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Monetary Policy Analysis in Practice

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Staff Memo

Monetary policy analysis in practice

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Norges Bank Monetary Policy*

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Monetary Policy Analysis in Practice

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25 October 2010

Abstract

Norges Bank is one of few central banks publishing an interest rate forecast. This paper discusses how we derive and communicate the interest rate forecast. To produce the forecasts, the Bank uses a medium-sized small open-economy DSGE model - NEMO. Judgments and information from other sources are added through conditional forecasting. The interest rate path is derived by minimizing a loss function representing the monetary policy mandate and the Board's policy preferences. Since optimal policy is vulnerable to model uncertainty, some weight is placed on simple interest rate rules. A weight on the deviation of the interest rate from the level implied by a simple rule is included in the loss function.

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[†]The views expressed in this paper are our own and do not necessarily reflect the views of Norges Bank. We thank Martin Seneca for useful comments. All errors are our own.

1 Introduction

Norges Bank started to publish interest rate forecasts in 2005. The decision to publish the forecast appeared as the next logical step in the development of the Bank's communication. Still, the novelty in the communication followed a thorough discussion of pros and cons of such an approach, see Holmsen, Qvigstad, Røisland, and Solberg-Johansen (2008).

As the Bank has gained experience with publishing interest rate forecasts, some concerns have been left behind and the internal analysis has developed. The introduction of interest rate forecasts demanded attenuated focus on making the framework comprehensible to financial market participants, to journalists, to banks and to a broader audience. A key issue was to convey the contingency and the uncertainty in the forecast.

As one of the reasons behind publishing the forecast is to improve the general understanding of the Bank's reaction pattern, it has been pertinent to explain the logic of the forecast, i.e. what considerations underlie the particular interest rate forecast, what are the objectives and the trade-offs between them. Consistency over time and across different states of the economy is a key factor behind a recognizable reaction pattern. Attention has been devoted to developing a framework that avoids clearly non-optimal outcomes and that ensures a consistent response to unanticipated developments.

In general, the interest rate forecasting has worked well, and the counter arguments that were discussed ex-ante have not proved unmanageable. We know of nobody today who argues that the Norges Bank should abandon interest rate forecasting, or analysts or observers who claim that they would be better off without this information.

As the interest rate expectations embedded in the markets tend to react on economic news between the Bank's reports – largely in line with the Bank's reaction pattern – there is little doubt that the contingency of the forecasts is well understood. There is also some evidence that the degree of surprise at the interest rate meetings has declined, although some extra volatility was introduced during the financial crisis which may obscure this observation.

Even though interest rate forecasts in principle can be drawn by hand, we believe that the quality and the consistency of the forecast will improve if some pre-announced principles guide the crafting of the forecast. A model of the economy, with forward-looking agents and a role for monetary policy forms the starting point. An optimal forecast refers to the interest rate path that minimizes an objective function subject to this model. Optimal forecasts can easily be produced using a medium-sized DSGE model (or even a smaller, canonical model).

In practice, developing an optimal interest rate forecast requires several considerations. Not only should the forecast comply with the inflation target, but there should be a reasonable, consistent and explainable treatment of the trade-off between inflation stabilization and stability in the real economy and other relevant objectives. Other considerations, such as interest rate smoothing, may also be relevant. We argue that all such considerations should be embedded in the use of the model and thus be treated within the optimizing framework. Consistency and story-telling will benefit

from having the model represent the forecast at all times.

Even though alternative policy strategies could be considered, the reaction pattern should preferably be consistent over time. Such considerations necessarily involve extensive use of economic models, and - since resources are limited - typically hinge on one particular DSGE model. Thus, it is desirable, to the extent possible, to guard against severe misspecification of that particular model, either because the model lacks a description of relevant variables or only poorly describes sectors in which relevant dynamics take place, or because abrupt shifts in the economy cannot be well described within a linear-quadratic framework. Whereas DSGE models seem to have won common ground among central banks as the main analytical tool, how central banks engineer their policy analysis, how the objectives and trade-offs are specified and how these are communicated, are different.

This paper aims to present a comprehensive guide to the steps and corners of crafting an optimal interest rate forecast in practice. We aim at describing how the model framework should be applied, how policy objectives could be formalized, how commitment could be built into the forecast, and how different controls and cross-checks should be taken into account to derive an optimal interest rate forecast. In addressing this set of questions, we attempt to describe a practical “handbook” of monetary policy, covering the necessary and sufficient steps to derive an appropriate interest rate forecast.

The paper is organised as follows: In Section 1, we describe and discuss the publication of the interest rate forecast. Section 2 describes our conditional forecasting system, based on our DSGE model. In Section 3, we discuss the analytical framework for deriving the interest rate path, with focus on optimal policy and robustness.

2 The gains from publishing interest rate forecasts

A published interest rate forecast was first introduced by the Reserve Bank of New Zealand in 1997. Publishing such forecasts was later introduced by the Norges Bank in 2005, the Riksbank in 2007 and the Czech National Bank in 2008. Holmsen, Qvigstad, Røisland, and Solberg-Johansen (2008) give an overview of the economic literature on transparency and pro and counter arguments for transparency. Most of the literature focuses on transparency in general terms and not on publishing interest rate forecasts per se. Only a few authors have evaluated the experience of interest rate forecasting or guiding.

Ferrero and Secchi (2009) find that the announcement of future policy intentions, either quantitative as in New Zealand, Norway or Sweden, or qualitative as in the ECB, improves the ability of market operators to predict monetary policy decisions. Andersson and Hofmann (2009) find that the central banks in New Zealand, Norway and Sweden have been highly predictable in their monetary policy decisions and that long-term inflation expectations have been well anchored in the three economies, irrespective of whether forward guidance involved publication of an own interest rate path or not. For New Zealand, they find weak evidence that a publication of a path could potentially enhance a central bank’s leverage on medium term interest rates.

Holmsen, Qvigstad, Røisland, and Solberg-Johansen (2008) find evidence of fewer monetary policy surprises in the Norwegian money market on the days with interest rate decisions, following the introduction of the interest rate forecasts. This suggests that communicating policy intentions improves the market participants' understanding of the central bank's reaction pattern.

2.1 Norges Bank's Communication

Seeing monetary policy as management of expectations, it is hard to omit or disregard the future course of interest rates when setting the interest rate. However, even though inflation targeting involves a distinctive approach to communication, and even though the actual publishing of the interest rate forecast in many ways have triggered the need for a more formal monetary policy analysis at the Norges Bank, the decision whether to publish the interest rate forecast can be considered a separate issue. For example, the Bank of England prefers to communicate indirectly in terms of density forecasts for inflation and GDP growth.

The policy analysis and communication of the Norges Bank leans on Woodford (2007) description of inflation forecast targeting as a combination of a decision procedure and a communication policy. The policy instrument should be adjusted in the way that is judged necessary in order to ensure that the bank's projections of the economy's future evolution satisfy the bank's targets. By clearly linking the interest rate forecast to the forecasts of the variables in the bank's objective function (or loss function), the logic of the interest rate forecast and the trade-offs therein, should (in principle) be easily observable and little debated. The communication policy should then follow the same structure, explaining the reasoning behind the forecasts, and impose discipline on the decision procedure.

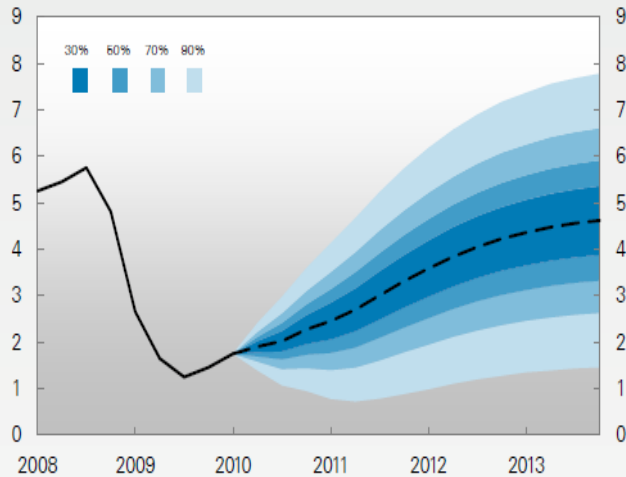
The forecast for the policy instrument and the main objective variables are communicated jointly in the Norges Bank's Monetary Policy Report (MPR), which is at the core of the communication. The main panel of the report, reprinted in figure 1, includes forecasts of the key policy rate, headline inflation, the output gap and a core inflation measure, all with fan-charts.

The forecast is guided by a list of criteria that the forecast should satisfy, see Section 4 below. First and foremost, the interest rate is set with the objective to bring inflation back to target over the medium term. In judging how quickly inflation should move towards target, attention is paid to the output gap, and there should be a reasonable balance between the two gaps. Moreover, interest rate changes are normally gradual, and policy should seek to be robust against separate factors, such as model misspecification and financial stability considerations.

Although the forecast gives a reasonably good insight into the Bank's reaction pattern, it is not easily observable whether the forecast is consistent over time, or whether revisions of the forecast from one report to the next predictably reflect changes in the Bank's assessment of economic conditions.

