ulf Söderström for making their program codes available to us. All remaining errors and shortcomings are, of course, our own. Address correspondence to: Felix Hammermann, Economics Department, Deutsche Bundesbank, Wilhelm-Epstein-Strasse 14, 60431 Frankfurt, Germany; e-mail: felix.hammermann@bundesbank.de.

 1365-1005/15

In this paper, we incorporate model uncertainty by following the robust control approach along the lines of Hansen and Sargent (2008). We do so by assuming that the true model is not known but lies in the neighborhood of a so-called reference model. The central bank is not able to formulate a probability distribution over plausible models in that neighborhood but recognizes that data might not be generated by the reference model. Robust control then provides a way for the central bank to find a policy that performs well in the worst possible outcome of a prespecified set of models.

We employ as a reference model a version of the New Keynesian model that is able to replicate stylized facts of the monetary transmission mechanism in the euro area, namely that (i) changes in the monetary policy rate have only temporary effects on euro-area output but long-lasting effects on prices; (ii) in "normal times," monetary policy affects the economy mainly through the interest rate channel; and (iii) changes in the policy rate are not completely passed through to retail lending rates.[1] Specifically, we use an extension of the New Keynesian model, as suggested by Kobayashi (2008), that incorporates commercial banks and allows for an endogenous spread between the interest rate received by savers and the rate paid by borrowers. Banks supply loans to intermediate-goods-producing firms but can adjust the loan rates only infrequently.[2] The associated staggered loan rate setting leads to imperfect interest rate pass-through from the policy rate to the loan rates. As intermediate-goods-producing firms take out loans, monetary policy affects inflation also via the cost channel. By explicitly using a model with incomplete pass-through, we are able not only to analyze how stickier loan rates influence the responses to different shocks under the robust policy but also to nest previous findings on the role of the cost channel as a special case [e.g., Ravenna and Walsh (2006)]. We go beyond much of the robust control literature analyzing optimal monetary policy under discretion based on ad hoc loss functions as we analyze optimal monetary policy under commitment based on a microfounded loss function. This setup allows us to assess the costs and benefits of the robust policy in terms of welfare. Because the model involves loan rate dispersion, the welfare criterion penalizes not only volatility in inflation and the output gap but also loan rate fluctuations.

Early applications of the robust control approach to the standard New Keynesian model stand in contrast to Brainard's (1967) classic advice of a more cautious policy response to uncertainty surrounding the underlying economic model. They typically find that in the New Keynesian model the robust policy warrants responding more aggressively. Giannoni (2002) analyzes structured uncertainty by focusing on uncertainty about parameters of the underlying New Keynesian model. He then derives robust optimal simple rules responding more aggressively under uncertainty. Giordani and Söderlind (2004) analyze unstructured uncertainty in the New Keynesian model and compare the robust policy responses for optimal monetary policy under commitment and under discretion, as well as simple rules, and find that a concern for robustness leads to more aggressive policies.[3] Subsequently, Leitemo and Söderström (2008b) solve analytically for the robust policy under discretion in the New Keynesian model. Recently, Dai and Spyromitros (2012) and Araújo (2013) extended the New Keynesian model by adding asset prices. All of them recommend a more aggressive policy under uncertainty.[4]

However, several extensions of the standard New Keynesian model reveal that the robust control approach per se does not necessarily imply responding more aggressively. Using an open economy version of the New Keynesian model, Leitemo and Söderström (2008a) demonstrate that depending on the source of misspecification and the type of disturbance, the optimal robust policy under discretion can be either less or more aggressive. The ambiguity has its origin in the fact that monetary policy affects inflation not only via output but also through a second channel: the exchange rate. The exchange rate channel works in the opposite direction to the traditional demand channel. Higher interest rates lead to an appreciation of the exchange rate that raises demand for imports, and therefore consumption, output, and inflation increase. If the exchange rate channel dominates, the central bank responds more cautiously to increases in inflation.

The ambiguity of the robust policy is also found in Tillmann (2009a, 2009b), where firms have to take out a loan to finance wages in advance and thus monetary policy affects inflation via the cost channel. In the benchmark calibration of Tillmann (2009b), the response to a demand shock under discretionary robust policy is therefore less aggressive. Similarly, Tillmann (2009a) revisits structured uncertainty along the lines of Onatski and Williams (2003) in a model with a cost channel. Analyzing monetary policy under discretion, he finds again that the policy maker is less aggressive than under certainty.

Our New Keynesian model also entails a cost channel, and therefore we are able to replicate the findings of Tillmann (2009b) as a special case. The ambiguity caused by the cost channel stems from the fact that the central bank seeks to avoid additional volatility in inflation when setting its policy rate. For a demand shock the policy response itself raises the volatility of inflation, and thus the central bank responds more cautiously.[5] In addition to the cost channel, the model we use also features an imperfect interest rate pass-through that matches the stylized facts of monetary transmission in the euro area. Our new results on the effects of the central bank's concern for robustness stemming in particular from the imperfect interest rate pass-through can be summarized as follows.

First, the incomplete pass-through amplifies the responses of the robust policy when the central bank has a concern for robustness. Stickier loan rates raise the degree of aggressiveness of the responses to a cost-push shock and a loan rate shock under the robust policy, whereas the response to a demand shock becomes even more cautious.

Second, the central bank dampens volatility in the inflation rate preemptively, which means that it accepts deliberately higher volatility in the output gap and the loan rate in order to stabilize inflation. However, for highly sticky loan rates the robust policy abstains from stabilizing inflation preemptively. As highly volatile inflation reduces welfare, insurance against the worst case becomes in this case particularly pricy.

Third, uncertainty surrounding just a single equation may imply a shift in the policy maker's concern for robustness. If the central bank faces uncertainty only in the Phillips curve, the changes of the variances coincide qualitatively with the benchmark case (misspecification in all equations). If, however, uncertainty is present only in the IS equation or the loan rate equation, the robust policy shifts its concern for stabilization. We find that in both cases the central bank reduces the volatility in the output gap and the loan rate at the expense of higher inflation volatility.

The remainder of the paper is organized as follows. In Section 2, we present the New Keynesian model with a banking sector and staggered loan rate setting. We describe the linearized model and its calibration. In Section 3, after introducing the robust control approach, we present the robust monetary policy under commitment when uncertainty prevails in all three model equations, i.e., in the Phillips curve, the IS equation, and the loan rate equation. We also vary the degree of loan rate stickiness. A calibration with completely flexible loan rates allows us to compare our results with a pure cost channel model. Furthermore, we investigate the cases when uncertainty surrounds only one equation at a time. Finally, Section 4 concludes.

2. MODEL

We briefly describe the New Keynesian model with a financial intermediary suggested by Kobayashi (2008). It features a cost channel and imperfect interest rate pass-through as documented for the euro area. The model not only replicates the stylized fact that changes in the policy rate are not completely passed through to retail lending rates but also allows us to show that the incorporation of financial intermediation might have ambiguous effects on model uncertainty.

2.1. Overview of the Model

The economy consists of a representative household, intermediate goods firms, final goods firms, commercial banks, and a central bank. The representative household consumes a bundle of final goods while supplying labor to the intermediate goods sector. He/she is required to use cash in purchasing consumption goods and also makes a one-period deposit. Each intermediate goods firm produces a differentiated intermediate good and sells it to final goods firms. The production of intermediate goods requires labor as the sole input. Following Christiano and Eichenbaum (1992) and Ravenna and Walsh (2006), among others, at the beginning of each period the intermediate goods firms pay wages in advance to workers. Because the firms receive revenues only at the end of each period, they need to borrow funds. There is only one bank active in each region, and loan markets are assumed to be geographically segmented. Hence, firms borrow exclusively from the commercial banks in their regions. The commercial banks receive deposits and money injection from the central bank and lend funds to intermediate goods firms.

