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Robust monetary policy in a New Keynesian model with imperfect interest rate pass-through

Rafael Gerke
Felix Hammermann

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Deutsche Bundesbank, Wilhelm-Epstein-Straße 14, 60431 Frankfurt am Main,
Postfach 10 06 02, 60006 Frankfurt am Main

Tel +49 69 9566-0
Telex within Germany 41227, telex from abroad 414431

Please address all orders in writing to: Deutsche Bundesbank,
Press and Public Relations Division, at the above address or via fax +49 69 9566-3077

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Abstract

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. The effects of the central bank's concern for robustness can be summarised as follows. First, depending on the shock, robust optimal monetary policy under commitment responds either more cautiously or more aggressively. Second, such robustness comes at a cost: the central bank dampens volatility in the inflation rate pre-emptively, but accepts higher volatility in the output gap and the loan rate. Third, if the central bank faces uncertainty only in the IS equation or the loan rate equation, the robust policy shifts its concern for stabilisation away from inflation.

Keywords: optimal monetary policy, commitment, model uncertainty

JEL Classification: E44, E58, E32

Non-technical summary

In general, the central bank acknowledges that every model is incomplete and, therefore, a misspecified description of reality. Consequently, it needs to design a policy that is 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 neighbourhood around a reference model.

We employ as a reference model a version of the New Keynesian model that is able to replicate stylised 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. The effects of the central bank's concern for robustness can be summarised as follows. First, we observe that 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 such that the volatility of inflation is not increased by the policy response. In those cases where the response itself raises the volatility of inflation, the central bank responds more cautiously; otherwise, it responds more aggressively.

Second, robustness comes at a cost: the central bank dampens volatility in the inflation rate pre-emptively, but simultaneously accepts higher volatility in the output gap and the loan rate. The central bank's concern for misspecification shows that the robust policy is oriented towards stabilising the inflation rate, although the central bank also cares about minimising the welfare costs of the imperfect interest rate pass-through.

Third, if the central bank faces uncertainty only in the IS equation or the loan rate equation, the robust policy shifts its concern for stabilisation. 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.

Nicht technische Zusammenfassung

Im Allgemeinen sind sich Zentralbanken bewusst, dass jedes Modell nur eine unvollständige und daher fehlerhafte Beschreibung der Realität darstellen kann. Deswegen müssen sie eine Politik wählen, die robust gegenüber Fehlspezifikationen ist. Wir berücksichtigen Modellunsicherheit und folgen dabei dem von Hansen und Sargent (2008) entwickelten Ansatz zur robusten Kontrolle. Wir unterstellen, dass das wahre Modell nicht bekannt ist, aber sich in der Umgebung eines Referenzmodells befindet.

Als Referenzmodell unterstellen wir eine Version des neukeynesianischen Modells, das in der Lage ist, wesentliche stilisierte Fakten des monetären Transmissionsmechanismus für den Euro-Raum abzubilden. Das Modell enthält einen Finanzintermediär, der Änderungen im geldpolitischen Leitzins nur verzögert über Kreditzinsen weitergibt. Die Ergebnisse hinsichtlich der Berücksichtigung von Modellunsicherheit können wie folgt zusammengefasst werden: Erstens, je nach Schock reagiert die Geldpolitik aggressiver oder zurückhaltender. Die uneinheitliche Reaktion liegt in der Tatsache begründet, dass die Zentralbank ihren Zins so wählt, dass sich die Volatilität der Inflation nicht durch die Zinsreaktion selbst erhöht. In den Fällen, in denen die Zinsreaktion selbst zu einer stärkeren Schwankung der Inflation führt, reagiert die Zentralbank zurückhaltender.

Zweitens, die robuste Politik ist mit Kosten verbunden. Die Zentralbank verringert präventiv die Volatilität der Inflation, akzeptiert aber dabei, dass Schwankungen der Produktionslücke und der Kreditzinsen zunehmen. Die Bedenken der Zentralbank hinsichtlich einer etwaigen Fehlspezifikation des Modells zeigen sich darin, dass die robuste Politik auf eine stärkere Stabilisierung der Inflationsrate abzielt, obwohl sie grundsätzlich auch anstrebt, diejenigen Wohlfahrtsverluste zu minimieren, die mit einer unvollständigen Zinsweitergabe des Bankensektors verbunden sind.

Drittens, wenn die Zentralbank allein die Unsicherheit in der IS Kurve oder in der Bestimmungsgleichung für die Kreditzinsen berücksichtigt, verschiebt sich der Fokus der Stabilisierung. In diesen Fällen zielt die Zentralbank auf eine stärkere Verringerung der Volatilität der Outputlücke und der Kreditzinsen ab und toleriert dabei eine höhere Volatilität der Inflation.

Contents

List of Tables

List of Figures

Robust monetary policy in a New Keynesian model with imperfect interest rate pass-through[1]

1 Introduction

Even similar models produce different predictions of how monetary policy affects the dynamics of policy-relevant variables. Cateau (2006), for example, illustrates that different New Keynesian models involve different policy transmission mechanisms. It is not obvious how monetary policy should cope with the different policy recommendations. The origin of the central bank's difficulty in setting the policy rate lies in the fact that the policymaker does not know the true model or is not able to fully capture it. In general, the central bank acknowledges 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.

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 neighbourhood around a chosen reference model. The central bank is not able to formulate a probability distribution over plausible models in that neighbourhood but recognises 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 pre-specified set of models.

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[1] Rafael Gerke and Felix Hammermann, Deutsche Bundesbank, Economics Department, Wilhelm-Epstein-Strasse 14, 60431 Frankfurt, Germany, email: firstname.lastname@bundesbank.de. 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 Heinz Herrmann, Teruyoshi Kobayashi, Peter Tillmann, Andreas Worms and participants at the Society of Computational Economics Conference in London, 2010. We are indebted to Paolo Giordani, Paul Söderlind, and Ulf Söderström for making their programme codes available to us. All remaining errors and shortcomings are, of course, our own.

We employ as a reference model a version of the New Keynesian model that is able to replicate stylised 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) monetary policy affects the economy mainly through the interest rate channel; and (iii) changes in the policy rates are not completely passed through to retail lending rates.[2] Specifically, we use an extension of the New Keynesian model, as suggested by Kobayashi (2008), which incorporates financial intermediaries 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.[3] The associated staggered loan rate setting leads to imperfect interest rate pass-through from the policy rate to the loan rate. The central bank optimises a welfare-based objective function and is able to commit. Since the model involves loan rate dispersion, the optimal monetary policy not only stabilises inflation and the output gap but also tries to avoid loan rate fluctuations.

We explore how model uncertainty affects monetary policy decisions if the true model is not known. The effects of the central bank's concern for robustness can be summarised as follows. First, we observe that 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 such that the volatility of inflation is not increased by the policy response. In those cases, where the response itself raises the volatility of inflation, the central bank responds more cautiously; otherwise, it responds more aggressively. Our result stands in contrast to the standard New Keynesian model where a preference for robustness always makes the central bank respond more aggressively (see, for instance, Giordani and Söderlind, 2004 or Leitemo and Söderström, 2008a).

Second, robustness comes at a cost: the central bank dampens volatility in the inflation rate pre-emptively, which means that it has to accept at the same time higher

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[2] See de Bondt, Mojon and Valla (2005) for an overview with respect to the imperfect interest rate pass-through. To the above short list may be added: (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 (2010).