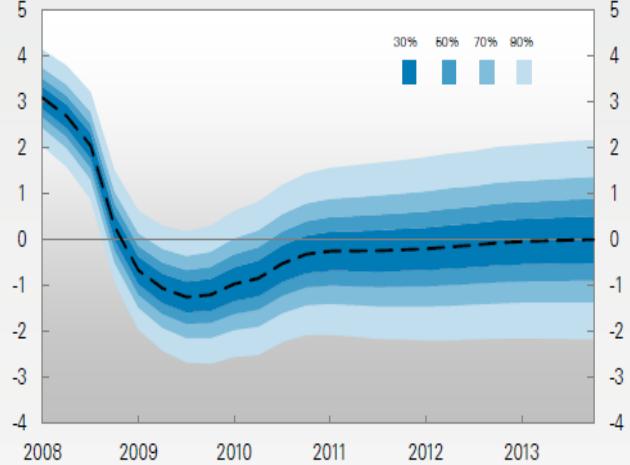
Consequently, the interest rate forecast is accompanied by a separate chart in the MPR (see figure 2) that attributes the revision since the previous report to the

Chart 1.12a Projected key policy rate in the baseline scenario with fan chart. Quarterly figures. Per cent. 2008 Q1– 2013 Q4



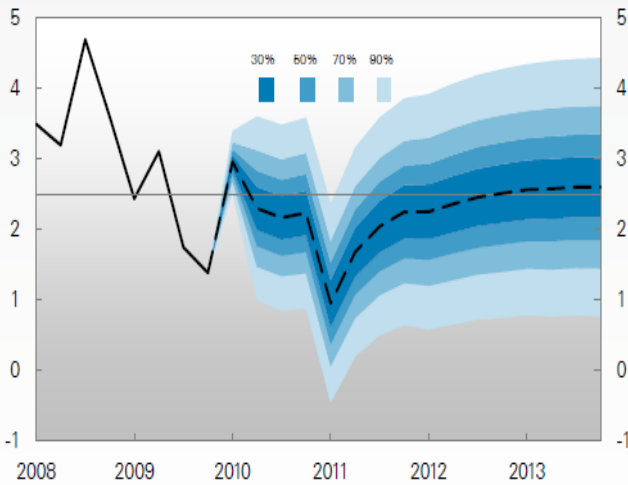
Source: Norges Bank

Chart 1.12b Estimated output gap¹⁾ in the baseline scenario with fan chart. Quarterly figures. Per cent. 2008 Q1 – 2013 Q4



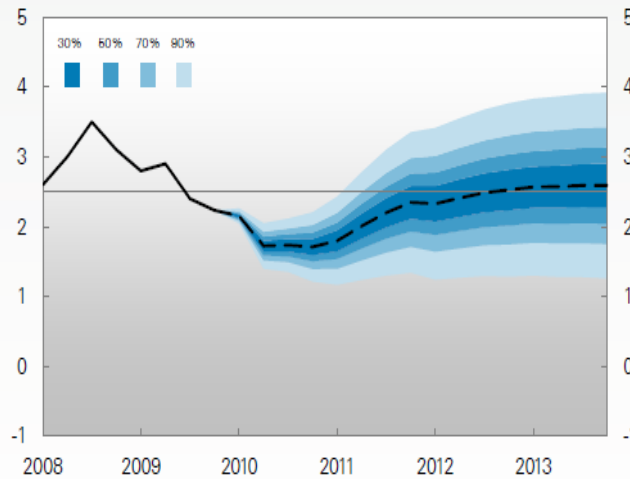
1) The output gap measures the percentage deviation between mainland GDP and projected potential mainland GDP
Source: Norges Bank

Chart 1.12c Projected CPI in the baseline scenario with fan chart. 4-quarter change. Per cent. 2008 Q1 – 2013 Q4



Sources: Statistics Norway and Norges Bank

Chart 1.12d Projected CPIXE¹⁾ in the baseline scenario with fan chart. 4-quarter change. Per cent. 2008 Q1 – 2013 Q4



1) CPI adjusted for tax changes and excluding temporary changes in energy prices. As from August 2008, CPIXE is a real time series. See *Staff Memo 7/2008* and *3/2009* from Norges Bank for a description of the CPIXE
Source: Norges Bank

Figure 1: The main panel of the Monetary Policy Report 1/10, reproduced

change in exogenous factors. Such a precise account makes it easier to outsiders to check whether the Bank is consistent over time, and also imposes discipline on the internal decision process. In addition, alternative scenarios are published, where the interest rate reacts to some relevant shocks to the forecast.

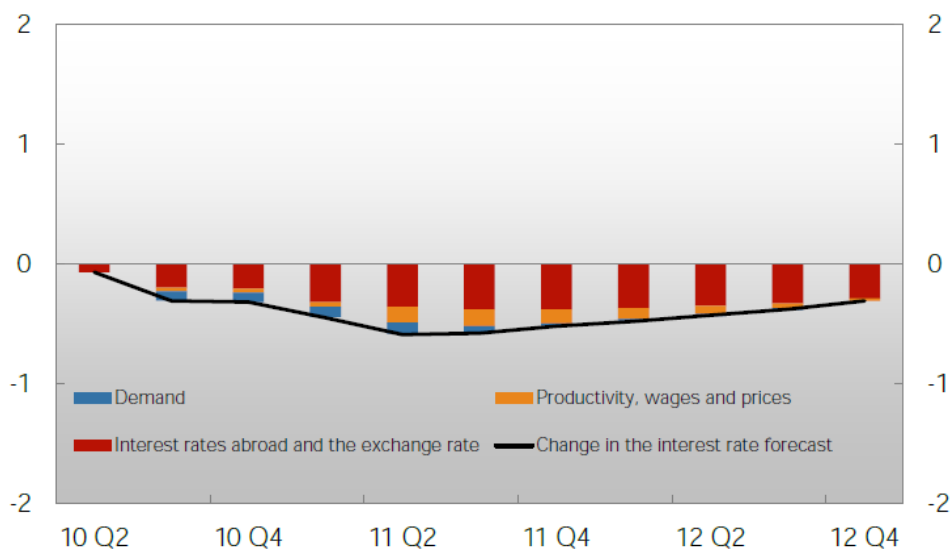


Figure 2: Factors behind changes in the interest rate forecast from MPR3/9 to MPR1/10. Accumulated contribution. Percentage points. 2010Q2-2012Q4.

3 The forecasting and policy analysis system

The overall structure of Norges Bank’s forecasting and policy analysis system (FPAS) is illustrated in figure 3. Medium-term projections and hence the policy advice is based on two premises in particular. The first is an assessment of the current economic situation and short-term forecasts up to four quarters ahead. The second key premise is forecasts for exogenous variables. On the basis of these premises, we use our core macroeconomic model NEMO to produce a set of projections for macroeconomic variables, including the key policy rate.

3.1 The Norwegian economy model (NEMO)

The forecasting system is organized around our core macroeconomic model, NEMO (Norwegian Economy Model).¹ NEMO is a medium-scale, small open economy DSGE model similar in size and structure to the DSGE models developed recently by many

¹NEMO has been used as the core model since 2007. A more detailed description of NEMO is provided in the appendix.

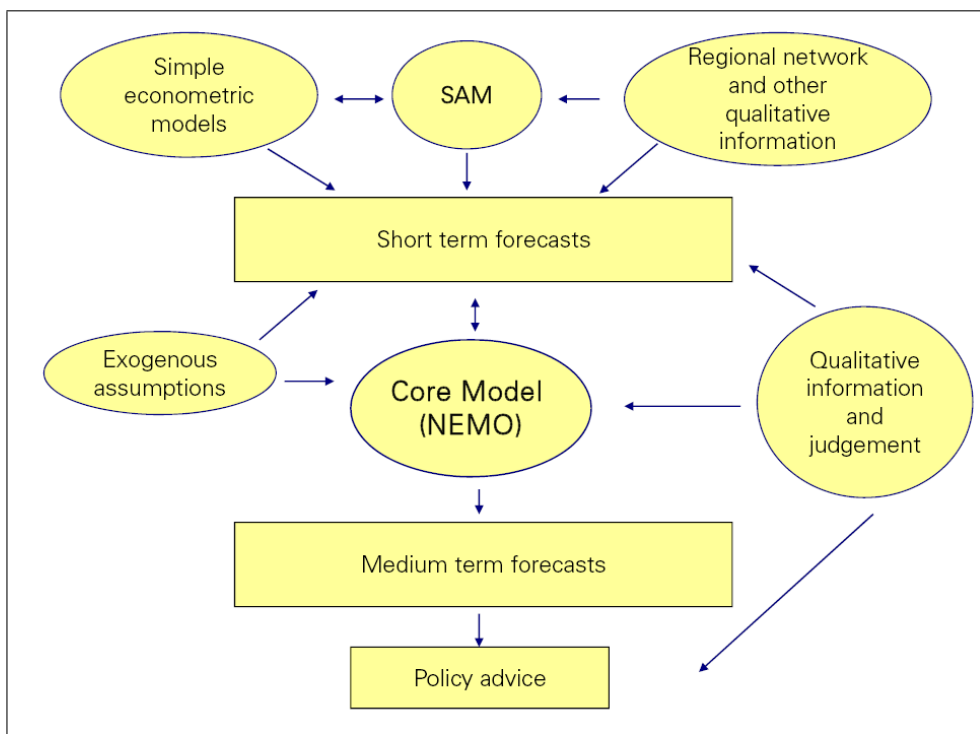


Figure 3: The Forecasting and Policy Analysis Process

other central banks. Organizing the policy process around a single core model adds discipline to the process and helps ensure that the analyses are consistent over time.

The economy has two production sectors. Firms in the intermediate goods sector produce differentiated goods for sale in monopolistically competitive markets at home and abroad, using labour and capital as inputs. Firms can vary the level of output within each period by varying the total number of hours and or by varying the degree of capital utilization. The production technology is subject to temporary (stationary) and permanent (non-stationary) labour augmenting technology shocks. Capital is firm-specific and firms choose the level of investment subject to quadratic adjustment costs. Intermediate goods firms' price-setting decisions are subject to quadratic costs of nominal price adjustment and prices are set in the currency of the importer (local currency pricing). Firms in the perfectly competitive final goods sector combine domestically produced and imported intermediate goods into an aggregate good that can be used for private consumption, private investment and government spending. The household sector consists of a continuum of infinitely-lived households that consume the final good, work and save in domestic and foreign bonds. Consumption preferences are characterized by (external) habit persistence. Each household is the monopolistic supplier of a differentiated labour input and sets the nominal wage subject to the labour demand of intermediate goods firms and subject to quadratic adjustment costs. The model is closed by assuming that domestic households pay a debt-elastic premium on the foreign interest rate when investing in foreign bonds. This gives rise to a modified uncovered interest rate parity condition for the exchange rate that includes an endogenous and exogenous risk premium term. The endoge-

nous risk premium is a function of the level of net foreign assets. The model evolves around a balanced growth path as determined by a permanent technology shock. The exogenous foreign variables are assumed to follow autoregressive processes. The fiscal authority runs a balanced budget each period, and the model can be solved under alternative assumptions about monetary policy, including simple instrument rules and optimal policy under varying degrees of commitment.

To solve the model we first transform the model into a stationary representation by detrending the relevant real variables by the permanent technology shock. Next, we take a first-order approximation (in logs) of the equilibrium conditions around the steady-state. In the computation of the optimal policy we treat the model as exactly linear.

NEMO has been estimated using Bayesian techniques on quarterly data for mainland Norwegian economy over the period 1981–2007 under two different assumptions regarding monetary policy: a simple instrument rule with the lagged interest rate, inflation, the output gap and the real exchange rate and optimal policy under commitment.² The variables that enter the loss function under optimal policy are inflation, the output gap and interest rate changes. The empirical fit of the model with optimal policy is found to be as good as the model with a simple rule. This result is robust to allowing for misspecification following the DSGE-VAR approach proposed by Del Negro and Schorfheide (2004). The unconditional interest rate forecasts from the DSGE-VARs are close to Norges Bank’s official forecasts since 2005.