Banks adjust their loan rates only infrequently, following a Calvo-type adjustment mechanism [see Calvo (1983)]. The model thus replicates the incomplete interest rate pass-through from policy rates to loan rates found in many empirical studies [for an overview, see de Bondt et al. (2005)]. Intermediate goods firms set prices flexibly, and price dispersion occurs at the intermediate goods level, because borrowing rates differ across the monopolistically competitive firms.[6] A composite of intermediate goods is the only required input for the production of final goods. Final goods producers are assumed to follow Calvo-type price setting, which leads to price stickiness in the final goods sector.

2.2. Equilibrium Dynamics

In the following, for any arbitrary variable X_t, we define $x_t \equiv \log\left(X_t / \bar{X}\right)$, where $\bar{X}$ denotes the steady-state value. Denote by π_t the rate of inflation, by y_t the output gap in the economy, and by r_t^l the average loan rate. Then the key (log-linearized) equilibrium relations can be summarized as follows. Starting with the first-order condition of final goods firms, the Phillips curve can be formulated as

$$\pi_t = \beta E_t \pi_{t+1} + \lambda_F \left[(\sigma + \omega) y_t + r_t^l \right] + e_t, \qquad \textbf{(1)}$$

where e_t denotes an aggregate supply disturbance such as a cost-push shock and $(\sigma + \omega) y_t + r_t^l$ represents real marginal cost, with σ being the inverse of the elasticity of intertemporal substitution and ω the elasticity of labor supply. The parameter λ_F is defined as $\lambda_F \equiv (1 - \phi)(1 - \beta\phi) / \phi$, with β the discount factor and $(1 - \phi)$ the probability that the final goods firms can adjust their prices. The Phillips curve differs from a standard New Keynesian Phillips curve by the presence of an additional interest-rate term, which reflects the fact that firms have to borrow funds to pay the wage bill in advance. In contrast to earlier versions of New Keynesian models with a cost channel [e.g., Ravenna and Walsh (2006)], the interest rate variable entering the Phillips curve is not the policy rate r_t but the average loan rate r_t^l. As the model incorporates the profit-maximizing behavior of commercial banks, retail loan rates differ from the policy rate in an endogenous manner. From (1) it is evident that the average loan rate determines, to some extent, current inflation, as a rise in the loan rate leads to higher marginal cost in final goods production. Further, as commercial banks face a Calvo-type constraint when setting their loan rates, the cost channel is weakened compared with the case of perfect interest rate pass-through.

The aggregate demand equation in this model is standard and can be derived from the household's intertemporal optimization problem. Log-linearizing the consumption Euler condition gives the IS equation

$$y_t = E_t y_{t+1} - \tfrac{1}{\sigma} (r_t - E_t \pi_{t+1}) + u_t, \qquad \textbf{(2)}$$

where u_t denotes an aggregate demand disturbance.

https://doi.org/10.1017/S136510051400100X Published online by Cambridge University Press

Based on the commercial banks' optimal loan rate setting, the economy's average loan rate can be expressed as a weighted average of the expected loan rate, the current policy rate, and the previous period's loan rate. Additionally, we introduce the possibility of an exogenous shift in the loan rate,

$$r_t^l = \frac{\beta}{1+\beta+\lambda_B} E_t r_{t+1}^l + \frac{\lambda_B}{1+\beta+\lambda_B} r_t + \frac{1}{1+\beta+\lambda_B} r_{t-1}^l + \frac{\lambda_B}{1+\beta+\lambda_B} l_t,$$

with $\lambda_B \equiv (1-q)(1-q\beta)/q$. The expression $(1-q)$ denotes the probability with which the commercial bank can adjust its loan rate. The loan rate shock l_t captures the idea that loan rates tend to fluctuate for reasons that are not directly linked to policy behavior. One possibility could be a shift in the loan rate triggered by changes in financial market conditions. The relative weights on the expected loan rate and the previous loan rate decrease as the flexibility of loan rates increases. From rewriting this expression as

$$\Delta r_t^l = \beta E_t \Delta r_{t+1}^l + \lambda_B \left(r_t - r_t^l\right) + \lambda_B l_t, \tag{3}$$

it becomes evident that a change in the loan rate will be caused by an expected change in the future loan rate, by a discrepancy between the policy rate and the average loan rate, and finally by a loan rate shock. Thus, l_t can be interpreted as a shock to the change in the loan rate or equivalently as a shock to the spread between the policy rate and the loan rate.

2.3. Calibration

We conclude the description of the core model with the calibration of the structural parameters and the shock processes. We assume that the shocks in the Phillips curve (1), in the IS equation (2), and in the average loan rate equation (3) follow first-order autoregressive processes of the form

$$s_t = \rho^s s_{t-1} + \varepsilon_t^s, \tag{4}$$

where ρ^s is the persistence parameter, ε_t^s a white-noise error term, and $s \in \{e, u, l\}$. Unlike Kobayashi (2008), we added the cost-push shock e_t and the demand shock u_t to the model in order to make the analysis more comparable with the literature. All three shocks are calibrated to a standard error of 0.005, and the persistence parameters are set to 0.9.

We follow Kobayashi (2008) in setting the fraction of banks that do not reset their loan rates q at 0.177, which equals the average of all the estimates reported by 13 studies surveyed in de Bondt et al. (2005, Table 1). On the average, banks set their lending rate for approximately one quarter and three weeks. We also consider the upper bound, $q = 0.422$, corresponding to five months of loan rate stickiness in the survey of de Bondt et al. (2005), as well as the case of completely flexible loan rates, because this allows us to highlight the importance of the cost channel and to disentangle it from the imperfect pass-through. We follow Kobayashi in taking the

TABLE 1. Calibration of parameters

β	σ	ω	ϕ	q	θ_f	θ_z	ρ^e	ρ^u	ρ^l
0.99	1.5	1	0.6229	0.177	7.88	7.88	0.9	0.9	0.9

baseline values of the parameters β, σ, and ω from Ravenna and Walsh (2006) and in setting the elasticity of substitution between the variety of intermediate goods θ_z equal to the elasticity of substitution for final goods, θ_f. The value of θ_f is taken from Rotemberg and Woodford (1997), and the degree of price stickiness ϕ is chosen so that the slope of the Phillips curve is equal to 0.58, the value reported by Lubik and Schorfheide (2004). The calibrated values of the parameters in the benchmark model are summarized in Table 1.

2.4. Social Welfare

Kobayashi (2008) derives a welfare criterion based on a second-order approximation to the household's utility function that involves interest-rate smoothing. Both price setting and loan rate setting follow Calvo-type staggering and therefore lead to inefficient dispersion of prices and loan rates.[7] Kobayashi (2008) shows that the present discounted value of the variance of lending rates can be expressed in terms of the squared change in the average loan rate, just as the present discounted value of the variance of prices can be expressed in terms of inflation squared. Economically, the variance in loan rates enters the social welfare function, as it affects the variance of intermediate goods' prices and thus the household's disutility from labor. Formally, social welfare can be stated as

$$\mathbb{W} = E_t \sum_{s=0}^{\infty} \beta^s U_{t+s} \cong -E_t \sum_{s=0}^{\infty} \beta^s \left\{ \psi_\pi \pi_{t+s}^2 + \psi_y y_{t+s}^2 + \psi_{rl} \left(\Delta r_{t+s}^l \right)^2 \right\} + \text{t.i.p.}, \tag{5}$$

where t.i.p. represents terms independent of policy, and $\psi_\pi \equiv \theta_f \big/ [\lambda_F (\sigma + \omega)]$, $\psi_y \equiv 1$, and $\psi_{rl} \equiv \theta_z \big/ [\lambda_B (1 + \omega\theta_z)(\sigma + \omega)]$ represent the relative weights on inflation, the output gap, and the rate of change in the average loan rate, respectively.