[3] For a similar model, see Teranishi (2008).

volatility in the output gap and the loan rate. The difference between the worst-case equilibrium and the approximating equilibrium suggests that the central bank's concern for misspecification, and therefore the robust policy, is oriented towards stabilising the inflation rate, although it also cares about minimising the welfare costs of the imperfect interest rate pass-through.[4]

Third, if the central bank faces uncertainty only in the Phillips curve, the changes of the variances coincide qualitatively with the benchmark model (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 stabilisation. 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 policymaker is not concerned about model uncertainty regarding the Phillips curve.

The remainder of the paper is organised as follows. In Section 2, we present the New Keynesian model with a banking sector and staggered loan rate setting. We describe the linearised model and its calibration. In Section 3, we give a short review of the robust control approach and present the robust monetary policy under commitment when uncertainty prevails in the Phillips curve, the IS equation, and the loan rate equation. We also investigate the cases when uncertainty surrounds only one equation at a time. Finally, Section 4 concludes.

2 Model

We describe briefly the New Keynesian model with a financial intermediary suggested by Kobayashi (2008) that features a cost channel and imperfect interest rate pass-through as documented for the euro area. The model not only replicates the stylised 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 with respect to model uncertainty.

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[4] In the worst-case equilibrium, the model is indeed misspecified, whereas in the approximating equilibrium, the model is not misspecified, but the policymaker acts as if the model were misspecified.

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 labour 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 labour as the sole input. Intermediate goods firms are able to set prices flexibly, whereas final goods producers are assumed to follow a Calvo-type price-setting (Calvo, 1983). The production of final goods requires only a composite of intermediate goods. 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. Since 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 from the commercial bank of the same region. 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. 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, Mojon and Valla, 2005).

Equilibrium dynamics

Below, 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.[5] Define by π_t the rate of inflation and by y_t the output gap in the economy and by rl_t the average loan rate. Then, the key (log-linearised) equilibrium relations can be summarised as follows. Starting with the first-order condition of final goods firms, the Phillips curve can be formulated as

$$\pi_t = E_t \beta \pi_{t+1} + \lambda_F \underbrace{\left[(\sigma + \omega) y_t + rl_t\right]}_{\text{marginal cost}} + e_t, \tag{1}$$

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[5] See Appendix A1 for a detailed exposition.

where e_t denotes an aggregate supply disturbance and $(\sigma+\omega)y_t + rl_t$ represent real marginal cost with σ being the inverse of the elasticity of intertemporal substitution, and ω the elasticity of labour 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 (eg Ravenna and Walsh, 2006), the interest rate variable entering the Phillips curve is not the policy rate r_t but the average loan rate rl_t. As the model incorporates the profit-maximising behaviour of commercial banks, retail loan rates differ from the policy rate in an endogenous manner. From equation (1) it is evident that the average loan rate determines, to some extent, current inflation, as a rise in the loan rate leads to a 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 optimisation problem. Log-linearising the consumption Euler condition gives

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

where u_t denotes an aggregate demand disturbance.

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

$$rl_t = \frac{\beta}{1+\beta+\lambda_B} E_t rl_{t+1} + \frac{\lambda_B}{1+\beta+\lambda_B} r_t + \frac{1}{1+\beta+\lambda_B} rl_{t-1}$$

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 relative weights on the expected loan rate and the previous loan rate increase as the sluggishness of loan rates deteriorates. From rewriting this expression as

$$\Delta rl_t = \beta E_t \Delta rl_{t+1} + \lambda_B \left(r_t - rl_t\right) + \lambda_B l_t \tag{3}$$

it becomes evident that a change in the loan rate will be caused by an expected change in the future loan rate and/or by a discrepancy between the policy rate and the average loan rate. The loan rate shock l_t captures the idea that loan rates tend to fluctuate for reasons that are not directly linked with policy behaviour. One possibility could be a shift in the loan rate premium triggered by changes in financial market conditions.

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. More precisely, the central bank is required to stabilise the rate of change in the average loan rate. Formally, social welfare can be stated as follows

$$\mathbb{W} = E_t \sum_{s=0}^{\infty} \beta^s U_{t+s} \cong -E_t \sum_{s=0}^{\infty} \beta^s \left\{ \psi_\pi \pi_{t+s}^2 + \psi_y y_{t+s}^2 + \psi_{rl} \left(\Delta rl_{t+s}\right)^2 \right\} + t.i.p., \tag{4}$$

where *t.i.p.* represents terms independent of policy and $\psi_\pi \equiv \theta_f / \left[\lambda_F \left(\sigma + \omega\right)\right]$, $\psi_y \equiv 1$, and $\psi_{rl} \equiv \theta_z / \left[\lambda_B \left(1 + \omega \theta_z\right)\left(\sigma + \omega\right)\right]$ represent the relative weights on inflation, the output gap, and the rate of change in the average loan rate, respectively. The parameters θ_f and θ_z denote the elasticity of substitution between the variety of final goods and the elasticity of substitution for intermediate goods, respectively. As equation (4) highlights, fluctuation in the average loan rate will reduce social welfare.

Calibration

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

$$s_t = \rho^s s_{t-1} + \varepsilon_t^s, \tag{5}$$

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, Mojon and Valla (2005, Table 1). On average, banks set their lending rate for approximately one quarter and three weeks. We also follow Kobayashi in taking the baseline values of the parameters β, σ, and ω from Ravenna and Walsh (2006) and in setting the elasticity of substitution for intermediate goods θ_z equal to θ_f. The value of θ_f is taken from Rotemberg and Woodford (1997), and the degree of price stickiness ϕ is chosen such that the slope of the Phillips curve is equal to 0.58, the value reported by Lubik and Schorfheide (2004). The calibrated values are summarised in Table 1.

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

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 is introduced merely by 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. Below, we relax this assumption and describe formally the general uncertainty surrounding the model. We follow the approach from the robust control literature along the lines of Hansen and Sargent (2008) and augment the model (henceforth called the “reference model”) with a vector of misspecification terms υ_{t+1}.

For ease of exposition, we focus only on the general structure of the equilibrium dynamics.[6] In state-space form, we formulate the linearised reference model as

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

where A_0, A_1 and B are matrices of model parameters, 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 $\begin{bmatrix} e_t & u_t & l_t & rl_{t-1} \end{bmatrix}'$ with $x_{1,0}$ given, $x_{2,t}$ is the n_2-vector of forward-looking variables $\begin{bmatrix} \pi_t & y_t & rl_t \end{bmatrix}'$ and r_t is the policy instrument. We obtain the “distorted” or “misspecified” model by including a vector with misspecification terms υ_{t+1}:

$$A_0 \begin{bmatrix} x_{1,t+1} \\ E_t x_{2,t+1} \end{bmatrix} = A_1 \begin{bmatrix} x_{1,t} \\ x_{2,t} \end{bmatrix} + B r_t + C\left(\varepsilon_{t+1} + \upsilon_{t+1}\right). \tag{7}$$

The misspecification is assumed to be bounded as

$$E_0 \sum_{t=0}^{\infty} \beta^t \upsilon_{t+1}' \upsilon_{t+1} \le \upsilon_0, \tag{8}$$

where υ_0 reflects the size of the potential misspecification. The central bank supposes that misspecifications are of the worst kind and maximises social welfare (4) by minimising the loss function

$$\mathbb{L}_t = \psi_\pi \pi_t^2 + \psi_y y_t^2 + \psi_{rl} \left(\Delta rl_t\right)^2 \tag{9}$$

subject to the distorted model (7) and the constraint (8). Hansen and Sargent (2008) and Giordani and Söderlind (2004) show that the central bank’s problem can be recast as

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

$$\min_{r_t} \max_{\upsilon_t} E_0 \sum_{t=0}^{\infty} \beta^t \left(\mathbb{L}_t - \theta\, \upsilon_{t+1}' \upsilon_{t+1} \right) \tag{10}$$

subject to (7). The parameter θ summarises the central bank's attitude towards model misspecification in setting its policy, which, at the same time, reflects its preference for robustness. In particular, $\theta > 0$ is related to υ such that, in the case of no misspecification, allowed $\lim_{\upsilon \to 0} \theta = \infty$, while a smaller value of θ implies greater misspecification.

