Optimal monetary policy in a medium-scale model of the euro area*

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Abstract

This paper studies monetary policy in the euro area using a medium-scale DSGE model in which agents have imperfect information on the state of the economy. The model is estimated assuming a Taylor rule for the European Central Bank and then used to derive the policy rate that would have been set according to this rule or, alternatively, on the basis of an optimal discretionary policy. According to both the Taylor and the optimal rule, the stance of monetary policy was excessively accommodative in the period 2003-2005; the removal of this accommodation, that started at the end of 2005, is consistent with the optimal discretionary policy, as well as with the Taylor rule prescriptions.

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1 Introduction

Theoretical research in the field of monetary economics has long sought to build macroeconomic models to rationalise the channels through which monetary policy decisions transmits to the economy. Over the last decades, the class of new Keynesian dynamic stochastic general equilibrium models (henceforth, NK-DSGE models) has witnessed an impressive deployment with innumerable applications both in theoretical and empirical works. NK-DSGE models, which combine a rigorous microeconomic derivation of the behavioural equations with a reasonable empirical fit of key macroeconomic time series, have brought new insights on various aspects of monetary policy-making. Among the many achievements, NK-DSGE models have allowed to shed light on the monetary policy transmission mechanism in the presence of forward-looking agents, to analyse in depth the dynamic properties of the inflation rate, to study the optimal design of monetary policy and the conditions under which price stability is socially desirable.[1] As a partial confirmation of their success, NK-DSGE models are becoming a practical policy toolkit in use at many central banks around the world, contributing to the decision-making process of monetary authorities.[2]

One distinct feature of most NK-DSGE models is the assumption that agents and the central bank have perfect information about the state of the economy, i.e. that they can observe with exactness all the relevant economic variables and thus identify what type of shock has hit the economy. For example, under perfect information the central bank knows whether an observed rise in inflation is due to an adverse cost-push shock or to a positive demand shock and thus can react in the appropriate way. By contrast, in reality the "art of monetary policy-making" is inevitably conducted in an environment of pervasive uncertainty. Orphanides (2003) underlines the importance of recognising "*...the complications resulting from the presence of noise for the study of monetary policy...*". In the case of inflation targeting over a medium-term horizon, in order to set the interest rate the central bank needs to forecast future inflation conditional on alternative scenarios. Therefore, the central bank must use appropriately all the available information to obtain the best possible estimate of the current state of the economy and its future development.

In this paper we address the issue of imperfect information for the conduct of monetary policy using a medium-scale NK-DSGE model of the euro area. Our work is closely linked

[1] See Woodford (2003), and the references therein, for a thorough treatment of these issues.

[2] Amongst macroeconomic DSGE models used for policy analysis and forecasting at central banks are: BEQM at the Bank of England, JEM at the Bank of Japan, TOTEM at the Bank of Canada, RAMSES at the Sveridge Riksbank and the New Area-Wide Model at the European central bank.

to a recent article by Lippi and Neri (2007). We extend the analysis along three important directions. First, we employ a more elaborate model of the euro area, which builds on Smets and Wouters (2003). Second, we assume that none of the endogenous state variables is perfectly observable but we equip agents with a collection of indicator variables which, in principle, should assist them to draw the best inference about the unobservable state of the economy. Third, we include in the agents' information set various indicators that do not have a direct counterpart in the model. This latter extension is quite important for at least two reasons: 1) the use of a relatively large array of economic indicators resembles more closely actual monetary policymaking. Hundreds of variables are continuously monitored and scrutinised before any policy action is actually taken; 2) it represents an expedient to assign a non trivial role to all those variables that are potentially informative about the state of the economy (for example, an indicator of consumer or business confidence) but lack a proper microfoundation.

An alternative approach to incorporate indicator variables has been used by Boivin and Giannoni (2006). Building on the factor model literature, the authors propose an empirical framework for the estimation of DSGE models that exploits the information contained in a large cross-section of data. Their methodology allows to obtain a better identification of the state variables that drive the model. However, the information contained in the data does not affect the behaviour of agents in the model since they observe with infinite precision the state variables that describe the dynamics of the economy. The assumption of imperfect information that characterises our approach may affect the transmission mechanism of shocks and increase the persistence of the dynamics of the model. Indeed, the response of agents to shocks may, in principle, be more muted if they are not able to identify the shocks that are hitting the economy.

The rest of the paper is organised as follows. Section 2 briefly presents the model and describes how monetary policy is conducted. Section 3 discusses the main implications of imperfect information and illustrates in detail the signal extraction problem faced by agents. Section 4 presents the data and the estimation results. Section 5 analyses through the lenses of the estimated model the stance of the ECB monetary policy in the period 1999-2007. Section 6 presents a projection exercise based on the optimal policy. Section 7 concludes.

2 A medium-scale new Keynesian DSGE model

The model is taken from Smets and Wouters (2003). It is a medium-scale NK-DSGE model which represents an economy populated by four types of agents: households, a final good-producing firm, a continuum of monopolistic competitive intermediate firms and the central bank. Interacting in markets for financial assets, consumption and capital goods, and labour, private agents maximise well-defined objective functions subject to a set of economic and technology constraints. To capture the complex interactions among the key macroeconomic variables that concern policy-makers and obtain a satisfactory degree of data coherence, the model features various nominal and real frictions. We refer to Smets and Wouters (2003) for the detailed derivation of all the equations.

Households maximise a separable utility function in consumption and labour over an infinite life horizon. Consumption appears in the instantaneous utility function relative to a time-varying external habit that depends on past aggregate consumption. Each household provides differentiated labour inputs. Monopoly power in the labour market results in an explicit wage schedule and allows to introduce sticky nominal wages. Each period households are allowed to reset their wage with an exogenous probability. Households rent capital services to intermediate firms and decide how much capital to accumulate subject to costs for adjusting investment. The introduction of variable capital utilisation implies that as the rental price of capital changes, the existing capital stock can be used with variable intensity according to some cost schedule. Intermediate firms produce differentiated goods, decide on labour and capital inputs, and set the prices for their products according to the Calvo model. The Calvo model in both wage and price setting is augmented by an indexation clause: wages and prices that are not re-optimised in a given period are partially indexed to past inflation.[3]

The model dynamics is driven by six structural shocks, which are assumed to be orthogonal to each other. Four of these processes are modeled as autoregressive processes of order one: a preference shock (that affects the intertemporal substitution of households), a labour supply shock (that affects the marginal disutility of labour), an investment shock (that affects the costs of adjusting investment), a neutral technology shock. The remaining price and wage mark-up shocks are assumed to be white noise.

Unlike Smets and Wouters (2003), we consider two different monetary regimes to close the model. This is what we turn to in the next section.

[3] Smets and Wouters (2003) assume that prices and wages that are not re-optimised in any given period are partially indexed to past inflation and partially to the central bank's inflation target.

2.1 Monetary policy

We assume that the central bank sets the short-term nominal interest rate and may operate under two alternative monetary regimes: a discretionary monetary policy or a simple interest rate rule.

2.1.1 Monetary policy under discretion

Under discretion the central bank expects itself to optimize at each successive date a welfare loss defined as the expected discounted sum of periods loss functions W_t:

$$L = E_0 \sum_{t=0}^{\infty} \beta^t W_t \tag{1}$$

where the period loss function is the weighted sum of the squared annual inflation rate $\pi_t^{(4)} \equiv p_t - p_{t-4}$, output y_t (in deviation from its trend[4]), and the changes in the nominal short-term interest rate $R_t - R_{t-1}$:

$$W_t = \frac{1}{2} \left\{ \left[\pi_t^{(4)} \right]^2 + \nu_y y_t^2 + \nu_R \left(R_t - R_{t-1} \right)^2 \right\}. \tag{2}$$

The (positive) parameters ν_Y and ν_R measures how much weight is attributed to the stabilisation of output and the nominal interest rate relative to inflation, while β is the discount factor. As long as ν_y and/or ν_R are different from zero then the central bank is said to be a flexible inflation targeter. In principle, these coefficients could be chosen so that the postulated loss function represented a second-order approximation of the representative household's utility function. However, in the present analysis, we prefer not to impose such restrictions on the preference parameters ν_Y and ν_R and leave them unconstrained.