2.5. Monetary Policy under Commitment

We close the model with the optimal policy function derived under commitment.[8] Optimal monetary policy under rational expectations serves as the relevant benchmark for policy makers in central banks.

The policy maker maximizes social welfare (5) subject to the model (1) to (4) (henceforth called the "reference model"). In state-space form, we formulate the linearized reference model as

$$A_0 \begin{bmatrix} x_{1,t+1} \\ E_t x_{2,t+1} \end{bmatrix} = A_1 \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + B r_t + C\varepsilon_{t+1}, \quad (6)$$

where A_0, A_1, and B are matrices of model parameters, and C is a vector that scales the impact of the vector of error terms ε_{t+1}. $x_{1,t}$ is the n_1-vector of predetermined variables $\begin{bmatrix} e_t & u_t & l_t & r^l_{t-1} \end{bmatrix}'$ with $x_{1,0}$ given, $x_{2,t}$ is the n_2-vector of forward-looking variables $\begin{bmatrix} \pi_t & y_t & r^l_t \end{bmatrix}'$, and r_t is the policy instrument.

The central bank maximizes social welfare (5) by minimizing the loss function

$$\boldsymbol{L}_t = \psi_\pi \pi_t^2 + \psi_y y_t^2 + \psi_{rl} \left(\Delta r^l_t\right)^2, \quad (7)$$

subject to the reference model (6). Among others, Söderlind (1999) provides an algorithm to find the optimal policy and the rational expectations equilibrium based on a generalized Schur decomposition.[9] The solution to the optimization problem may be written as a VAR(1) in the predetermined variables and a linear relationship between the forward-looking and predetermined variables [e.g., Giordani and Söderlind (2004, Appendix C)]:

$$\begin{bmatrix} x_{1,t} \\ \rho_{2,t+1} \end{bmatrix} = M \begin{bmatrix} x_{1,t-1} \\ \rho_{2,t} \end{bmatrix} + \begin{bmatrix} C\varepsilon_{t+1} \\ 0 \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} x_{2,t} \\ r_t \\ \rho_{1,t} \end{bmatrix} = N \begin{bmatrix} x_{1,t} \\ \rho_{2,t} \end{bmatrix}, \quad (9)$$

where $\rho_{1,t}$ represents the Lagrange multiplier of the predetermined variables and $\rho_{2,t}$ the Lagrange multiplier of the forward-looking variables. The matrices M and N give the solution based on the structural parameters of the model. The optimal policy function under commitment[10] depends on the predetermined variables $x_{1,t}$ and the Lagrange multipliers on the forward-looking variables $\rho_{2,t}$,

$$r_t = N_r \begin{bmatrix} x_{1,t} \\ \rho_{2,t} \end{bmatrix}, \quad (10)$$

where N_r is a $1 \times (n_1 + n_2)$ submatrix of N. With respect to Kobayashi's model, the state of the economy is given by the predetermined variables and the Lagrange multipliers $\begin{bmatrix} e_t & u_t & l_t & r^l_{t-1} & \rho^\pi_{2,t} & \rho^y_{2,t} & \rho^{rl}_{2,t} \end{bmatrix}'$. The first line of Panel (b) in Table 2 displays the optimal policy function under rational expectations. Monetary policy responds negatively to a cost-push shock e_t and a loan rate shock l_t but positively to a demand shock u_t.

Optimal monetary policy under commitment and the key dynamics of the model may be understood most easily by tracing the transmission of a shock to the loan rate. A higher loan rate increases firms' borrowing costs in the Phillips curve (1). Via the cost channel, this increases inflation. The central bank counteracts a loan rate increase by cutting the policy rate immediately and thus does not

TABLE 2. Coefficients of optimal policy functions

	e_t	u_t	l_t	r^l_{t-1}	$\rho^{\pi}_{2,t}$	$\rho^{y}_{2,t}$	$\rho^{rl}_{2,t}$
(a) Cost channel with flexible loan rates							
RE policy function	−1.49	0.98	−0.35	0.00	0.06	4.21	−1.69
Robust policy function	−1.52	0.97	−0.35	0.00	0.06	4.21	−1.69
Change in percentage	2.42	−1.28	2.42	−0.05	0.02	−0.04	0.00
(b) Benchmark $q = 0.177$							
RE policy function	−0.76	1.06	−0.29	0.10	−0.03	1.68	−1.02
Robust policy function	−0.81	1.04	−0.30	0.10	−0.03	1.67	−1.02
Change in percentage	7.15	−1.74	4.21	−0.27	−0.06	−0.17	0.00
(c) Highly sticky loan rates $q = 0.422$							
RE policy function	−0.40	1.16	−0.23	0.12	−0.07	0.62	−0.77
Robust policy function	−0.48	1.14	−0.24	0.12	−0.07	0.62	−0.77
Change in percentage	18.67	−2.10	7.22	−1.12	−0.14	−0.34	0.04
(d) Cost channel, flexible loan rates, but loan rate smoothing							
RE policy function	−0.86	0.90	−0.40	0.18	0.01	2.00	−0.93
Robust policy function	−0.89	0.89	−0.41	0.18	0.01	2.00	−0.93
Change in percentage	4.49	−1.46	2.18	−0.09	−0.15	−0.09	0.01
(e) Cost channel, sticky loan rates, but no loan rate smoothing							
RE policy function	−0.97	1.16	−0.23	0.00	−0.03	2.28	−1.33
Robust policy function	−1.02	1.14	−0.24	0.00	−0.03	2.28	−1.33
Change in percentage	6.08	−1.75	5.93	−3.79	−0.16	−0.17	−0.03

Notes: "Change in percentage" gives the percentage changes in the coefficients of the robust policy function relative to the RE policy function. All five models are calibrated to a detection error probability of 20%.

give rise to an additional increase in inflation via the cost channel. The initial interest rate cut is possible because, under commitment, the entire policy path affects expectations and, as a result, the central bank has an additional instrument at its disposal. However, the staggered loan rates prevent the policy rate cut from completely offsetting the initial inflationary effect. To bring back inflation to its steady state, the central bank therefore engineers a recession by raising the policy rate accordingly in subsequent periods. Output is lowered for an extended period of time so that inflation expectations $E_t\pi_{t+1}$ fall below steady-state inflation.

3. ROBUST MONETARY POLICY

3.1. Robust Control

Up to now, we have assumed that the economic agents know the true model of the economy with certainty. Uncertainty exists only in terms of additive errors such that certainty equivalence holds; that is, the actions of the agents depend solely on their expectations of future variables, but not on the uncertainty surrounding those expectations. We now relax this assumption and describe formally the general uncertainty surrounding the model. We follow the robust control literature along the lines of Hansen and Sargent (2008) and augment the reference model with a vector of misspecification terms.