The equilibrium in the worst-case model can be described by substituting the solution into the distorted model (7). The resulting system describes the worst-case model the central bank and the private sector wants to guard against. 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.

In order to calibrate the preference for robustness $\theta,$ the concept of a detection error probability is adopted. The detection error probability is the probability of making the wrong choice between the approximating 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 equilibriums. Hence, a smaller θ reduces the detection error probability. We choose a preference for robustness that corresponds to a detection error probability of 20 percent, as suggested by Hansen and Sargent (2008, p 219) and Giordani and Söderlind (2004, p 2376).

To illustrate how a preference for robustness alters the dynamics of the model and the optimal monetary policy response, we write the solution as a VAR(1) in the predetermined variables and a linear relationship between the forward-looking and predetermined variables (eg Giordani and Söderlind, 2004, Appendix B):

$$\begin{bmatrix} x_{1,t} \\ \rho_{2,t+1} \end{bmatrix} = M \begin{bmatrix} x_{1,t-1} \\ \rho_{2,t} \end{bmatrix} + \begin{bmatrix} C\varepsilon_{t+1} \\ 0 \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} x_{2,t} \\ r_t \\ v_{t+1} \\ \rho_{1,t} \end{bmatrix} = N \begin{bmatrix} x_{1,t} \\ \rho_{2,t} \end{bmatrix}, \tag{12}$$

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. The optimal implicit instrument rule under commitment depends on the predetermined variables $x_{1,t}$ and the Lagrange multipliers on the forward-looking variables $\rho_{2,t}$:

$$r_t = N_r \begin{bmatrix} x_{1,t} \\ \rho_{2,t} \end{bmatrix}, \tag{13}$$

where N_r is a $\left(1 \times n_1 + n_2\right)$ sub-matrix of $N.$ With respect to Kobayashi's model the state of the economy is given by the predetermined variables and the Lagrange multipliers $\begin{bmatrix} e_t & u_t & l_t & rl_{t-1} & \rho_{2,t}^{\pi} & \rho_{2,t}^{y} & \rho_{2,t}^{rl} \end{bmatrix}'$.

3.2 The robust policy: More and less aggressive

We now turn to the effects of robustness on the central bank's optimal implicit instrument rule given by (13) and compare the coefficients of the robust rule with the policy rule of the rational expectations (RE) equilibrium (Table 2). As a first notable result, we observe that monetary policy responds either more cautiously or more aggressively depending on the shock. Specifically, monetary policy responds more aggressively to cost-push shocks and loan rate shocks, but less aggressively to demand shocks. Thus, much like in recent work such as that by Leitemo and Söderström (2008b) and Tillmann (2009), we also find that aggressiveness is not a general feature of the robust control approach. Rather, the response of the central bank depends on the type of shock.

Table 2: Parameters of optimal implicit instrument rule

	e_t	u_t	l_t	rl_{t-1}	$\rho_{2,t}^{\pi}$	$\rho_{2,t}^{y}$	$\rho_{2,t}^{rl}$
RE rule	-0.76	1.06	-0.29	0.10	-0.03	-1.02	1.68
Robust rule	-0.81	1.04	-0.30	0.10	-0.03	-1.02	1.67
Change in percent	7.15	-1.74	4.21	-0.27	-0.06	0.00	-0.17

Note: The model is calibrated to a detection error probability of 20 percent by setting $\theta = 0.01129$. Differences due to rounding errors.

The last row of Table 2 displays by how much the robust policy changes relative to the RE response. In the case of the cost-push shock e_t the coefficient increases by more than 7 percent[7] and in case of a loan rate shock l_t the relevant coefficient increases by more than 4 percent. The latter increase is a remarkable result since *a priori* it is not obvious that a loan rate shock should be a concern for the policymaker at all: model uncertainty worries the policymaker only if an unexpected shock gives rise to a meaningful trade-off between the variables in the loss function. In the present model, such a trade-off occurs because the model features a cost channel. The rise in the policy rate – the immediate response of monetary policy to a loan rate shock (Figure 1, solid line) – not only dampens aggregate demand, it is also passed through to the loan rate, thereby increasing firms' borrowing costs. 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 give rise to an additional increase in inflation via the cost channel. The initial interest rate cut is possible since, 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. Under commitment, output is lowered for an extended period of time such

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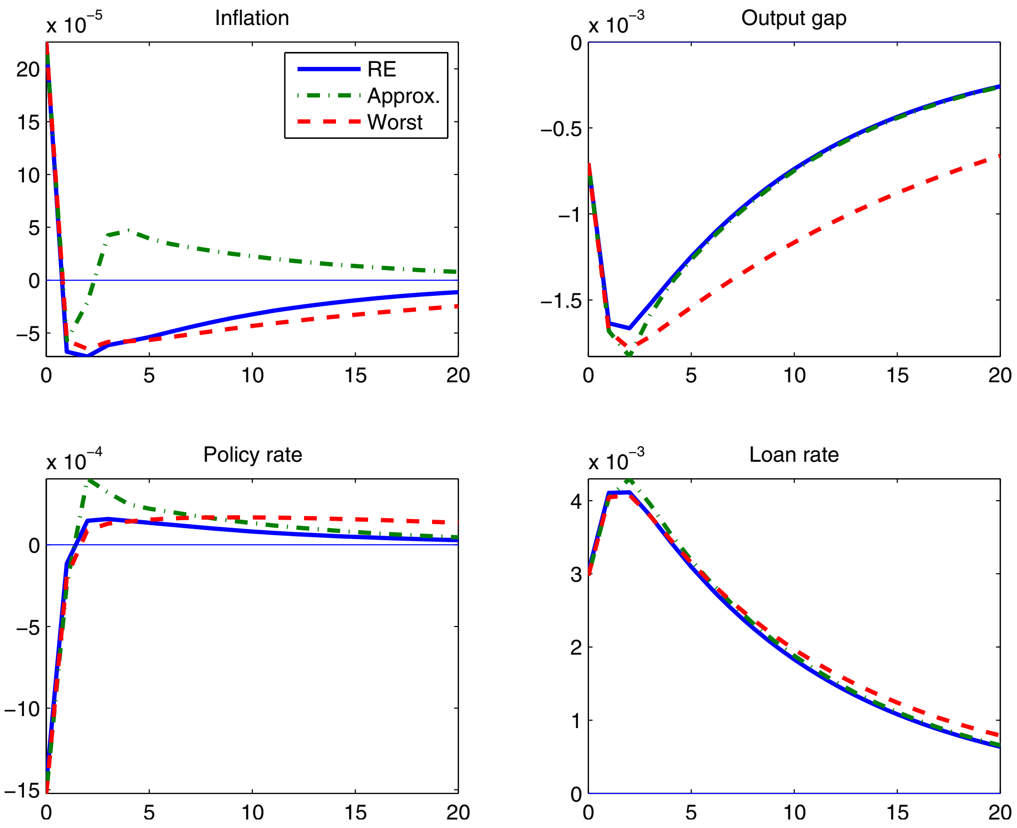
[7] The 7 percent corresponds to an additional increase of 7 basis points for a 100 basis points increase of the policy instrument in the RE equilibrium.

that inflation expectations fall below steady-state inflation.[8] As the initial policy rate cut does not imply higher inflation, the robust policymaker is able to respond more aggressively (Figure 1, dashed and dash-dotted line). To understand the last result fully, we now turn to the demand shock.