2.1.2 Monetary policy under the Taylor rule

In recent years, there has been a lot of interest in Taylor rules. Simple interest rate rules based on few targeted variables have performed reasonably well in explaining interest rate setting by central banks. Moreover, these rules represent good approximations to more complex optimal monetary polices and are fairly robust across different models (see for example Taylor, 1993).

[4] We assume that the central bank is interested in stabilising output instead of the output gap since it is notoriously difficult to estimate the level of potential output or the alternative methods can provide quite different results.

In our model the central bank sets the nominal interest rate according to the rule:

$$R_t = \phi_R R_{t-1} + (1 - \phi_R) \left[\phi_\pi \pi^{(4)}_{t-j|t} + \phi_y y_{t|t} \right] \tag{3}$$

where the positive coefficients ϕ_R, ϕ_π and ϕ_y are such to ensure equilibrium determinacy.[5]

Mirroring the period loss function (2), the policy rate responds to contemporaneous annual inflation, output and the previous period policy rate. In particular, this latter term is meant to capture the inertia observed in policy interest rates.

3 Imperfect information and signal extraction

In this Section we introduce imperfect information in the model and illustrate how this assumption affects the central bank's behaviour and the dynamics of the system.

In a situation of (symmetric) imperfect information the private sector and the central bank cannot directly observe the state of the economy. Some state variables may only be measured with errors and/or with lags. As an example, one may think of data for real Gross Domestic Product (GDP) which are available only with a substantial delay and that are often subject to later revisions. Other state variables, such as structural shocks, are simply unobservable. This makes the task of making decisions under imperfect information more complex than under complete information. Broadly speaking, the difference is due to the fact that agents in the model need to estimate the current state of the economy and its future development distilling information from the set of noisy indicators at their disposal. Thus, agents face a signal extraction problem and must weigh all available information to draw the most efficient inference.

Let us now define the law of motion of the linearized model economy as:

$$\begin{bmatrix} X_{t+1} \\ x_{t+1|t} \end{bmatrix} = \mathbf{A} \begin{bmatrix} X_t \\ x_t \end{bmatrix} + \mathbf{B} R_t + \begin{bmatrix} u_{t+1} \\ 0 \end{bmatrix} \tag{4}$$

where X_t is a n_X-vector of all state variables (both endogenous and exogenous), x_t is a n_x-vector of forward-looking variables and R_t is the monetary policy rate. Finally, u_t is a n_u-vector of innovations to the model structural shocks.[6] The notation $z_{t+j|t}$ denotes the expectation $E\left[z_{t+j} | \Omega_t \right]$, i.e., the expectation of z_t in period $t + j$ conditional on the

[5] In other words, we make sure the postulated Taylor rule (3) does not lead to multiple equilibria or to instability. For further details see Blanchard and Kahn (1980).

[6] The matrix $\mathbf{A}_2$ that shows up in the representation of Svensson and Woodford (2003) is nil.

information set Ω available in period t. Finally, $\mathbf{A}$ and $\mathbf{B}$ are matrices of appropriate dimension.

In a recent contribution, Svensson and Woodford (2003) show that in a linear-quadratic model with a partially observable state of the economy, the optimal nominal interest rate that arises under discretion is a linear function of the current estimate of the states vector, i.e., $X_{t|t}$, rather than of its actual value, i.e., X_t:

$$R_t = \mathbf{F}^d X_{t|t} \tag{5}$$

where the matrix $\mathbf{F}^d$ contains the optimal feedback coefficients. Notice that the closed-form solution (5) fulfils the so called separation principle. With a partially observable state of the economy, the central bank can treat as two separate tasks the optimization problem, which concerns the finding of matrix $\mathbf{F}^d$, and the filtering problem, which has to do with the computation of the vector $X_{t|t}$. As regards the former problem, the optimal feedback coefficients can be computed as if the vector X_t were perfectly observable, using one of the various numerical toolkit that solve linear-quadratic optimal problem under perfect information.[7] As regards the filtering problem we briefly describe how agents in the model may use the Kalman filter to compute $X_{t|t}$.

We assume that in period t agents have access to a number of observable indicators which are stacked in the n_Z-vector named Z_t. Observable indicators represent noisy measures of the true endogenous variables in the economy, through the linear mapping:

$$Z_t = \begin{bmatrix} \mathbf{D}_1 & \mathbf{D}_2 \end{bmatrix} \begin{bmatrix} X_t \\ x_t \end{bmatrix} + v_t, \tag{6}$$

where $\mathbf{D}_1$ and $\mathbf{D}_2$ are matrices of appropriate dimension and the n_Z-vector v_t contains the measurement errors which are assumed to be independent from u_t at all leads and lags. Substituting the interest rate rule (5) into the system (4) and partitioning matrices $\mathbf{A}$ and $\mathbf{B}$ conformably to X_t and x_t yields:

$$\begin{bmatrix} X_{t+1} \\ x_{t+1|t} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} \\ \mathbf{A}_{21} & \mathbf{A}_{22} \end{bmatrix} \begin{bmatrix} X_t \\ x_t \end{bmatrix} + \begin{bmatrix} \mathbf{B}_1 \\ \mathbf{B}_2 \end{bmatrix} \mathbf{F} X_{t|t} + \begin{bmatrix} u_{t+1} \\ 0 \end{bmatrix} \tag{7}$$

Using the result $x_{t|t} = \mathbf{G} X_{t|t}$ (see Svensson and Woodford (2003) for a derivation), the dynamics for X_t, Z_t and x_t obey the equations:

[7] See Soderlind (1999) and Gerali and Lippi (2003).

$$X_{t+1} = \mathbf{H}X_t + \mathbf{J}X_{t|t} + \mathbf{C}\eta_{t+1}, \quad (8)$$
$$Z_t = \mathbf{L}X_t + \mathbf{M}X_{t|t} + \nu_t, \quad (9)$$
$$x_t = \mathbf{G}X_{t|t} + \mathbf{G}^1\left(X_t - X_{t|t}\right). \quad (10)$$

It is left to specify the optimal filter of $X_{t|t}$. Notice first that, by looking at (8) and (9), the estimation of the predetermined vector X_t has been transformed to a problem without forward-looking variables x_t. This means that one can easily apply the standard Kalman Filter. Thus, to carry out the efficient estimate of the contemporaneous state vector $X_{t|t}$, agents update the previous period forecast by applying the Kalman Filter to the most recent information embedded in Z_t. The law of motion of the optimal prediction $X_{t|t}$ fulfills:

$$X_{t|t} = X_{t|t-1} + \mathbf{K}\left(Z_t - Z_{t|t-1}\right) \quad (11)$$

where $\mathbf{K}$ is the (steady state) Kalman gain matrix:

$$\mathbf{K} \equiv \mathbf{PL}'\left(\mathbf{LPL}' + \Sigma_{vv}\right)^{-1} \quad (12)$$

where the matrix $\mathbf{P} \equiv Cov\left[X_t - X_{t|t-1}\right]$, which denotes the covariance matrix of the prediction errors, solves the equation:

$$\mathbf{P} = \mathbf{H}\left[\mathbf{P} - \mathbf{PL}'\left(\mathbf{LPL}' + \mathbf{\Sigma}_{vv}\right)^{-1}\mathbf{LP}\right]\mathbf{H}' + \mathbf{\Sigma}_{uu}. \quad (13)$$

where $\mathbf{\Sigma}_{uu}$ and $\mathbf{\Sigma}_{vv}$ are the covariance matriced of, respectively, the structural shocks u_t and the measurement errors v_t.[8] The Kalman gain matrix determines the optimal weights to be attached to the innovations in the observable indicators, i.e., $Z_t - Z_{t|t-1}$, when updating the current estimate $X_{t|t}$. In case these innovations display fairly large variances, i.e., their informative power is scant, then the weights placed on them will be limited. Conversely, greater importance will be given to those innovations that present smaller variances. Because of this signal extraction problem, imperfect information represents, together with the various nominal and real rigidities, a source of persistence in macroeconomic variables. Even in a fully forward-looking model, in which the adjustment path after a shock would be immediate under perfect information, agents behave prudently and respond with gradualism because they are unable to discern exactly the type of shock that is hitting the economy.

[8] We refer to Svensson and Woodford (2003) for the detailed derivation.