3.2 The forecasting process

3.2.1 Conditional forecasts

In the practical projection exercise we have adopted a conditional forecast approach. As shown by Maih (2010) it may be possible to improve the forecast performance of DSGE models by conditioning on e.g., financial market information or short-term forecasts from models that are able to exploit recent data and information from large datasets. Conditioning information may also come in the form of policymaker judgment that is not directly interpretable in terms of the DSGE model.³ The conditional forecasting approach allows us to exploit this information in a consistent manner without changing the structure of the model.⁴

Conditional forecasting involves adding a sequence of structural shocks to the model over the forecasting period so that the model exactly reproduces the conditioning information. The conditioning information used in NEMO comes in the form

²See Bache, Brubakk, and Maih (2010) for a more detailed exposition.

³As emphasized by Maih (2010), however, when the DSGE model is misspecified, conditioning could in principle lead to a deterioration in forecast performance, even if the conditioning assumptions turn out to be correct.

⁴An alternative to publishing model consistent conditional forecasts is to start out with the pure unconditional model forecasts and then, ex post, adjust the projections in the direction suggested by off-model considerations and judgement. In our experience, however, both the internal consistency of forecasts and the level of discussion of policy is improved by the practice of publishing conditional forecasts in which the key macro variables have been derived from a single model.

of nowcasts and short-term forecasts provided by sector experts. Sector experts monitor a large amount of data from disparate sources, including qualitative information. For some variables (e.g., government spending, oil investment and foreign variables) we condition on off-model information for the whole forecasting horizon. An additional tool for short-term forecasting is the recently developed System for Model Averaging (SAM). SAM is used to produce density forecasts for the current and the next few quarters by averaging forecasts from a large set of different models. Currently, the system only provides forecasts for inflation and output growth, but the goal is to extend the set of variables to comply with the set of observables used in the core model.

The type of conditioning method employed in a DSGE model depends on whether the conditioning information is anticipated or not. As rational agents exploit any available information that can improve their forecasts, anticipated events matter for their current decisions. Hence, when conditioning on leading information in DSGE models, an important question is to what extent private agents can be assumed to internalize this information. Our baseline forecasts are based on the assumption that the conditioning information is known to all agents in the model at the beginning of the forecast period. This ensures that the central bank will not be surprised by, and monetary policy will not react to, outcomes that turn out as projected.⁵

3.2.2 An iterative process

In practice, the forecasting process is iterative. The first step involves computing forecasts from NEMO given the initial short-term forecasts provided by the sector experts. Then, based on the implications of the short-term forecasts for the structural shocks and the endogenous variables, the sector experts revise their short-term forecasts. Subsequently, the revised short-term forecasts are used as new conditioning information in NEMO. The iteration continues until convergence is reached. For some variables, the sector experts also produce forecasts beyond the short-term horizon that serve as cross-checks for the medium-term NEMO forecasts.

We also produce unconditional forecasts from NEMO in each forecast round. These provide valuable insight about the mechanisms in the model and serve as a cross-check on the short-term forecasts. Moreover, they allow us to assess the amount of judgment added to the forecasts and the implications of that judgment for the interest rate path.

In analyzing the implications of new information we take as given the view of the monetary policy transmission mechanism and the preferences of the policymaker implicit in the most recent interest rate path. This involves computing forecasts based on the same model specification and the same specification of monetary policy as in the previous forecast round, see section 4.4.

⁵A second issue is whether to treat the conditioning information as certain (referred to in the literature as 'hard' conditioning) or uncertain ('soft' conditioning). Most of the literature on conditional forecasting has focused on hard conditioning. So far, this has also been the approach taken at Norges Bank. See Bache, Brubakk, Jore, Maih, and Nicolaisen (2010) for more details on the conditional forecast approach.

The first step in every forecast round is to assess how new and revised historical data affect the interpretation of recent economic developments. Technically, this involves running the Kalman-filter on the state-space representation of the model up to the start of the forecast horizon. The Kalman-filter will produce new estimates of the historical disturbances affecting the economy (e.g., technology shocks, demand shocks, mark-up shocks) and unobservable variables such as the output gap. This estimate of the output gap from the model is cross-checked against estimates from statistical models such as the Hodrick-Prescott filter, unobserved component models and the production function method

The second step is to analyze the implications of the new conditioning information. In NEMO the conditioning information includes some of the exogenous variables (e.g., foreign variables, government spending, oil investments) over the entire forecast horizon and short-term forecasts for observable endogenous variables. Our baseline assumption is that the conditioning information is anticipated.⁶

3.2.3 Conditionality and uncertainty

There is considerable uncertainty surrounding the projections. In the MPR, the uncertainty is illustrated using fan charts. So far, the fan charts published in the reports have been based on estimated historical disturbances to the supply and demand side in the Norwegian economy identified from a small macroeconomic model (see Inflation Report 3/05 for details). Thus, the fan charts express historical average uncertainty.

In normal circumstances, the fan charts are symmetric and there is no distinction between the mean, mode and the median forecasts. During the recent financial crisis, the key policy rate was reduced to a historically low level. Since the key policy rate in principle has a lower bound close to zero, we set all outcomes implying a negative interest rate, to zero. Technically, the mean value for the interest rate was then marginally higher than the interest rate forecast, which could be interpreted as the median forecast. In the MPR, we also present scenarios based on alternative conditioning assumptions. The scenarios serve to highlight assumptions that have received particular attention in the course of the forecast process. The exact specification of the scenarios differ from one report to the next. The shifts are specified such that, should these outcomes materialize, the alternative interest rate path is the Bank's best estimate of how monetary policy would respond. The shifts are consistent with the main scenario in the sense that they are based on the same loss function guiding the response of the central bank.

A key ingredient in Norges Bank's communication approach is the interest rate account in figure 2. The interest rate account is a technical model-based illustration of how the change in the interest rate forecast from the previous report can be decomposed into the contributions from different exogenous shocks to the model. In the MPR, the disturbances are grouped together in five main categories; demand shocks, shocks to prices, costs and productivity, shocks to the exchange rate risk premium

⁶We do not, however, allow the conditioning information to affect the estimate of the state of the economy at the beginning of the forecast period.

and foreign interest rates and shocks to money market spreads. If parameters in the model are changed from one forecast round to the next, the contribution from that change is attributed to the relevant category of shocks (e.g., effects of changes in the parameters in the Euler equation for consumption would be attributed to the category ‘demand shocks’). Changes in the policymaker’s preferences, or the loss function, will also appear. This was the case in October 2008 when the reduction in the key policy rate was moved forward because of an unusually high level of uncertainty and a desire to stave off particularly adverse outcomes. The contribution from this change in policy preferences was made explicit in the interest rate account in MPR 3/08. Since the interest rate account follows from a specific model, the exact decomposition is model-dependent and should thus be interpreted as a model-based illustration rather than a precise description of the Executive Board’s reaction pattern. Still, the account imposes some discipline on the internal decision process and the external communication, and we have observed that market analysts tend to pre-guess the account before the release of the Monetary Policy Report.

4 Modelling monetary policy

When modelling monetary policy, one has to take into account the purpose of the model. If the purpose is a positive analysis, the choice of specification could be different than if the purpose is normative analysis. When the central bank publishes its own forecast of future interest rate decisions, the interest rate path has both a positive aspect and a normative aspect. It should both give a good description of actual policy, but also represent the policy that gives the maximum achievement of the monetary policy objectives given the central bank’s information. The choice of specification of monetary policy should therefore be suited for being a tool for internal discussions on the appropriate interest rate path as well as having good forecasting properties. The two most common general approaches to modelling monetary policy are instrument rules on the one hand, and solving for the interest rate path that minimizes some loss function subject to a model, referred to as optimal policy, on the other. We shall discuss each approach in turn and describe how we apply them in practice.

4.1 Instrument rules

Both among central banks and in the academic literature, the most common way to specify monetary policy is by a simple interest rate rule, e.g., a generalized Taylor rule:

$$i_t = \rho i_{t-1} + (1 - \rho)(r_t^* + \pi^* + \alpha_1(E_t \pi_{t+k} - \pi^*) + \alpha_2(E_t y_{t+l} - \eta E_t y_{t+l-1})), \quad (1)$$

where i_t is the policy rate, r_t^* is the neutral real interest rate, π^* is the inflation target, $E_t \pi_{t+k}$ is the expected inflation in period $t+k$ based on period t information, and y_t is the output gap. Although simple rules like (1) do not implement the fully optimal policy, they can, if calibrated appropriately, come quite close to optimal

policy. Moreover, they give a reasonable description of actual monetary policy. When Norges Bank started publishing its interest rate forecasts, the Bank used such a rule, where the coefficients were calibrated to yield an interest rate path that "looked good". Interest rate rules like (1) has the advantage of being relatively simple to implement in the type of DSGE models used by central banks, and they give a reasonable description of interest rate setting. From a positive perspective, specifying monetary policy as a simple interest rate rule has been quite successful, at least when the criterion is empirical fit.⁷ Also from a normative perspective, simple interest rate rules could be a useful specification. Forward-looking versions of the Taylor rule incorporates more information and can be a good approximation to fully optimal policy when the coefficients in the rule are optimized.

Our experience with using simple interest rate rules to model the interest rate path is that this approach has some limitations. First, even if optimal simple rules could come quite close to fully optimal policy, there is no obvious reason why one should not go the whole way of deriving an interest rate path that gives the maximum achievement of the monetary policy objectives. If the decision-makers ask the staff if it is possible to do even better, and is so, how this can be done, the staff must have an answer. Second, since the rule is likely to be changed from one forecasting round to the other in order to capture the Board's preferred interest rate path, there is a danger that these changes can reflect reoptimizations. This might lead to inconsistent forecasts, since the forecasts are made under the assumption of commitment to a specific rule, while there could be a risk that the rule is changed in a systematic manner that reflects discretionary policy. Since simple rules are not fully optimal and not uncertainty equivalent, it is easier to find arguments for changing the specification of simple rules than for changing the loss function when applying fully optimal policy.

4.2 Optimal policy

Optimal policy, in the meaning of minimizing a loss function given a specific model, has the advantage of distinguishing explicitly between objectives and constraints⁸. From a normative perspective, optimal policy constitutes a natural benchmark, as it gives the maximum achievement of the objectives given the constraints (the model). The simple rule approach is often motivated from a positive perspective, in the sense that it gives a good description of central banks' behavior. However, as shown by Adolfson, Laséen, Lindé, and Svensson (2009) and Bache, Brubakk, and Maih (2010), the empirical fit of simple rules is not necessarily better than the empirical fit of optimal policy.