Figure 1: Impulse responses to loan rate shock



The demand shock u_t induces a more cautious response, since the relevant parameter in the implicit instrument rule decreases by almost 2 percent. The result differs from the findings for the standard New Keynesian model (eg Leitemo and Söderström, 2008a), where the demand shock can be fully stabilised. There is no trade-off and, therefore, model uncertainty does not alter the optimal monetary policy response. In the present model, the cost channel gives rise to a policy trade-off, and this explains why the optimal monetary policy differs under model uncertainty.

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[8] In general, the endogenous model dynamics are more clearly visible if the shocks are not autocorrelated.

To obtain intuition as to why monetary policy responds less aggressively to a demand shock, it is useful to describe the model dynamics for the RE equilibrium. Figure 2 displays the impulse responses after u_t goes up (solid line). The central bank responds by raising the policy rate. Yet the existence of the cost channel prevents an easy stabilisation. The increase in the policy rate is passed through to the loan rate and thus causes an immediate increase in marginal cost and inflation, but dampens output via aggregate demand. To stabilise the inflation rate, the central bank increases the interest rate even more. After the initial hike, inflation eventually converges back to its steady state. The inflationary effect of the cost channel (in addition to the inflationary effect of the shock itself) is, however, dampened since the commercial banks can adjust their loan rate only infrequently with probability $1-q$.

Taking model uncertainty into account, the central bank raises the interest rate, but less aggressively, because it is aware that the optimal policy response implies an initial increase in marginal cost and, thus, inflation (Figure 2, dashed and dash-dotted line). Such a cautious response is quite intuitive: the policymaker 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 in equation (4). To contain the additional volatility, the policymaker reacts more cautiously (see also Barlevy, 2009).[9]

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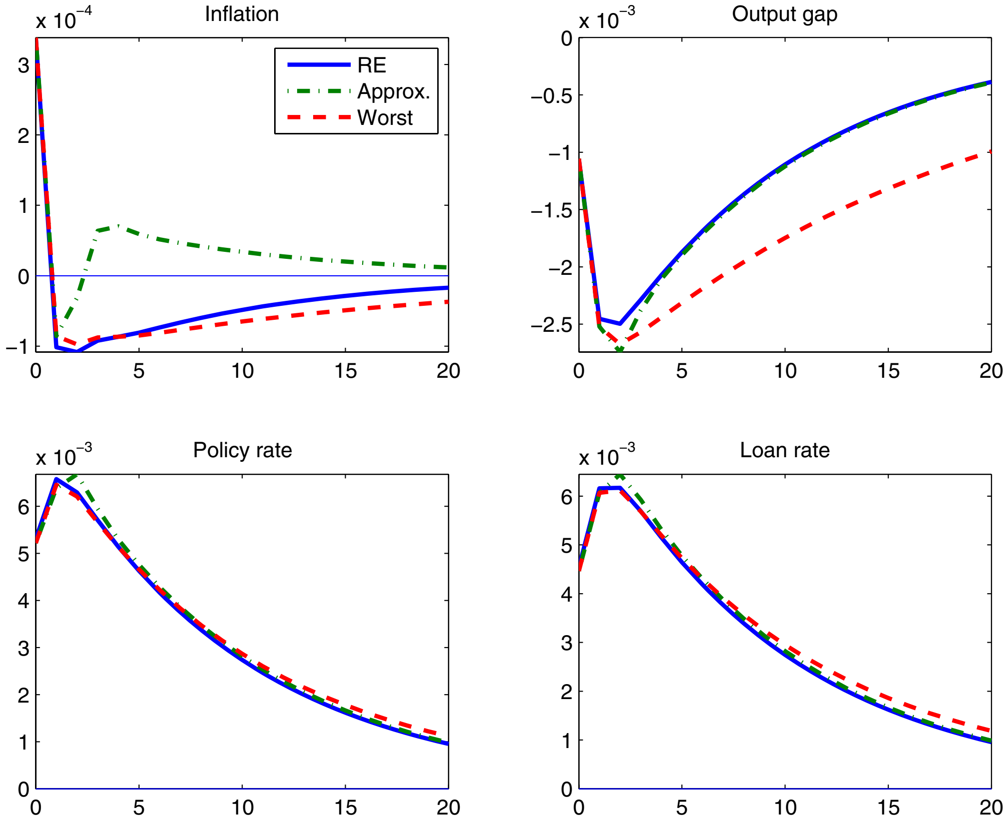
[9] Barlevy (2009) shows in a few simple examples that neither a less aggressive nor a more aggressive policy response is a general feature of robust control.

Figure 2: Impulse responses to demand shock



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 policymaker sets the interest rate such that – given the high weight for inflation stabilisation in the loss function (4) – the volatility of inflation is not increased by the policy response. In those cases where the response itself raises the volatility of inflation, the policymaker reacts more cautiously.[10] Our result stands in contrast to the standard New Keynesian model, where a preference for robustness always makes the central bank respond more aggressively (see, for instance, Giordani and Söderlind, 2004 or Leitemo and Söderström, 2008a).

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[10] 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 policymaker reacts always more cautiously. In Appendix A2, Table A1 gives the changes of the policymaker's optimal implicit instrument rule under discretion. Figures A1 to A3 display the corresponding impulse responses for each of the three shocks.

3.3 The price of robustness: The approximating equilibrium

After having described in which ways the robust policymaker deviates from the RE equilibrium, we now turn to the costs of such a robust policy. The losses for the RE equilibrium, the worst-case equilibrium, and the approximating equilibrium summarise succinctly how robustness affects social welfare following equation (4). 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 policymaker acts as if the model were misspecified. Obviously, such a strategy yields a higher loss than the RE rule, 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 which amounts to 5.91 percent in the present model.

Table 3: Comparison of losses

RE equilibrium	Worst-case equilibrium	Approximating equilibrium	Insurance premium in percent
4.62×10^{-4}	8.16×10^{-4}	4.83×10^{-4}	5.91

Note: Loss as a percentage of steady-state consumption. Differences due to rounding errors.

The variances in Table 4 allow us to disentangle further the variables through which model uncertainty affects social welfare. In the worst-case equilibrium, the three target variables “inflation”, “output gap” and “loan rate” as well as the policy instrument become more volatile. In the approximating equilibrium, the robust policy comes at a cost: the central bank dampens volatility in the inflation rate pre-emptively, but simultaneously accepts higher volatility in the output gap and the loan rate. The policy instrument also becomes more volatile. As a second result, we note that the difference between the worst-case equilibrium and the approximating equilibrium suggests that the central bank’s concern for misspecification and, therefore, the robust policy is oriented towards stabilising the inflation rate, although the central bank also cares about minimising the welfare costs of the imperfect interest rate pass-through.

Table 4: Comparison of variances

	RE equilibrium	Worst-case equilibrium	Approximating equilibrium	Difference between worst-case and RE	Difference between approximating and RE
Inflation	22.8×10^{-7}	25.5×10^{-7}	18.3×10^{-7}	2.7×10^{-7}	-4.5×10^{-7}
Output gap	4262.9×10^{-7}	7770.7×10^{-7}	4529.8×10^{-7}	3507.7×10^{-7}	266.9×10^{-7}
Loan rate	3990.8×10^{-7}	4413.8×10^{-7}	4258.1×10^{-7}	423.0×10^{-7}	267.3×10^{-7}
Policy rate	3033.6×10^{-7}	3223.7×10^{-7}	3276.2×10^{-7}	190.1×10^{-7}	242.6×10^{-7}

The second result hinges on the assumption that every equation of the model is prone to misspecification. In principle, this may not necessarily be the case if the policymaker is particularly concerned about a specific economic relation, while neglecting uncertainty in others. For instance, the policymaker might be uncertain in particular regarding the imperfect interest rate pass-through or might be particular concerned about price stickiness. Uncertainty surrounding only one equation allows us to reveal that the policymaker shifts its focus in stabilising the target variables. In the following, we therefore illustrate three special cases when uncertainty surrounds only one equation.