The effect of imperfect information on monetary policy can be gauged by combining equations (5) and (11):

$$R_t = \mathbf{F}^d \left[X_{t|t-1} + \mathbf{K} \left(Z_t - Z_{t|t-1} \right) \right]. \tag{14}$$

As the estimate of the current state of the economy is a distributed lag of observable variables, the central bank learns the value of $X_{t|t}$ only slowly. In other words, the optimal policy rate will exhibit a certain degree of gradualism or caution in response to movements in macroeconomic variables.

Before turning to the estimation of the model, it is useful to say something about the solution under the Taylor rule. In this case, it turns out that it is sufficient to provide an expression analogous to (5) but where the matrix that pre-multiply $X_{t|t}$ (and possibly $x_{t|t}$) is structured as to replicate the postulated monetary policy rule (3):

$$R_t = \begin{bmatrix} \mathbf{F}_1^{tr} & \mathbf{F}_2^{tr} \end{bmatrix} \begin{bmatrix} X_{t|t} \\ x_{t|t} \end{bmatrix}. \tag{15}$$

4 Estimation

In order to estimate the model, we first construct its state-space representation:

$$Q_{t+1} = \mathbf{A} Q_t + \mathbf{B} \epsilon_{t+1} \tag{16}$$

where Q_t is a vector that includes the true state variables X_t and the agents' estimates $X_{t|t}$, while ϵ_{t+1} consists of shocks u_{t+1} and the measurement errors of the indicator variables v_t. Equation (16) allows to express the vector of observable variables and the short-run nominal interest rate:

$$d_t = \begin{bmatrix} Z_t \\ R_t \end{bmatrix} = \mathbf{L} Q_t + \mathbf{M} v_t, \tag{17}$$

in terms of Q_t. The conformable matrices $\mathbf{A}$,$\mathbf{B}$, $\mathbf{L}$ and $\mathbf{M}$ are defined in Lippi and Neri (2007). The indicators are presented in the following section.

4.1 Indicator variables

In the estimation we use nine indicator variables, which are mapped into their model counterparts by the set of equations reported in Table 1.

Table 1. Indicator variables and model counterparts

Indicator variables		Relationship with model counterparts
Harmonised index of consumer prices (HICP)	$HICP^o$	$\sum_{j=0}^{3} \pi_{t-j} + v_{\pi,t}$
Real gross domestic product*	GPD^o	$\lambda^{gdp} \left(s_C C_{t-1} + s_I I_{t-1} \right) + v_{gdp,t}$
Industrial production (excl. construction and energy sectors)	IP^o	$\lambda^{ip} Y_t + v_{ip,t}$
Purchasing managers' index	PMI^o	$\lambda^{pmi} Y_t + v_{pmi,t}$
Private consumption	C^o	$C_{t-1} + v_{c,t}$
Gross fixed capital formation	I^o	$I_{t-1} + v_{i,t}$
Number of employees (total economy)	$EMPL^o$	$L_t + v_{e,t}$
Consumer confidence indicator (EC)	$CONF^o$	$\lambda^{cc} C_t + v_{cc,t}$
Real hourly wages	$\frac{WAGE^o}{HICP^o}$	$\frac{W_{t-1}}{P_{t-1}} + v_{w,t}$

* The coefficients s_C and s_I in denote the share of consumption and investment on output, respectively.

Several comments are noteworthy. First we have assumed that the measurement errors in equation (6) are the same as those entering the structural model with the only exception of the policy rate. Since the latter variable is linear combination of all the indicator variables we need to add a measurement error to its equation in order to avoid stochastic singularity of state-space representation. Second, the parameters λ's can be interpreted as scaling factors. They are attached to those observable variables that lack a precise counterpart in the theoretical model. For example, the inclusion of λ^{gdp} in the measurement equation for real GDP is due to the fact that our theoretical model describes a closed economy in which the fiscal authority is absent; however, according to the national accounting, the GDP indicator also includes government spending and net exports in addition to consumption and investment. Industrial production and the purchasing managers' index are not defined in the theoretical model. Nonetheless, through the scaling parameters λ^{ip} and λ^{pmi} we postulate that these variables are (linearly) linked to the level of output and may be informative to better estimate the unobservable state of the economy. Consumer confidence is assumed to be a noisy measure of current real private consumption. Third, it is useful to stress the time structure used in the above equations. We assume that real GDP, consumption, investment and real wages are all available only with a quarter lag. In contrast, employment and inflation are observed without lags. We assume that the latter variable is observed with errors. Indeed, Coenen *et al.* (2005) report that the index of consumer prices in the euro area is revised, on average, by 0.03 per cent in the first month after the release of the official figure.

4.2 Data and estimation results

We use quarterly data for the euro area for the period 1997:3-2007:4. We chose to start in a period in which convergence in nominal interest rates across the euro area countries was to a large extent already achieved. Data on the interest rate R refer to the minimum bid rate (henceforth, MBR) on the main refinancing operations. We opted for this rate instead of a short-term nominal interest rate, such as the 3-month Euribor rate, in order to avoid possible estimation biases due to the money market turmoil that started in the summer of 2007.[9] The variables with a trend have been made stationary by using the Hodrick-Prescott filter. Consumer confidence and the PMI have been de-meaned and normalised by their standard deviation. Inflation and the MBR have also been de-meaned. Figure 1 reports the data used in the estimation and the one step ahead predictions of the model. A similar treatment of the raw data has been used in Lippi and Neri (2007).

Some of the parameters of the model are calibrated either because the data we use are likely to be non informative (i.e. the depreciation rate) or because previous analyses have documented their weak identification (i.e. the inverse of the labour supply elasticity, the cost for adjusting capacity utilisation). Table 1 presents the parameters that are calibrated. Table 2 describes the parameters that are estimated while table 3 reports the summary statistics of their posterior distribution estimated with 200,000 draws from the Metropolis algorithm. With regards to the estimated Taylor rule, the posterior distribution indicates a low response to year-on-year inflation, a high degree of interest rate smoothing and a fairly large response to output. Concerning the response to inflation, it must be noted that since the interest rate responds to year-on-year changes in prices, the coefficient must be approximately multiplied by 4 to assess whether the so-called "Taylor principle" is satisfied.

Some of the parameters (the Calvo probabilities for prices and wages and risk aversion coeffcient) are weakly identified as the prior and posterior statistic marginal distribution nearly overlap each other. This result, which contrasts with alternative evidence based on a model with perfect information (see for example Smets and Wouters, 2003), suggests that imperfect information *per se* might be an important source of persistence in the model.

[9] From August to December of 2007, the average spread between the 3-month Euribor rate and the MBR was about 65 basis points.

5 Assessment of the ECB monetary policy stance

In this section we assess the monetary policy stance of the ECB over the period 1999:1-2007:4 using the Taylor rule and the optimal policy under discretion. The simulations have been carried out with the toolkit developed by Gerali and Lippi (2003).

5.1 Monetary policy in the euro area: prescriptions from the Taylor rule

Figure 2 shows the interest rate implied by the Taylor rule, together with the 0.95 probability interval and the MBR.[10] Three periods can be identified. In the first one, from 1999:1 to 2001:1, the prescription of the Taylor rule is in line with the actual path of the MBR. The decisions to increase the policy rate were motivated by the presence of upside risks to price stability in the medium term in the context of strong economic activity.

The second period goes from 2001:2 to 2005:3. A substantial divergence between the MBR and the prescriptions of the Taylor rule is observed since 2001:2, when the ECB reduced the policy rate by 25 basis points, while according to the rule, it should have been raised by additional 25 basis points, to 5.0 per cent. The 2001 May reduction was motivated by lower inflationary pressure over the medium term, partly related to the ongoing moderation in monetary growth.[11] The fact that the rule predicts the first cut in the policy rate only in the second half of 2001 might be explained by the absence of any money or credit aggregates in our model (consistently with Lippi and Neri 2007, who found no role for M3 in their small-scale model of the euro area) or the forward-looking nature of the ECB policy actions, which aims at maintaining price stability in the medium term, whereas the rule in our model mostly responds to current inflation. The ECB reduced the MBR to 2.0 per cent between mid-2001 and 2003. Over this period the difference between the rate implied by the Taylor rule and the policy rate is between 50 and 100 basis points. The motivations behind the decision to keep the MBR at very low levels between 2003 and 2005 included a decline in inflationary pressures, partly related to the appreciation

[10] It must be borne in mind that the analysis based on the estimated Taylor rule does not have normative implications. Nonetheless, we think it is useful in its own to identify periods in which the ECB deviated from the estimated rule that characterizes its behaviour over time.

