
NOTES D'ÉTUDES

ET DE RECHERCHE

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Does uncertainty make a time-varying natural rate of interest irrelevant for the conduct of monetary policy?*

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Abstract

We compute optimized monetary policy rules for the ECB when the euro area economy is described by a small empirical macroeconomic model with a time-varying natural interest rate which is positively correlated with fluctuations in trend output growth. We investigate the consequences of both measurement uncertainty with respect to unobservable variables and uncertainty about key model parameters. An optimized Taylor rule with time-varying neutral rate appears to perform well compared to the unconstrained optimal policy, and better than other simple rules found in the literature, even when it is penalized by taking into account both types of uncertainty.

JEL classification: E52; E37

Keywords: Monetary policy rules; Natural rate of interest; Uncertainty

Résumé

Nous calculons des règles de politique monétaire optimales pour la BCE dans le cadre d'un petit modèle macroéconomique de la zone euro avec un taux d'intérêt naturel variable qui est positivement corrélé aux fluctuations de la croissance tendancielle du PIB. Nous examinons les conséquences pour la politique monétaire de l'incertitude relative à la mesure des variables inobservables et de l'incertitude relative aux paramètres du modèle. Nos simulations montrent qu'une règle de Taylor optimisée intégrant le taux naturel estimé présente de bonnes performances stabilisatrices comparée à la politique monétaire optimale non-contrainte et s'avère supérieure aux autres règles simples proposées par la littérature, malgré la prise en compte pénalisante des deux types d'incertitude.

Classification JEL: E52; E37

Mots-clés: règles de politique monétaire; taux d'intérêt naturel; incertitude

Non-technical summary

Numerous empirical studies have tackled the issue of the normative content of Taylor rules for the conduct of monetary policy. It has in particular been shown that simple policy rules of that kind achieve good stabilization results for a broad class of simulated small macroeconomic models, while they also prove to be quite robust to model uncertainty. A limit of many such experiments is that the neutral or "natural" level of the real rate of interest (NRI), which can be defined as the equilibrium level of the real short term rate of interest consistent with stable inflation in the medium run, is generally supposed to be a constant, hence being commonly captured by the intercept term in the monetary policy rule. However, this neutral rate of interest is theoretically bound to fluctuate with a series of exogenous real shocks affecting consumer preferences, technology, fiscal policy etc.

The trouble is that the natural rate is unobservable, which makes its shifts difficult to ascertain in real time. The question that motivates this paper is then: should the admittedly large and multifaceted uncertainty that blurs the perception of changes in the NRI in real-time deter an optimizing central bank from using the relevant information it can derive from simple estimated models of the economy? We thus aim at assessing the potential benefit for the ECB to include a time-varying intercept in benchmark monetary policy rules, which would be positively correlated with low-frequency fluctuations in trend output growth. To this end, we suppose that the euro area economy is correctly depicted by the small empirical macroeconomic model of Mésonnier and Renne (2006) and that the ECB estimates the current level of the output gap and the natural rate of interest within this consistent setup, using the Kalman filter. The central bank then aims at minimizing a standard quadratic loss function but faces two types of uncertainty. First, it must be aware of a measurement problem regarding the level of unobservable "natural" variables in real time. Second, even if the policymaker believes in the model, he may well have doubts about the reliability of his estimates of the underlying model parameters, and may consequently try to optimize his behavior in accordance with that specific form of model uncertainty. Our findings suggest that, in spite of these combined sources of uncertainty, the policymaker could be better off taking into account estimated low-frequency variations in the neutral rate while designing optimal policy.

Résumé non-technique

De nombreuses études empiriques ont abordé la question du contenu normatif des règles simples de politique monétaire à la Taylor. On a ainsi pu montrer, dans le cadre d'une large classe de modèles empiriques, que des règles simples de ce type obtiennent de bons résultats en termes de stabilisation de l'économie et qu'elles sont également plutôt robustes à l'incertitude relative au modèle pertinent de l'économie. Pourtant, une limite commune à nombre de ces travaux tient à ce que le taux d'intérêt réel neutre ou naturel -le taux compatible avec une inflation stabilisée à moyen terme- y est généralement supposé constant et égal au terme constant qui apparaît dans la règle de politique monétaire. Pourtant, la théorie enseigne que ce taux naturel d'intérêt doit fluctuer en fonction de divers chocs réels exogènes qui affectent l'économie (chocs sur les préférences des consommateurs, chocs technologiques, fiscaux etc.)

Le taux d'intérêt naturel est une variable inobservable, dont les modifications sont par essence difficiles à appréhender en temps réel. La question qui motive cette étude est donc la suivante : l'incertitude large et multiforme qui brouille la perception de ces évolutions doit-elle décourager la banque centrale de prendre en compte l'information qu'elle peut tirer de modèles empiriques simples utilisés pour estimer ce taux naturel ? Pour y répondre, nous évaluons le bénéfice pour la BCE de l'inclusion d'un taux neutre variable dans une règle standard de politique monétaire, taux dont les fluctuations de moyen terme seont positivement corrélées à celles de la croissance tendancielle du PIB. Pour ce faire, nous supposons que l'économie de la zone euro est correctement décrite par le modèle empirique de Mésonnier et Renne (2006) et que la BCE estime dans ce cadre le niveau courant du taux d'intérêt naturel et de l'écart de production, grâce au filtre de Kalman. La banque centrale, qui cherche à minimiser une fonction de perte quadratique standard, fait alors face à deux types d'incertitude. Tout d'abord, elle ne peut mesurer ces variables inobservables en temps réel qu'avec erreur : il y a incertitude sur les variables. Ensuite, même si les Gouverneurs croient que le modèle utilisé est pertinent, ils peuvent douter de la précision des paramètres estimés : il y a donc aussi incertitude sur les paramètres. Nos résultats montrent que, malgré l'impact de cette double incertitude, le décideur monétaire peut avoir avantage à réagir aux fluctuations estimées du taux d'intérêt naturel.

1 Introduction

"The concept of a natural interest rate refers to an equilibrium real interest rate that reflects productivity and population growth. Although most recent analyses seem to indicate that in the euro area it lies within a corridor of 2% to 3%, I would not be surprised if the lower bound (...) is revised downwards as a result of the lower growth in productivity in the euro area during the past ten years. Owing to the high level of uncertainty surrounding the estimates of the natural interest rate, great caution is called for when using them." Lucas Papademos, ECB Vice-President (31 March 2005)

Since Taylor (1993), it is commonplace to describe short term interest rate setting by monetary policymakers as a simple feedback rule where the policy rate reacts to a linear combination of a small set of endogenous variables, which are classically inflation and an empirical measure of the gap between output and its potential level. A voluminous literature, for instance, has investigated the ability of such simple policy rules to describe accurately major central banks' behavior (see e.g. Clarida et al., 1998). Numerous empirical studies have also tackled the issue of their normative content. It has in particular been shown that simple policy rules of that kind achieve good stabilization results for a broad class of simulated small macroeconomic models, while they also prove to be quite robust to model uncertainty.¹

A limit of many such experiments is that the neutral or "natural" level of the real rate of interest (NRI), which can be defined intuitively as the equilibrium level of the real short term rate of interest consistent with stable inflation in the medium run, is generally supposed to be a constant, hence being commonly captured by the intercept term in the policy rule for a defined inflation target of the monetary authorities. However, this neutral rate of interest is theoretically bound to fluctuate with a series of exogenous real shocks affecting consumer preferences, technology, fiscal policy etc.²

¹See e.g. Rotemberg and Woodford (1999), Clarida et al. (2000), and Rudebusch and Svensson (1999) for stabilization properties and Levin, Wieland and Williams (1999, 2003) on robustness issues.

²This point was already made clear by the coiner of the modern concept of the natural rate of interest, the Swedish economist Knut Wicksell, who wrote more than one century ago that the "natural rate of

The trouble is that the natural rate is unobservable, which makes its shifts difficult to ascertain in real time. Following Laubach and Williams (2003) among others, we restrict our focus here to the low-frequency fluctuations of the NRI and take a medium term perspective that should have appeal to European central bankers.³ Nevertheless, even overlooking sources of higher-frequency fluctuations, the reference to an estimated natural rate of interest as a potential anchor for the policy rate is made difficult by the same kind of practical measurement issues that hinder a solid reference to the estimated output gap (see e.g. Orphanides and van Norden, 2002). As a consequence, it has been argued that the monetary policymaker would be better off overestimating its own measurement error about the true current level of the natural rate of interest than underestimating it (Orphanides and Williams, 2002). In this case, he should turn to so-called "difference" rules that are specifically designed so as to eliminate any reference to the level of "starred variables" – i.e. potential output, the NAIRU or the natural rate of interest – (see notably Orphanides and Williams, 2006a, 2006b, and the review by Walsh, 2004).⁴

The question that motivates this paper is then: should the admittedly large and multifaceted uncertainty that blurs the perception of changes in the NRI in real-time deter

interest is not fixed or unalterable in magnitude (...). In general (...), it depends on the efficiency of production, on the available amount of fixed and liquid capital, on the supply of labour and land (...) ; and with them it constantly fluctuates". (Wicksell, 1898, p. 106)

³The approach followed here then belongs to the "semi-structural" strand of the empirical NRI literature (Larsen and McKeown, 2004) and departs from the microfounded New-Keynesian (or "Neo-Wicksellian") view as developed notably by Woodford (2001,2003). According to Woodford's approach, the NRI is technically defined as the level of the real equilibrium rate of interest that obtains in an hypothetical fully flexible-prices version of the economy, and it constantly fluctuates with a series of real shocks affecting the modelled economy. For a useful survey of differences opposing the two views, see Giammarioli and Valla (2004).

⁴As argued by their proponents, such rules are also very much in the spirit of the genuine Wicksellian rule: "This does not mean that the banks ought actually to ascertain the natural rate before fixing their own rates of interest. That would of course be impracticable, and would also be quite unnecessary. For the current level of commodity prices provides a reliable test of the agreement or diversion of the two rates. The procedure should rather be simply as follows: so long as prices remain unaltered the banks' rate of interest is to remain unaltered. If prices rise, the rate of interest is to be raised (...)" (Wicksell, 1898, p. 189).

an optimizing central bank from using the relevant information it can derive from simple estimated models of the economy? More precisely, would it make sense to include a time-varying intercept in benchmark monetary policy rules, which would be positively correlated with low-frequency fluctuations in potential output growth or trend productivity? Our findings suggest that, in spite of this uncertainty, the policymaker could be better off taking into account estimated low-frequency variations in the neutral rate while designing optimal policy.

Very few studies have extended the empirical analysis of these issues to other economies than the United States, notably the Euro area. In this paper, we try to fill this gap and aim at assessing the potential benefit for the ECB to use its estimate of medium term changes in the natural rate of interest. To this end, we suppose that the euro area economy is correctly depicted by the small empirical macroeconomic model of Mésonnier and Renne (2006) and that the ECB estimates the current level of the output gap and the natural rate of interest within this setup, using the Kalman filter. In doing this, the ECB faces two types of uncertainty. First, it must be aware of a measurement problem regarding the level of unobservable "natural" variables in real time. This may be viewed as additive data uncertainty, although we focus on measurement problems of these unobservable variables only and do not consider the broader case of "noisy information" about inflation and output growth.⁵ Second, even if the policymaker believes in the model, he may well have doubts about the reliability of his estimates of the underlying model parameters, and may consequently try to optimize his behavior in accordance with that specific form of model uncertainty.

