Monetary policy rules and estimated reaction functions for the European Central Bank

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Tiivistelmä – Referat – Abstract

This thesis studies the interest-rate policy of the ECB by estimating monetary policy rules using real-time data and central bank forecasts. The aim of the estimations is to try to characterize a decade of common monetary policy and to look at how different models perform at this task. The estimated rules include: contemporary Taylor rules, forward-looking Taylor rules, nonlinear rules and forecast-based rules. The nonlinear models allow for the possibility of zone-like preferences and an asymmetric response to key variables. The models therefore encompass the most popular sub-group of simple models used for policy analysis as well as the more unusual non-linear approach. In addition to the empirical work, this thesis also contains a more general discussion of monetary policy rules mostly from a New Keynesian perspective. This discussion includes an overview of some notable related studies, optimal policy, policy gradualism and several other related subjects.

The regression estimations are performed with either least squares or the generalized method of moments depending on the requirements of the estimations. The estimations use data from both the Euro Area Real-Time Database and the central bank forecasts published in ECB Monthly Bulletins. These data sources represent some of the best data that is available for this kind of analysis.

The main results of this thesis are that forward-looking behavior appears highly prevalent, but that standard forward-looking Taylor rules offer only ambivalent results with regard to inflation. Nonlinear models are shown to work, but on the other hand do not have a strong rationale over a simpler linear formulation. However, the forecasts appear to be highly useful in characterizing policy and may offer the most accurate depiction of a predominantly forward-looking central bank. In particular the inflation response appears much stronger while the output response becomes highly forward-looking as well.

Avainsanat – Nyckelord – Keywords
ECB, monetary policy, Taylor rules, non-linear reaction functions, real-time data, central bank forecasts

Contents

1 Introduction

The empirical analysis of monetary policy is an active field with a great number of studies that attempt to characterize and analyze monetary policy. There are also new methods and developments that try to better capture the practice of monetary policy and the changes in policy over time. Now that more than ten years have passed since the beginning of the common monetary union, it is a relatively opportune time to evaluate the behavior of the European Central Bank by estimating linear and nonlinear models to examine the interest rate policy of the ECB. This thesis should also give some idea of how different models perform at this task. The empirical estimation of monetary policy rules is a very commonly applied method for the evaluation of monetary policy. Monetary theory has increasingly endeavored to apply a systematic approach to policy behavior in a modern theoretical context. This has resulted in an ever growing literature on rules-based monetary policy of which Woodford (2003) has been the most dominant account. One strand of research in this vein has been an analysis of monetary policy reaction functions with different specifications of policy rules, most commonly with Taylor rules functioning as relatively simple approximations of optimal monetary policy. There is no shortage of such studies for the ECB either, but this thesis should offer at least a few new potentially significant contributions. The results in this thesis also suggest that rational expectations modeling may well be less reliable for the ECB than the alternative of employing explicit forecasts. The empirical contributions of this thesis include the estimated reaction functions based on real-time data for a time period spanning from January 1999 to June 2009, and the estimated reaction functions that are based on biannual and quarterly forecasts published in the ECB Monthly Bulletins from December 2000 to June 2010. The estimated models include standard Taylor rules and less common nonlinear models.

Monetary policy issues are often analyzed with both simple and optimal rules in different contexts. Such rules can be used as rough guidelines for monetary policy, in theoretical models, and in econometric research. The rules can be useful for both external and internal analysis (Berg et al. 2004). Externally, it is possible to study past policy and to forecast future policy. Internally, central banks can evaluate policy alternatives and use them for communication purposes. The theoretical and general section of this thesis covers a discussion of some of the main ideas of this literature. A policy rule is understood in this thesis in the flexible manner that it is often treated in modern analysis. This means that a policy rule is loosely considered to be a “prescribed guide to monetary policy”, as defined by Svensson (1999). The main virtue of this definition is to allow for optimal rules, targeting rules, instrument rules and simple feedback rules. These concepts will be covered in the thesis as part of an overview on monetary policy rules. The treatment will be fairly broad since the overview attempts to reflect at least some of the main ideas of the literature on this matter. This exposition therefore mostly concentrates on some of the core concepts.