[11] In the Introductory statement of May, 10 2001 the Governing Council aknowledged that "... as regards the first pillar, also taking into account the latest available information, monetary developments no longer pose a risk to price stability. M3 growth has been on a gradual downward trend since spring 2000, reflecting the increase in the key ECB interest rates which occurred in the period from November 1999".

of the euro, subdued economic growth and falling consumer confidence.[12] There could be two reasons why the model cannot explain the low level of the MBR in this period. First, the model abstracts from open economy considerations. A strong appreciation of the euro may lead to lower inflation and economic growth thus calling for a lower interest rate. Second, the coefficients in the rule might have changed over time.

In the last period, running from 2005:4 to 2007:4, the policy rate rate was raised by a total of 200 basis points. These decisions are in line with the prescriptions of the Taylor rule. At the end of the estimation period the rule indicates that the MBR should have reached 4.4 per cent (reacting to strong economic activity and raising inflation). The decision of the Governing Council to keep the policy rate at 4.0 per cent after the outburst of the financial turmoil in August 2007 was motivated by the high level of uncertainty concerning the possible consequences for the economy of the reappraisal of risk in financial and credit markets, although the outlook for price stability was clearly characterised by upward risks.

To what extent do the above results depend on the particular indicators included in the information set? To answer this question we simulate the model switching off those indicators that do not have a direct counterpart in the model. Specifically, we assume agents do not observe employment, industrial production, the consumer confidence index and the purchasing managers index. Figure 3 shows that the differences are modest, reaching at most 25 basis points in a few instances.

5.2 Monetary policy in the euro area: prescriptions from the optimal interest rate under discretion

In this Section we conduct a simple exercise and address the following question: taking as given the predicted state of the economy throughout the whole sample period, how would have the ECB behaved had it operated under the discretionary optimal monetary policy? To answer this question we simulate the policy rate using the solution under discretion but projected onto the vector $X_{t|t}^{tr}$, which represents the estimate of states of the economy:

$$R_t = \mathbf{F}^d X_{t|t}^{tr}. \tag{18}$$

which can be computed invoking the separation principle between the problems of optimization of the policy and filtering. The matrix $\mathbf{F}^d$ is evaluated at the median of the

[12] In the course of both 2003 and 2004 the Governing Council also highlighted that inflation expectations were well anchored at levels below but close to 2 per cent.

posterior distribution of the parameters and setting the preference parameters ν_R and ν_y at 3.0 and 0.25, respectively. Figure 4 plots the optimal short-term nominal interest rate, together with the 0.95 probability intervals, and the MBR. Figure 5 several indicates that the optimal policy prescriptions are similar to those obtained under the Taylor rule. At the peak of the tightening cycles in 2001, according to the optimal policy the ECB should have raised the MBR more than it has, and also more than suggested by the Taylor rule. At the end of 2007 the interest rate should have reached 4.5 per cent.

The effects on the optimal interest resulting from varying the preference parameters in the central bank's loss function on the policy rate are presented in Figure 6. The first panel highlights, *ceteris paribus*, what would have happened if the central bank had been relatively more concerned with output stabilisation. This experiment amounts to increasing the value of ν_y from 0.25 to 1. Two results stand out. First, the optimal monetary policy would have recommended a more marked rise of the policy rate in 2000 and 2001. Second, between 2003 and 2005 such configuration of preferences would have implied a lower interest rate than under the benchmark parameterisation but still not as low as the actual MBR. The second panel of Figure 6 shows, *ceteris paribus*, what would have happened if the central bank had been relatively more concerned to stabilise the nominal interest rate. This experiment amounts to increase the value of ν_R from 3.0 to 5.0. The effects on the policy rate are hardly distinguishable. In light of the results, the prolonged phase between 2003 and 2005 could be rationalised with a change in the policy preferences, i.e. with an increase in the weight on output fluctuations in the ECB loss functions only over this period. Indeed, by raising ν_y to 5, the optimal rate decreases to 2.16 on average over the 2003-2005 period, very close to the actual policy rate.

Overall, a comparison between the actual MBR and the prescriptions of the Taylor rule suggests the following: first, between mid-2001 and the end of 2005 the ECB monetary policy has been more accommodative than the model would suggest, no matter how monetary policy is set; second, the removal of the policy accommodation that started in December 2005 is consistent with both policies; third, the level of the ECB rate at the end of 2007 should have been higher that 4.0 per cent, according to both prescriptions.

5.3 The optimal interest rate in the years to come

In this Section we use the model solved under discretion to derive the optimal policy rate for the period 2008-2010. For this scenario analysis we use two sources of information. We employ the March 2008 Macroeconomic Projection Exercise (MPE) of the ECB for real GDP growth, real consumption growth, real investment growth, HICP inflation, real wages, employment and the MBR. For industrial production we use the forecast provided by Consensus Economics while for the consumer confidence index we estimate the relation with actual consumption and use the MPE forecast for the latter variable to obtain consistent projections for the confidence indicator. Finally, it is assumed that the PMI is not observed. Table 4 reports the baseline projection for the period running from 2008 to 2010. According to the baseline projection real GDP growth should converge to its long-run level while inflation should increase to 2.9 per cent in 2008 and then slide back to 2.0 percent by 2010.[13]

The evolution of the economy and the policy interest rate are characterized by equations (16) and (17). In practice we use the model to estimate the unobserved states with the Kalman filter under the Taylor rule for the period up to 2010:4 and then we switch to the optimal discretionary policy for the period 2008:2 - 2010:4. Concerning the parameters in the loss function we set ν_R to its benchmark value 3.0, while we experiment two values for ν_y, namely 0.25 and 2.0. For comparison, we also simulate the interest rate under the Taylor rule.

Figure 7 reports the simulated paths for the policy rate under the Taylor rule and the optimal monetary policy. Under the former, the interest rate should be kept at around 4.5 per cent in the second quarter of 2008 and then lowered to 4.0 per cent at the beginning of 2009 and to 3.3 per cent by the end of 2010. This pattern would be the result of inflation converging slowly to its steady state level (2.0 per cent) and output stabilising slightly below its long-run trend. Under the optimal policy the interest rate should be raised up to 4.75 per cent in the second quarter of 2008 regardless of the value of ν_y. The higher level reached in the latter case reflects the high level of current inflation which calls for tighter monetary policy if the interest rate is chosen optimally. In 2009 and 2010 since the deviations of real GDP from its long-run trend become slightly negative and inflation slowly converges to 2.0 per cent, the optimal prescription is to decrease the MBR. The prescribed rate at the end of 2010 is slightly higher (3.6) or lower (3.2) than under the Taylor rule depending on the weight attached to output stabilisation in the loss function. It is important to note that the model cannot capture important facts in the recent period, among which the turmoil that has characterized financial markets since the summer of 2007.

[13] In order to minimise the effects of the assumptions for the policy rate on the simulation we set its measurement error σ_R^v to 10 per cent. In this case the baseline assumptions on the MBR does not influence the computation of the optimal policy rate.

6 Concluding remarks

This paper has studied optimal monetary policy in the euro area in the context of a medium-scale model in which agents are assumed to have imperfect information. The model, which has been first estimated assuming that the monetary policy of the ECB can be described by a simple Taylor rule, has been then used to derive the optimal interest rate under discretion.

Four results emerge form the analysis. First, between mid-2001 and the end of 2005 the ECB monetary policy has been more accommodative than the model would suggest under both the Taylor rule and the optimal policy. Second, the removal of the policy accommodation that started in December 2005 is consistent with both policies. Third, the level of the MBR at the end of 2007 and the beginning of 2008 should have been higher than 4.0 per cent. In this regard, it is to be noted that the model cannot capture important facts in the recent period, among which the relevance that uncertainty on the macroeconomic consequences of the financial turmoil has played in the ECB Governing Council's decisions to keep the MBR unchanged. Fourth, based on macroeconomic projections carried out in March 2008, the optimal policy would imply a rate at the end of 2010 between 3.2 and 3.6 depending on the weight attached to output stabilisation in the loss function.