This paper improves upon the existing empirical literature on optimal rules in several directions. While several previous papers rely on exogenous sources (such as the CBO estimate of the output gap in the American case) or simple univariate filters for getting estimates of unobservable variables (e.g. in Rudebusch and Svensson, 1999, 2002, or Söderström, 1999), we follow the lines of Peersman and Smets (1999) and derive our analysis from a complete unobserved components model where unobservable variables and

⁵see Rudebusch (2001), Aoki (2003) or Orphanides (2003) for analyses of optimal monetary policy when the central bank's perception of current inflation and economic activity is subject to measurement errors.

model parameters are consistently estimated. Thus, we also depart from the methodology of Orphanides and Williams (2002), who evaluate the policy rules using a simple estimated model of the economy and construct estimates of the natural rate of interest – and the misperception thereof – using other, unrelated models (including univariate smoothers without any theoretical content).⁶ Compared to Peersman and Smets’ (1999), however, our model allows for an assessment of the consequences of both uncertain output gap and interest rate gap for an optimizing central bank. Finally, we conduct the analysis in such a way as to combine the effects of additive uncertainty about the natural rate of interest and multiplicative uncertainty about the model parameters. This contrasts with several earlier contributions where both types of uncertainty are mainly studied separately (Rudebusch, 2001, Peersman and Smets, 1999, Söderlind, 1999, to cite a few).

The rest of the paper is organized as follows. Section 2 presents our small empirical model of the euro area economy. Section 3 details the optimizing framework, including a discussion of the ECB preferences and the selection of alternative policy rules. Section 4 presents the optimization results both under complete information and when the ECB distrusts its own current estimates of unobservable variables. In section 5, the scope is extended to include the consequences of parameter uncertainty. Section 6 concludes.

2 An estimated model of the euro area with time-varying natural interest rate

The analysis of monetary policy conducted in this paper is based on the empirical model of the euro area economy detailed in Mésonnier and Renne (2006). The model consists of the following six equations:

⁶This has been criticized by Parker (2002), who suggests that using the same model for both evaluating the optimal policy rule and constructing the natural rate estimates would be a valuable direction for improvements of the analysis. He also hints that this could lead to less severe a statement about the practical importance of natural rate estimates in the conduct of monetary policy.

$$\pi_t = \alpha_1 \pi_{t-1} + \alpha_2 \pi_{t-2} + \alpha_3 \pi_{t-3} + \beta z_{t-1} + \varepsilon_t^\pi \quad (1)$$

$$z_t = \Phi z_{t-1} + \lambda(i_{t-2} - \pi_{t-1|t-2} - r_{t-2}^*) + \varepsilon_t^z \quad (2)$$

$$r_t^* = \mu_r + \theta a_t \quad (3)$$

$$\Delta y_t^* = \mu_y + a_t + \varepsilon_t^y \quad (4)$$

$$a_t = \psi a_{t-1} + \varepsilon_t^a \quad (5)$$

$$y_t = y_t^* + z_t \quad (6)$$

where π_t stands for inflation and is defined as the (annualized) quarterly rate of growth in the harmonized index for consumer prices (HICP, in logs) which is used by the ECB for the definition of its inflation objective, y_t denotes the log real GDP, i_t is the 3-month nominal rate of interest, z_t is the output gap, defined as the relative gap between actual GDP and potential GDP (y_t^*) in percent (equation 6).

The first equation is an aggregate supply equation, or “Phillips curve”, that relates consumer price inflation to its own lags and the lagged output gap. The second one is an aggregate demand equation, or “IS curve”, expressing the output gap as a function of the real interest rate gap – i.e. the difference between the short term ex ante real rate and the natural rate of interest r_t^* –, here with a lag of two quarters. Note that the real rate of interest is defined as $i_t - \pi_{t+1|t}$, where $\pi_{t+1|t}$ is the expected quarterly rate of inflation (at an annual rate) for the next quarter. Note also that in this setup, inflation expectations are not taken out from exogenous surveys, as is commonly done, but solved for in equation (2) using equation (1) and are thus consistent with the rest of the model.

According to the insights gained from the standard neoclassical growth model, a key hypothesis links the natural rate of interest to the persistent process a_t that drives the low-frequency fluctuations in potential output growth (denoted by Δy_t^*): medium-run changes in potential growth are reflected in parallel changes in the level of the NRI and then amplified by a factor θ (see equations 3 to 5). The θ parameter, which is akin to the coefficient of risk aversion in a standard CES utility-of-consumption setup, is calibrated to 16 (which corresponds to a value of 4 when both the NRI and potential growth are expressed on an annual basis), as well as the noise-to-signal ratio $\sigma_y/\sigma_z = 0.5$. Note that,

as shown in Mésonnier and Renne (2006), estimates of the other model parameters are very robust to this calibration.

The two core unobservable variables, namely a_t and z_t , are jointly estimated with the Kalman filter, as explained in details in Mésonnier and Renne (2006), and estimates of the parameter are obtained by maximization of the likelihood function.⁷ The number and the choice of lags in equations (1) and (2) are entirely determined by the data, so that our model can be seen as a restricted VAR, where restrictions are justified by standard information criteria. Table 1 reports the value of the parameters (with the associated Student-t statistics), when the model is estimated over the period 1979Q1 to 2006Q2. Eurostat data have been used over their maximal period of availability (since the early 1990s for GDP and consumption prices, since 1999 for the three-months Euribor) and backpolated using historical series from the ECB's AWM database (version 2, ending in 2004Q4).

Such simple backward-looking models are commonly used in the empirical literature for an analysis of the optimal monetary policy.⁸ Frequent motivations for this choice are notably the simplicity of the setup, its congruence with actual macro-models used in central banks and the empirical fit to the data (Rudebusch and Svensson, 2002). As a matter of fact, backward-looking models of that kind do arguably a better job in fitting the data as do forward-looking models with firmer micro-foundations, which are then often partly calibrated (as in Ehrmann and Smets, 2002). However, in a purely backward-looking framework, the Lucas critique may apply with force to policy evaluation exercises that compare the merits of alternative policy rules possibly differing from the (unobserved) historical regime. Besides, one can expect this critique to be much of an issue when considering continental Europe, where institutional change and policy regime breaks have shaped the past two to three decades.

To alleviate the impact of this critique, a common strategy is to check formally for the stability of the model parameters over time, using for instance Andrews (1993) test for

⁷The model written in state-space form for Kalman filtering is presented in Appendix A.

⁸See e.g. Rudebusch and Svensson (1999, 2002), Peersman and Smets (2001), Orphanides (2003), Rudebusch (2001).

parameter stability. Indeed, as Rudebusch (2005) emphasizes, the practical relevance of the Lucas critique is ultimately an empirical issue. However, while Andrews-like tests are relatively straightforward to implement when the model equations are estimated separately with OLS, as in Rudebusch and Svensson (1999, 2002) or O'Reilly and Wheelan (2006), things are much trickier in an unobserved component framework, so that we are not aware of any implementation of Andrews' test in such a framework.⁹ Nevertheless, a simple plot of the recursive estimates of our key model parameters over increasing samples from 1979Q1-1994Q4 to 2006Q2 and decreasing samples from 1979Q1 to 1985Q1-2006Q2 provides ample evidence of their stability (see Figure 1).

A critical feature of this model is that, not only we assume inflation to be purely backward-looking, but we constrain the α_i coefficients of lagged inflation in equation (1) to sum to unity since this restriction is not rejected by the data. In other words, the natural rate hypothesis holds in our model. However, the assumption of a high and stable persistence parameter for inflation may be deemed somewhat irreconcilable both with the substantial shifts in monetary regime in continental Europe since 1979 and with the intuition that the importance of backward-looking determinants of inflation should decrease as the credibility of the ECB's commitment to low inflation increases. This notwithstanding, there is ample empirical evidence that the Phillips curve in the euro area has still a strong backward-looking component (see e.g. Jondeau and Le Bihan, 2005). Furthermore, a recent study by O'Reilly and Wheelan (2005) shows using a broad range of econometric methods that the persistence parameter in the euro area inflation process has been remarkably stable over the last three decades and that its estimates are generally close to unity. Of course, such historical evidence does not preclude any future change in euro area inflation dynamics as the credibility of the ECB gets more firmly established. However it also gives little basis, as pointed out by these authors, to the idea that institutional changes should necessarily alter inflation persistence dramatically.

Admittedly, as Walsh (2004) puts it, the degree of endogenous inertia in the inflation

⁹Andrew's test applies basically to equations estimated with GMM and is based on the maximum value of the likelihood ratio test statistic for structural stability over all possible breakpoints in the middle 70% of the sample

process is probably one of the most critical parameters affecting the evaluation of alternative policies. More generally, conclusions based on a single reference model must be taken with due caution. Nevertheless, Levin and Williams (2003) examine the robustness of simple rules across a range of models and find that policies obtained from backward-looking model are the most robust when used in competing frameworks.

3 The optimization framework

3.1 Setting the preferences of the ECB

The computation of optimized policy rules under the constraint of a linear model of the economy requires the explicit formulation of preferences for the central bank. In quite a standard way¹⁰, we postulate that the policy-maker aims at minimizing the following quadratic intertemporal loss function:

$$E_t \sum_{\tau=0}^{\infty} \delta^\tau [\gamma(\bar{\pi}_{t+\tau} - \pi_{t+\tau}^*)^2 + (1 - \gamma)z_{t+\tau}^2 + \nu(i_{t+\tau} - i_{t+\tau-1})^2]$$

where E_t stands for the expectation operator, δ is the discount factor and $\pi_{t+\tau}^*$ is the inflation target of the central bank, while $\bar{\pi}_t$ denotes the annual rate of inflation, z_t the output gap and i_t the short term nominal rate of interest, as stated above.

Since we are interested in the fluctuations of policy variables around the constant targets only, the previous form of the objective function boils down to a simple weighted mean of unconditional variances. Without loss of generality we can thus abstract from the level of the discount factor and minimize the unconditional mean of the one-period loss function (cf. Rudebusch and Svensson, 1999, for details):

$$L(\Theta) = \gamma Var(\bar{\pi}_t) + (1 - \gamma)Var(z_t) + \nu Var(i_t - i_{t-1}) \tag{7}$$

Note that this simplified form implicitly assumes that the inflation target is equal to its unconditional mean. Furthermore, the central bank's output objective is not biased upward.

¹⁰For a recent example, see e.g. Lippi and Neri (2007).

Following Rudebusch and Svensson (1999) among many others, this objective function also postulates that the ECB is concerned by interest rate stabilization *per se*. Indeed, the theoretical hypothesis of a gradual conduct of monetary policy, also commonly termed policy inertia, is consistent with many empirical estimates of central banks' reaction functions (see e.g. Clarida, Gali and Gertler, 2000), while optimized policy rules on the basis of objective functions without any concern for interest rate smoothing very often imply considerably more aggressive policy than what is observed empirically (see e.g. Rudebusch and Svensson, 1999, Rudebusch, 2001). However, the issue of intrinsic monetary policy inertia is highly controversial in the literature.