3.4 A specific concern: Uncertainty surrounding only one equation

Now, the central bank and the private sector face uncertainty in only one of the three economic relations.[11] In other words, we allow no more than one of the three model equations to be misspecified.[12] To highlight in which way the central bank guards itself against misspecification, we report in Table 5 the percentage change in the variance of the approximating equilibrium relative to the RE equilibrium. If the central bank faces uncertainty only in the Phillips curve (1), the changes in the variances coincide qualitatively with the benchmark model (misspecification in all equations). Volatility in

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[11] In Appendix A3, Table A2 gives the changes of the policymaker's optimal implicit instrument rules. Figures A4 to A6 display the corresponding impulse responses for each of the three shocks.

[12] 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 for a meaningful comparison, all models are calibrated again to a detection error probability of 20 percent.

inflation is dampened pre-emptively, whereas volatility increases for the other variables, including the policy instrument. If uncertainty is present only in the IS equation (2) or the loan rate equation (3), the robust policy shifts its concern for stabilisation. As a third notable result, 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 policymaker 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.

Table 5: Percentage change in variances for approximating equilibrium

Uncertainty surrounding…	Inflation	Output gap	Loan rate	Policy rate
… all three equations	-19.80	6.26	6.70	8.00
… only Phillips curve	-1.82	7.98	116.72	87.39
… only IS equation	48.03	-2.15	-1.28	-1.08
… only loan rate equation	52.69	-2.31	-1.37	1.17

Note: Percentage change in variance of the approximating equilibrium relative to the RE equilibrium. All four models are calibrated to a detection error probability of 20 percent.

4 Conclusions

In general, the central bank acknowledges that every model is incomplete and, therefore, a misspecified description of reality. In order to prevent very bad outcomes, the central bank needs to design a policy that is 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 neighbourhood around a reference model.

We employ as a reference model a version of the New Keynesian model that is able to replicate key stylised 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. The effects of the central bank's concern for robustness can be summarised as follows. First, we observe that 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 such that the volatility of inflation is not increased by the policy response. In those cases where the response itself raises the volatility of inflation, the central bank responds more cautiously otherwise it responds more aggressively. Our result stands in contrast to the standard New Keynesian model, where a preference for robustness always makes the central bank respond more aggressively.

Second, robustness comes at a cost: the central bank dampens volatility in the inflation rate pre-emptively, but simultaneously accepts higher volatility in the output gap and the loan rate. The difference between the worst-case equilibrium and the approximating equilibrium suggests that the central bank's concern for misspecification and, therefore, the robust policy is oriented towards stabilising the inflation rate, although the central bank also cares about minimising the welfare costs of the imperfect interest rate pass-through.

Third, if the central bank faces uncertainty only in the Phillips curve, the changes of the variances coincide qualitatively with the benchmark model (misspecification in all equations). If uncertainty is present only in the IS equation or the loan rate equation, however, the robust policy shifts its concern for stabilisation. 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 policymaker is not concerned about model uncertainty regarding the Phillips curve.

Appendix

A1 New Keynesian model with imperfect interest rate pass-through

We describe the New Keynesian model following Kobayashi (2008). The economy consists of a representative household, intermediate goods firms, final goods firms, commercial banks, and a central bank.

Households

The household obtains utility from a consumption bundle and disutility from supplying labour according to

$$U_t = \frac{C_t^{1-\sigma}}{1-\sigma} - \int_0^1 \frac{L_t(i)^{1+\omega}}{1+\omega} di, \tag{A1}$$

where $C_t \equiv \left[\int_0^1 C_t(j)^{\frac{\theta_f - 1}{\theta_f}} dj\right]^{\frac{\theta_f}{\theta_f - 1}}$ and $C_t(j)$ and $L_t(i)$ indicate the consumption of differentiated final good j and hours worked at intermediate goods firm in region i. The parameter σ denotes the inverse of the elasticity of intertemporal substitution and ω denotes the elasticity of labour supply. Below, the index $i \in (0, 1)$ denotes a specific *region* as well as a *variety* of intermediate goods. By assumption, there is only one intermediate goods firm in each region. The parameter $\theta_f > 1$ symbolises the elasticity of substitution between the varieties of consumption (ie final) goods. The aggregate price index can be obtained from the optimal allocation of consumption goods and is defined as $P_t \equiv \left[\int_0^1 P_t(j)^{1-\theta_f} dj\right]^{\frac{1}{1-\theta_f}}$.

The household needs cash in order to purchase consumption goods. At the beginning of period t, the amount of cash available for the purchase of consumption goods is $M_{t-1} + \int_0^1 W_t(i) L_t(i) di - \int_0^1 D_t(i) di$ where M_{t-1} stands for the nominal balance held from period $t-1$ to t, and $\int_0^1 W_t(i) L_t(i) di$ denotes total wage income paid in advance by intermediate goods firms. The household has the possibility of making a one-period deposit $D_t(i)$ at commercial bank i and receives the principle plus interest $R_t D_t(i)$ at the end of the period. The household holds deposits at all of the commercial banks. At the beginning of period t, the following cash-in-advance constraint must be satisfied:

$$\int_0^1 P_t(j) C_t(j) dj \leq M_{t-1} + \int_0^1 W_t(i) L_t(i) di - \int_0^1 D_t(i) di. \tag{A2}$$

The household's budget constraint can be stated as

$$\begin{aligned} M_t + \int_0^1 D_t(i) di + \int_0^1 P_t(j) C_t(j) dj + T_t = M_{t-1} + \int_0^1 W_t(i) L_t(i) di + \Pi_t \\ + R_t \int_0^1 D_t(i) di, \end{aligned} \tag{A3}$$

where Π_t denotes the sum of profits transferred from firms and commercial banks, and T_t denotes a lump-sum tax.

The demand for good j is given by

$$C_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\theta_f} C_t. \tag{A4}$$

Intermediate goods firm

Each intermediate goods firm i produces a differentiated intermediate good $Z_t(i)$ by using labour of type i as the only input factor. The production function is simply given by the following linear technology $Z_t(i) = L_t(i)$. Each intermediate goods firm must pay the wage bill before the goods markets open. Specifically, at the beginning of period t firm i borrows funds $W_t(i) L_t(i)$ from commercial bank i at the gross nominal rate R_t^i. At the end of the period, intermediate goods firm i has to repay $R_t^i W_t(i) L_t(i)$ to bank i. The nominal marginal cost for firm i is therefore $MC_t(i) = R_t^i W_t(i)$. By assumption, firm i borrows funds only from the regional bank i since the loan markets are geographically segmented. This assumption rules out arbitrage and implies that lending rates may differ across banks. For simplicity, it is assumed that intermediate goods firms are able to set their prices fully flexibly. As the intermediate goods firm needs to borrow funds, the lending rate is an additional production cost. A rise in the lending rate raises marginal cost and, thus, the intermediate goods price.[13]

Final goods firms

Each final goods firm uses a composite of intermediate goods as the only input for production. The production function is given by

$$Y_t(j)=\left[\int_0^1 Z_t^j(i)^{\frac{\theta_z-1}{\theta_z}}di\right]^{\frac{\theta_z}{\theta_z-1}} \tag{A5}$$

with $\theta_z>1$ denoting the elasticity of substitution between the varieties of intermediate goods and $Y_t(j)$ and $Z_t^j(i)$ denoting a differentiated consumption good and the firm j's demand for individual intermediate good i, respectively. Choosing the optimal allocation of inputs gives the price index for intermediate goods $P_t^z\equiv\left[\int_0^1 P_t^z(i)^{1-\theta_z}di\right]^{\frac{1}{1-\theta_z}}$. Consequently, the firm j's demand for the individual intermediate good i is given by

$$Z_t^j(i)=\left(\frac{P_t^z(i)}{P_t^z}\right)^{-\theta_z}Y_t(j). \tag{A6}$$

Aggregate output is defined as $Y_t\equiv\left[\int_0^1 Y_t(j)^{\frac{\theta_f-1}{\theta_f}}dj\right]^{\frac{\theta_f}{\theta_f-1}}$.