Tables and Figures

Table 1. Calibrated parameters

parameter	name	value
ψ	Inverse of the elasticity of the labour supply	2.0
λ_w	Mark-up in the labour market	0.50
μ	Mark-up in the goods market	0.20
β	Discount factor	0.9925
δ	Depreciation rate	0.025
α	Capital share in the production function	0.30
γ_p	Degree of indexation of prices to past ones	0.50
γ_w	Degree of indexation of wages to past prices	0.50
ψ	Adjustment cost for capacity utilisation	0.25

Table 2. Parameters

Parameter	Name
σ_l^u	Standard deviation labour supply shock
σ_w^u	Standard deviation wage mark-up shock
σ_b^u	Standard deviation intertemporal preference shock
σ_i^u	Standard deviation investment specific technology shock
σ_a^u	Standard deviation technology shock
σ_p^u	Standard deviation cost-push shock
σ_e^v	Standard deviation measurement error employment
σ_{ip}^v	Standard deviation measurement error industrial production
σ_c^v	Standard deviation measurement error real consumption
σ_i^v	Standard deviation measurement error real investment
σ_π^v	Standard deviation measurement error HICP inflation
σ_w^v	Standard deviation measurement error real wages
σ_{cc}^v	Standard deviation measurement error consumer confidence
σ_{gdp}^v	Standard deviation measurement error real GDP
σ_{pmi}^v	Standard deviation measurement error purchasing managers' index
σ_R^v	Standard deviation measurement error short-term interest rate
ρ_b	Persistence intertemporal preference shock
ρ_a	Persistence technology shock
ρ_i	Persistence investment specific technology shock
ρ_l	Persistence labour supply shock
ρ_c	Persistence cost-push shock
ϕ_r	Degree of interest rate inertia
ϕ_π	Response of policy rate to year-on-year inflation
ϕ_Y	Response of policy rate to output
λ_{ip}	Scaling factor industrial production
λ_{cc}	Scaling factor consumer confidence
λ_{pmi}	Scaling factor purchasing managers' index
λ_{gdp}	Scaling factor real GDP
ξ_p	Probability of firms not being able to adjust prices
ξ_w	Probability of firms not being able to adjust nominal wages
h	Degree of external habit formation in consumption
σ	Risk aversion coefficient
ς	Investment adjustment cost

Table 3. Prior and posterior distribution of the parameters: summary statistics

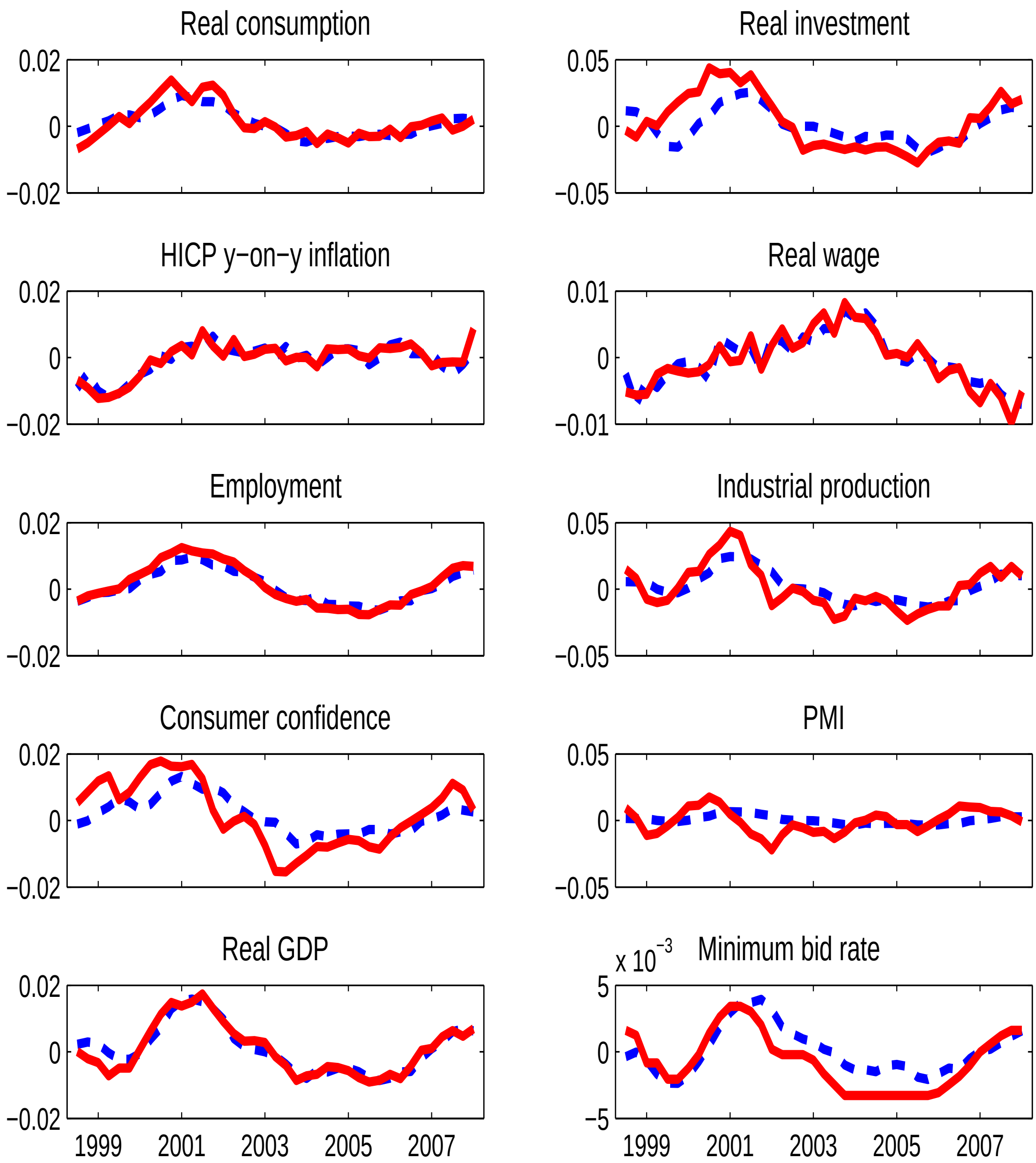
		Prior		Posterior			
Parameter	Distr.	Mean	St. Dev	Mean	2.5^{th} percentile	Median	97.5^{th} percentile
σ_l^u	Gamma	0.01	0.005	0.0223	0.0140	0.0219	0.0335
σ_w^u	Gamma	0.01	0.005	0.0112	0.0029	0.0107	0.0237
σ_b^u	Gamma	0.01	0.005	0.0150	0.0109	0.0144	0.0241
σ_i^u	Gamma	0.01	0.005	0.0160	0.0117	0.0158	0.0215
σ_a^u	Gamma	0.01	0.005	0.0015	0.0009	0.0015	0.0020
σ_p^u	Gamma	0.01	0.005	0.0165	0.0110	0.0161	0.0250
σ_e^v	Gamma	0.01	0.005	0.0007	0.0003	0.0006	0.0012
σ_y^v	Gamma	0.01	0.005	0.0070	0.0054	0.0069	0.0086
σ_c^v	Gamma	0.01	0.005	0.0027	0.0020	0.0026	0.0037
σ_i^v	Gamma	0.01	0.005	0.0139	0.0087	0.0142	0.0191
σ_{pi}^v	Gamma	0.01	0.005	0.0004	0.0002	0.0004	0.0007
σ_w^v	Gamma	0.01	0.005	0.0010	0.0007	0.0010	0.0013
σ_{cc}^v	Gamma	0.01	0.005	0.0053	0.0034	0.0054	0.0070
σ_{gdp}^v	Gamma	0.01	0.005	0.0022	0.0013	0.0022	0.0035
σ_{pmi}^v	Gamma	0.01	0.005	0.0073	0.0069	0.0073	0.0077
σ_r^v	Gamma	0.01	0.005	0.0015	0.0011	0.0015	0.0021
ρ_b	Beta	0.70	0.10	0.7315	0.5982	0.7357	0.8198
ρ_a	Beta	0.70	0.10	0.7733	0.6627	0.7745	0.8774
ρ_i	Beta	0.70	0.10	0.5963	0.4768	0.5998	0.7118
ρ_l	Beta	0.70	0.10	0.7785	0.6519	0.7855	0.8694
ρ_p	Beta	0.70	0.10	0.5590	0.4117	0.5569	0.7087
ϕ_π	Gamma	1.50	0.50	0.1798	0.1102	0.1768	0.2633
ϕ_Y	Normal	0.0	0.25	0.2987	0.2001	0.2864	0.4633
ϕ_r	Beta	0.70	0.10	0.6085	0.4738	0.6112	0.7225
λ_y	Normal	1.0	0.50	2.2624	1.5556	2.2751	2.8924
λ_{cc}	Normal	1.0	0.50	1.6115	1.1800	1.6059	2.0239
λ_{pmi}	Normal	1.0	0.50	0.5945	0.2539	0.6050	0.9505
λ_{gdp}	Normal	1.0	0.50	1.1992	0.9030	1.2089	1.5080
ξ_p	Beta	0.667	0.05	0.6480	0.5849	0.6486	0.7127
ξ_w	Beta	0.667	0.05	0.6132	0.5592	0.6101	0.6829
h	Normal	0.5	0.10	0.6035	0.4576	0.6004	0.7552
σ	Beta	2.0	0.50	1.9659	1.2500	1.9240	2.8453
ς	Beta	2.0	0.50	2.7469	1.4006	2.7785	3.7381