We may think of flexible inflation targeting as the implementation of the interest rate path that is implied by the solution to the following linear-quadratic minimization problem:

$$\min_{\{x_t\}_{t=0}^{\infty}} E_0 \sum_{t=0}^{\infty} \beta^t \left[x_t' W x_t \right] \quad (2)$$

⁷See e.g., Clarida, Gali, and Gertler (1998).

⁸We use the term optimal policy in the sense of minimizing an ad hoc loss function here, not in the sense of minimizing the true welfare loss.

subject to

$$E_t[A_{-1}x_{t-1} + A_0x_t + A_1x_{t+1} + B\varepsilon_t] = 0.$$

The constraint represents the model of the economy on linearized state space form, x_t is the vector of predetermined and non-predetermined variables⁹, β is the discount factor, and W is the weighting matrix that expresses the policymakers preferences. Typically, W will include positive weights to inflation, the output gap and the change in the interest rate.

When computing optimal policy, one has to make an assumption about the central bank's commitment technology. In one sense, one could consider inflation targeting as a commitment to minimize a loss function which penalizes deviations from the inflation target, and which does not have targets for output or employment which are inconsistent with their natural levels. In other words, the central bank commits to a loss function without any terms leading to an inflationary bias. Commitment to stabilizing inflation is the type of commitment many practitioners have in mind when talking about commitment in monetary policy. However, in addition to this "first-order commitment", there is a gain from commitment even if the loss function is consistent with average inflation being on target. By managing the expectations channel by committing credibly to a certain reaction pattern, the central bank is able to achieve a better trade-off between stabilizing inflation and stabilizing the real economy.

It is common in the literature to consider the cases of either full commitment or pure discretion. However, one could argue that full commitment and pure discretion are built on extreme assumptions, and an intermediate could in some cases be interesting to explore. To relax the extreme assumptions of both commitment and discretion, Roberds (1987) consider stochastic replanning. Based on Roberds' work, Schaumburg and Tambalotti (2007) develop "quasi commitment" and their work is extended in Debortoli and Nunes (2007), who use the term "loose commitment". With loose commitment or stochastic replanning, the central bank is assumed to formulate optimal plans, to be tempted to renege on them and to succumb to this temptation. Formally, there is a given probability $0 \leq \gamma \leq 1$ that the central bank commits and a probability $1 - \gamma$ that it reneges. The problem can be formalized as follows¹⁰:

$$\min_{\{x_t\}_{t=0}^{\infty}} E \sum_{t=0}^{\infty} (\beta\gamma)^t [x_t' W x_t + \beta(1 - \gamma) x_{t+1}^{D'} P x_{t+1}^D] \quad (3)$$

subject to

$$A_{-1}x_{t-1} + A_0x_t + \gamma A_1 E x_{t+1}^C + (1 - \gamma) A_1 E x_{t+1}^D + B\varepsilon_t = 0,$$

⁹Unlike e.g. Svensson (2010a), we do not distinguish between predetermined and non-predetermined variables.

¹⁰The code that we use to solve the loose commitment or stochastic replanning problem is based on the algorithm sketched here. It is written by Junior Maih.

where Ex_{t+1}^C is the expected value of x_t under commitment and Ex_{t+1}^D its expected value under discretion. P solves the Sylvester equation

$$P = W + \beta H'_{xx} P H_{xx}, \quad (4)$$

where H_{xx} is part of the solution to (3): if a solution of (3) exists, it takes the form:

$$\begin{bmatrix} \lambda_t \\ x_t \end{bmatrix} = \begin{bmatrix} H_{\lambda\lambda} & H_{\lambda x} \\ H_{x\lambda} & H_{xx} \end{bmatrix} \begin{bmatrix} \lambda_{t-1} \\ x_{t-1} \end{bmatrix} + \begin{bmatrix} G_\lambda \\ G_x \end{bmatrix} \varepsilon_t. \quad (5)$$

λ_t is the vector of Lagrange multipliers associated with the constraint facing the central bank. Under discretion $H_{\lambda\lambda} = 0$ and $H_{x\lambda} = 0$. Using the results in Marcet and Marimon (1998), the solution to (2) and in particular (3) may be solved under different degrees of commitment using recursive methods.

Taking the first-order conditions of (3) and using a guessed solution of the form (5) for the law of motion of the variables, and the expression for P in terms of the guessed solution derived from (4), one arrives at a system

$$\Gamma_0 \begin{bmatrix} \lambda_t \\ x_t \end{bmatrix} + \Gamma_1 \begin{bmatrix} \lambda_{t-1} \\ x_{t-1} \end{bmatrix} + \Gamma_\varepsilon \varepsilon_t = 0,$$

where the Γ -matrixes are functions of A, B, W and the guess for the H -matrixes. The solution algorithm assumes that Γ_0 is invertible, in which case the equation above can be re-written as

$$\begin{bmatrix} \lambda_t \\ x_t \end{bmatrix} = -\Gamma_0^{-1} \Gamma_1 \begin{bmatrix} \lambda_{t-1} \\ x_{t-1} \end{bmatrix} - \Gamma_0^{-1} \Gamma_\varepsilon \varepsilon_t. \quad (6)$$

Hence, to solve the model, one can initialize a guess for H in (5), and update the guess by setting $H = -\Gamma_0^{-1} \Gamma_1$, then update the Γ -matrixes, and continue to iterate. After convergence is obtained, one can solve for G in equation (5) by using $G = -\Gamma_0^{-1} \Gamma_\varepsilon$.

Since the model of loose commitment assumes a given probability, γ , of reoptimization, taken literally one should observe stochastic jumps in policy when a reoptimization is realized. Although such jumps are consistent with the model and could be realistic for other areas of economic policy, we find such stochastic reoptimizations not reasonable for monetary policy in practice. A reoptimization would imply a stochastic change in the interest rate that cannot be attributed to any new information about the economic developments. Unless there is a totally new board of decision-makers, such changes are difficult to explain to the public, and central banks would therefore be reluctant to such abrupt changes in policy. One may therefore interpret γ more loosely as the degree to which the central bank is able to, or wants to, honour past promises. In other words, γ measures the central bank's commitment technology and the system (6) is as the law of motion. Note that from equation (3), γ enters in the same way as the discount factor β . Thus, from (3) we can alternatively interpret γ as how heavily the central bank discounts the future when making commitments. With less credibility, i.e., γ is "low", the central bank is less able (or willing) to make commitments for policy far into the future. Figure (4) illustrates the response to a cost push shock under optimal policy in NEMO given different degrees of commitment.

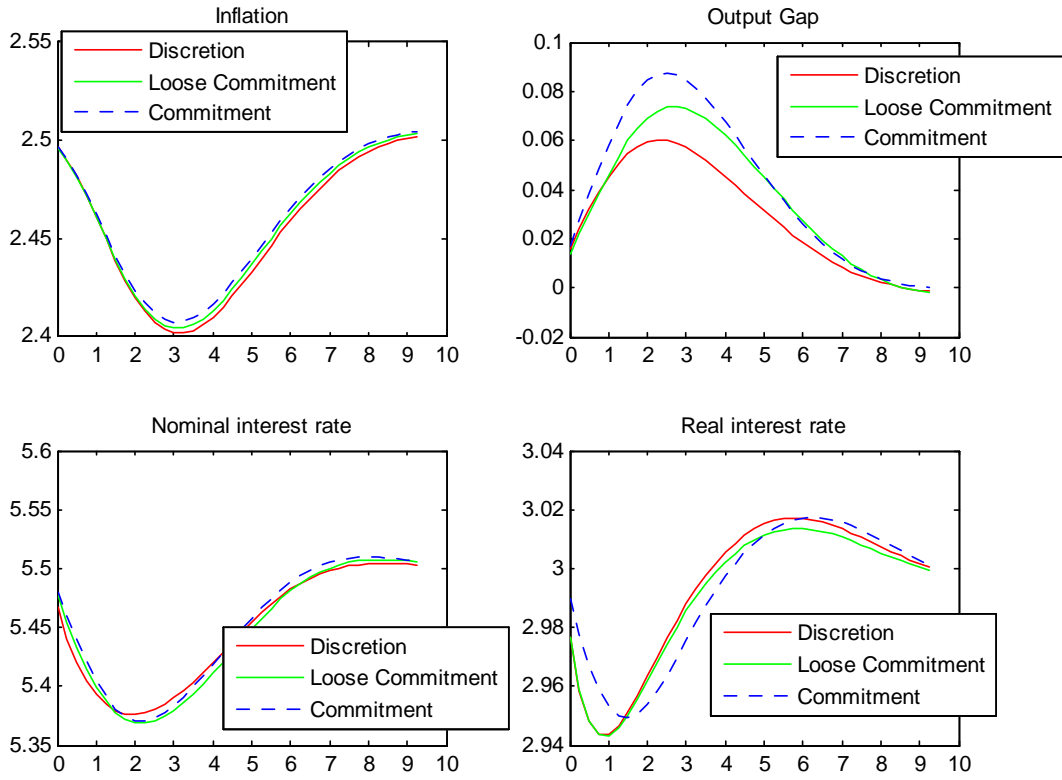


Figure 4: Impulse-responses, NEMO, negative cost-push shock.

4.2.1 Initial Lagrange multipliers

Under Ramsey optimal policy, the initial Lagrange multipliers associated with the forward-looking variables in the constraints in (2) are zero, while later multipliers are expected to be non-zero. If there is reoptimization in later periods, the multipliers will be reset to zero. Hence, Ramsey policy is not a feasible rational expectations equilibrium when the policymaker reconsiders policy in every period. However, if the policymaker behaves as if the Lagrange multiplier is a state variable inherited from the past in all periods including the first, as explained for example in Svensson (2010a), the policymaker will be able to implement optimization under commitment in a timeless perspective, see Woodford (2003a), ch 9.

Initializing optimal policy given commitment in a timeless perspective, or some lower degree of commitment as discussed in the previous subsection - with the interpretation we give above to the γ - parameter - requires a starting value for the Lagrange multipliers associated with the forward looking variables (that is, the initial value of the predetermined Lagrange multipliers). Our approach to this is to calculate the history of the smoothed shocks in the past given a simple monetary policy rule. Next, we initialize the multipliers at zero some time in the past, and calculate the artificial history of the multipliers that would follow if the smoothed shocks were structural shocks and optimal policy had been followed in the past. As explained in Adolfson, Laséen, Lindé, and Svensson (2009), the artificial history of the multipliers following any systematic policy in the past would also be possible to calculate.