Final goods firms are not able to adjust prices flexibly. Following Calvo (1983), a fraction $1-\phi$ of firms can change their prices, while the remaining fraction ϕ cannot. The price-setting problem of final goods firms can be stated as following:

$$\max_{\tilde{P}_t} E_t\sum_{s=0}^{\infty}\phi^s\,\Gamma_{t,t+s}\left[\left(1+\tau^f\right)\tilde{P}_t-P_{t+s}^z\right]\underbrace{\left(\frac{\tilde{P}_t}{P_{t+s}}\right)^{-\theta_f}C_{t+s}}_{C_{t+s}(j)}, \tag{A7}$$

---

[13] Note, since lending rates can differ across firms, they are a potential source of price dispersion.

where $\tilde{P}_t$ is the price of final goods set by firms that can adjust prices in period t and $\Gamma_{t,t+s}$ represents the stochastic discount factor up to period $t+s$. The parameter τ^f denotes a subsidy rate given by $\tau^f = 1/(\theta_f - 1)$ to remove the distortions due to monopolistic competition in the final goods sector.

Commercial bank

At the start of every period, each intermediate goods firm i is required to borrow funds from commercial bank i of the same region in order to pay the wage bill in advance. Commercial bank i lends funds $W_t(i)L_t(i)$ to intermediate goods firm i. Also at the beginning of period t, commercial bank i receives deposit $D_t(i)$ from the household and money injection $M_t - M_{t-1} \equiv \Delta M_t$ from the central bank.[14] In equilibrium, the following must hold:

$$W_t(i)L_t(i) = D_t(i) + \Delta M_t, \quad \forall\, i \in (0,1). \tag{A8}$$

The left-hand side can be understood as representing the demand for funds, whereas the right-hand side represents the supply of funds. At the end of period t commercial bank i repays its principle plus interest $R_t D_t(i)$ to the household. The household receives the money injection indirectly from the central bank through the profit transfer from commercial banks.

As shown in Appendix 1 of Kobayashi (2008), firm i's demand for funds can be formulated as

$$W_t(i)L_t(i) = \Psi\left(R_t^i, \Lambda_t\right), \tag{A9}$$

where Λ_t is a function of aggregate variables that individual firms and commercial banks take as given. Firm i's demands for funds $\Psi\left(R_t^i, \Lambda_t\right)$ decreases in the loan rate R_t^i as an increase in R_t^i raises the marginal cost, thereby decreasing production.

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[14] The former is a liability of the commercial bank, the latter is net worth.

By assumption, a commercial bank can adjust its loan rate only with probability $1-q$. This probability of adjustment is independent of the time between adjustments. The problem of the commercial bank i can then be stated as

$$\max_{R_t^i} E_t \sum_{s=0}^{\infty} q^s \, \Gamma_{t,t+s} \left[\left(1+\tau^b\right) R_t^i \, \Psi\left(R_t^i, \Lambda_{t+s}\right) - R_{t+s} \, \Psi\left(R_t^i, \Lambda_{t+s}\right) \right], \tag{A10}$$

where τ^b denotes a subsidy rate. The commercial bank in region i takes as given P_t, $\tilde{P}_t^z$, Y_t, C_t, ΔM_t, and R_t while taking into account the effect of a change in R_t^i on $W_t(i) L_t(i)$. Kobayashi (2008) shows that the optimality condition implies that all commercial banks which adjust in the same period set an identical loan rate $\tilde{R}_t$. Newly adjusted loan rates depend largely on the expectations of future policy rates as well as the current policy rate. This stems essentially from the forward-looking staggered loan rate setting of commercial banks.

A2 Robust monetary policy under discretion

Table A1: Parameters of optimal implicit instrument rule under discretion

	e_t	u_t	l_t	rl_{t-1}
RE rule	0.61	1.54	0.03	0.10
Robust rule	0.50	1.50	0.00	0.10
Change in percent	-18.02	-2.46	-89.50	-0.37

Note: The model is calibrated to a detection error probability of 30 percent by setting $\theta = 0.0216$. Differences due to rounding errors.