Note: Results based on 200,000 draws from the Metropolis algorithm.

Table 4. Forecasts for the years 2008-2010

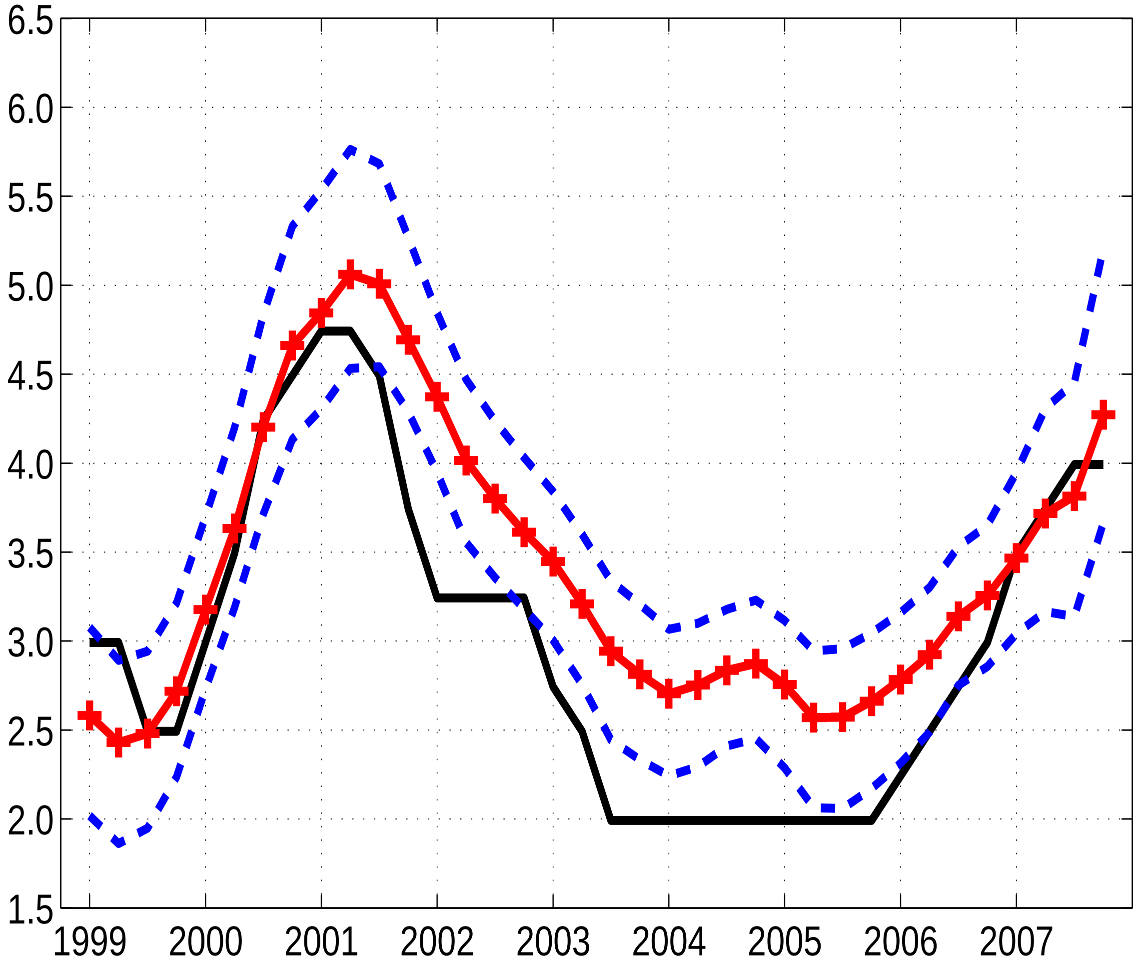
variable	2008	2009	2010
Real GDP growth	1.7	1.8	2.0
Real consumption growth	1.4	1.7	1.8
Real investment growth	1.8	1.8	2.2
HICP inflation	2.9	2.1	2.0
real wage growth	1.5	1.8	2.0
industrial production	1.9	1.9	1.9
employment	0.8	0.6	0.8
minimum bid rate	4.0	4.0	4.0

Note: Year-on-year percentage changes, except for the minimum bid rate (MBR) on the main refinancing operations.



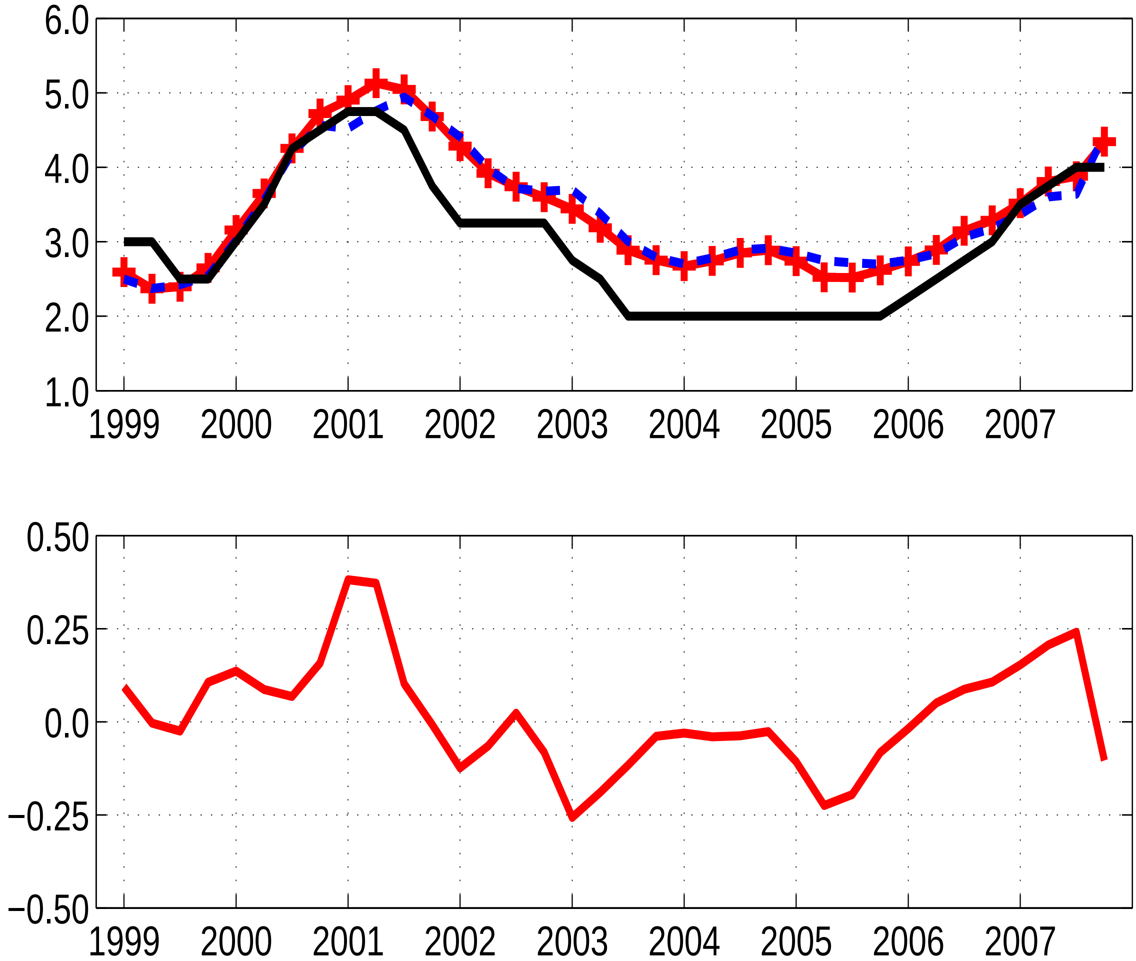
(Solid red line - data; blue dashed lines fitted values)