The standard case for explicit interest smoothing in the central bank's objective function refers to central bankers' concerns for financial markets stability (Goodfriend, 1989, Cukierman, 1999), their fear that frequent policy turns could damage credibility (e.g. Mishkin, 1999) or uncertainty about the economic environment (e.g. Goodhart, 1999). More recently, Woodford (1999) has shown in a forward-looking environment that monetary policy inertia could be optimally used as a commitment technology which achieves in a reduction of the stabilization bias. However, some authors have also argued that a proper account given to the impact of multiplicative parameter uncertainty could explain a significant part of the apparent smoothing behaviour of the policy rate (Sack, 2000, Söderström, 2002). Furthermore, Rudebusch (2002, 2005) has claimed that a diagnosis of policy inertia based on estimated policy rules using quarterly data is merely the result of a statistical illusion and could be explain by the persistence of shocks that central banks face. As noted recently by Castelnovo (2005), most of the empirical evidence that the policy inertia hypothesis is irrelevant is based on American data. Using reconstructed euro area data over two decades, this author implements a direct test for the interest rate smoothing hypothesis in the Euro area and finds that the null hypothesis of no inertia is strongly rejected by the data. He concludes that both partial interest rate adjustment and serial correlations due to persistent shocks are likely to have shaped the path of policy rates in Europe.

Direct estimates of central bank preferences shed additional light on this debate and may provide guidance for the calibration of the loss function in equation (7). Indeed, several recent papers provide estimates of these weights for the ECB. The results in both

Aguiar and Martin (2005) over the period 1995-2002 and Lippi and Neri (2007) over the last two decades indicate that the ECB is weakly concerned by output stabilization in itself (i.e. their estimated γ is close to one), but they diverge as to the degree of intrinsic interest rate inertia featured in euro area monetary policy. Whereas the former authors find a positive but very small weight on interest rate volatility (equivalent to $\nu = 0.034$), the latter point to a high preference for interest rate inertia (equal to $\nu = 1.9$ in our notation). All in all, these results contrast with the popular calibrations for a flexible inflation targeting policy as in Svensson (1997), who postulates a high coefficient for output stabilization relative to inflation stabilization and a small amount of policy inertia (see also the baseline specifications of Rudebusch and Svensson, 1999, Peersman and Smets, 1999, or Ehrmann and Smets, 2003, where $\gamma = 0.5$ and $\nu \leq 0.25$). However, the estimates in Lippi and Neri (2007) qualitatively parallel the findings in empirical papers for the Federal Reserve, such as Dennis (2006), Ozlale (2003), Favero and Rovelli (2003) or Södertström, Söderlind and Vredin (2005), at least regarding the latest period (the Volcker-Greenspan era).¹¹

To reflect the diversity of these results, we consider in the following four possible sets of preferences for the ECB. First, for comparison purpose with the results presented in Peersman and Smets (1999), we adopt their benchmark "flexible targeting" case where $\gamma = 0.5$ and $\nu = 0.25$, which we denote FTPS. Second, we posit a stricter inflation targeting regime, but holding constant the ratio γ/ν (we label this case ITI, for inflation targeting with inertia). Hence, we set $\gamma = 0.9$ and $\nu = 0.45$. Finally, the cases of a flexible inflation targeting regime with either high inertia or low inertia, that is where $\gamma = 0.5$ and $\nu = 1$, respectively $\nu = 0.05$, are also examined, in order to illustrate the consequences of

¹¹Their estimate appear nevertheless to be at some variance with the results in Assenmacher-Wesche (2006) for the Bundesbank prior to 1999. This author infers the preference parameters of several major central banks out of estimated reaction functions that allow for regime shifts in the policy rule parameters, otherwise following the same methodology than Dennis (2006). She finds that the low inflation regime which prevailed over the most recent period in Germany – and is likely to be also relevant for the ECB – is characterized by preference parameters of $\gamma = 0.62$ and $\nu = 0.12$ (in our notation). However, compared to estimates by other studies (e.g. Dennis, 2006), the estimates she obtains for the United States in the low-inflation regime (with $\gamma = 0.46$ and $\nu = 0.34$) suggest that the method used may overvalue concerns for output gap stabilization and underweight intrinsic policy rate inertia.

raising or reducing ν compared to the benchmark. These last two cases are denoted by FTHI (high inertia) and FTLI (low inertia) below.

3.2 Simple monetary policy rules

We consider both the optimal unrestricted policy rule and six optimized restricted instrument rules. Given the linear-quadratic nature of the optimization problem, the optimal policy rule is linear in each of the nine independent state variables entering the system (see Appendix A for a reformulation of the model in state-space form):¹²

$$i_t = \vartheta_1 i_{t-1} + \vartheta_2 a_t + \vartheta_3 a_{t-1} + \vartheta_4 \pi_t + \vartheta_5 \pi_{t-1} + \vartheta_6 \pi_{t-2} + \vartheta_7 \pi_{t-3} + \vartheta_8 z_t + \vartheta_9 z_{t-1} \quad (8)$$

The restricted rules are all variants of the popular Taylor (1993) rule. In its simplest form, this rule states that the policy instrument reacts to a linear combination of contemporaneous annual inflation and the output gap. This basic rule is labelled TR in the following. Besides, we also consider the possibility that the policy rate is only partly adjusted to the notional Taylor-rule level (TRS). Such smoothed policy rules usually better fit the data than rules expressed in levels and are very common in empirical research on monetary policy reaction functions (see e.g. Clarida et al., 1998).

$$\text{TR} : \quad i_t = \alpha_\pi \bar{\pi}_t + \alpha_z z_t \quad (9)$$

$$\text{TRS} : \quad i_t = \rho i_{t-1} + \alpha_\pi \bar{\pi}_t + \alpha_z z_t \quad (10)$$

Further, the TN and TNS rules allow us to assess the consequences of adding fluctuations in the NRI to these simple benchmarks:

$$\text{TN} : \quad i_t = \alpha_a a_t + \alpha_\pi \bar{\pi}_t + \alpha_z z_t \quad (11)$$

$$\text{TNS} : \quad i_t = \rho i_{t-1} + \alpha_a a_t + \alpha_\pi \bar{\pi}_t + \alpha_z z_t \quad (12)$$

¹²Since innovations do not enter the feedback function, expectational terms for the output gap, inflation and the NRI can be suppressed as they are linear combinations of the remaining variables. The same is true for the Δy term.

Some authors have argued in favour of modified Taylor-type rules, where the output gap, which is unobservable and whose measure is blurred by sizeable data and model uncertainty, is replaced either by output growth or by the change in the gap. The latter proposal, often referred to as a speed-limit policy, implies that the central bank tries to keep observed demand growth in line with its estimate of supply growth, which is plausibly subject to smaller and less persistent measurement errors in real time than is the level of potential output itself. These two alternatives can be further reconciled under the assumption of negligible structural change, or in other words assuming that potential output growth is more or less constant over a short period of time. Further common proposals to enhance the robustness of simple policy rules also include the case for "difference rules", where the change in interest rate is determined by inflation and output growth, and for nominal income growth rules.¹³

Having this in mind, we examine the case where the central bank would set its policy rate according to developments in both inflation and real output growth (TG) instead of the output gap, or would enter this variable into a traditional Taylor-framework with smoothing (TRGS):

$$\text{TG} : \quad i_t = \alpha_\pi \bar{\pi}_t + \alpha_y \Delta y_t \quad (13)$$

$$\text{TRGS} : \quad i_t = \rho i_{t-1} + \alpha_\pi \bar{\pi}_t + \alpha_z z_t + \alpha_y \Delta y_t \quad (14)$$

Finally, we also consider a "speed limit" policy, where the policy rate reacts to changes in the output gap (TC), and, similarly, a generalized Taylor-rule augmented with the latter variable (TRCS):

$$\text{TC} : \quad i_t = \alpha_\pi \bar{\pi}_t + \alpha_{\Delta z} \Delta z_t \quad (15)$$

$$\text{TRCS} : \quad i_t = \rho i_{t-1} + \alpha_\pi \bar{\pi}_t + \alpha_z z_t + \alpha_{\Delta z} \Delta z_t \quad (16)$$

¹³For a defence of the robustness of difference rules compared to Taylor-type rules, see Orphanides and Williams (2002, 2005). The review by Walsh (2004) comments on the desirability of "speed limit policies" reacting to changes in the output gap or to nominal income growth, as advocated e.g. by Jensen (2002).

3.3 Modelling data uncertainty

An important issue is the extent to which the central bank can trust its current estimates \tilde{z}_t and \tilde{r}_t^* of the unobservable state variables z_t and r_t^* (or equivalently z_t and a_t , see equation 3). In the framework of our model, we tackle this issue comparing the outcomes in two alternative cases of perfect and imperfect information about these variables. Under perfect information, the central bank is able to measure the unobservable variables with perfect accuracy, i.e. $\tilde{\rho}_t = \rho_t$ where ρ_t stands for the (*a priori* unknown) true value of the vector of unobservable variables and $\tilde{\rho}_t$ for the real time estimate of the same vector. Alternatively, the central bank faces imperfect information and its real time measurement error is supposed equal to the Kalman filtering error, that is $\tilde{\rho}_t = \rho_{t|t}$ where $\rho_{t|t}$ stands for the one-sided filtered estimate of ρ_t . Thus we have:

$$\tilde{\rho}_t = \rho_t + s(\rho_{t|t} - \rho_t) \quad (17)$$

with $s = 0$ in the perfect information case and $s = 1$ otherwise.¹⁴

A key empirical issue is whether, and to what extent, the real time estimates of the natural variables can reasonably be proxied by the one-sided estimates $r_{t|t}^*$ and $z_{t|t}$, as we do assume here. In practice, real time measurement errors are indeed likely to exceed simple filtering errors, because the latter are calculated under the simplifying assumption that the policymaker always knows the correct model of the economy (including the final "true" values of parameters that are based on the whole sample of data) and ignore issues of data revisions by statisticians.

To get an intuition of how much such additional sources of real time measurement uncertainty may affect the size of measurement error, we construct a series of real time NRI estimates based on successive real time GDP vintages, as they have been collected since the inception of the euro in 1999.¹⁵ Figure 3 shows "filtering" errors in the measurement

¹⁴As shown in Appendix (A.1) the filtering error $\rho_t - \rho_{t|t}$ follows a VAR(1) process whose innovations are linear combinations of the innovations entering the Kalman filter recursive equations. This allows to rewrite the whole model – including real-time errors – in its companion form as a VAR(1) model. It is then relatively easy to compute the unconditional variances of the target variables and the associated loss.

¹⁵Inflation and real interest rate series are comparatively subject to little revisions, thus we rely on the

of the NRI – as approximated by the gap between one-sided and two-sided Kalman filter estimates –, together with "real time" errors over the period 1999-2005 – as approximated by the gap between the estimated value of the NRI at time t using information available up to this time only, and its final two-sided estimate –. It is apparent from the figure that taking account of revisions of underlying observed data as well as reestimating the model parameters as time passes does not dramatically increase the size of the measurement problem. In particular, the standard deviation of real time errors is larger by a small 5% only than the standard deviation of filtering errors over their period of common availability. Note that this preliminary finding echoes the conclusions of Orphanides and van Norden (2002) that data revisions are responsible for a minor part only of the real time uncertainty surrounding output gap measures.