For ease of comparison, we stick to the general structure of the equilibrium dynamics.[11] Based on the linearized reference model (6), we obtain the so-called "distorted" or "misspecified" model by including a vector with misspecification terms υ_{t+1}:

$$A_0 \begin{bmatrix} x_{1,t+1} \\ E_t x_{2,t+1} \end{bmatrix} = A_1 \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + B r_t + C (\varepsilon_{t+1} + \upsilon_{t+1}). \tag{11}$$

The misspecification is assumed to be bounded as

$$E_0 \sum_{t=0}^{\infty} \beta^t \upsilon'_{t+1} \upsilon_{t+1} \leq \upsilon_0, \tag{12}$$

where υ_0 reflects the size of the potential misspecification. The central bank assumes that misspecifications are of the worst kind and minimizes the loss function (7) subject to the distorted model (11) and the constraint (12). Giordani and Söderlind (2004) and Hansen and Sargent (2008) show that the central bank's problem can be recast as

$$\min_{r_t} \max_{\upsilon_t} E_0 \sum_{t=0}^{\infty} \beta^t \left(\boldsymbol{L}_t - \theta\, \upsilon'_{t+1} \upsilon_{t+1} \right), \tag{13}$$

subject to (11). The parameter $\theta > 0$ summarizes the central bank's attitude to model misspecification in setting its policy, which, at the same time, reflects its preference for robustness. In particular, θ is related to υ_{t+1} in such a way that, in the case of no misspecification allowed, $\lim_{\upsilon \to 0} \theta = \infty$, whereas a smaller value of θ implies greater misspecification.

To calibrate the preference for robustness, θ, the concept of a detection error probability is adopted. The detection error probability is the probability of making the wrong choice between the undistorted model and the worst-case model. Smaller values of θ allow for greater specification errors, which makes it easier for the econometrician to distinguish statistically between the two possible equilibria. Hence, a smaller θ reduces the detection error probability. We choose a preference for robustness that corresponds to a detection error probability of 20%, as suggested by Giordani and Söderlind (2004, p. 2376) and Hansen and Sargent (2008, p. 219).

To illustrate how a preference for robustness alters the dynamics of the model and the optimal monetary policy response, we write the solution again as a VAR(1):[12]

$$\begin{bmatrix} x_{1,t} \\ \rho_{2,t+1} \end{bmatrix} = M^{\mathrm{RC}} \begin{bmatrix} x_{1,t-1} \\ \rho_{2,t} \end{bmatrix} + \begin{bmatrix} C\varepsilon_{t+1} \\ 0 \end{bmatrix} \tag{14}$$

https://doi.org/10.1017/S136510051400100X Published online by Cambridge University Press

$$\begin{bmatrix} x_{2,t} \\ r_t \\ \upsilon_{t+1} \\ \rho_{1,t} \end{bmatrix} = N^{\mathrm{RC}} \begin{bmatrix} x_{1,t} \\ \rho_{2,t} \end{bmatrix}, \qquad (15)$$

where the robust optimal policy function under commitment is given by

$$r_t = N_r^{\mathrm{RC}} \begin{bmatrix} x_{1,t} \\ \rho_{2,t} \end{bmatrix}, \qquad (16)$$

with N_r^{RC} being a $1 \times (n_1 + n_2)$ submatrix of N^{RC}.

The system (14) and (15) describes the worst-case equilibrium. The approximating equilibrium (or model) can be obtained by assuming that there are no misspecification errors $\upsilon_{t+1} = 0$, but retaining the robust policy and expectation formation under the worst-case model. This gives the equilibrium dynamics under robust decision-making by the central bank and the private sector.

3.2. The Robust Policy under Flexible Loan Rates: More and Less Aggressive

We are now ready to turn to the effects of robustness on the central bank's optimal policy function given by (16) and compare in Table 2 the coefficients of the robust policy function with the coefficients of the policy function of the rational expectations (RE) equilibrium (10). To put our results into context, it is instructive to recall the following two findings of the literature. First, model uncertainty worries the policy maker only if an unexpected shock gives rise to a meaningful trade-off between the variables in the loss function. Second, recent research has shown that the direction of a response under the robust policy hinges on the structure of the model economy.[13] In other words, robust monetary policy may be either more aggressive or more cautious than the response of the RE equilibrium depending inter alia on the type of shock. To replicate earlier findings of the literature—now under commitment—and to carve out the contribution of the imperfect interest rate pass-through later, we start with completely flexible loan rates. We thereby isolate the role of the cost channel and subsequently investigate the effects of loan-rate smoothing in the loss function. This allows us to disentangle some of the effects that are at play simultaneously.

We begin with a perfect interest rate pass-through from the policy rate to loan rates [Table 2, Panel (a)]. Hence, the model boils down to the standard New Keynesian model with a cost channel like those in Ravenna and Walsh (2006) and Tillmann (2009a, 2009b).[14] Monetary policy responds more aggressively to cost-push shocks e_t and loan rate shocks l_t, but less aggressively to demand shocks u_t.[15] Some comments are in order.

First, the results differ from the findings for the standard New Keynesian model [see, for instance, Giordani and Söderlind (2004) or Leitemo and Söderström (2008b)], where the demand shock can be fully stabilized. Because in those models

https://doi.org/10.1017/S136510051400100X Published online by Cambridge University Press

there is no policy trade-off, model uncertainty does not alter the optimal monetary policy response. In the present model, however, the cost channel gives rise to a policy trade-off, and this explains why the optimal monetary policy differs if model uncertainty is taken into account. To obtain an intuition as to why monetary policy actually responds less aggressively to a demand shock, it is useful to recall the model dynamics for the RE equilibrium when certainty equivalence holds: the central bank's increase in the policy rate is passed through to the loan rate and thus causes an immediate rise in marginal cost and inflation, but dampens output via aggregate demand. Yet to stabilize the inflation rate, the central bank is forced to increase the interest rate even more. Taking model uncertainty into account, the central bank raises the interest rate, but less aggressively. Such a cautious response is quite intuitive: the policy maker is aware that the increase in the interest rate in combination with the cost channel causes, on impact, a deviation of inflation from its steady state. In turn, the deviation increases volatility of inflation and raises the loss (7). To contain the additional volatility, the policy maker reacts more cautiously.[16]

Second, a priori it is not obvious whether a loan rate shock l_t should be a concern for the policy maker taking into account that the model could be misspecified. The cost channel also induces a policy trade-off for a loan rate shock between the variables in the loss function, as higher loan rates raise inflation. The central bank responds by initially cutting the policy rate drastically to attenuate the impact of the loan rate shock on inflation via the cost channel. Subsequently, the central bank increases the interest rate to engineer a recession and stabilize inflation. Such a response works best under commitment, where the entire policy path affects agents' expectations. As the initial policy rate cut does not imply higher inflation, the policy maker is able to respond more aggressively when taking model uncertainty into account.