Figure 1 - Data and fitted values



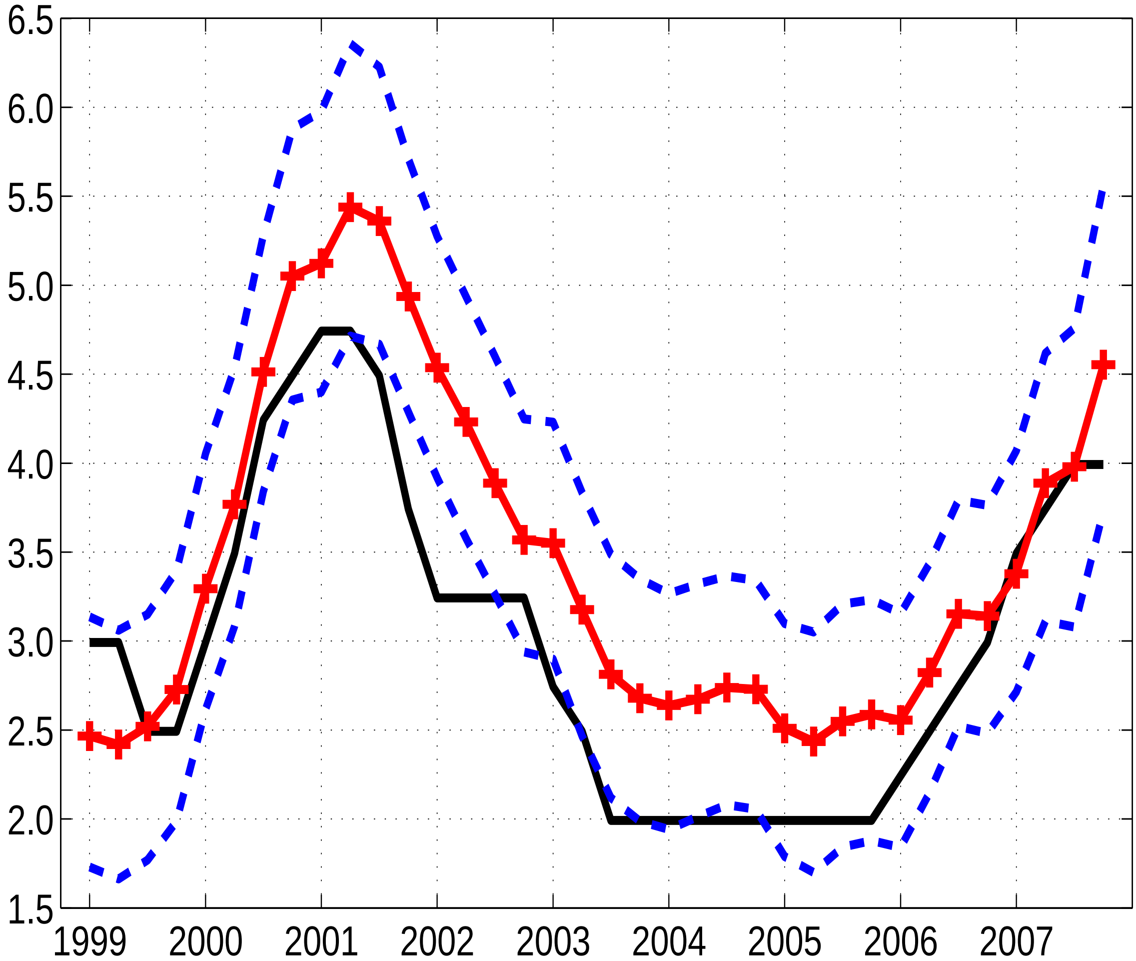
(red solid line with plus - median, blue dashed lines - 2.5^{th} and 97.5^{th} percentiles, - black solid line minimum bid rate)

Figure 2 - Minimum bid rate (MBR) predicted by the Taylor rule



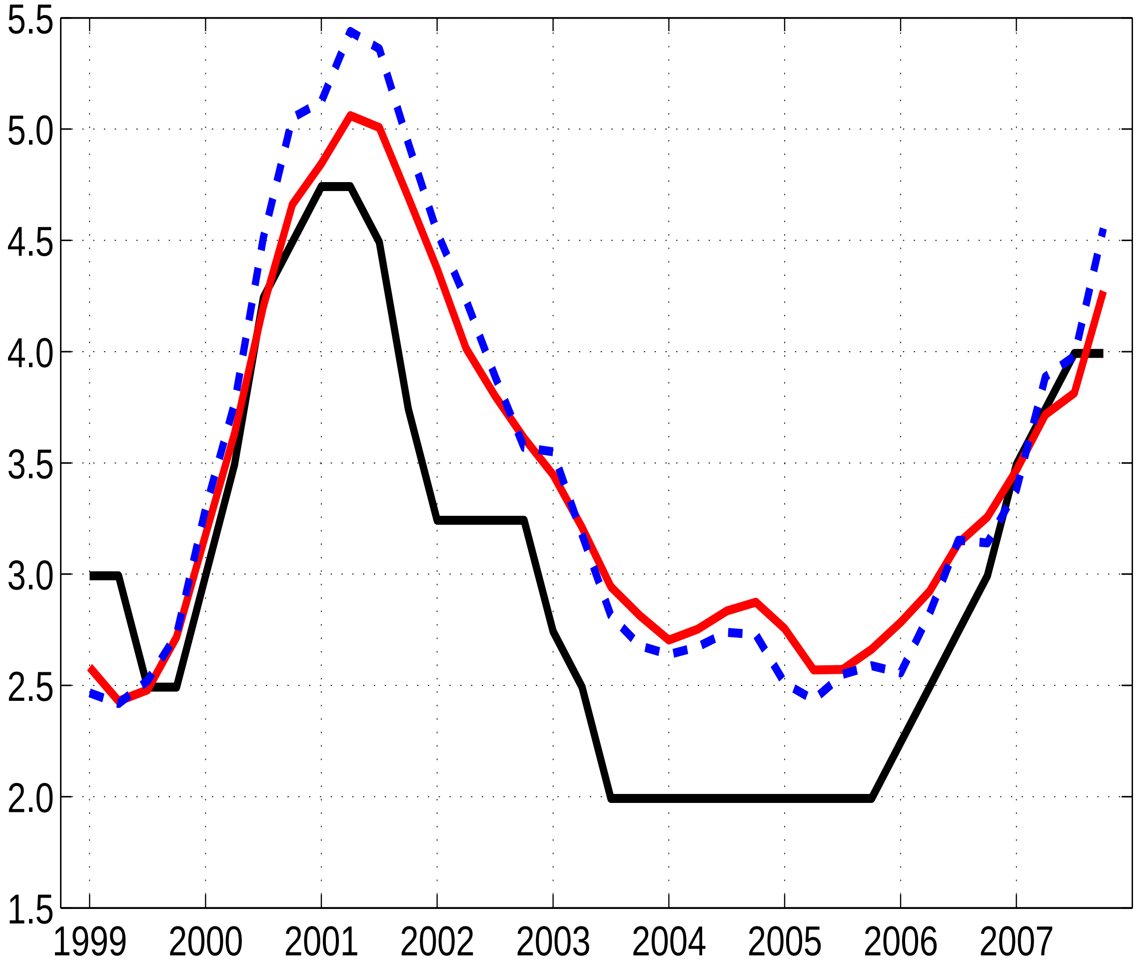
(Top panel: red solid line with plus - Taylor rule interest rate with all indicators - blue dashed line - Taylor rule interest rate without the following indicator variables: industrial production, consumer confidence, PMI and employment - black solid line minimum bid rate. Bottom panel: difference between the Taylor rule rates in the models with and without some indicators)