After timeless commitment policy, or some lower degree of commitment has been initialized, one may use the inherited Lagrange multipliers as starting values in subsequent periods. A question then is whether one should recalculate the history of Lagrange multipliers as historic data are revised, or whether one should use the past Lagrange multiplier based on last periods vintage of data.

4.2.2 What to assume about the commitment technology?

The assumption about the commitment technology can be seen from two perspectives; a positive perspective and a normative perspective. From a positive perspective, the question is what describes best the actual policy of the central bank. Very little is known about the degree to which central banks commit. It is reasonable to assume that the most realistic assumption is somewhere between pure discretion and full commitment.

From a normative perspective, one could argue that the staff should derive forecasts that gives the best possible achievement of the monetary policy objectives. Since commitment is superior to discretion, one could thus argue that the staff should produce forecasts based on commitment. Svensson (2010b) argues that the staff should produce *efficient* forecasts based on commitment in a "timeless perspective" Woodford (2003b). However, as shown by Dennis (2010) and Sauer (2010), it is not always the case that timeless commitment gives lower loss than discretion, and Ramsey policy - the fully optimal policy - is not an option in practice.

If the central bank lacks a perfect commitment technology, one can consider con-

strained discretion, in the meaning of minimizing a modified loss function (a loss function that differs from the loss function that describes the true preferences of the authorities, or the mandate) under discretion. The loss measured by the true loss function may then be lower than the discretionary loss. Various modified loss functions have been considered in the literature. Rogoff (1985) suggested a lower weight on the output gap, which also improves the discretionary outcome in New Keynesian models without an overambitious output target, as shown by Clarida, Galí, and Gertler (1999). Woodford (2003c) showed that interest rate inertia could implement commitment gains. Jensen (2002) and Walsh (2003) suggested nominal income targeting and "speed limits" respectively, while Vestin (2006) suggested price-level targeting.

In a general model, Svensson and Woodford (2003) show that adding a term depending on the lagged Lagrange multipliers to the loss function and minimizing this modified loss function under discretion implements a solution identical to the outcome under commitment in a timeless perspective. This serves to illustrate that minimizing an adjusted loss function under discretion is a different way of expressing commitment to a time invariant policy - of which the timeless perspective is one special case. Commitment to a simple or optimal rule are yet other ways of expressing commitment to a time invariant policy. But no time-invariant policy can beat Ramsey optimal policy. The type of time-invariant policy that comes closest to Ramsey optimal policy probably depends on the model and on initial conditions.

Since central banks do aim to affect expectations, and since this is the main motivation for publishing the interest rate forecast, it is evident that pure discretion is not an appropriate assumption. So far, we have applied the algorithm described in subsection 4.2 in our published interest rate paths with either $\gamma = 1$ (full commitment) or $\gamma = 0$ (discretion) only. That is, Norges Bank has used commitment in a timeless perspective or constrained discretion as assumptions behind published optimal policy paths. One may consider the adjustment to the loss function that one does under constrained discretion as an alternative way of expressing some degree of commitment, instead of using a γ between zero and one. The Bank derives paths based on several assumptions, but recently the reference paths have been based on constrained discretion. We recognize, however, that there are advantages and disadvantages to using any of these assumptions, and we seek to gain more experience with using alternative assumptions by taking into account both recommendations from academic research and practical considerations.

4.3 Robustness

As in many other central banks, Norges Bank has a core model, described in section 3.1, from which the forecasts are derived. The optimal policy path is then by construction only optimal in that particular model. However, there is uncertainty attached to both the values of the parameters in the model, the judgements that are added in terms of shocks and the economic mechanisms specified by the model.

There is a large literature on monetary policy under uncertainty. Generally, the policy implications depend on what the uncertainty relates to, for example, whether there is parameter uncertainty or model uncertainty, and whether the uncertainty

is quantifiable or not. If uncertainty is quantifiable, Bayesian model averaging, as suggested by Brock, Durlauf and West (2003), is a natural approach. However, even if optimal policy in a Bayesian model averaging framework in principle could deal with model uncertainty, it is a very computationally demanding approach, and existing work focus on simple, as opposed to fully optimal, interest rate rules, see e.g., Cogley et al. (2010) and the references therein. Deriving optimal forecasts based on Bayesian model averaging is therefore, at least at the current stage, not practical for a central bank staff that shall produce model forecasts added with judgments in a hectic forecasting round. There is thus a practical argument for producing forecasts within one core model, while using other models as cross-checks and inputs to the judgmental adjustments of the forecasts of the core model.

If uncertainty is not quantifiable, i.e., there is Knightian uncertainty, a minimax approach is a common way to deal with such uncertainty. Under minimax, one aims to minimize the loss in a worst case situation. In robust control theory, adapted and applied to economics by Hansen and Sargent (2008), this is modelled as a game between a policymaker and an "evil agent". The "evil agent" maximizes the policymaker's loss, given a "budget" of disturbances, and the policymaker minimizes the loss.¹¹ For a central bank with a core model, robust control could be a useful tool for discussing alternative interest rate paths reflecting different preferences on robustness. One is also able to identify in which parts of the model that misspecification is particularly costly, so that resources can be devoted to improving those parts. Moreover, a robust control exercise is carried out within the core model itself and does thus not require other models. This advantage has, however, also its costs. As argued by Levin and Williams (2003), a robustly optimal policy in one model may give poor results in another model, and may be better suited for dealing with local model uncertainty, i.e., uncertainty within the constrained class of model.

A common approach to deal with global (i.e., across-model) uncertainty is to use simple interest rate rules that are specified and calibrated to give reasonably good results in a variety of models. The rationale for simple rules is elegantly phrased by Taylor and Williams (2010), page 29:

"[O]ptimal policies can be overly fine tuned to the particular assumptions of the model. If those assumptions prove to be correct, all is well. But, if the assumptions turn out to be false, the costs can be high. In contrast, simple monetary policy rules are designed to take account of only the most basic principle of monetary policy of leaning against the wind of inflation and output movements. Because they are not fine tuned to specific assumptions, they are more robust to mistaken assumptions".

Most of the literature on simple robust rules deals with a closed economy and considers various versions of the Taylor rule. There is less research on simple robust rules for small open economies. Some results show that inclusion of variables like the exchange rate in addition to output and inflation yields relatively modest gains in model-based evaluations because they are typically highly correlated with the in-

¹¹Dennis, Leitemo, and Söderström (2007) provides an application of robust control in a small open economy model estimated on Australian data.

terest rate itself or closely related with the measures of inflation and output gap.¹² Since the exchange rate is a highly endogenous variable, movements in this rate may already be reflected in inflation and the output gap. Uncertainty associated with the determination of the equilibrium exchange rate may also partly explain the exclusion of the exchange rate from the rule. If movements in exchange rates are mostly due to fundamentals and not due to portfolio shocks, this reduces the added value of having an exchange rate term in the targeting rule. If monetary authorities try to smooth fluctuations in the exchange rate, this might undermine the ability of the exchange rate to act as a shock absorber, hence causing output and inflation to be more volatile. One of the advocates of this view is Taylor (2001), who finds no clear advantages of including the exchange rate in the policy rule. Ball (2000) concludes differently. He finds that in order to stabilize an open economy, the inflation measure that is targeted must be adjusted to remove the transitory effects of exchange-rate movements. In open economies Taylor rules should then be modified to give a role to the exchange rate. Ball suggests targeting “long run inflation”, which is a measure of inflation that filters out the transitory effects of exchange rate fluctuations.

Despite different results and views on the design of simple robust rules, many central banks and individual policymakers use simple rules such as the Taylor rule as crosschecks and guidelines, see Asso, Kahn, and Leeson (2007) for an overview and discussion. The challenge of using simple rules as guidelines is that it is not clear how one should use them in practice. Hardly anyone recommends that central banks should adhere mechanically to a simple rule. Svensson (2003) addresses this challenge and expresses some scepticism to the use of such rules: *"The proposal to use simple instrument rules as mere guidelines is incomplete and too vague to be operational"*.

As explained above, Norges Bank aims to be as precise and consistent as possible when implementing judgment in the monetary policy analysis. This requires that the use of simple rules as guidelines should also be modelled, at least if the policymakers do place some weight on these rules when assessing an appropriate interest rate (path). One way to model policy decisions that are partially based on guidance from simple rules is to extend the loss function with terms penalizing deviations of the interest rate from the level implied by the simple rules. The (period) loss function which is minimized is then given by

$$L_t = (\pi_t - \pi^*)^2 + \lambda y_t^2 + \gamma (i_t - i_{t-1})^2 + \eta [a_1 (i_t - i_{1,t})^2 + a_2 (i_t - i_{2,t})^2 + \dots + a_n (i_t - i_{n,t})^2], \quad (7)$$

where $i_{j,t}$ is the interest rate prescribed by interest rate rule j and n is the number of interest rate rules which the central bank puts weight on. If the simple rules are chosen to be robust across models, the weight η determines how much the central bank aims to guard against bad results due to model uncertainty. By specifying η and the weights a_j on the various rules, the use of simple rules as cross-checks and guidelines can be modelled in a precise way. It is of course difficult to choose relevant robust simple rules and find the appropriate weights η and a_1, \dots, a_n . Future research will hopefully give more insights to both the specification of robust rules and to how much weight the central bank should place on them. A first step of investigating this

¹²See e.g., Leitimo and Söderström (2005).

is found in Roisland and Sveen (2010). Notwithstanding the difficulty of choosing the relevant robust rules and the appropriate weights on them, if the central bank actually puts some judgmental weights on rules, being forced to model it explicitly has evidently some advantages. First, it ensures consistency over time and provides more discipline in the internal discussions. Second, by treating simple rules within an optimal policy framework, one is able to deviate from simple rules in an optimal way given the reference model.

The optimizing framework is also flexible, as new rules can replace existing rules when research gives new insights to the specification of simple robust rules. For example, it will be useful to derive both optimal simple rules in a Bayesian model averaging framework and simple minimax rules based on alternative models of the Norwegian economy, or different versions of NEMO. Such simple rules could replace or supplement the variants of the Taylor rule used by the Bank today and provide better insurance against the costs of model uncertainty.