4 Optimal policy rules under perfect and imperfect information on natural interest rate and output gap

We then compute the coefficients of the various policy rules (8) to (16) that minimize the central bank's loss function, conditionally on the model presented in section 2 and assuming that the central bank faces a measurement problem of size s regarding the unobservable output gap and NRI (see Appendix A for details). The results are summarized in Tables 2 to 4, one for each of the four retained sets of the central bank's preferences, as explained above. For ease of comparison with earlier studies, we discuss primarily the FTSP case ($\gamma = 0.5$, $\nu = 0.25$).

First of all, absent any uncertainty linked with measurement issues of natural variables ($s = 0$), optimal coefficients suggest a much more aggressive policy reaction to inflation and output gaps than what is conventionally assumed on the basis of simple policy rules regressions. For instance, estimates of α_π of α_z for the ECB range in an interval of 0.2 to 1.2, if one considers a simple rule without smoothing, and between almost 0 and 0.6 and between 0.1 and 0.9 respectively, if one considers the smoothed version of this simple

final series for these variables. See Mésonnier (2006) for a detailed presentation of the real time database.

rule (TRS).¹⁶ However, the fact that the optimal policy prescribed on the basis of simple monetary policy models is more aggressive than what is commonly observed in practice is well known.¹⁷ This is of course reflected in the associated high volatility of interest rates as compared to historical standards (with a typical variance of the change in interest rates between 0.75 and 1.74, compared to 0.36 over the whole sample of data). Nevertheless, one may note that the variances obtained in table 2 are of the same order of magnitude as those in Peersman and Smets (1999) and Rudebusch and Svensson (1999).

This being said, a ranking of the competing rules according to the associated loss shows that a simple smoothed Taylor-type rule with an intercept whose fluctuations are in sync with the estimated natural rate of interest (TNS rule) performs remarkably well in stabilizing the economy, at least nearly as well as the unconstrained optimal policy. Its non-smoothed counterpart (TN) immediately follows, while the standard Taylor rule, with or without smoothing, achieves somewhat poorer results. Interestingly enough, comparing alternative rules based on the same number of state variables, it appears that augmenting a standard smoothed Taylor rule with either output growth or the change in the output gap (TRGS or TRCS) does not help to improve noticeably the outcome. In contrast, the performance of simple income growth or speed limit policies is markedly worse than that of competitors (TG and TC).

Finally, it may be worth noting that, even under complete information, a central bank that would choose to follow a TN rule should not try to pass entirely the estimated fluctuations in the natural rate of interest into the level of the key rate, but only about three quarters of it. A possible explanation is to be found in the required degree of interest rate smoothing: as a matter of fact, allowing for the lagged interest rate to enter the rule (TNS rule) leads to an optimal coefficient of 0.31 for the lagged rate and a markedly higher implicit coefficient for the reaction to the natural rate (0.87 once corrected for the effect

¹⁶See notably Gerdesmeier and Roffia (2004) and Sauer and Sturm (2003) for estimated Taylor rules with contemporaneous inflation (using either final or real time data). Forward-looking Taylor rules regressions yield similarly low inflation and output gap coefficients, in particular due to the the apparent smoothing behaviour of the ECB. See for instance Hayo and Hoffman (2006).

¹⁷See Söderström (1999) for an explanation pointing to the impact of model restrictions and insufficient account given to parameter uncertainty.

of partial adjustment).

The good properties of the TN and TNS rules, compared with more standard Taylor-type rules (TR and TRS) that disregard NRI fluctuations, could intuitively be expected under perfect information, considering the structure of the model and in particular the decisive role of the NRI in stabilizing inflation. However, the ranking of competing rules is not affected by an increase in measurement uncertainty. When the central bank assumes that measurement errors are equal to the real time filtering error ($s = 1$), the optimized TNS rule entails a larger loss than under perfect information, but keeps performing better than would an optimized Taylor rule do (TR or TRS alike). However, under imperfect information, the distance between those simple rules is reduced, while their distance to fully optimal policy increases. The intuition behind this result is that there may be a trade-off between simplicity and efficiency: when the awareness of measurement errors increases, the practical advantage of focusing on a handful of selected variables becomes doubtful as their informational content deteriorates. By the way, it may be noted here that, in spite of the linear-quadratic nature of the optimization problem, the certainty equivalence principle does not hold: indeed, the coefficients of the optimized constrained rules do change when data uncertainty increases. This is however not at odds with standard theory, which predicts that the unconstrained optimal policy only, and not simpler constrained policy rules, should be invariant to additive uncertainty.¹⁸

Finally, we turn to changes in the coefficients of the various rules when the degree of measurement error in natural variables increases. As found in other studies, the output gap coefficient in a standard Taylor rule tends to decrease with rising data uncertainty (cf. e.g. by Peersman and Smets, 1999, or Orphanides and Williams, 2002), while the inflation coefficients increase. The same holds for the reaction to estimated natural rate fluctuations and to inflation in the TN or TNS rules. However, in the latter two, it appears that the output gap coefficients increase with s . This trade-off between reacting to the output gap or to the natural rate of interest echoes some of the results in a close experiment by Rudebusch (2001), who finds that uncertain persistent shifts in the (in his case presumably constant) estimated natural rate of interest tend to push the optimal

¹⁸See also Orphanides and Williams (2002), Peersman and Smets (1999) or Rudebusch (2001).

output gap coefficient of the policy rule higher.¹⁹ This outcome may be also related to the way the NRI is estimated in our model through the IS equation: the more the estimated level of the NRI appears to be flawed, the bigger the impact on the output gap. Hence, to minimize the impact of possible measurement error, it is optimal to distrust a bit less the output gap and a bit more the estimated natural interest rate.

Tables 3 to 5 show the results for the alternative sets of ECB preferences: flexible targeting with high or low interest inertia (denoted FTHI and FTLI respectively) and strict inflation targeting with baseline inertia (denoted ITI). The view provided by the tables is complemented by figures 4 and 5 which show the trade-offs between inflation and output gap volatility that result for varying the relative weight on inflation stabilization γ in equation 7 from 0 to 1, assuming that $\nu = 0.05$ and $\nu = 2$ respectively. The figures focus on a selection of simple rules as compared to the efficiency frontier of the unconstrained policy rule (the solid bold line). For increasing values of γ (higher concern for inflation stabilization), the optimized rules correspond to points further on the northwest of the respective lines. Note that increasing intrinsic inertia globally shifts all the frontiers down and on the right, which hints that additional interest rate inertia is achieved primarily at the costs of lower inflation stabilization, especially when the concern for inflation stabilization is already low.

The main insights gained from the baseline case remain valid. In particular, the optimized rule with time-varying natural rate and smoothing still outperforms its competitors and the corresponding loss keeps in the neighborhood of the fully optimal policy loss. Importantly, this holds even when the preference of the ECB for interest rate smoothing comes close to zero, as evidenced in Table 5 and figure 4. Indeed, a rebuttal to our results in favour of an integration of the time-varying NRI in simple policy rules could have been

¹⁹This author uses a small backward-looking estimated model and considers various types of uncertainty in an attempt to reconcile simulated optimal Taylor rules with, usually less aggressive, historical estimated rules. In particular, he looks at changes in optimal Taylor rule coefficients of the TR type when he simulates his model with random draws of the constant natural rate of interest that are renewed every four years as a proxy for the impact of uncertain persistent shift in this parameter. Although in Rudebusch's framework such shifts refer to some form of parameter uncertainty, it is close to measurement error of a fluctuating NRI variable in an UC framework like ours.

that such results directly stem from the choice of a high enough value for ν , since taking account of a very persistent variable like our estimated NRI would help a lot satisfying the preferences of an inertial central bank. However, the comparison of efficiency frontiers in figures 4 and 5 clearly indicates that the better stabilization performance of policy rules that incorporate a time-varying NRI (the TN and TNS rules) –even when compared to an output-growth-augmented smoothed Taylor rule– is not a mere artefact resulting from the postulated preferences. Note also in table 5 that, when ν tends to zero, optimized rules tend to respond one-for-one to fluctuations in the natural rate.

In contrast to the low-inertia case, the obtained variances under the various policy rules come closer to observed levels when the relative degree of intrinsic inertia increases (FTHI case), which suggests that some non-negligible amount of aversion to short term interest rate volatility effectively belongs to the policy followed by the ECB and/or its precursors, as found e.g. by Lippi and Neri (2007).²⁰ The obtained optimized rules are correspondingly less aggressive than in the baseline FTPS case. Whatever, the optimizing policy maker still adapts to a rising distrust in its own real time estimates of natural variables by reacting less to these estimates, while still trading-off the output gap against the NRI.

To sum it up, keeping an eye on low-frequency fluctuations of the intercept in an optimized Taylor rule appears to promise a significant increase in the utility of the central bank, even if natural variables estimates are surrounded with a large uncertainty. The benefit is smaller the more intrinsically inertial is monetary policy (ν increases) and if the central bank is uncertain about its NRI and output gap estimates ($s = 1$), but even in the worst case (here the highly inertial case FTHI with $s = 1$), the parsimonious optimized Taylor rule with time-varying NAIRI and smoothing (TNS rule) yields a loss that is only 4.4% bigger than the loss associated with the unconstrained optimal rule and nevertheless corresponds to a reduction of the "historical" loss by 38%. Furthermore, comparing the historical loss (as given on the first row of Table 2) with the loss yielded by a dynamic simulation of the model over the whole sample (as shown on the second

²⁰However, this could also signal that the ECB and its predecessors in the ERM had to face very persistent shocks.

row of the same table), this large cut in the central bank's loss appears unambiguously to be a consequence of the optimization process (see Appendix B for a presentation of the dynamic simulation exercise). Hence, obviously, our results do *not* imply that the sole inclusion of the estimated NRI on the RHS of an otherwise standard Taylor rule regression would yield a relevant benchmark for the ECB.

Finally, figures 6 to 7 give the dynamic impulse responses of the model for the baseline specification (FTPS) under a selection of optimal rules and for the two different values of s : the unconstrained rule, the traditional Taylor rule with smoothing and constant intercept (TRS) and a less traditional Taylor rule with time-varying neutral rate of interest (TN). The three rules have similar properties regarding responses of the model to inflation and output gap or demand shocks (of one standard deviation each). In particular, the nominal interest rate reacts in all cases vigorously to either positive shocks, leading to a prompt decline in the output gap and a more protracted decline of inflation after the initial increase. Responses differ however to a larger extent when one considers a positive shock to the natural rate of interest (that is, a persistent upward shock to trend output growth). Indeed, contrarily to a smoothed Taylor rule with constant intercept, a rule with a time-varying neutral rate reacts on impact to the shock, which entails a much smaller response of inflation and almost no response of demand. This difference tends to vanish however under imperfect information about natural variables, as shown in figure 7.²¹

5 Effects of uncertainty with respect to the model parameters

So far, we have computed optimized policy rules when the ECB believes that the point estimates of the model parameters are correct measures of the "true" reduced-form parameters. However, optimal policy design may well be sensitive to even small measurement

²¹Qualitatively similar impulse response functions obtain under alternative sets of preference parameters. Note that, when the degree of intrinsic interest rate inertia increases (e.g. in the FTHI case), the responses to a NRI shock of an optimized Taylor rule with smoothing (TRS) and of a rule with a time-varying neutral rate but without smoothing (TN) are almost identical.

errors in some of the parameters, in particular those parameters which govern the transmission of monetary policy impulses. Unfortunately, as Rudebusch (2001) states it, almost nothing can be said *a priori*, even qualitatively, about changes in the optimal policy rule when *multiple* parameter uncertainty is added : it is unclear for instance whether a given policy rule coefficient would be increased or reduced. Therefore, it is conceptually and practically of interest to quantify within the framework of our model the implications of uncertainty with respect to a combination of the estimated model parameters.