To sum up, an increase in the preference for robustness has an ambiguous effect on optimal monetary policy. The ambiguity stems from the fact that the policy maker sets the interest rate so that—given the high weight for inflation stabilization in the loss function (7)—the volatility of inflation is not increased by the policy response. In those cases where the response itself raises the volatility of inflation, the policy maker reacts more cautiously.[17]

3.3. The Robust Policy and Loan Rate Stickiness: Amplification of Responses

After having delineated the role of the cost channel, we can next describe how loan rate stickiness changes the deliberations thus far. Based on the empirical findings for the monetary transmission mechanism in the euro area as reported by de Bondt et al. (2005), we now calibrate loan rate stickiness in our benchmark model to the survey's average at $q = 0.177$ (b) and to the survey's upper bound at $q = 0.422$ (c), which is based on the studies of Sander and Kleimeier (2002) and Hofmann (2003). From a comparison of the results of the cost channel with flexible loan rates

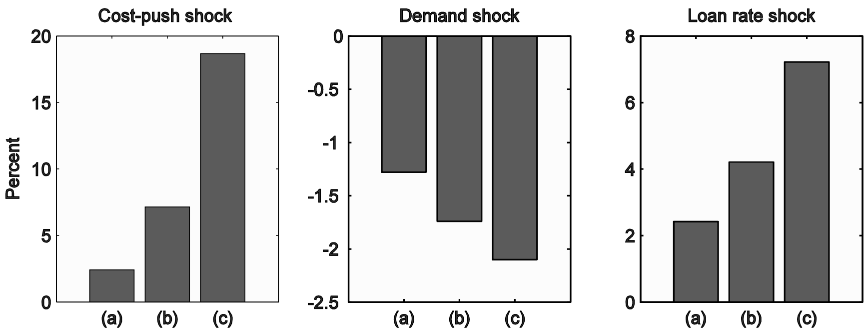

FIGURE 1. Percentage changes in the coefficients of the robust policy function relative to the RE policy function. (a) Model with cost channel and flexible loan rates, (b) benchmark calibration of a model with cost channel and imperfect interest rate pass-through, and (c) model with cost channel and highly sticky loan rates.

[Table 2, Panel (a)] with the model with an imperfect interest rate pass-through [Panel (b) and (c)], a common feature emerges. The stickiness in the loan rates amplifies the effects of robustness.[18] The relative change in responses, i.e., the percentage change in the coefficient of the robust policy function relative to the coefficient of the RE policy function, increase for a cost-push and a loan rate shock, i.e., policy becomes more aggressive, and decrease in the case of a demand shock, i.e., policy becomes more cautious.[19] The three bars in Figure 1, (a), (b), and (c), summarize the relative change in responses of the robust policy for an increasing degree of loan rate stickiness. The pattern confirms that a higher degree of loan rate stickiness leads to stronger effects of robustness; i.e., the already aggressive responses to the cost-push and the loan rate shock become more aggressive and the already cautious response to the demand shock becomes more cautious.

From Section 2.4 we know that the changes in the calibration of the degree of loan rate stickiness not only affect the loan rate equation (3) but also alter the microfounded welfare function. Specifically, more stickiness in loan rates raises their weight in the loss function (7). To disentangle the effects of loan rate smoothing in the loss function from the effects of more loan rate stickiness in the interest rate pass-through, we now conduct a ceteris paribus analysis based on two ad hoc loss functions. Specifically, we consider a model with a cost channel and flexible loan rates, but keep loan rate smoothing in the loss function, indicated by (d), and a model with a cost channel and sticky loan rates, but without loan rate smoothing in the loss function, indicated by (e). The relative change in responses of the robust policy is given by the two lightly colored bars of Figure 2. Keeping only loan rate smoothing in the loss function but leaving out any stickiness in the interest pass-through also amplifies to some extent the effects of robustness [Table 2, Panel (d)].[20] The response to cost-push shocks becomes more aggressive and the response to demand shocks more cautious. The effect of robustness on loan rate shocks is slightly muted, as changes in the loan rate come at a cost. The

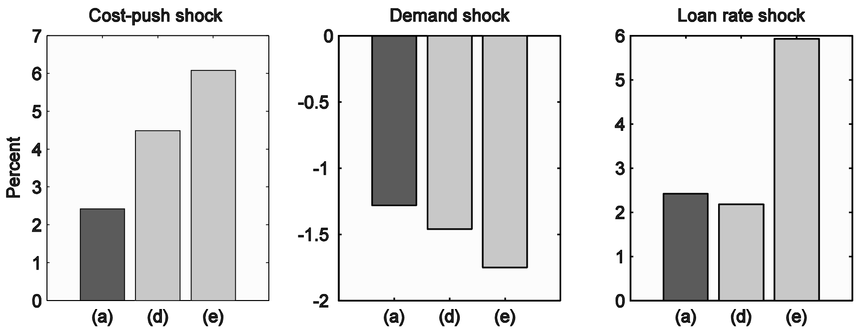

FIGURE 2. Percentage changes in the coefficients of the robust policy function relative to the RE policy function. (a) Model with cost channel and flexible loan rates, (d) model with cost channel and flexible loan rates, but loan rate smoothing in the loss function, and (e) model with cost channel and sticky loan rates, but no loan rate smoothing in the loss function.

last variant, case (e), reveals that ultimately most of the observed amplification stems from the stickiness in the loan rates (and not from loan rate smoothing in the loss function): the relative changes due to taking into account model uncertainty in Panel (e) of Table 2 come close to those of the benchmark model in Panel (b). However, with no penalty on loan rate movements in the loss function, the response to loan rate shocks is even more aggressive.

Summing up, the cost channel drives the results qualitatively, as it introduces the policy trade-off in the case of a demand shock and a loan rate shock. However, as a *first key result*, we note that the imperfections stemming from the incomplete interest rate pass-through amplify the relative change in responses of the robust policy when the policy maker has a preference for robustness. Under the robust policy the responses to a cost-push shock and a loan rate shock become more aggressive, whereas the response to a demand shock becomes more cautious.

3.4. The Price of Robustness: Expensive Insurance for Highly Sticky Loan Rates

After having described in which ways the robust policy maker deviates from the RE equilibrium and how a higher degree of loan rate stickiness amplifies the relative change in responses of the robust policy, we now turn to the overall costs of such a robust policy. The losses for the RE equilibrium, the worst-case equilibrium, and the approximating equilibrium summarize succinctly in percentages of steady-state consumption how robustness affects social welfare, described by (5). In the worst-case equilibrium, the model is indeed misspecified and, therefore, the corresponding impulse responses become generally more persistent. Accordingly, the loss in the worst case turns out to be the highest (Table 3). In the approximating equilibrium, the model is not misspecified, but the policy maker acts as if the model

TABLE 3. Comparison of losses

	RE equilibrium	Worst-case equilibrium	Approximating equilibrium	Insurance premium as a percentage
(a) Cost channel with flexible loan rates	0.000453	0.000791	0.000461	2.38
(b) Benchmark, $q = 0.177$	0.000462	0.000816	0.000483	5.91
(c) Highly sticky loan rates, $q = 0.422$	0.000465	0.000901	0.000551	19.80

Notes: Loss as a percentage of steady-state consumption. All three models are calibrated to a detection error probability of 20%. Differences are due to rounding errors.

were misspecified. Obviously, robustness comes at a cost, as such a strategy yields a higher loss than the RE policy function, but offers a kind of *insurance* against misspecification. The difference between the loss of the approximating equilibrium and the loss of the RE equilibrium over the difference between the worst-case equilibrium and the RE equilibrium gives an insurance premium [similarly to Kuester and Wieland (2010, p. 885)]. The premium measures how much the policy maker is willing to pay, as a percentage of the "damage" caused in the worst case, to insure against model misspecification. In the benchmark model, the premium amounts to 5.91% [Table 3, Panel (b)].

A higher degree of loan rate stickiness raises the loss in all three equilibria, but for the RE equilibrium itself the increases across calibrations turn out to be small. However, the insurance premium mirrors the amplification found in our first key result, as the robust policy becomes much more costly if the reference model is characterized by highly sticky loan rates. In fact, insurance against model misspecification may require paying an insurance premium of almost 20% in terms of welfare [Table 3, Panel (c)]. It seems unlikely to us that a central bank would be willing to insure itself against model misspecification at such a high price.