Figure 3 - The role of indicator variables



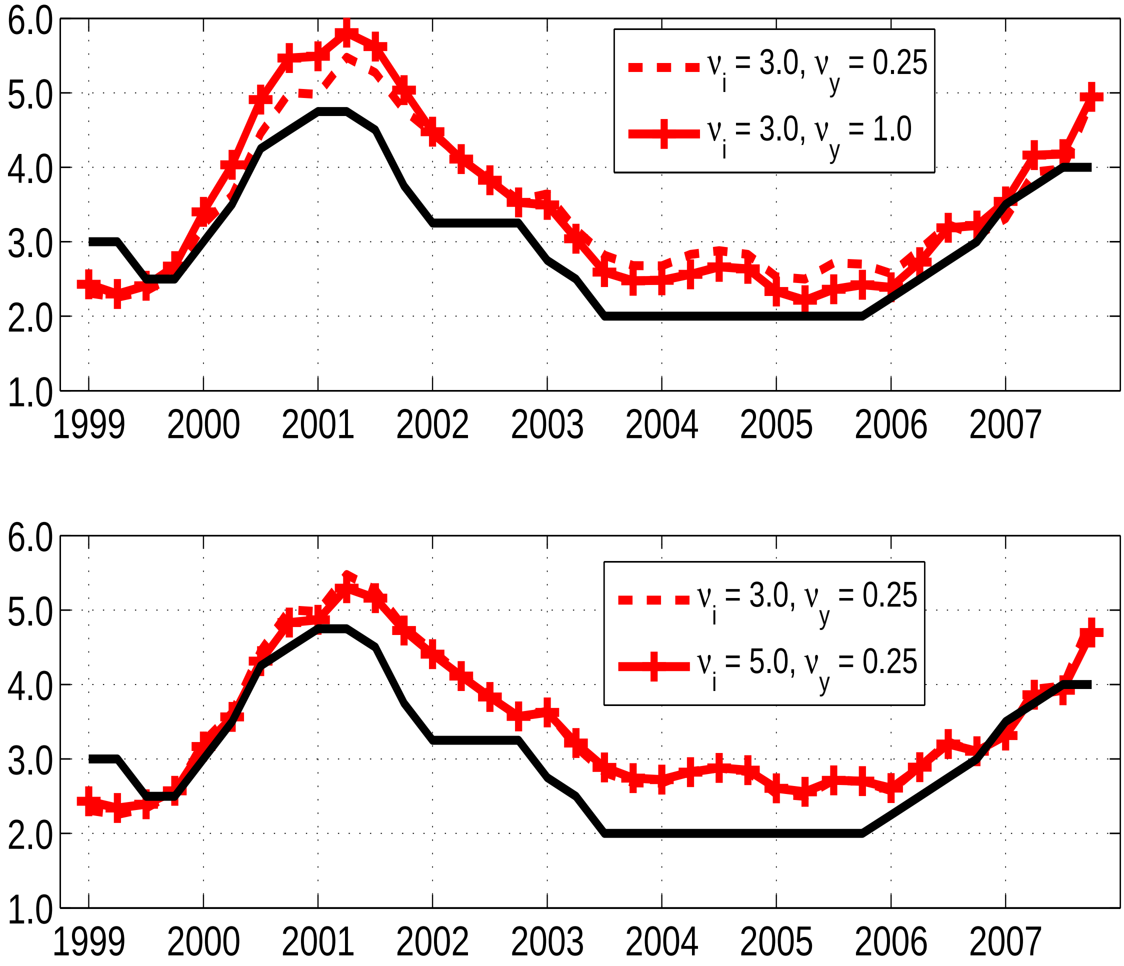
(red solid line with plus - median, blue dashed lines - 2.5^{th} and 97.5^{th} percentiles, - black solid line minimum bid rate)

Figure 4 - Minimum bid rate (MBR) predicted by the optimal discretionary policy



(Red solid line - median Taylor rule rate, blue dashed line - median optimal interest rate, - black solid line MBR rate)

Figure 5 - Comparison of the Taylor rule and the optimal discretionary policy prescriptions for the minimum bid rate (MBR)



(black solid line minimum bid rate)

Figure 6 - Minimum bid rate (MBR) predicted by the optimal policy under discretion: sensitivity analysis with respect to weights in the loss function

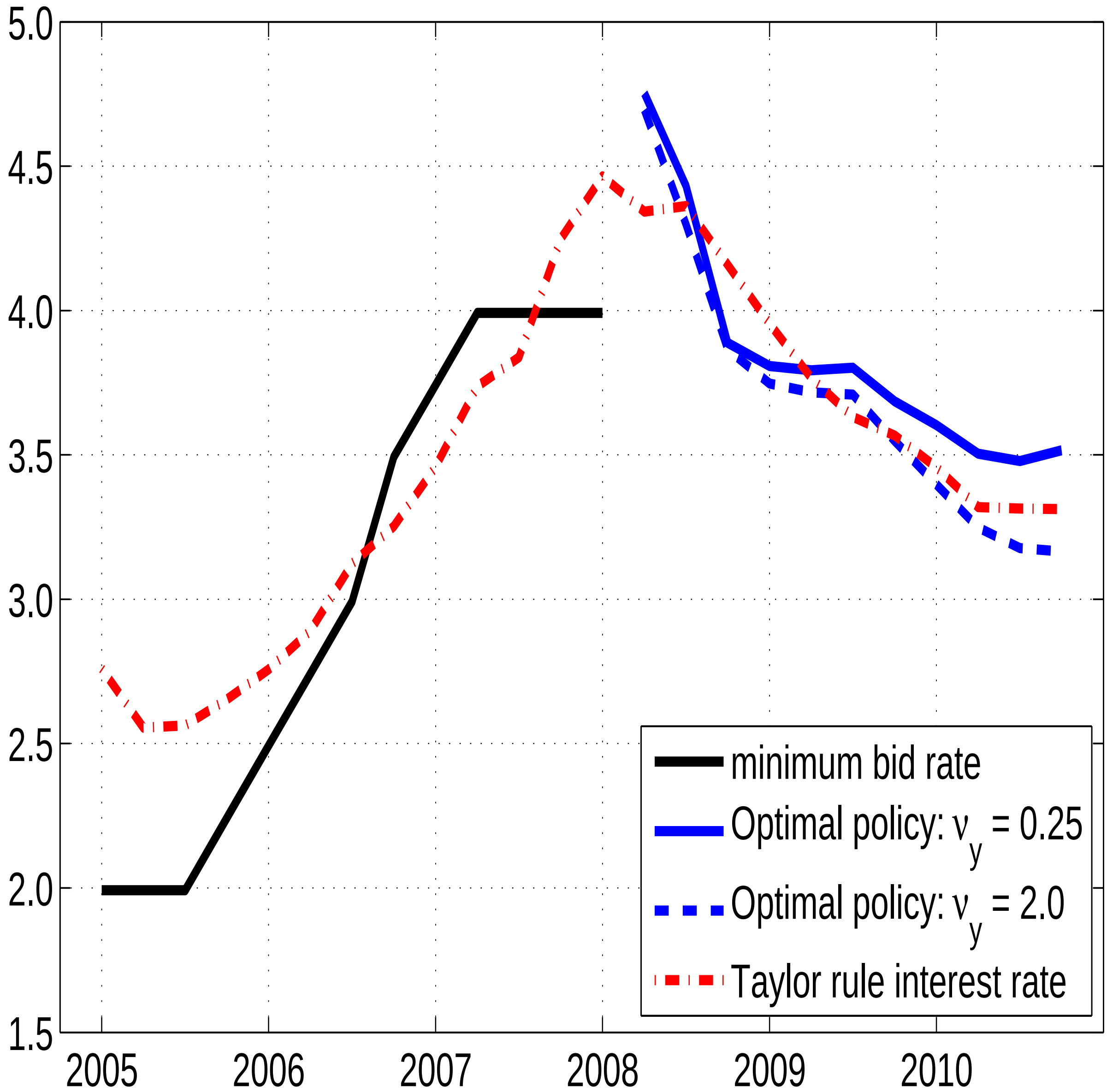


Figure 7 - Optimal interest rate for the years 2008-2010

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