In this section, we allow for parameter uncertainty while we restrict our attention to three parameters: two estimated parameters, namely β , the slope of the Phillips curve and λ , the interest rate sensitivity of the economy, as well as one calibrated parameter, the "coefficient of risk aversion" θ . As reviewed in Mésonnier and Renne (2006), values for this coefficient in the empirical literature range in a broad interval of 1 to 5, and we have set $\theta = 4$ (for annualized output growth data) for our baseline specification on the basis of various statistical tests. However, it is fair to say that the tests performed are not very discriminating. Besides, the amplitude of NRI fluctuations obtained when $\theta = 4$ may be deemed difficult to reconcile with economic intuition. Indeed, recent estimates of the coefficient of risk aversion of consumers for the Euro area indicate that a lower value, comprised between 1 and 2, may be more appropriate.²² On the basis of such evidence, we thus consider as an alternative calibration $\theta = 1.5$.

More precisely, we assume that, although the policymaker may not be confident with the point estimates of β and λ anymore, they still trust the empirical distributions yielded for a given calibration of θ . Besides, as they can not tell *a priori* what is the best calibration for θ , they also weigh equally the probabilities that the true model corresponds to $\theta = 1.5$ or to $\theta = 4$.²³ The idea underlying the optimization process is thus the following: for any

²²For instance, estimating a DSGE model with Bayesian techniques for the Euro area, Smets and Wouters (2003) find a median of 1.371 for the posterior distribution of their coefficient of risk aversion. Using the same model but different estimation periods, these authors find estimated values of between 1.13 and 1.84 (Smets and Wouters, 2004, 2005). Casares (2001) derives its estimate from the estimated interest rate elasticity of a reduced form consumption equation for the euro area and also find a value that fits within this interval (1.25).

²³For quarterly output growth expressed in annualized terms.

given set of policy rule coefficients and for each possible calibration of θ , the policymaker draws $N/2$ realizations of the uncertain model parameters out of the empirical distributions and computes the average loss over the N randomly drawn models. In a second step, the policymaker tries another guess about the policy rule coefficients and computes again the average loss over N models. They then repeat the whole procedure, using a standard optimization algorithm, until a global minimum for the average loss is found.²⁴ The rule coefficients obtained for this minimal loss are the optimized coefficients under parameter uncertainty. Note that the convergence of the optimization process is very slow in practice. We set the number of parameter draws for each set of rule coefficients equal to $N = 10,000$ in order to ensure that the simulated average loss is close enough to the expected loss. Details of the methodology are given in Appendix C.

Our methodology makes it possible to examine both the impact of parameter uncertainty alone and the consequences of parameter uncertainty when compounded with data uncertainty. Tables 6 and 7 present the results for the flexible targeting case with low inertia and the flexible targeting case with high inertia (denoted FTPS and FTHI respectively). Since the computations are very time-consuming, results are presented for a selection of policy rules only.

Let us first consider what happens when the policymaker takes account of parameter uncertainty alone ($s = 0$). First, a quick comparison with Tables 2 and 3 shows that parameter uncertainty is much more detrimental to welfare, as captured by the level of the loss function, than would be data uncertainty alone (with $s = 1$). Second, it is noticeable that the ranking of the different rules does not appear affected by parameter uncertainty. For instance, the TN rule which features a time-varying intercept but without interest rate smoothing still performs better than the more traditional TRS rule when policy is not very inertial (FTPS case), and at least as well in the opposite case (FTHI case). This rule performs also systematically better than a smoothed Taylor rule augmented with output growth instead of the NRI. Third, the optimal output gap coefficient in a standard Taylor rule (TR), as well as the degree of interest rate smoothing the case being (TRS), tend to decrease when uncertainty about β is added, which is consistent with the traditional view

²⁴The optimization process is performed using the Matlab `fminsearch` procedure.

due to Brainard (1967) that giving account to multiplicative uncertainty leads to more cautious policies in response to shocks to the related variables. This notwithstanding, when the policy rule reacts to both the output gap and the NRI under parameter uncertainty as under natural variables uncertainty (see above subsection 4), the optimization process entails a greater sensitivity to the output gap at the cost of a smaller response to NRI fluctuations. Finally, when data uncertainty combines with parameter uncertainty, response coefficients to unobservable variables tend then to decrease, by up to roughly a third for the NRI coefficient, and by somewhat less for the output gap coefficient.

Overall, our previous finding, that including the estimated time-varying NRI in a standard policy rule would yield a lower loss for the central bank, appears robust to parameter uncertainty.

6 Conclusion

In this paper, we have examined empirically whether an estimated time-varying natural rate of interest, whose fluctuations are in sync with low frequency variations in trend growth or productivity, could be a useful guideline in analyzing monetary policy in the euro area. Although policy discussions often allude to the concept of natural or neutral rate of interest (NRI), academics as well as central bankers generally agree that real time statistical estimates of the natural rate are too imprecise to provide a reliable benchmark in practice. Nevertheless, whether letting the intercept of a simple Taylor-type rule fluctuate with estimated changes in the NRI could provide useful insights for policy making remains an open empirical issue. In particular, the answer depends on how close such an augmented rule would be to the optimal policy, in absolute terms and compared to other standard benchmarks.

Using a small estimated unobserved components (UC) model for the euro area, we compute in a standard linear-quadratic framework various simple optimized reaction functions for the ECB. We show that a smoothed version of the NRI-augmented Taylor rule performs quite well compared to the optimal rule, even when the degree of distrust of the central bank towards its own real time measures of the natural variables is high. Besides, this rule remains the best performer, even when account is jointly given to uncertainty

with respect to model parameters. However, even with uncertain data and parameters, the optimized Taylor-type rules still look quite aggressive and can not be reconciled with the outcome of usual Taylor rules regressions for the Euro area. To conclude with, it is worth emphasizing that our findings about optimized rules do clearly not imply that the mere addition of our estimated NRI in a standard Taylor rule regression could have any normative content for the ECB.

A noticeable advantage of our approach is that the unobservable variables – the NRI and the output gap – are estimated consistently within the macroeconomic model upon which the policymaker bases his optimization. However, an obvious limit of the exercise conducted here is its strong dependency to that particular backward-looking macro model. Although the model is plausible and correctly estimated, alternative specifications, e.g. encompassing forward-looking or hybrid versions of the Phillips curve, could also be considered and yield different conclusions. An interesting further step would thus be to run the same kind of exercise over several alternative small UC models, and look for optimized rules that would also prove robust to such model uncertainty. However, this is left for future research.

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A Optimal control of the model

A.1. The model in state-space form and the computation of filtering errors

Technically, the two unobservable variables, namely a_t (or equivalently r_t^*) and z_t , are jointly estimated with the Kalman filter, which requires the system of equations (1) to (6) to be written in its state-space form:

$$Y_t = c + G_1 \rho_t + G_2 \Xi_{t-1} + \varepsilon_t \quad (18)$$

$$\rho_t = \mu + H_1 \rho_{t-1} + H_2 \Xi_{t-1} + \xi_t \quad (19)$$

where $Y_t = [\Delta y_t, \pi_t]'$ is the vector of observed variables,
 $\Xi_{t-1} = [i_{t-1}, i_{t-2}, \pi_{t-1}, \pi_{t-2}, \pi_{t-3}, \pi_{t-4}]'$ a vector of predetermine variables,
 $\rho_t = [a_t, a_{t-1}, z_t, z_{t-1}]'$ is the vector of unobservable variables,
 while $\varepsilon_t = [\varepsilon_t^y, \varepsilon_t^\pi]'$ and $\xi_t = [\varepsilon_t^a, 0, \varepsilon_t^z, 0]$ gather the innovations to observed variables and unobservable variables respectively.

As is standard, equation (18) is the measurement equation and equation (19) is the transition equation. The details of the matrices entering these two equations can be easily computed from the developed form of the model.

$$\text{In particular, } G_1 = \begin{bmatrix} 1 & 0 & 1 & -1 \\ 0 & 0 & 0 & \beta \end{bmatrix} \text{ and } H_1 = \begin{bmatrix} \psi & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & -\lambda\theta & \Phi & -\beta\lambda \\ 0 & 0 & 1 & 0 \end{bmatrix}.$$

Let us write $\rho_{t|\tau}$ the estimate of ρ_t using information available up to time τ : $Y^\tau = (Y_1, \dots, Y_\tau)$. The so-called "filtered" estimate yielded by the one-sided version of the Kalman filter is $\rho_{t|t}$, while $\rho_{t|T}$ denotes the output of the two-sided version of the filter (Kalman "smoother"), where T is the total number of observations. We also write $\Sigma_{t|\tau}$ the covariance matrix of ρ_t based upon information Y^τ . The usual prediction equations within the Kalman filter read:

$$\rho_{t|t-1} = \mu + H_1 \rho_{t-1|t-1} + H_2 \Xi_{t-1} \quad (20)$$

$$\Sigma_{t|t-1} = Q + H_1 \Sigma_{t-1|t-1} H_1 \quad (21)$$

and

$$Y_{t|t-1} = c + G_1\rho_{t|t-1} + G_2\Xi_{t-1} \quad (22)$$

$$\Omega_{t|t-1} = R + G_1\Sigma_{t|t-1}G_1' \quad (23)$$

where $R = Var(\varepsilon_t)$, $Q = Var(\xi_t)$, $Y_{t|t-1} = E(Y_t|Y^{t-1})$ and $\Omega_{t|t-1} = Var(Y_t|Y^{t-1})$.

The updating equations read in turn:

$$\rho_{t|t} = \rho_{t|t-1} + K_t(Y_t - Y_{t|t-1}) \quad (24)$$

$$\Sigma_{t|t} = (Id - K_tG_1)\Sigma_{t|t-1} \quad (25)$$

where K_t , the gain of the filter, is given by:

$$K_t = \Sigma_{t|t-1}G_1'(R + G_1\Sigma_{t|t-1}G_1')^{-1} \quad (26)$$

Combining the prediction and updating equations of the standard Kalman filter, it is then straightforward to express the DGP of the filtering error as an AR(1) process:

$$\rho_t - \rho_{t|t} = (I - KG_1)H_1(\rho_{t-1} - \rho_{t-1|t-1}) + (I - KG_1)\xi_t - K\varepsilon_t \quad (27)$$

A.2. Optimal monetary policy

In order to derive the optimized coefficients of the different instrument rules, it is convenient to write the model in its companion form.²⁵ The state-space representation of the economy is then of the general form:

$$X_t = AX_{t-1} + Bi_{t-2} + \eta_t \quad (28)$$

where η_t is a linear combination of the model innovations. Regarding the state vector X_t , we stack in it both the state variables Z_t and the filtering errors ν_{t-1} :

²⁵To save space, all the matrices are not developed here. Although these can be retrieved using the equations presented in this paper, the full description of the matrices is of course made available upon request to the corresponding author.

$$X_t = \begin{bmatrix} Z_t & \nu_{t-1} \end{bmatrix}$$

where $Z_t = [\Delta y_{t-1}, z_t, z_{t-1}, z_{t-2}, a_t, a_{t-1}, a_{t-2}, \pi_t, \pi_{t-1}, \pi_{t-2}, \pi_{t-3}, \pi_{t-4}, i_{t-2}]'$
and $\nu_{t-1} = \rho_{t-1|t-1} - \rho_{t-1}$.