Figure A1: Impulse responses to cost-push shock under discretion

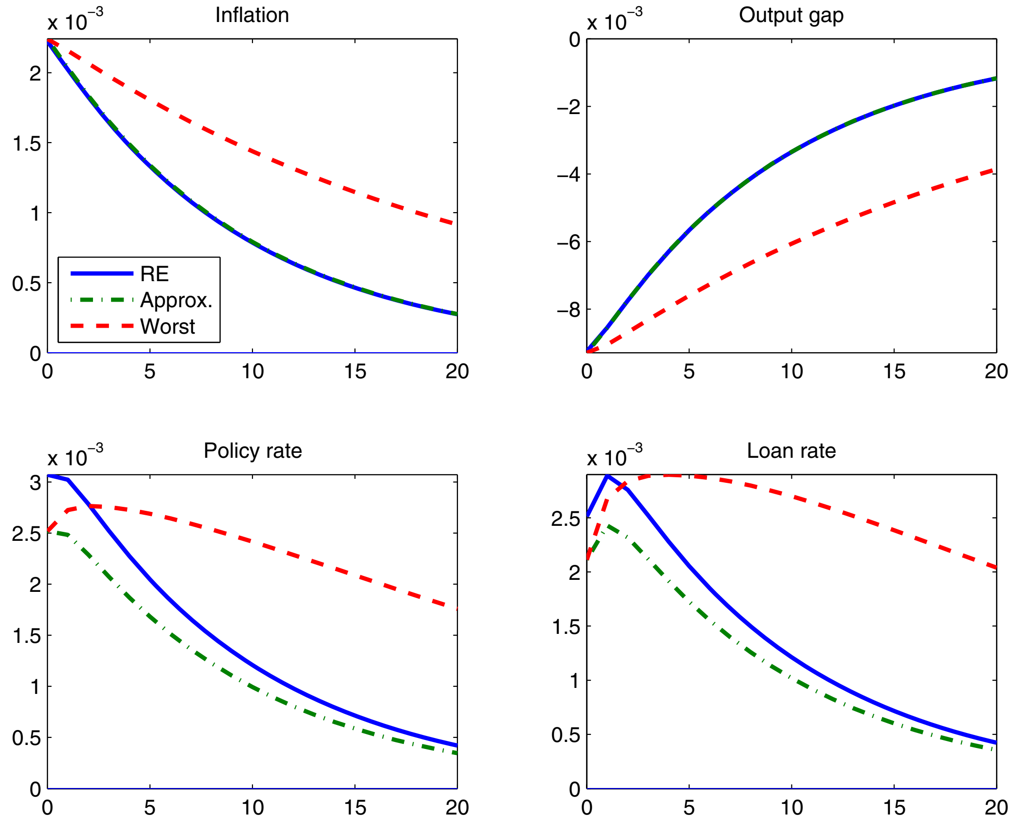


Figure A2: Impulse responses to demand shock under discretion

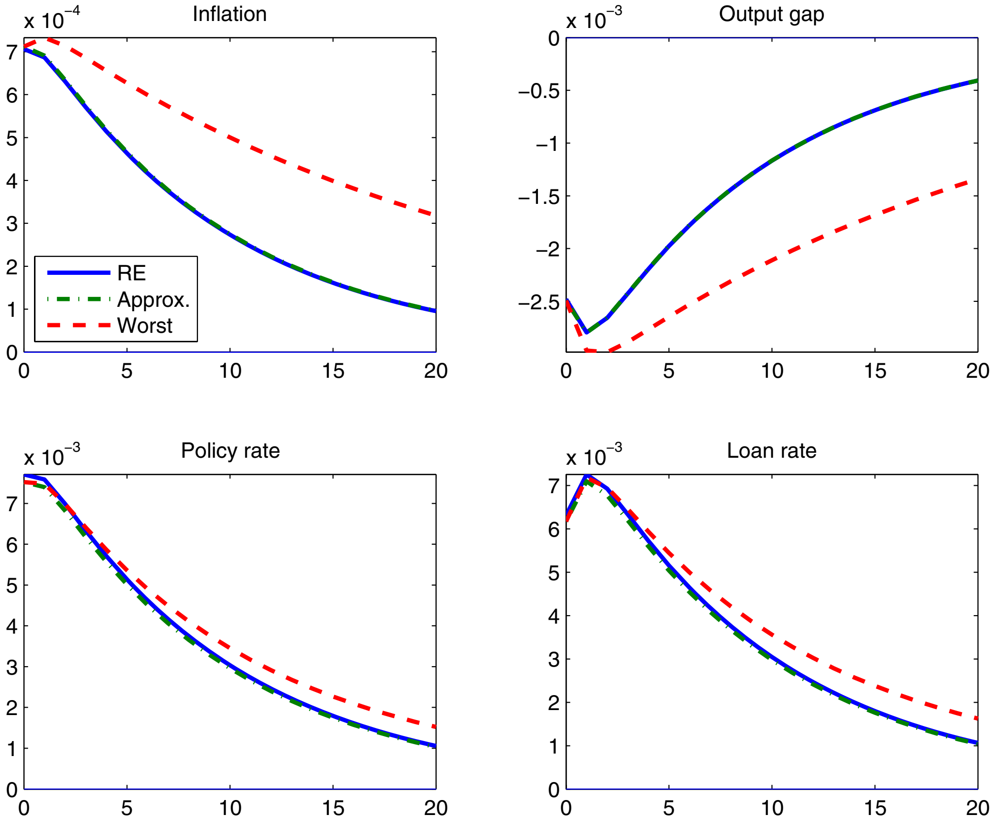
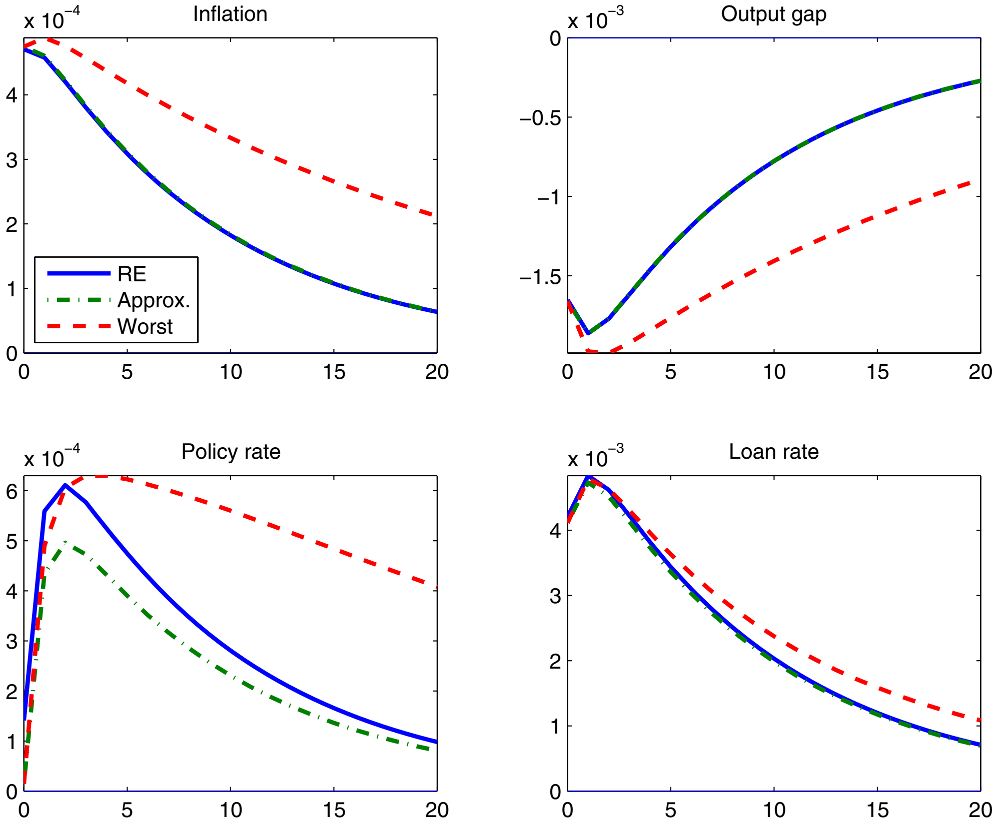


Figure A3: Impulse responses to loan rate shock under discretion



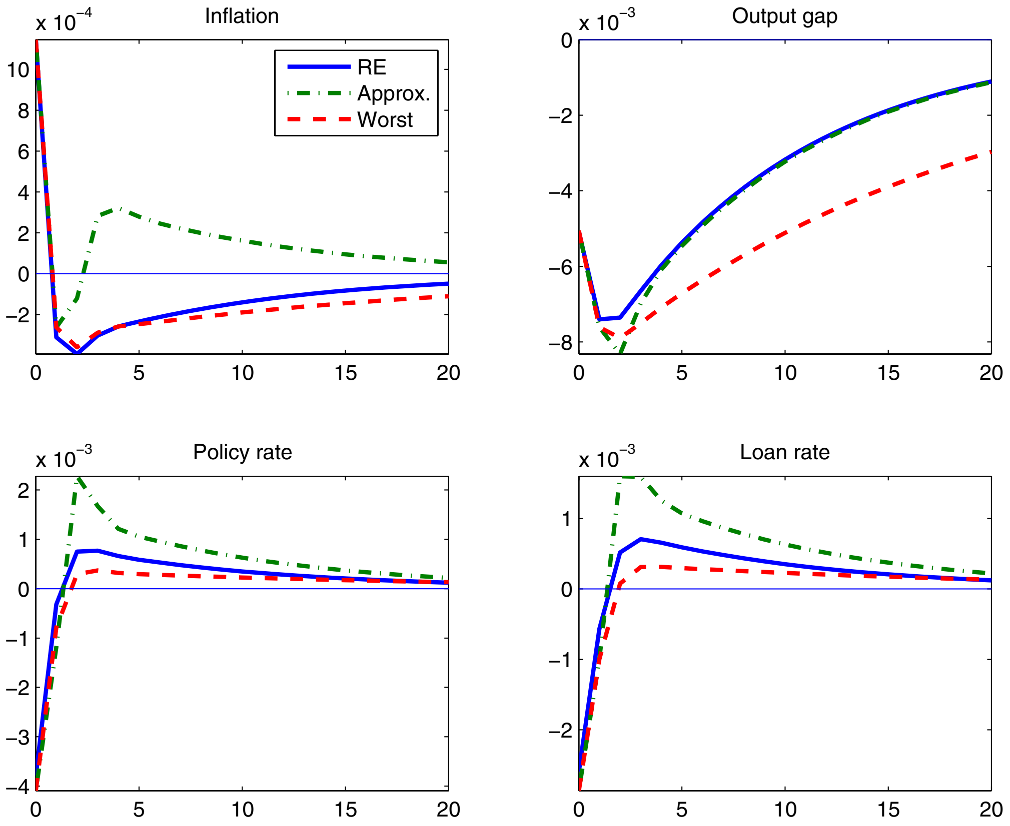
A3 Uncertainty surrounding only one equation