The variances in Table 4 allow us to understand what drives the insurance premium. The table gives the changes in the variances of the worst-case equilibrium and the approximating equilibrium, relative to the RE equilibrium as percentages. Overall, the percentage changes in the variances are similar for models with the same degree of loan rate stickiness, and the effects from the presence or absence of loan rate smoothing are small. In the worst-case equilibrium of the benchmark model, the three welfare-relevant variables inflation, output gap, and loan rate, as well as the policy instrument, become more volatile [Table 4, Panel (b)].[21] Output in particular fluctuates more (increase of 82.29% relative to the RE equilibrium), as its weight in the loss function is small compared to that of inflation (thus, the volatility of output does not matter much for welfare). In the approximating equilibrium, the robust policy comes at a cost: the central bank dampens volatility

TABLE 4. Comparison of changes in the variances

	Percentage changes in the variances for worst-case equilibrium (approximating equilibrium in italics) relative to RE equilibrium			
	Inflation	Output gap	Loan rate	Policy rate
(a) Cost channel with flexible loan rates	12.69	78.95	8.56	5.15
	−32.31	*4.02*	*4.09*	*4.62*
(b) Benchmark, $q = 0.177$	11.87	82.29	10.60	6.27
	−19.80	*6.26*	*6.70*	*8.00*
(c) Highly sticky loan rates, $q = 0.422$	17.82	101.15	15.42	7.90
	107.68	*12.64*	*14.31*	*21.29*
(d) Cost channel, flexible loan rates,	11.20	79.57	9.51	5.92
but loan rate smoothing	*−29.92*	*4.75*	*5.21*	*6.03*
(e) Cost channel, sticky loan rates,	11.90	81.22	10.28	6.03
but no loan rate smoothing	*−22.15*	*5.86*	*6.23*	*7.36*

Note: All models are calibrated to a detection error probability of 20%.

in the inflation rate preemptively (-19.80% relative to RE equilibrium), but simultaneously accepts higher volatility in the output gap and the loan rate. The policy instrument also becomes more volatile. We note that in the benchmark model the central bank's concern for misspecification and, therefore, the robust policy is clearly oriented toward stabilizing the inflation rate.

Figure 3 displays the changes in the variances for a spectrum of loan rate stickiness. We note that the robust policy manages to keep the increase in volatility of inflation in the worst case for all calibrations below 20% (dashed line in the upper left panel). To do so, the robust policy needs to respond more aggressively. The increase in aggressiveness is reflected in the higher volatility of the policy rate in the approximating equilibrium (solid line in the lower left panel), which in turn affects inflation via the cost channel. The preventive aggressiveness, together with the frictions in the interest rate pass-through, thus drives inflation in the approximating equilibrium (solid line in the upper left panel). Eventually, the robust policy cannot stabilize inflation preemptively. For a high loan rate stickiness of $q = 0.422$, corresponding to banks re-setting loan rates on the average every five months, the volatility of inflation increases by over 100% relative to the RE equilibrium [Table 4, Panel (c)].

To sum up, as a *second key result*, we note that insurance against model misspecification is particularly pricy when the degree of loan rate stickiness is high: sticky loan rates may imply an insurance premium of up to one-fifth of the loss under certainty equivalence, which is largely driven by inflation being twice as volatile as in the RE equilibrium.[22]

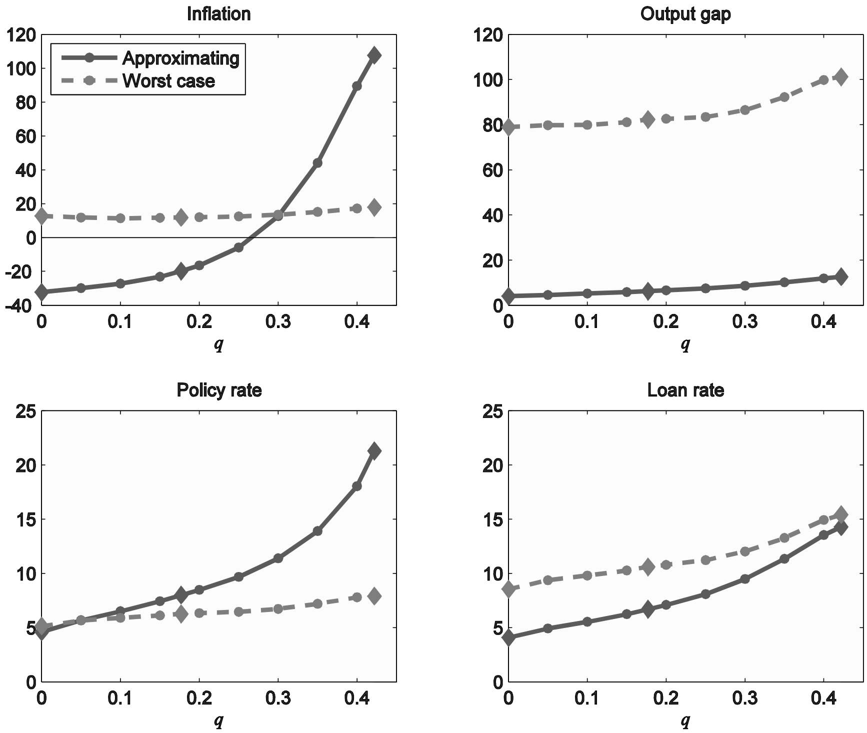

FIGURE 3. Percentage changes in the variances for different degrees of loan rate stickiness q. The degree of loan rate stickiness increases from 0.05 to 0.40 in steps of 0.05 [in addition to the values for (a), (b), and (c) of Table 4, indicated by diamonds]. All models are calibrated to a detection error probability of 20%.

3.5. Uncertainty Surrounding Only One Equation: Shifts in Concerns for Robustness

So far, the results hinge on the assumption that every equation of the reference model is prone to misspecification. In principle, this may not necessarily be the case if the policy maker is concerned about a specific economic relation, while neglecting uncertainty in others. For instance, the policy maker might be uncertain especially regarding the imperfect interest rate pass-through and thus the loan rate equation or might be concerned just about the Phillips curve. Uncertainty surrounding only one equation allows us to reveal that the policy maker shifts its focus in stabilizing the target variables.

In the following, we therefore illustrate three special cases when the central bank and the private sector face uncertainty in only one of the three economic relations.[23] In other words, we allow no more than one of the three equations in the benchmark model with $q = 0.177$ to be misspecified.[24] To highlight in which way the central bank guards itself against misspecification, we report in

https://doi.org/10.1017/S136510051400100X Published online by Cambridge University Press

TABLE 5. Percentage changes in the variances for shifts in concerns for robustness

Uncertainty surrounding...	Percentage changes in the variances for worst-case equilibrium (approximating equilibrium in italics) relative to RE equilibrium			
	Inflation	Output gap	Loan rate	Policy rate
all three equations	11.87	82.29	10.60	6.27
	−19.80	*6.26*	*6.70*	*8.00*
only Phillips curve	12.22	88.07	1.53	3.53
	−1.82	*7.98*	*116.72*	*87.39*
only IS equation	16.04	85.40	82.05	78.01
	48.03	*−2.15*	*−1.28*	*−1.08*
only loan rate equation	18.44	98.03	94.17	2.20
	52.69	*−2.31*	*−1.37*	*1.17*

Note: All four models are calibrated to a detection error probability of 20%.