4.4 Our practical approach

The process of producing an interest rate forecasts can briefly be described as follows: First, new information is inserted into the monetary reaction function used in the previous forecasting round. The new information generally implies a different forecast, and this revised forecast is a benchmark for ensuring a consistent reaction pattern. However, this approach assumed that the previous forecast (or reaction function) was the correct one, and there is a danger of inheriting past errors or dubious judgments if the new forecast based solely on new information is adopted. Therefore, the staff also conducts a thorough assessment of the interest rate path independently of the previous forecast. As a general guidance for assessing the interest rate path, the Bank has developed a set of criteria for a good interest rate path¹³:

1. **Inflation targeting.** Inflation should be stabilized around the target in the medium term.
2. **Weight on output stability.** There should be a reasonable balance between the inflation gap and the output gap.
3. **Gradualism and consistency.** Interest rate adjustments should normally be gradual and consistent with the Bank's previous response pattern.
4. **Robustness and cross-checks.** The interest rate path should be robust to uncertainty about the economic developments and the functioning of the economy. The interest rate path should be cross-checked against other information such as market expectations and simple rules.

The criteria serve two roles. First, they represent a guidance for the staff when producing the interest rate path, and second, they represent an agenda for the Board's discussion and assessment of the interest rate path.

¹³See Qvigstad (2006) for a discussion of the criteria.

The first two criteria could be interpreted as minimizing the standard loss function

$$E \sum_{t=0}^{\infty} \beta^t [(\pi_t - \pi^*)^2 + \lambda y_t^2]. \quad (8)$$

As described above, the loss function is minimized under the assumption of constrained discretion, that is, discretion with a modified loss function designed to implement outcomes closer to the commitment solution. However, the timeless commitment solution is also monitored. Figure 5 illustrates the outcome of minimizing the loss function (8) using NEMO with the initial conditions as of March 2010 when the MPR 1/10 was published. For any reasonable weight λ on output, optimal policy given this loss function implied a considerably lower than the path actually decided by the Board (see figure 1).

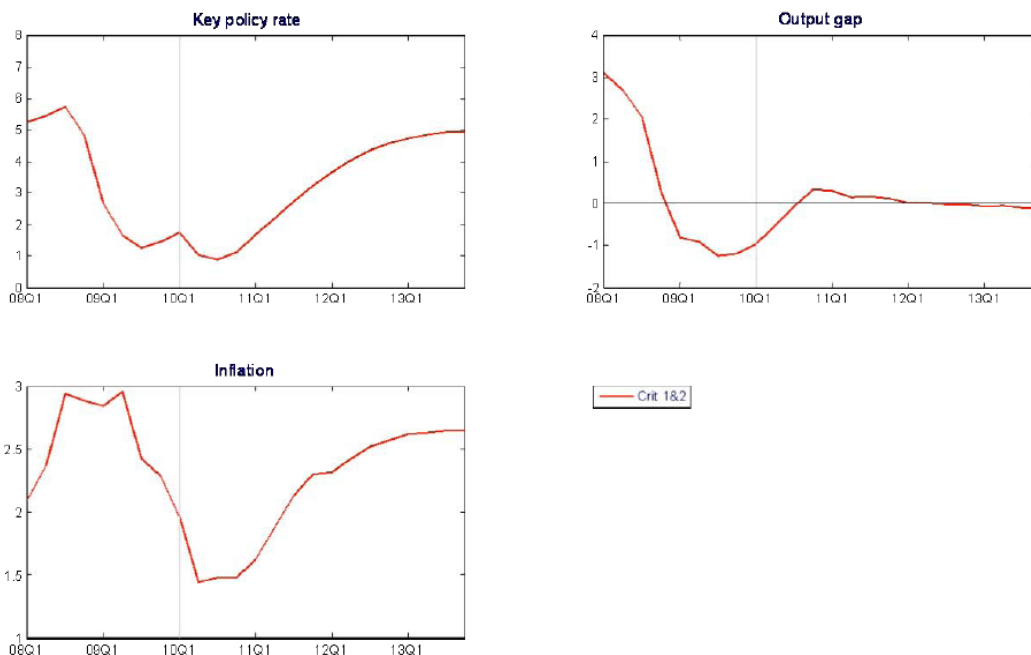


Figure 5: NEMO as of MPR 1/2010. Minimizing adjusted loss function under discretion, criteria 1 and 2

Taking gradualism, as prescribed by criterion 3, into account could be interpreted as adding an interest rate smoothing term in the loss function:

$$E \sum_{t=0}^{\infty} \beta^t [(\pi_t - \pi^*)^2 + \lambda y_t^2 + \gamma (i_t - i_{t-1})^2]. \quad (9)$$

Minimizing the loss function (9) gives a more moderate interest rate path, as illustrated in figure 6.

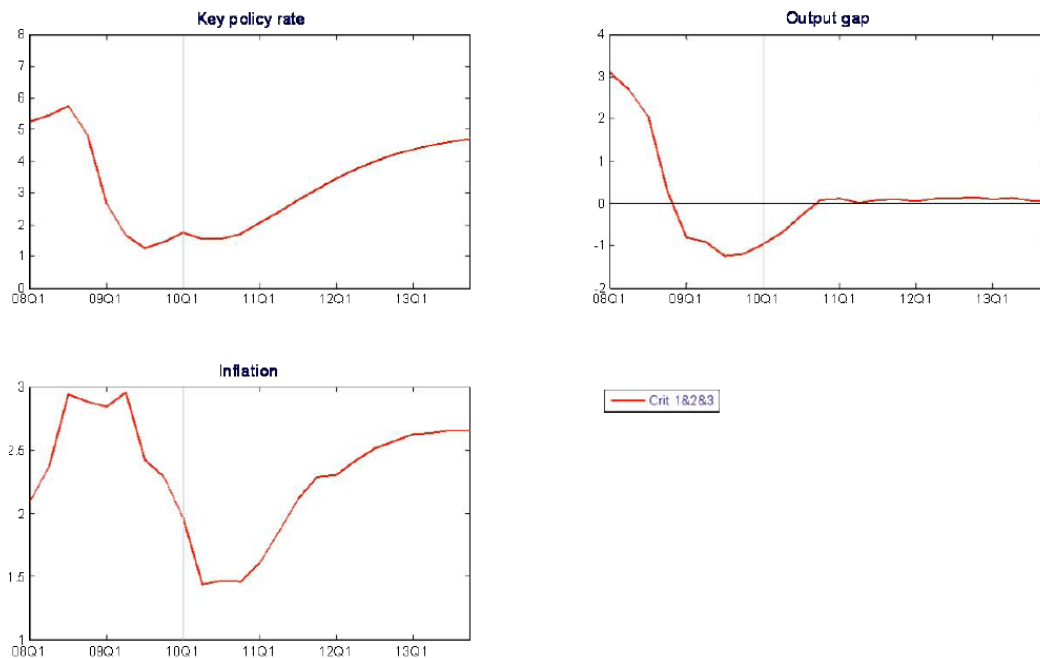


Figure 6: NEMO as of MPR 1/2010, minimizing adjusted loss under discretion, criteria 1,2 and3.

The fourth criterion is about robustness and cross-checks. As discussed above, there economic literature has developed several approaches to deal with robustness, and the Bank aims to apply more of these approaches in the future. Currently, our practical approach to robustness is to cross-check our interest rate path with simple interest rate rules, which are assumed to be robust. Norges Bank usually look at three alternative Taylor-type rules. First, we consider the original Taylor rule (Taylor (1993)). Then, we use a version where the output gap is replaced by the output *growth* gap, i.e., $i_t = r_t^* + \pi^* + 1.5(\pi_t - \pi^*) + 0.5(y_t - y_{t-1})$. This version is meant to be more robust against misperceptions of potential output and is inspired by work by Orphanides and van Norden (2002) and Rudebusch (2002). Third, we use a version of the Taylor rule where the foreign real interest rate is added to the rule, i.e., $i_t = r_t^* + \pi^* + 1.5(\pi_t - \pi^*) + 0.5y_t + 0.5r_t^f$. The choice of coefficient values for these rules are based on the original Taylor rule and have not been subject to any optimization. Obviously, more research is required on how one should calibrate simple robust rules. Another feature of the rules we have used so far is that there is no inertia in terms of a lagged interest rate. However, when optimizing simple rules in most models, a positive coefficient on the lagged interest rate tends to occur.¹⁴ The motivation for considering rules with no lagged interest rate response is that the Bank has used them as a cross-check on whether the current interest rate is on the

¹⁴Taylor and Wieland (2009) find, however, that a simple rule without the lagged interest rate term has good robustness properties.

right level. When used as cross-checks, the interest rate implied by the rules today and in next few quarters (based on short-term forecasts of output and inflation) are compared to the current level of the policy rate, as illustrated in figure 7.

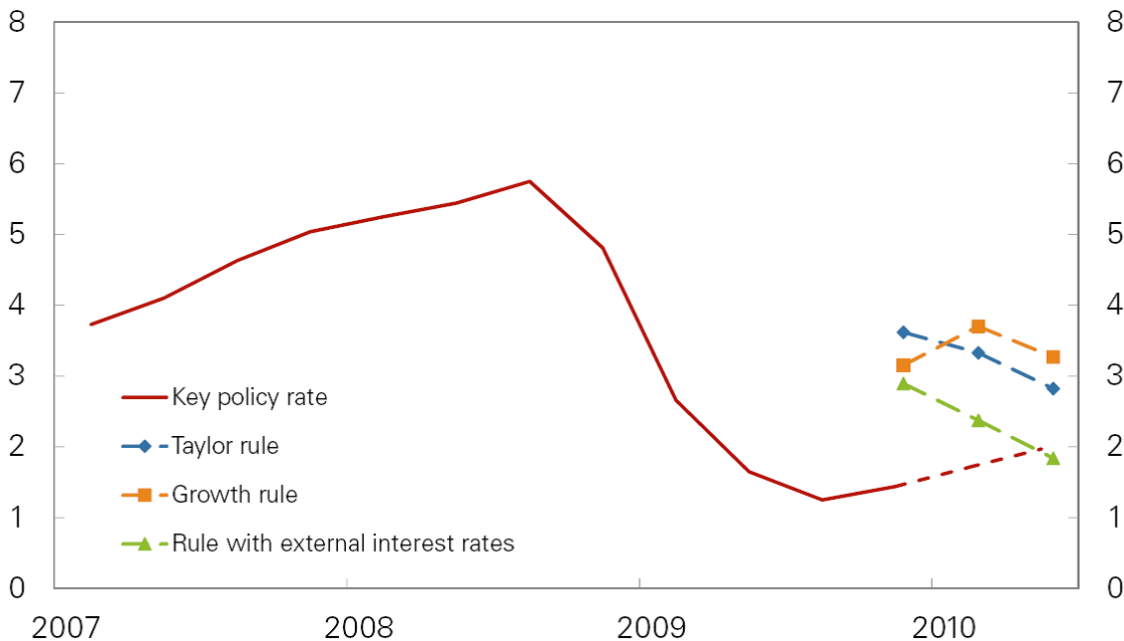


Figure 7: Cross-checks against simple rules based on short term forecast.