Table A2: Percentage change in parameters of optimal implicit instrument rules

Uncertainty surrounding…	e_t	u_t	l_t	rl_{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	-0.002	-0.170
… only Phillips curve	7.926	-1.922	4.658	-0.330	-0.036	-0.009	-0.207
… only IS equation	4.546	-1.124	2.725	-0.007	-0.199	0.036	0.002
… only loan rate equation	4.900	-1.212	2.937	-0.008	-0.211	0.038	0.002

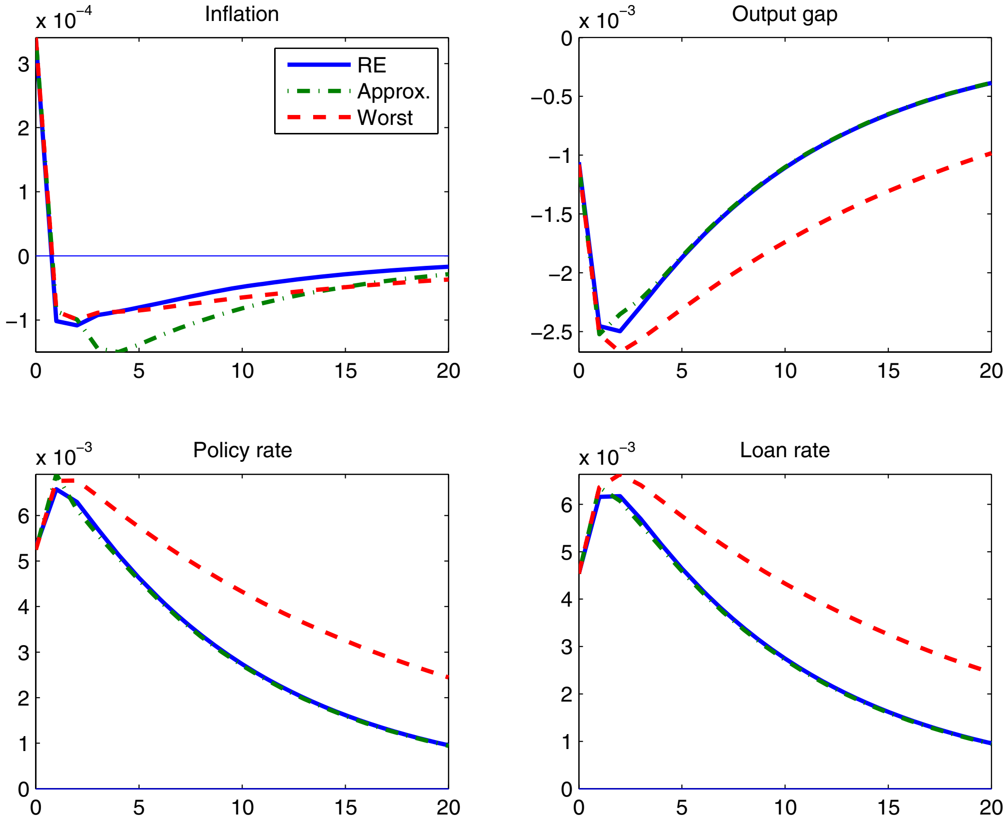
Note: Percentage change in coefficient of the robust rule relative to the RE rule in percent. All four models are calibrated to a detection error probability of 20 percent.

Figure A4: Impulse responses if uncertainty only in the Phillips curve



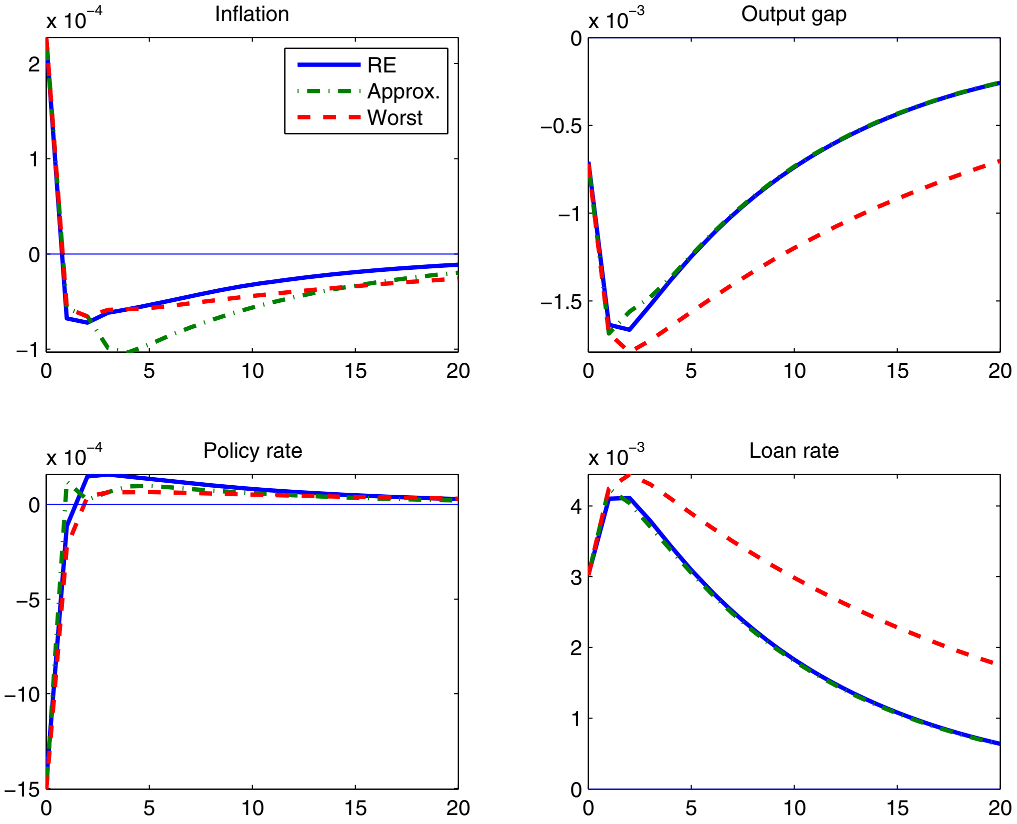
Note: Impulse responses to a cost-push shock. The model is calibrated to a detection error probability of 20 percent by setting $\theta = 0.009336$.

Figure A5: Impulse responses if uncertainty only in the IS equation



Note: Impulse responses to a demand shock. The model is calibrated to a detection error probability of 20 percent by setting $\theta = 0.001172$.

Figure A6: Impulse responses if uncertainty only in the loan rate equation



Note: Impulse responses to a loan rate shock. The model is calibrated to a detection error probability of 20 percent by setting $\theta = 0.000495$.

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