Note that identifying the stochastic error process with a VAR(1) as is done in equation (27) above makes it possible to define the state vector and rewrite the model that way.

Finding the optimal rule coefficients is tantamount to finding an optimal vector g such that $i_{t-2} = gE_{t-2}(X_{t-1})$. Note that g may contain only a few non-zero entries, depending on the considered rule. For equation (28) to be cast in a simple VAR(1) form, which would bring our problem back to the standard linear-quadratic regulator problem (see e.g. Chow, 1975), we need a matrix P such that $gE_{t-2}(X_{t-1}) = gPX_{t-1}$ for any X_{t-1} . Fortunately, it is relatively easy to find such a matrix without any loss of generality if the state vector X_t is adequately defined and if we limit the investigation to contemporaneous or backward-looking policy rules, as we do in this paper. The model written in companion form then reads:

$$X_t = \begin{bmatrix} Z_t \\ \nu_{t-1} \end{bmatrix} = A \begin{bmatrix} Z_{t-1} \\ \nu_{t-2} \end{bmatrix} + BgP \begin{bmatrix} Z_{t-1} \\ \nu_{t-2} \end{bmatrix} + \eta_t$$

Matrices A and P may be decomposed by blocks to match the decomposition of X_t between state variables Z_t and filtering errors ν_{t-1} :

$$A = \begin{bmatrix} A_1 & \mathbf{0} \\ \mathbf{0} & (I - KG)H \end{bmatrix}, P = \begin{bmatrix} P_1 & P_2 \\ \mathbf{0} & \mathbf{0} \end{bmatrix}$$

$$\text{where } P_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \Phi & -\lambda\beta & 0 & 0 & -\lambda\theta & 0 & 0 & -\lambda\alpha_1 & -\lambda\alpha_2 & -\lambda\alpha_3 & \lambda \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \psi & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \beta & 0 & 0 & 0 & 0 & 0 & \alpha_1 & \alpha_2 & \alpha_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\text{and } P_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & \lambda\theta & -\Phi & \lambda\beta \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ -\psi & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -\beta & 0 \\ 0 & \dots & 0 & 0 \\ \vdots & & & \vdots \\ 0 & \dots & & 0 \end{bmatrix}$$

Besides, the (13,13) matrix A_1 is given by:

$$A_1 = \begin{bmatrix} 0 & 1 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Phi & -\lambda\beta & 0 & 0 & -\lambda\theta & 0 & 0 & -\lambda\alpha_1 & -\lambda\alpha_2 & -\lambda\alpha_3 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \psi & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \beta & 0 & 0 & 0 & 0 & 0 & \alpha_1 & \alpha_2 & \alpha_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Since both the true value of the unobservable vector ρ_{t-1} and the filtering error $\rho_{t-1|t-1} - \rho_{t-1}$ appear in state vector X_t , we can now switch easily from the perfect to the imperfect information case which correspond to alternative choices for variable s in text (see section 3). Let us suppose for instance that the central bank follows an optimized simple Taylor rule (TR), where the policy rate only reacts to deviations in inflation and the output gap. If the policymaker observes the output gap with certainty ($s = 0$), only the third and ninth elements of g (corresponding to z_{t-1} and π_{t-1} respectively) are non-zero. In the alternative case of real-time measurement errors ($s = 1$), the sixteenth entry of g , which relates to $z_{t-1|t-1} - z_{t-1}$, is also non-zero and it equals the third entry –the coefficient for z_{t-1} in the rule–. This implies that the policy rule now reacts to $z_{t-1|t-1} = z_{t-1} + (z_{t-1|t-1} - z_{t-1})$ instead of z_{t-1} .

With $M = A + BgP$, equation (28) now reads:

$$\begin{aligned} X_t &= AX_{t-1} + Bi_{t-2} + \eta_t = MX_{t-1} + \eta_t \\ &= \eta_t + M\eta_{t-1} + M^2\eta_{t-2} + M^3\eta_{t-3} + \dots \end{aligned} \tag{29}$$

Since the η_t vectors are serially uncorrelated, we thus have

$$\Sigma_X = \Sigma_\eta + M\Sigma_\eta M' + M^2\Sigma_\eta M^{2'} + M^3\Sigma_\eta M^{3'} + \dots$$

To end with, let Υ_t stand for the vector of target variables and be expressed as a function of the state variables:

$$\begin{aligned} \Upsilon_t &= \begin{bmatrix} \bar{\pi}_t \\ z_t \\ i_{t-1} - i_{t-2} \end{bmatrix} \\ &= \begin{bmatrix} 0 & \dots & \dots & 0 & 1/4 & 1/4 & 1/4 & 1/4 & 0 & \dots & \dots & 0 \\ 0 & 1 & 0 & \dots & & & & & & & \dots & 0 \\ 0 & \dots & & & & & & & \dots & 0 & -1 & 0 & \dots & & 0 \end{bmatrix} X_t + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} i_{t-1} \\ &= C_X X_t + C_i i_{t-1} \end{aligned}$$

The loss function in equation (7) can then be written $L = \text{trace}(T\Sigma_\Upsilon)$ with $\Sigma_\Upsilon =$

$$C\Sigma_X C' \text{ and } T = \begin{bmatrix} \gamma & 0 & 0 \\ 0 & 1 - \gamma & 0 \\ 0 & 0 & v \end{bmatrix}$$

B Dynamic model simulation

In this appendix, we complement the presentation of the baseline model with a quick description of how it behaves in dynamic simulations. To perform such simulations, we first need a reconstruction of historical shocks and second a separately estimated policy rule in order to close the model. We get the shocks simply from the two-sided estimation of the model. Regarding the specification of the additional nominal interest rate equation, we are technically constrained by, first, the apparent non-stationarity of the interest

rate and inflation series over the sample²⁶ and second, the backward-looking nature of the model that hinders the implementation of a forward-looking policy rule in dynamic simulations. We therefore opt for a simple reaction function, where interest rate changes react to changes in lagged inflation and in the lagged level of the one-sided estimate of the output gap. Reacting to lagged variables is deemed more realistic since information is only available with some delay in the real world. The very persistent nature of the interest rate process is furthermore captured by the inclusion of lagged changes on the right-hand side²⁷ :

$$\begin{aligned} \Delta i_t &= \underset{(0.07)}{0.39} \cdot \Delta i_{t-1} + \underset{(0.04)}{0.09} \Delta \pi_{t-1} + \underset{(0.04)}{0.08} z_{t-1|t-1} + \varepsilon_t^I & (30) \\ \overline{R^2} &= 0.31, DW = 1.83 \end{aligned}$$

Whereas a motivation of equation (30) as a standard Taylor-type rule expressed in first difference would imply a reaction to *changes* in the output gap, we prefer to include the *level* of the estimated output gap as a measure of future inflationary risks. This is both consistent with the logic of our model and with the official communication of the ECB and at least some of its major predecessors which claim that they have mainly pursued an objective of price stability, and were not specifically committed to stabilize output. Figure 2 compares historical series with the simulated paths when equation (30) is added to the model (1) to (6). The results are quite satisfying if we consider that important policy shifts are likely to have occurred in the euro area at the beginning of the 1990s, for instance due to the official launch of the run-up to EMU, which means that a simple linear rule as in equation (30) is probably a poor description of actual policy. Moreover, the obtained variances of simulated inflation, output gap and interest rates are of the same order of magnitude as the empirical variances of historical series, as shown on the first and second rows of Table 2.

²⁶Standard unit-root tests (not reproduced here) fail to reject the null of non-stationarity for both series over 1979 to 2006.

²⁷Estimation is performed over 1981:1-2006:2 using OLS. Standard errors are given in parentheses and are corrected for heteroscedasticity (Newey-West). The adjusted R^2 is 0.30 and the Durbin-Watson statistic 1.89.

C The loss function under parameter uncertainty

To simplify the notations, let ω_1 stand for the vector of the parameters entering the reaction function and ω_2 for the vector of the remaining parameters. The loss function can be expressed as

$$L(\tilde{\omega}_1, \tilde{\omega}_2) = \lim_{t \rightarrow \infty} \mathbf{E} [l_t | \omega_1 = \tilde{\omega}_1, \omega_2 = \tilde{\omega}_2]$$

where $l_t = \gamma(\bar{\pi}_t - \bar{\pi})^2 + (1 - \gamma)z_t^2 + \nu\Delta i_t^2$. This suggests that the loss only depends on the unconditional variance of the output gap, inflation and short rate variations.

Using these notations, the first step (section 4) formally consists in solving the optimization problem:

$$\min_{\omega_1} L(\omega_1, \hat{\omega}_2)$$

where $\hat{\omega}_2$ is the vector of parameters obtained by log-likelihood maximization (excluding reaction function parameters).

In a second step (section 5), the parameter uncertainty is (partly) taken into account by considering that some of the parameters in ω_2 are randomly distributed. Let p and Ω be the density of ω_2 and the corresponding space respectively. The central bank then aims at solving the following optimization problem:

$$\min_{\omega_1} L^*(\omega_1)$$

with $L^*(\omega_1) = \int_{\omega_2 \in \Omega_2} L(\omega_1, \omega_2) p(\omega_2) d\omega_2$

α_1	α_1	α_1	β	ϕ	λ	μ_r	μ_y	ψ	σ^π	σ^z	σ^a
0.53 (6.19)	0.14 (1.46)	0.34 (3.96)	0.16 (2.18)	0.76 (5.84)	-0.16 (-2.83)	3.00 2.59	0.52 (8.91)	0.92 (15.17)	0.90 (14.74)	0.33 (8.40)	0.05 (2.21)

Table 1: Estimates of the model parameters - Student-T in parenthesis - Estimation period: 1979:01 to 2006:02 - Two remaining parameters have been calibrated: $\theta = 16$ and $\sigma^y = 0.5\sigma^z$, see Mésonnier and Renne (2006) for details.