As seen in figure 7, the simple rules implied a somewhat higher interest rate than the current level.

If we assume that the Board places some weight on, e.g., the Taylor rule, one could minimize the loss function

$$E \sum_{t=0}^{\infty} \beta^t [(\pi_t - \pi^*)^2 + \lambda y_t^2 + \gamma(i_t - i_{t-1})^2 + \eta(i_t - i_t^T)], \quad (10)$$

where $i_t^T = r_t^* + \pi^* + 1.5(\pi_t - \pi^*) + 0.5y_t$.

Figure 8 illustrates optimal policy with a moderate weight on the original Taylor rule. Although a given interest rate path can be replicated by different specifications of the loss function, the published interest rate path is consistent with optimal policy minimizing the loss function (10).¹⁵

Based on the loss function, the staff can produce a menu of alternative forecasts conditional on different sets of weights in the loss function. Then, the Board can choose the forecast that most consistent with their preferences. Such an approach is similar to letting the Board decide on the bases of a set of *efficient* forecasts, as proposed and described by Svensson (2010b). Svensson does not, however, consider loss functions with weight on simple rules. By modelling the menu of choice, the staff

¹⁵The published path could also be replicated by a loss function with a weight on deviation of the interest rate *level* from the normal level.

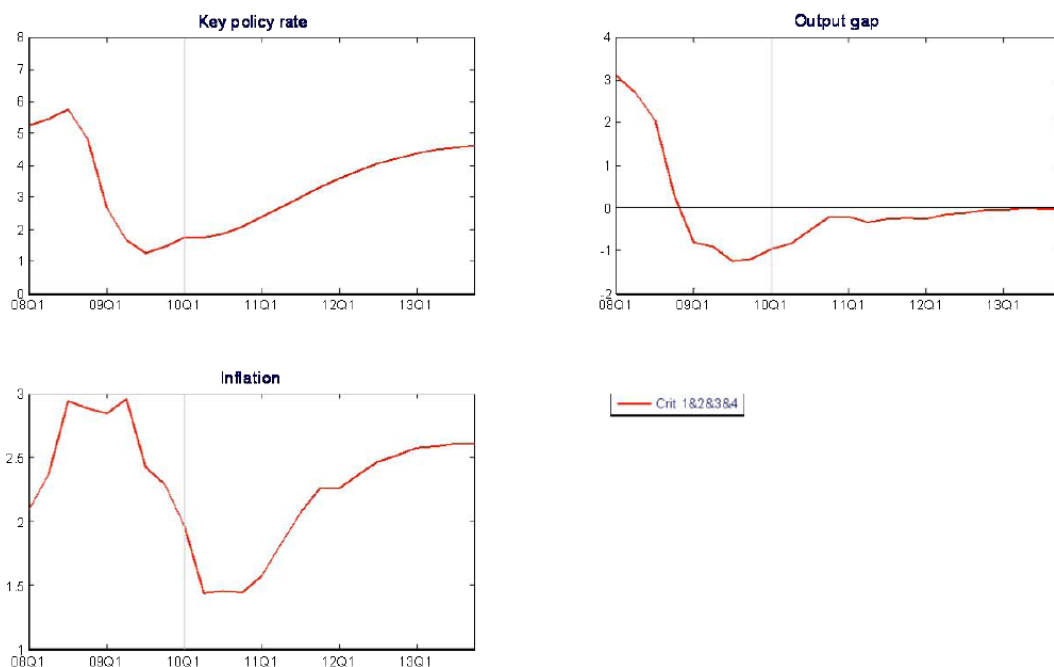


Figure 8: NEMO as of MPR 1/2010, minimizing adjusted loss under discretion, criteria 1,2,3 and 4.

is able to inform the Board if the choice is not consistent with previous choices and is thus able to detect whether the Board seems to re-optimize and not honour past commitments in the for of previous published conditional forecasts with corresponding communicated reaction function. Even if there could sometimes be appropriate to deviate from the earlier reaction pattern, since new insights to the working of the economy and new economic conditions can warrant such deviations, predictability is a norm.

5 Concluding remarks

This paper has described the analytical framework for monetary policy decisions currently used at Norges Bank. The Bank aims to utilize relevant analytical tools developed in the academic literature and apply them in practical monetary policy analysis. Since international research on monetary policy is under continuous development, so is our practical monetary policy analysis. There will, however, generally be a lag between research advances and implementation in practical policy. The lag reflects both limited human resources and that the academic literature often use simpler models than the ones used for forecasting and policy analysis at central banks. However, Norges Bank aims to make the lag between theoretical advances and practical implementation as short as possible. We believe that trying to be at the forefront in applying new tools for monetary policy analysis makes the staff more focused and

the policy discussions richer and more disciplined. That said, one must also recognize that new theoretical advances must be applied with care, as every analytical approach has some limitations. It is therefore important to use considerable judgment when applying new tools.

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Appendix: NEMO

Final goods sector The perfectly competitive final goods sector consists of a continuum of final good producers indexed by $x \in [0, 1]$ that aggregates composite domestic intermediate goods, Q , and imports, M , using a constant elasticity of substitution (CES) technology:

$$A_t(x) = \left[\eta^{\frac{1}{\mu}} Q_t(x)^{1-\frac{1}{\mu}} + (1-\eta)^{\frac{1}{\mu}} M_t(x)^{1-\frac{1}{\mu}} \right]^{\frac{\mu}{\mu-1}}, \quad (11)$$

The degree of substitutability between the composite domestic and imported goods is determined by the parameter $\mu > 0$, whereas η ($0 \leq \eta \leq 1$) measures the steady-state share of domestic intermediates in the final good for the case where relative prices are equal to 1.

The composite good $Q(x)$ is an index of differentiated domestic intermediate goods, produced by a continuum of firms $h \in [0, 1]$:

$$Q_t(x) = \left[\int_0^1 Q_t(h, x)^{1-\frac{1}{\theta_t}} dh \right]^{\frac{\theta_t}{\theta_t-1}}, \quad (12)$$

where the time-varying elasticity of substitution between domestic intermediates is captured by θ_t and evolves according to:

$$\ln \left(\frac{\theta_t}{\theta} \right) = \lambda_\theta \ln \left(\frac{\theta_{t-1}}{\theta} \right) + \varepsilon_t^\theta, \quad 0 \leq \lambda_\theta < 1, \quad \varepsilon_t^\theta \sim iid(0, \sigma_\theta^2) \quad (13)$$

where $\theta > 1$ is the steady-state value.

Similarly, the composite imported good is a CES aggregate of differentiated import goods indexed by $f \in [0, 1]$:

$$M_t(x) = \left[\int_0^1 M_t(f, x)^{1-\frac{1}{\theta^f}} df \right]^{\frac{\theta^f}{\theta^f-1}}, \quad (14)$$

where $\theta^f > 1$ is the steady-state elasticity of substitution between imported goods.

Intermediate goods sector Each intermediate goods firm h is assumed to produce a differentiated good $T_t(h)$ for sale in domestic and foreign markets using the following CES production function:

$$T_t(h) = \left[(1-\alpha)^{\frac{1}{\xi}} (Z_t z_t^L l_t(h))^{1-\frac{1}{\xi}} + \alpha^{\frac{1}{\xi}} \bar{K}_t(h)^{1-\frac{1}{\xi}} \right]^{\frac{\xi}{\xi-1}}, \quad (15)$$

where $\alpha \in [0, 1]$ is the capital share and ξ denotes the elasticity of substitution between labour and capital. The variables $l_t(h)$ and $\bar{K}_t(h)$ denote, respectively, hours used and effective capital of firm h in period t . There are two exogenous shocks

to productivity in the model: Z_t refers to an exogenous permanent (level) technology process, which grows at the gross rate π_t^z , whereas z_t^L denotes a temporary (stationary) shock to productivity (or labour utilization). The technology processes are modelled as

$$\ln(Z_t) = \ln(Z_{t-1}) + \ln(\pi^z) + \ln\left(\frac{\pi_t^z}{\pi^z}\right), \quad (16)$$

where

$$\ln\left(\frac{\pi_t^z}{\pi^z}\right) = \lambda_z \ln\left(\frac{\pi_{t-1}^z}{\pi^z}\right) + \varepsilon_t^z, \quad 0 \leq \lambda_z < 1, \quad \varepsilon_t^z \sim iid(0, \sigma_z^2), \quad (17)$$

and

$$\ln\left(\frac{z_t^L}{z^L}\right) = \lambda_L \ln\left(\frac{z_{t-1}^L}{z^L}\right) + \varepsilon_t^L, \quad 0 \leq \lambda_L < 1, \quad \varepsilon_t^L \sim iid(0, \sigma_L^2). \quad (18)$$

The variable $K_t(h)$ is defined as firm h 's capital stock that is chosen in period t and becomes productive in period $t + 1$. Firm h 's *effective* capital in period t is related to the capital stock that was chosen in period $t - 1$ by

$$\bar{K}_t(h) = u_t(h) K_{t-1}(h), \quad (19)$$

where $u_t(h)$ is the endogenous rate of capital utilization. When adjusting the utilization rate the firm incurs a cost of $\gamma_t^u(h)$ units of final goods per unit of capital. The cost function is

$$\gamma_t^u(h) = \phi_1^u \left(e^{\phi_2^u (u_t(h) - 1)} - 1 \right), \quad (20)$$

where ϕ_1^u and ϕ_2^u are parameters determining the cost of deviating from the steady state utilization rate. The steady state utilization rate is normalized to one.¹⁶

Firm h 's law of motion for physical capital reads:

$$K_t(h) = (1 - \delta) K_{t-1}(h) + \kappa_t(h) K_{t-1}(h), \quad (21)$$

where $\delta \in [0, 1]$ is the rate of depreciation and $\kappa_t(h)$ denotes capital adjustment costs. The adjustment costs take the following form:

$$\begin{aligned} \kappa_t(h) = & \frac{I_t(h)}{K_{t-1}(h)} - \frac{\phi_1^I}{2} \left[\left(\frac{I_t(h)}{K_{t-1}(h)} - \left(\frac{I}{K} + z_t^I \right) \right) \right]^2 \\ & - \frac{\phi_2^I}{2} \left(\frac{I_t(h)}{K_{t-1}(h)} - \frac{I_{t-1}}{K_{t-2}} \right)^2, \end{aligned} \quad (22)$$

where I_t denotes investment and z_t^I is an investment shock¹⁷ that evolves according to

$$\ln\left(\frac{z_t^I}{z^I}\right) = \lambda_I \ln\left(\frac{z_{t-1}^I}{z^I}\right) + \varepsilon_t^I, \quad 0 \leq \lambda_I < 1, \quad \varepsilon_t^I \sim iid(0, \sigma_I^2). \quad (23)$$

¹⁶Note that ϕ_1^u is not a free parameter. It is set to ensure that the marginal cost of utilisation is equal to the rental rate of capital in steady-state.