Table 5 the percentage changes in the variances relative to the RE equilibrium, but focus on the approximating equilibrium given in italics. If the central bank faces uncertainty only in the Phillips curve (1), the changes in the variances coincide qualitatively with the benchmark case of misspecification in all three equations. Volatility in inflation is dampened preemptively, whereas volatility increases for the other variables, including the policy instrument.[25] If uncertainty is present only in the IS equation (2) or the loan rate equation (3), the robust policy shifts its concern for stabilization. As a *third key result*, we find that, in the latter two cases, the central bank reduces the volatility in the output gap and the loan rate preemptively, but accepts higher volatility in inflation. Obviously, this result hinges on the assumption that the policy maker is not concerned about model uncertainty regarding the Phillips curve. With respect to the policy instrument, there is a marked difference. Uncertainty in the loan rate equation leads to a more volatile policy instrument, whereas uncertainty in the IS equation reduces volatility in the policy rate. The central bank responds more aggressively to a loan rate shock but less aggressively to a demand shock.

4. CONCLUSIONS

In general, central banks acknowledge that every model is incomplete and, therefore, a misspecified description of reality. To prevent very bad outcomes, central banks need to design policies that are robust against model misspecification. We incorporate model uncertainty by following the robust control approach along the lines of Hansen and Sargent (2008) and assume that the true model is not known but lies in the neighborhood of a reference model.

We employ as a reference model a version of the New Keynesian model that is able to replicate key stylized facts of the monetary transmission mechanism in the euro area. The model incorporates financial intermediaries and features imperfect interest rate pass-through from the policy rate to the loan rate. Taking model uncertainty into account replicates the ambiguity found in earlier studies with a cost channel but flexible loan rates. Monetary policy responds either more cautiously or more aggressively, depending on the type of shock. The ambiguity stems from the fact that the central bank sets the interest rate so that the volatility of inflation is not increased by the policy response. In cases where the response itself raises the volatility of inflation, the central bank responds more cautiously; otherwise, it responds more aggressively. The finding stands in contrast to the standard New Keynesian model, where a preference for robustness always makes the central bank respond more aggressively. The effects of interest rate stickiness on a central bank's concern for robustness can be summarized as follows.

First, the imperfections stemming from the incomplete interest rate pass-through amplify the relative change in responses of the robust policy when the central bank has a concern for robustness to model misspecification. For stickier loan rates the responses to a cost-push shock and a loan rate shock under the robust policy become more aggressive, whereas the response to a demand shock becomes more cautious.

Second, insurance against model uncertainty is particularly pricy when the degree of loan rate stickiness is high. Under the benchmark calibration with loan rate stickiness corresponding to a quarter and three weeks, the central bank dampens volatility in the inflation rate preemptively, but simultaneously accepts higher volatility in the output gap and the loan rate. However, for highly sticky loan rates, when banks set their loan rates on the average only every five months, the volatility of inflation increases even when the model is not in fact misspecified. In this case, the robust policy raises the insurance premium to one-fifth of the loss under certainty equivalence.

Third, uncertainty surrounding a single equation may imply a shift in the policy maker's concern for robustness. If the central bank faces uncertainty only in the Phillips curve, the changes of the variances coincide qualitatively with the benchmark case (misspecification in all equations). But if uncertainty is present only in the IS equation or only in the loan rate equation, the robust policy shifts its concern for stabilization. We find that, in both cases, the central bank reduces the volatility in the output gap and the loan rate, but accepts higher volatility in inflation. The result hinges crucially on the assumption that the central bank is not concerned about model uncertainty regarding the Phillips curve.

NOTES

1. See de Bondt et al. (2005) for an overview with respect to the imperfect interest rate pass-through. To the preceding short list may be added that (iv) credit constraints are probably not crucial

at the aggregate level, and (v) it is difficult to detect systematic differences across countries. See, for instance, Cecioni and Neri (2011).

2. For a similar model, see Teranishi (2015).

3. For the distinction between structured and unstructured uncertainty see, among others, Tetlow and von zur Muehlen (2001) and Williams (2008, p. 223).

4. Onatski and Stock (2002) show that model uncertainty induces also more aggressive policy responses in a backward-looking model.

5. Otherwise, for a cost-push shock and a loan rate shock, the central bank responds more aggressively.

6. At the intermediate goods level, sticky loan rates are the only relevant distortion, because a subsidy eliminates the distortions induced by monopolistic competition and a positive steady-state interest rate; see Kobayashi (2008, p. 86).

7. In line with the literature using the Calvo mechanism, the model abstracts from direct costs of adjustment in prices and loan rates.

8. Note that Gerke and Hammermann (2011) provide results for optimal monetary policy under discretion.

9. The size of the model, together with the persistence of the shocks, both necessary to capture the stylized facts of the monetary transmission mechanism, renders it impossible to derive the model solution analytically. The particular advantage of an analytical solution would be that the optimal policy function would respond to observable variables such as inflation and output gap and not to unobservable shocks. Walsh (2004) achieves an analytical solution in a smaller New Keynesian model (without sticky loan rates). He assumes a welfare loss function that also penalizes (in addition to variation in inflation and in the output gap) variation in the nominal interest rate in levels.

10. Also known as the optimal reaction function [Svensson (2010, p. 7)] or optimal policy rule (Leitemo and Söderström 2008a, p. 3235, and 2008b, p. 132).

11. See also Giordani and Söderlind (2004), Kilponen and Leitemo (2008), and Leitemo and Söderström (2008a, 2008b).

12. Note that the presence of robustness does not affect the optimal trade-off between inflation and output (gap) volatility even in the presence of imperfect pass-through of interest rate variations. This is mainly because the misspecifications are introduced as additive shocks to the original equations. See Tillmann (2011) for an alternative specification that has consequences for this trade-off. See also Walsh (2004) and, among others, Leitemo and Söderström (2008a, 2008b) and Tillmann (2009b) on the equivalence of robustly optimal targeting rules and robust control.

13. Barlevy (2009) shows by a few simple examples that neither a more cautious nor a more aggressive policy response is a general feature of robust control.

14. Technically, we set $q = 0.000001$.

15. The last row of Panel (a) in Table 2 displays how much the robust policy changes relative to the RE response. For a cost-push shock and a loan rate shock the relevant coefficients increase by more than 2%, whereas for a demand shock the relevant coefficient declines by more than 1%. For instance, a change in the coefficient by 2% corresponds to an additional increase of 2 basis points for a 100-basis-point increase of the policy instrument in the RE equilibrium.

16. The result is compatible with the findings of Tillmann (2009b), who analyzes a model with a cost channel with optimal monetary policy under discretion, and also shows that monetary policy responds more cautiously to a demand shock. Similarly, Leitemo and Söderström (2008a) find the ambiguity of the central bank's response in an open economy model, where the robust policy does not always respond more aggressively, but responds more cautiously when the exchange rate channel dominates.

17. It is interesting to note that, under discretion, the central bank's response itself raises the volatility of inflation for each shock. Consequently, the robust policy maker always reacts more cautiously; see Gerke and Hammermann (2011).

18. In the RE equilibrium under certainty equivalence, we observe that for a higher degree of loan rate stickiness the policy maker cuts the policy rate by less after a cost-push and a loan rate shock.

Essentially, with the subdued response, the policy maker avoids the repercussions on inflation induced by the high degree of loan rate stickiness.