$\gamma = 0.5, \nu = 0.25$	α_π	α_z	$\alpha_a, \alpha_y, \alpha_{\Delta z}$	ρ	$Var(\pi)$	$Var(z)$	$Var(\Delta i)$	$Loss$	s
Historical	–	–	–	–	7.69	1.60	0.36	4.74	–
Simulated	–	–	–	–	11.46	4.29	0.08	7.90	–
Optimal	–	–	–	–	2.57	1.45	1.02	2.27	0
TR	3.30	1.85	–	–	2.80	1.78	1.75	2.73	0
TRS	2.09	1.43	–	0.43	2.81	1.81	1.38	2.65	0
TN	2.73	1.17	12.60	–	2.67	1.45	1.35	2.40	0
TNS	2.04	1.06	9.54	0.31	2.68	1.49	1.07	2.35	0
TG	2.37	–	1.13	–	4.18	3.49	1.11	4.11	0
TC	2.38	–	0.47	–	4.29	3.82	0.78	4.25	0
TRGS	1.51	1.15	0.59	0.62	2.83	1.77	1.31	2.63	0
TRCS	2.01	1.39	0.09	0.46	2.83	1.80	1.37	2.65	0
Optimal	–	–	–	–	2.65	1.64	1.12	2.42	1
TR	3.26	1.69	–	–	2.85	1.91	1.73	2.81	1
TRS	2.21	1.37	–	0.38	2.87	1.93	1.40	2.75	1
TN	2.92	1.33	8.03	–	2.75	1.66	1.53	2.59	1
TNS	2.08	1.12	6.33	0.34	2.77	1.69	1.19	2.53	1
TG	2.37	–	1.13	–	4.18	3.49	1.11	4.11	1
TC	2.38	–	0.41	–	4.29	3.83	0.78	4.25	1
TRGS	1.78	1.18	0.44	0.52	2.88	1.91	1.36	2.74	1
TRCS	2.29	1.41	–0.11	0.35	2.87	1.93	1.41	2.75	1

Table 2: Results with and without output gap and natural rate uncertainty - FTFS preferences - Nota bene: a coefficient $\alpha_a = 16$ corresponds to a NRI coefficient of one in the policy rule.

$\gamma = 0.5, \nu = 1$	α_π	α_z	$\alpha_a, \alpha_y, \alpha_{\Delta z}$	ρ	$Var(\pi)$	$Var(z)$	$Var(\Delta i)$	$Loss$	s
Historical	–	–	–	–	7.69	1.60	0.36	5.01	–
Simulated	–	–	–	–	11.46	4.29	0.08	7.96	–
Optimal	–	–	–	–	3.10	1.43	0.51	2.78	0
TR	2.58	1.12	–	–	3.58	1.83	0.92	3.63	0
TRS	1.12	0.79	–	0.64	3.50	1.83	0.64	3.31	0
TN	2.20	0.62	10.08	–	3.26	1.41	0.82	3.15	0
TNS	1.20	0.55	6.24	0.52	3.25	1.46	0.53	2.88	0
TG	2.21	–	0.45	–	4.64	3.42	0.67	4.70	0
TC	2.22	–	0.21	–	4.71	3.55	0.64	4.77	0
TRGS	0.89	0.69	0.39	0.74	3.48	1.80	0.63	3.27	0
TRCS	1.03	0.76	0.15	0.68	3.50	1.84	0.64	3.31	0
Optimal	–	–	–	–	3.22	1.63	0.56	2.98	1
TR	2.55	1.01	–	–	3.64	1.94	0.92	3.71	1
TRS	1.21	0.75	–	0.60	3.57	1.97	0.66	3.43	1
TN	2.37	0.82	5.60	–	3.42	1.65	0.88	3.41	1
TNS	1.19	0.60	4.00	0.55	3.38	1.68	0.58	3.11	1
TG	2.21	–	0.45	–	4.64	3.42	0.67	4.70	1
TC	2.22	–	0.18	–	4.71	3.56	0.64	4.77	1
TRGS	1.01	0.67	0.33	0.68	3.56	1.94	0.65	3.39	1
TRCS	1.18	0.74	0.04	0.61	3.56	1.97	0.66	3.43	1

Table 3: Results with and without output gap and natural rate uncertainty - FTHI preferences - Nota bene: a coefficient $\alpha_a = 16$ corresponds to a NRI coefficient of one in the policy rule.

$\gamma = 0.9, \nu = 0.45$	α_π	α_z	$\alpha_a, \alpha_y, \alpha_{\Delta z}$	ρ	$Var(\pi)$	$Var(z)$	$Var(\Delta i)$	$Loss$	s
Historical	–	–	–	–	7.69	1.60	0.36	7.24	–
Simulated	–	–	–	–	11.46	4.29	0.08	10.78	–
Optimal	–	–	–	–	2.05	2.47	1.18	2.63	0
TR	3.74	1.19	–	–	2.30	2.83	1.84	3.18	0
TRS	2.08	0.95	–	0.53	2.29	2.94	1.45	3.01	0
TN	3.24	0.78	10.88	–	2.15	2.41	1.56	2.88	0
TNS	2.15	0.75	7.36	0.42	2.16	2.53	1.23	2.75	0
TG	2.98	–	0.47	–	3.38	5.14	1.28	4.13	0
TC	2.97	–	0.12	–	3.41	5.32	1.26	4.17	0
TRGS	1.77	0.87	0.40	0.63	2.29	2.92	1.41	2.99	0
TRCS	1.97	0.92	0.15	0.57	2.29	2.95	1.44	3.01	0
Optimal	–	–	–	–	2.12	2.70	1.26	2.75	1
TR	3.71	1.10	–	–	2.33	2.97	1.84	3.23	1
TRS	2.20	0.91	–	0.49	2.33	3.09	1.49	3.07	1
TN	3.43	0.91	6.40	–	2.23	2.66	1.70	3.03	1
TNS	2.15	0.78	4.80	0.44	2.23	2.78	1.33	2.88	1
TG	2.98	–	0.47	–	3.38	5.14	1.28	4.13	1
TC	2.96	–	0.08	–	3.42	5.31	1.26	4.17	1
TRGS	1.97	0.86	0.31	0.56	2.33	3.08	1.46	3.06	1
TRCS	2.18	0.91	0.03	0.49	2.33	3.09	1.49	3.07	1

Table 4: Results with and without output gap and natural rate uncertainty - ITI preferences - Nota bene: a coefficient $\alpha_a = 16$ corresponds to a NRI coefficient of one in the policy rule.

$\gamma = 0.5, \nu = 0.05$	α_π	α_z	$\alpha_a, \alpha_y, \alpha_{\Delta z}$	ρ	$Var(\pi)$	$Var(z)$	$Var(\Delta i)$	$Loss$	s
Historical	–	–	–	–	7.69	1.60	0.36	4.66	–
Simulated	–	–	–	–	11.46	4.29	0.08	7.88	–
Optimal	–	–	–	–	2.20	1.51	2.45	1.98	0
TR	4.27	2.90	–	–	2.38	1.76	3.67	2.25	0
TRS	3.95	2.75	–	0.09	2.39	1.77	3.46	2.25	0
TN	3.59	2.15	14.40	–	2.33	1.52	2.57	2.05	0
TNS	3.52	2.13	14.10	0.03	2.33	1.52	2.52	2.05	0
TG	2.40	–	2.52	–	4.04	3.18	3.33	3.77	0
TC	2.43	–	0.95	–	4.25	3.81	0.98	4.08	0
TRGS	3.38	2.40	0.44	0.24	2.40	1.77	3.32	2.25	0
TRCS	4.29	2.97	–0.35	–0.01	2.38	1.77	3.52	2.25	0
Optimal	–	–	–	–	2.29	1.66	2.67	2.11	1
TR	4.19	2.67	–	–	2.43	1.90	3.62	2.34	1
TRS	4.01	2.59	–	0.05	2.43	1.91	3.49	2.34	1
TN	3.76	2.19	10.08	–	2.37	1.72	2.91	2.19	1
TNS	3.66	2.17	9.84	0.03	2.39	1.71	2.83	2.19	1
TG	2.40	–	2.52	–	4.04	3.18	3.33	3.77	1
TC	2.43	–	0.87	–	4.23	3.84	0.98	4.08	1
TRGS	3.71	2.41	0.27	0.13	2.44	1.91	3.43	2.34	1
TRCS	4.45	2.85	–0.50	–0.07	2.42	1.90	3.55	2.34	1

Table 5: Results with and without output gap and natural rate uncertainty - FTLI preferences - Nota bene: a coefficient $\alpha_a = 16$ corresponds to a NRI coefficient of one in the policy rule.

$\gamma = 0.5, \nu = 0.25$	α_π	α_z	$\alpha_a, \alpha_y, \alpha_{\Delta z}$	ρ	<i>Loss</i>	<i>s</i>
Optimal	–	–	–	–	4.41	0
TR	3.32	1.69	–	–	4.67	0
TRS	2.35	1.41	–	0.35	4.61	0
TN	3.12	1.45	6.41	–	4.53	0
TNS	2.36	1.27	5.25	0.30	4.48	0
TRGS	1.76	1.15	0.50	0.55	4.60	0
Optimal	–	–	–	–	4.50	1
TR	3.24	1.54	–	–	4.74	1
TRS	2.34	1.30	–	0.33	4.70	1
TN	3.13	1.43	4.39	–	4.62	1
TNS	2.28	1.21	3.56	0.32	4.57	1
TRGS	2.10	1.19	0.34	0.41	4.69	1

Table 6: Results with parameter uncertainty - FTPS preferences

$\gamma = 0.5, \nu = 1.0$	α_π	α_z	$\alpha_a, \alpha_y, \alpha_{\Delta z}$	ρ	<i>Loss</i>	<i>s</i>
Optimal	–	–	–	–	4.20	0
TR	2.61	0.98	–	–	5.55	0
TRS	1.32	0.77	–	0.57	5.30	0
TN	2.47	0.79	4.82	–	5.35	0
TNS	1.36	0.69	3.28	0.52	5.11	0
TRGS	1.06	0.68	0.35	0.68	5.26	0
Optimal	–	–	–	–	4.29	1
TR	2.56	0.89	–	–	5.61	1
TRS	1.40	0.74	–	0.53	5.39	1
TN	2.50	0.81	2.96	–	5.46	1
TNS	1.39	0.69	2.31	0.51	5.23	1
TRGS	0.16	0.63	0.39	0.69	5.37	1

Table 7: Results with parameter uncertainty - FTHI preferences

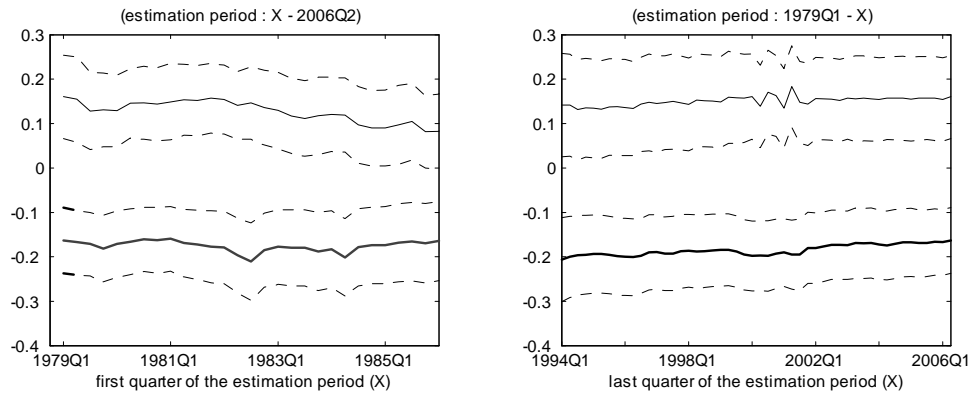


Figure 1: Recursive estimates of β (thin line) and λ (thick line) with 90% confidence intervals.