¹⁷This shock could e.g., represent changes in the relative price of consumption and investment.

The labour input is a CES aggregate of hours supplied by a continuum of infinitely-lived households indexed by $j \in [0, 1]$:

$$l_t(h) = \left[\int_0^1 l_t(h, j)^{1-\frac{1}{\psi_t}} dj \right]^{\frac{\psi_t}{\psi_t-1}}, \quad (24)$$

where ψ_t denotes the elasticity of substitution between different types of labour that evolves according to:

$$\ln \left(\frac{\psi_t}{\psi} \right) = \lambda_\psi \ln \left(\frac{\psi_{t-1}}{\psi} \right) + \varepsilon_t^\psi, \quad 0 \leq \lambda_\psi < 1, \quad \varepsilon_t^\psi \sim iid(0, \sigma_\psi^2). \quad (25)$$

Firms sell their goods in markets characterized by monopolistic competition. International goods markets are segmented and firms set prices in the local currency of the buyer. An individual firm h charges $P_t^Q(h)$ in the home market and $P_t^{M^f}(h)$ abroad, where the latter is denoted in foreign currency. Nominal price stickiness is modelled by assuming that firms face quadratic costs of adjusting prices,

$$\gamma_t^{P^Q}(h) \equiv \frac{\phi^Q}{2} \left[\frac{P_t^Q(h)}{\pi P_{t-1}^Q(h)} - 1 \right] \quad (26)$$

$$\gamma_t^{P^{M^f}}(h) \equiv \frac{\phi^{M^f}}{2} \left[\frac{P_t^{M^f}(h)}{\pi P_{t-1}^{M^f}(h)} - 1 \right] \quad (27)$$

in the domestic and foreign market, respectively and π denotes the steady-state inflation rate in the domestic economy. In every period cash-flows are paid out to the households as dividends.

Firms choose hours, capital¹⁸, investment, the utilization rate and prices to maximize the present discounted value of cash-flows, adjusted for the intangible cost of changing prices, taking into account the law of motion for capital, and demand both at home and abroad, $T_t^D(h)$. The latter is given by:

$$T_t^D(h) = \int_0^1 Q_t(h, x) dx + \int_0^1 M_t^f(h, x^f) dx^f \quad (28)$$

Households The period utility function is additively separable in consumption and leisure. The lifetime expected utility of household j is:

$$U_t(j) = E_t \sum_{i=0}^{\infty} \beta^i [z_{t+i}^u u(C_{t+i}(j)) - v(l_{t+i}(j))], \quad (29)$$

¹⁸Capital is firm-specific, but since all firms are identical and there is no price dispersion this assumption does not affect the linearised dynamics of the model.

where C denotes consumption, l is hours worked and β is the discount factor $0 < \beta < 1$. The consumption preference shock, z_t^u , evolves according to

$$\ln \left(\frac{z_t^u}{z^u} \right) = \lambda_u \ln \left(\frac{z_{t-1}^u}{z^u} \right) + \varepsilon_t^u, \quad 0 \leq \lambda_u < 1, \quad \varepsilon_t^u \sim iid(0, \sigma_u^2). \quad (30)$$

The current period utility functions for consumption and labour choices, $u(C_t(j))$ and $v(l_t(j))$, are

$$u(C_t(j)) = (1 - b^c/\pi^z) \ln \left[\frac{(C_t(j) - b^c C_{t-1})}{1 - b^c/\pi^z} \right], \quad (31)$$

and

$$v(l_t(j)) = \frac{1}{1 + \zeta} l_t(j)^{1+\zeta}. \quad (32)$$

where the degree of external habit persistence in consumption is governed by the parameter b^c ($0 < b^c < 1$) [and the disutility of supplying labour is governed by the parameter $\zeta > 0$.]

Each household is the monopolistic supplier of a differentiated labour input and sets the nominal wage subject to the labour demand of intermediate goods firms and subject to quadratic costs of adjustment, γ^W :

$$\gamma_t^W(j) \equiv \frac{\phi^W}{2} \left[\frac{W_t(j)/W_{t-1}(j)}{W_{t-1}/W_{t-2}} - 1 \right]^2 \quad (33)$$

where W_t is the nominal wage rate.

The flow budget constraint for household j is:

$$\begin{aligned} P_t C_t(j) + S_t B_{H,t}^f(j) + B_t(j) &\leq W_t(j) l_t(j) [1 - \gamma_t^W(j)] \\ &+ [1 - \gamma_{t-1}^{B^f}] (1 + r_{t-1}^f) S_t B_{H,t-1}^f(j) \\ &+ (1 + r_{t-1}) B_{t-1}(j) + DIV_t(j) - TAX_t(j), \end{aligned} \quad (34)$$

where S_t is the nominal exchange rate, $B_t(j)$ and $B_{H,t}^f(j)$ are household j 's end of period t holdings of domestic and foreign bonds, respectively. Only the latter are traded internationally. The domestic short-term nominal interest rate is denoted by r_t , and the nominal return on foreign bonds is r_t^f . The variable DIV includes all profits from intermediate goods firms and nominal wage adjustment costs, which are rebated in a lump-sum fashion. Finally, home agents pay lump-sum (non-distortionary) net taxes, TAX_t , denominated in home currency.

A financial intermediation cost, γ^{B^f} , is introduced to guarantee that aggregate net foreign assets follow a stationary process. This cost depends on the average net foreign asset position of the domestic economy. The intermediation cost takes the following form¹⁹

$$\gamma_t^{B^f} = \phi^{B1} \frac{\exp \left(\phi^{B2} \left(\frac{S_t B_{H,t}^f}{P_t Z_t} \right) \right) - 1}{\exp \left(\phi^{B2} \left(\frac{S_t B_{H,t}^f}{P_t Z_t} \right) \right) + 1} + z_t^B, \quad (35)$$

¹⁹See e.g., Laxton and Pesenti (2003) for a discussion of this specification of the intermediation cost.

where $0 \leq \phi^{B1} \leq 1$ and $\phi^{B2} > 0$. The exogenous ‘risk premium’, z_t^B , evolves according to

$$\ln \left(\frac{z_t^B}{z^B} \right) = \lambda_B \ln \left(\frac{z_{t-1}^B}{z^B} \right) + \varepsilon_t^B, \quad 0 \leq \lambda_B < 1, \quad \varepsilon_t^B \sim iid(0, \sigma_B^2). \quad (36)$$

Government The government purchases final goods financed through a lump-sum tax. Real government spending (adjusted for productivity), $g_t \equiv G_t/Z_t$, is modelled as a first-order autoregressive process

$$\ln \left(\frac{g_t}{g} \right) = \lambda_G \ln \left(\frac{g_{t-1}}{g} \right) + \varepsilon_t^G, \quad 0 \leq \lambda_G < 1, \quad \varepsilon_t^G \sim iid(0, \sigma_G^2) \quad (37)$$

where G_t is real per capita government spending.

The central bank sets a short-term nominal interest rate, r_t^* . We consider two alternative specifications of monetary policy. First, we assume that the behavior of the central bank can be represented by a simple instrument rule. Specifically, the central bank sets the interest rate according to a rule which in its log-linearized version takes the form

$$r_t^* = \omega_r r_{t-1}^* + (1 - \omega_r) [\omega_\pi \pi_t + \omega_y gdp_t + \omega_{rer} rer_t], \quad (38)$$

where π_t is the aggregate inflation rate, and rer_t is the real exchange rate defined as $\ln(S_t P_t^f / P_t)$. The parameter $\omega_r \in [0, 1)$ determines the degree of interest rate smoothing. Output (gdp_t) is measured in deviation from the stochastic productivity trend²⁰, the remaining variables are in deviation from their steady-state levels.

The alternative assumption about monetary policy is that the central bank sets the interest rate to minimize the intertemporal loss function.

$$E_t \sum_{i=0}^{\infty} \beta^i [\pi_{t+i}^2 + \omega_y^2 (gdp_{t+i})^2 + \omega_{\Delta r} (r_{t+i}^* - r_{t+i-1}^*)^2]. \quad (39)$$

The loss function is minimized subject to the log-linearized first-order conditions of the private sector and the exogenous shock processes.

The interest rate that enters into the decisions of households and firms, r_t , equals the interest rate set by the monetary policy authority, r_t^* , plus a shock, z_t^r , that is

$$r_t = r_t^* + z_t^r \quad (40)$$

where

$$\ln \left(\frac{z_t^r}{z^r} \right) = \lambda_r \ln \left(\frac{z_{t-1}^r}{z^r} \right) + \varepsilon_t^r, \quad 0 \leq \lambda_r < 1, \quad \varepsilon_t^r \sim iid(0, \sigma_r^2) \quad (41)$$

This shock could be interpreted e.g., as variations in the banks interest rate margins or in the spread between the key policy rate and the short-term interest rate in the money market.

²⁰Empirically, and under both assumptions about monetary policy, this measure of the output gap turns out to be quite similar to the output gap obtained using a standard Hodrick-Prescott filter which again resembles the preferred measure of the output gap published by Norges Bank.

Foreign variables The foreign variables that enter the model are the real marginal cost of foreign firms, mc_t^f , the output gap, y_t^f , the interest rate r_t^f and the inflation rate π_t^f . There are two shocks originating in the foreign economy.²¹ Specifically, foreign marginal costs and the output gap in the foreign economy are assumed to follow first-order autoregressive processes

$$\ln \left(\frac{mc_t^f}{mc^f} \right) = \lambda_{mc^f} \ln \left(\frac{mc_{t-1}^f}{mc^f} \right) + \varepsilon_t^{mc^f}, \quad 0 \leq \lambda_{mc^f} < 1, \quad \varepsilon_t^{mc^f} \sim iid(0, \sigma_{mc^f}^2) \quad (42)$$

$$y_t^f = \lambda_{y^f} y_{t-1}^f + \varepsilon_t^{y^f}, \quad 0 \leq \lambda_{y^f} < 1, \quad \varepsilon_t^{y^f} \sim iid(0, \sigma_{y^f}^2) \quad (43)$$

²¹As we have not included shocks to foreign inflation or the interest rate in the model, we cannot separate the risk premium shock in the UIP condition from a foreign interest rate shock. Moreover, all movements in the real exchange rate will be attributed to shocks affecting the nominal exchange rate or the domestic inflation rate.