19. Note that Tillmann (2009b) finds for robust monetary policy operating under discretion in a model with a cost channel that a high cost channel leads to a less aggressive policy response to a demand shock, whereas a low cost channel to a more aggressive policy. Our results show that in a model with imperfect interest rate pass-through we do not observe such a switch for robust optimal monetary policy under commitment.

20. The weight on loan rate smoothing in the loss function equals the weight of the benchmark model.

21. For ease of comparison, we report the volatility of the loan rate in levels, although it is the *change* in the loan rate that matters for welfare.

22. Robustness checks confirm that the second result is not driven by loan rate dispersion in the loss function but stems from the effects of stickier loan rates on the volatility of key variables causing a deterioration in welfare.

23. The Appendix gives the changes in the policy maker's optimal policy functions.

24. Technically, we set the standard error of two of the three shocks to zero, so that they practically disappear from the model. Note that the degree of misspecification in an equation depends positively on the variance of the shock associated with the equation, given the preference for robustness. To allow meaningful comparison, all models are calibrated again to a detection error probability of 20%.

25. In contrast, when uncertainty surrounds only one equation but analyzing robust monetary policy under discretion, we find that the central bank responds always more cautiously. The more cautious response for uncertainty surrounding only the Phillips curve (1) is in line with the findings of Tillmann (2009a), who analyzes parameter uncertainty in a model with a cost channel but no frictions in the interest rate pass-through.

REFERENCES

Araújo, E. (2013) Robust monetary policy with the consumption–wealth channel. *Journal of Economic Dynamics and Control* 37, 296–311.

Barlevy, G. (2009) Policymaking under uncertainty: Gradualism and robustness. *Economic Perspectives* 33, 38–55.

Brainard, W. (1967) Uncertainty and the effectiveness of policy. *American Economic Review* 57, 411–425.

Calvo, G.A. (1983) Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics* 12, 383–398.

Cateau, G. (2006) Guarding against Large Policy Errors under Model Uncertainty. Bank of Canada working paper 2006–13.

Cecioni, M. and S. Neri (2011) The Monetary Transmission Mechanism in the Euro Area: Has It Changed and Why? Banca d'Italia working paper 808.

Christiano, L.J. and M. Eichenbaum (1992) Liquidity effects and the monetary transmission mechanism. *American Economic Review* 82, 346–353.

Dai, M. and E. Spyromitros (2012) A note on monetary policy, asset prices, and model uncertainty. *Macroeconomic Dynamics* 16, 777–790.

de Bondt, G., B. Mojon, and N. Valla (2005) Term Structure and the Sluggishness of Retail Bank Interest Rates in Euro Area Countries. ECB working paper 518.

Gerke, R. and F. Hammermann (2011) Robust Monetary Policy in a New Keynesian Model with Imperfect Interest Rate Pass-Through. Deutsche Bundesbank discussion paper series 1, 02/2011.

Giannoni, M.P. (2002) Does model uncertainty justify caution? Robust optimal monetary policy in a forward-looking model. *Macroeconomic Dynamics* 6, 111–144.

Giordani, P. and P. Söderlind (2004) Solution of macromodels with Hansen–Sargent robust policies: Some extensions. *Journal of Economic Dynamics and Control* 28, 2367–2397.

Hansen, L.P. and T.J. Sargent (2008) *Robustness.* Princeton, NJ: Princeton University Press.

Hofmann, B. (2003) EMU and the Transmission of Monetary Policy: Evidence from Business Lending Rates. Mimeo, ZEI, University of Bonn.

Kilponen, J. and K. Leitemo (2008) Model uncertainty and delegation: A case for Friedman's *k*-percent money growth rule? *Journal of Money, Credit and Banking* 40, 547–556.

Kobayashi, T. (2008) Incomplete interest rate pass-through and optimal monetary policy. *International Journal of Central Banking* 4, 77–118.

Kuester, K. and V. Wieland (2010) Insurance policies for monetary policy in the euro area. *Journal of the European Economic Association* 8, 872–912.

Leitemo, K. and U. Söderström (2008a) Robust monetary policy in a small open economy. *Journal of Economic Dynamics and Control* 32, 3218–3252.

Leitemo, K. and U. Söderström (2008b) Robust monetary policy in the New Keynesian framework. *Macroeconomic Dynamics* 12, 126–135.

Lubik, T.A. and F. Schorfheide (2004) Testing for indeterminacy: An application to U.S. monetary policy. *American Economic Review* 94, 190–217.

Onatski, A. and J.H. Stock (2002) Robust monetary policy under model uncertainty in a small model of the U.S. economy. *Macroeconomic Dynamics* 6, 85–110.

Onatski, A. and N. Williams (2003) Modelling model uncertainty. *Journal of the European Economic Association* 1, 1087–1122.

Ravenna, F. and C.E. Walsh (2006) Optimal monetary policy with the cost channel. *Journal of Monetary Economics* 53, 199–216.

Rotemberg, J.J. and M. Woodford (1997) An optimization-based econometric framework for the evaluation of monetary policy. *NBER Macroeconomics Annual* 12, 297–346.

Sander, H. and S. Kleimeier (2002) Asymmetric adjustment of commercial bank interest rates in the euro area: An empirical investigation into interest rate pass-through. *Kredit und Kapital* 35, 161–192.

Söderlind, P. (1999) Solution and estimation of RE macromodels with optimal policy. *European Economic Review* 43, 813–823.

Svensson, L.E.O. (2010) Optimization under Commitment and Discretion, the Recursive Saddlepoint Method, and Targeting Rules and Instrument Rules. Lecture notes, Sveriges Riksbank and Stockholm University.

Teranishi, Y. (2015) Smoothed interest rate setting by central banks and staggered loan contracts. *Economic Journal* 125, 162–183.

Tetlow, R.J. and P. von zur Muehlen (2001) Robust monetary policy with misspecified models: Does model uncertainty always call for attenuated policy? *Journal of Economic Dynamics and Control* 25, 911–949.

Tillmann, P. (2009a) Optimal monetary policy with an uncertain cost channel. *Journal of Money, Credit and Banking* 41, 885–906.

Tillmann, P. (2009b) Robust monetary policy with cost channel. *Economica* 76, 486–504.

Tillmann, P. (2011) Parameter uncertainty and nonlinear monetary policy rules. *Macroeconomic Dynamics* 15, 184–200.

Walsh, C.E. (2004) Robustly optimal instrument rules and robust control: An equivalence result. *Journal of Money, Credit and Banking* 36, 1105–1113.

Williams, N. (2008) Robust control. In S.N. Durlauf and L.E. Blume (eds.), *The New Palgrave: Dictionary of Economics*, 2nd ed., Vol. 7, pp. 220–225. London: Palgrave McMillan.

APPENDIX: UNCERTAINTY SURROUNDING ONLY ONE EQUATION

Uncertainty surrounding ...	Percentage changes in the coefficients of optimal policy functions						
	e_t	u_t	l_t	r^l_{t-1}	$\rho^{\pi}_{2,t}$	$\rho^{y}_{2,t}$	$\rho^{rl}_{2,t}$
all three equations	7.153	−1.737	4.211	−0.273	−0.061	−0.170	−0.002
only Phillips curve	7.926	−1.922	4.658	−0.330	−0.036	−0.207	−0.009
only IS equation	4.546	−1.124	2.725	−0.007	−0.199	0.002	0.036
only loan rate equation	4.900	−1.212	2.937	−0.008	−0.211	0.002	0.038

Notes: Percentage changes in the coefficients of the robust policy function relative to the RE policy function. All four models are calibrated to a detection error probability of 20%.