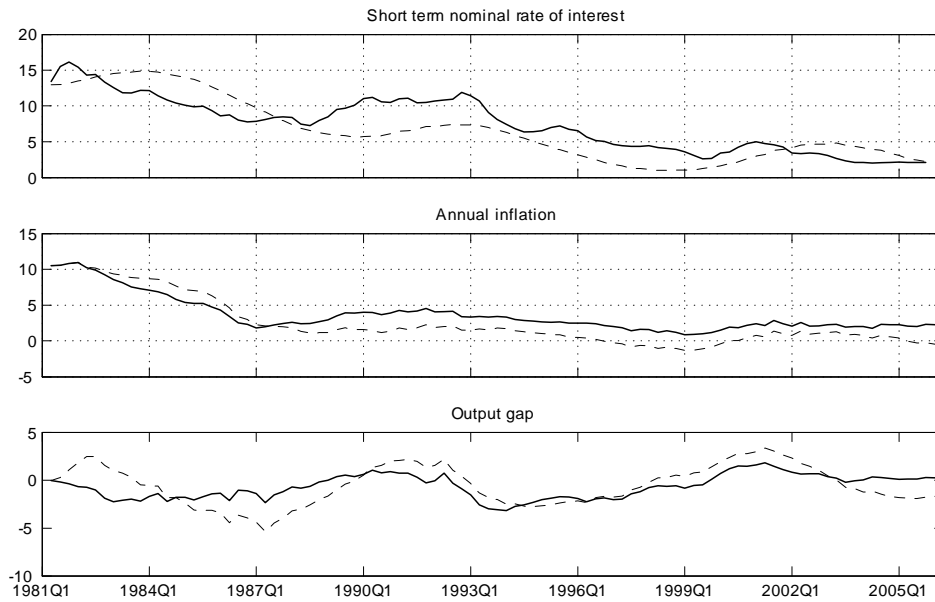


Figure 2: Historical (solid lines) and simulated (dashed lines) paths of endogenous variables.

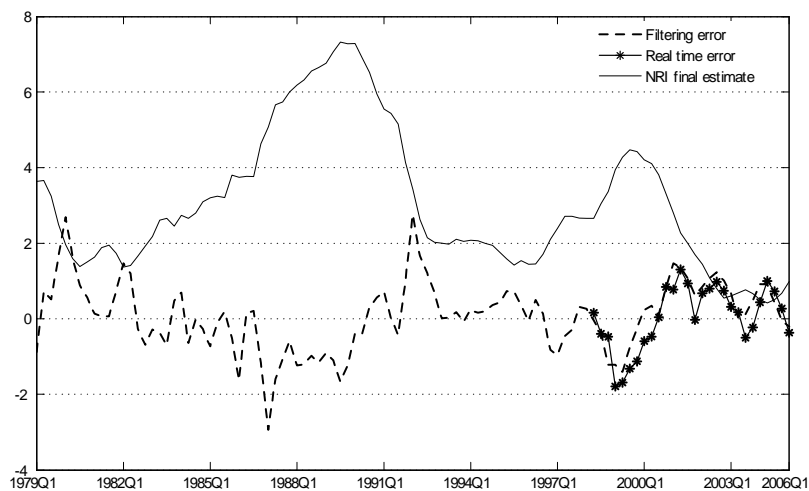


Figure 3: Estimated Natural rate of interest and real-time measurement error.

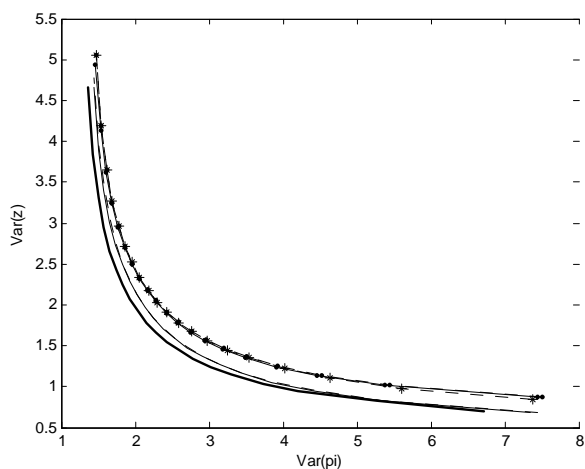


Figure 4: Policy rule efficiency frontiers under data uncertainty ($s = 1$) and very low inertia ($\nu = 0.05$). Unconstrained rule: solid bold line, TN: solid, TNS: dashed, TR: solid with circles, TRS: dashed with circles, TRGS: dashed with stars.

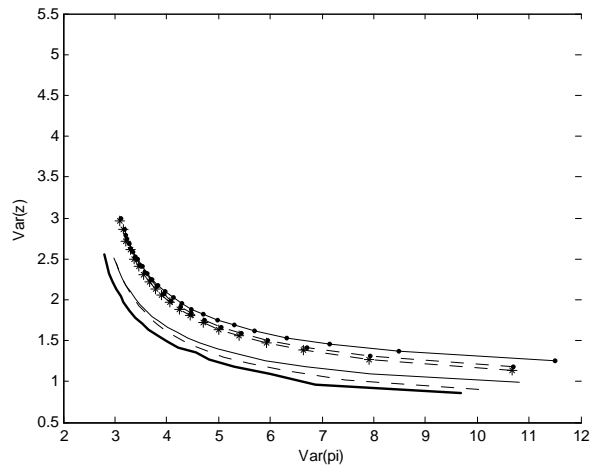


Figure 5: Policy rule efficiency frontiers under data uncertainty ($s = 1$) and high inertia ($\nu = 2$). Unconstrained rule: solid bold line, TN: solid, TNS: dashed, TR: solid with circles, TRS: dashed with circles, TRGS: dashed with stars.

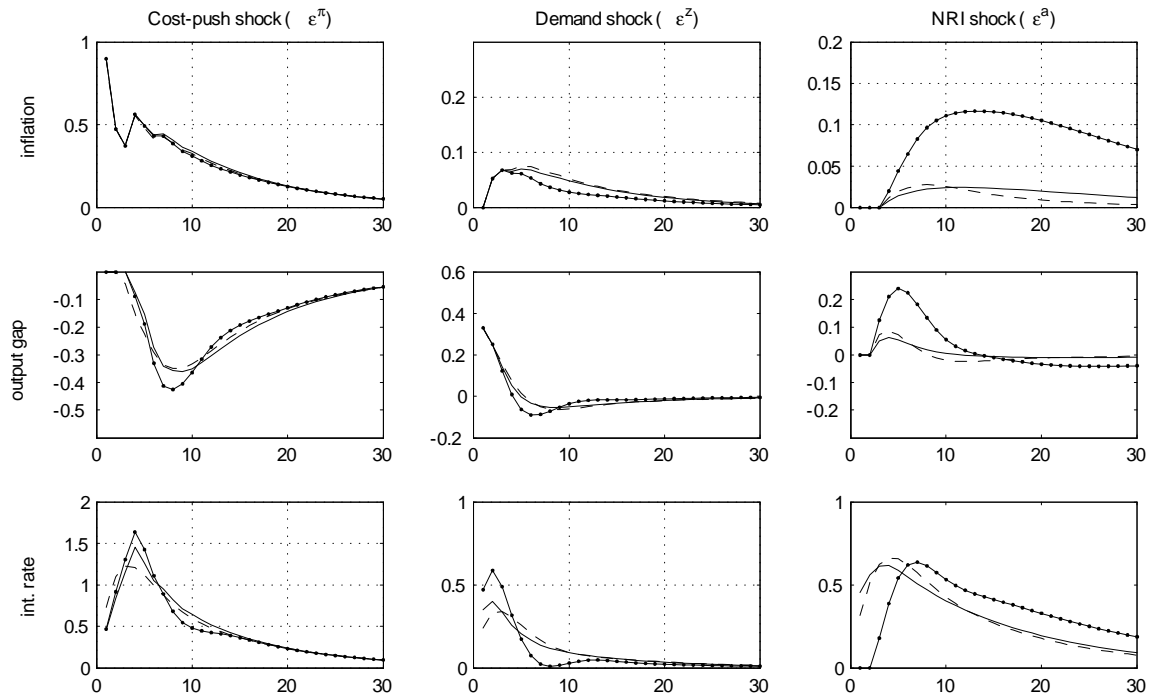


Figure 6: Impulse responses under complete information about natural variables ($s = 0$), baseline central bank's preferences. Dashed: unconstrained optimal rule; circles: TRS rule; solid: TN rule.

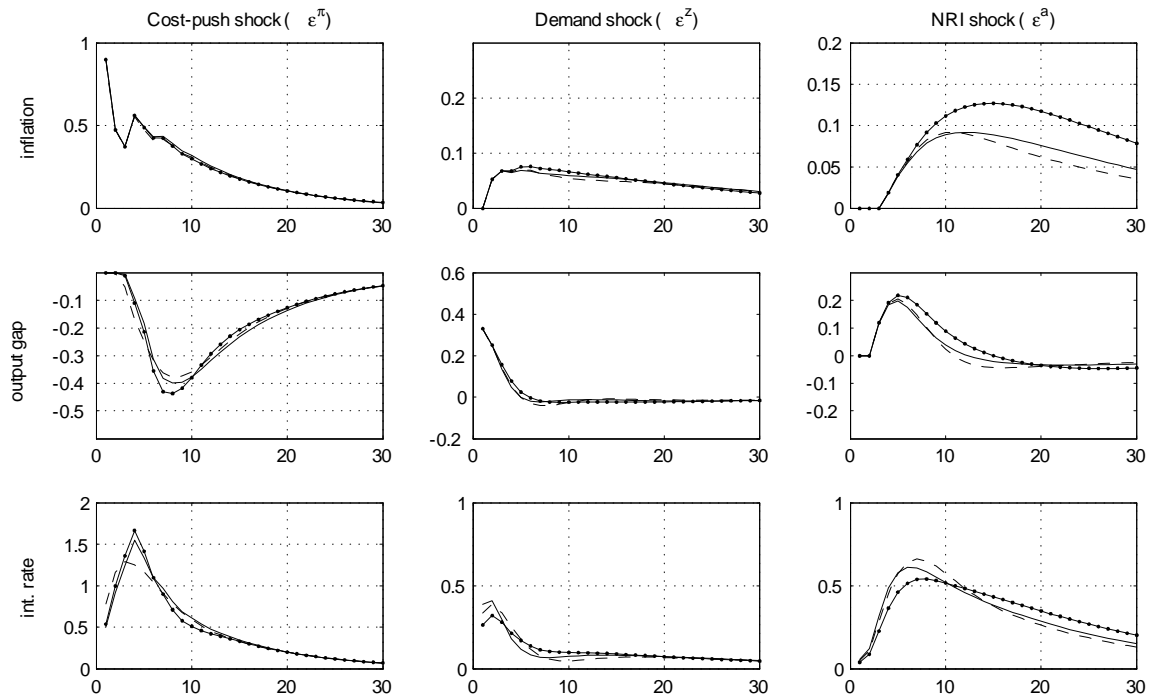


Figure 7: Impulse responses when natural variables are uncertain ($s = 1$), baseline central bank's preferences (FTPS). Dashed: unconstrained optimal rule; circles: TRS rule; solid: TN rule.

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