Since a large number of similar empirical studies do exist, it is worth underlining some of the potentially noteworthy aspects of this thesis. The ECB has had the task of conducting monetary policy for more than ten years, which should make the estimation of reaction functions an increasingly palatable approach due to an increasingly lengthy sample period. This should make estimation results more reliable and potentially more accurate than they have been in the past. This thesis is also entirely focused on using real-time data in all circumstances, which is often seen as preferable to revised data. The difference between real-time data and revised data can have an important effect on results, as argued by Orphanides (2001) in particular. The real-time database that facilitates the use of real-time data has only recently become easily available, which is probably why it has been previously used very rarely. This study also employs Eurosystem and ECB staff forecasts, another potentially extremely useful source of data that probably has not been made use of up to this point. This is likely because of the sporadic nature of these forecasts, which is admittedly still a practical difficulty. In spite of that, this thesis will show that actual forecasts paint a significantly different picture of monetary policy, while also avoiding some of the issues with forward-looking models that rely on instrumented variables. This thesis also contains several nonlinear estimations, which are uncommon in comparison to linear counterparts. The nonlinear model used for this purpose is a recent proposal of Boinet and Martin (2008), which provides a fairly flexible monetary policy model, and which allows the analysis of some non-standard aspects of monetary policy.

The structure of this thesis is as follows. The first few chapters discuss monetary policy modeling in a general way and introduce a number of issues relevant to the empirical section and also cover empirical studies similar to this one. Chapter two begins with a general discussion of monetary policy rules and includes a short history of such rules, while the main modern alternatives are considered more extensively. The distinction between optimal and simple rules is discussed, as well as concepts such as discretion and commitment. The New Keynesian model is also introduced since it is used on several occasions in this thesis. Chapter three covers Taylor rules, which in their various forms are the most popular empirical formulas. Chapter four is quite broad in scope and covers certain important extensions such as the empirically significant phenomenon of interest rate smoothing. Chapter five is an overview of some related studies, with examples particularly for the US Fed and the ECB. Chapter six is a short chapter on ECB policy. This chapter covers some of the general principles of ECB policy and includes a short look at how policy is conducted and some of the recent changes in the operative framework brought on by the financial crisis.

The empirical section of this thesis begins in chapter seven, which gives details about the data that is used in this thesis. This section explains the data sources, the variables that are used and how the variables have been transformed before estimation. Chapter eight details the estimation method and the estimations. First, there is a section that deals with the choice of estimation method. Since this thesis makes extensive use of the generalized method of moments (GMM) estimation, it is covered in some detail. The reason for using GMM for forward-looking rules is explained, as well as other issues relevant to carrying out the estimations. Chapter eight also contains the results for all the estimations. These include estimates for contemporary Taylor rules, forward-looking rules with the rational expectations method, the nonlinear rules and the forecast-based estimations. Chapter nine offers some final conclusions.

2 Monetary policy rules

2.1 Background on policy rules

Policy rules have been commonly advocated to stabilize the economy, to make monetary policy more consistent and transparent, or even to make it more accountable. Prescriptively these rules have attempted to define what would be good monetary policy. For instance, discretionary policy can lead to a suboptimal outcome, as shown by Barro and Gordon (1983). Discretionary policy refers to policy that is chosen freely in any time period. A discretionary central bank with an overly ambitious output goal will result in an incentive to inflate. The implication is that optimal policy is not time-consistent. By committing to not exploit this incentive the bias could be eliminated. In the New Keynesian models that do not have the problem of an overambitious output goal there can still be a stabilization bias caused by discretionary policy.

In general systematic policy is widely perceived as valuable. This is something that Woodford (2003) has also emphasized in his comprehensive work on policy rules. Systematic policy can be important when expectations about policy are important, as they very commonly are in modern analysis, like in the dichotomy between discretion and commitment. Systematic policy will also be more transparent, and the need for transparency has become increasingly underscored in modern monetary policy. At the same time policy also needs to be comprehensible. It is possible to state goals for monetary policy, such as the now typical announcement of an explicit inflation target. These goals are not directly controlled by policymakers, however, so more specificity is necessary. In addition to different normative considerations about good monetary policy, policy rules are commonly used for descriptive purposes. Simple rules are often quite useful for this purpose. Monetary policy is most often modeled in the literature as something akin to a Taylor rule or more rigorously as optimal policy under either discretion or commitment. These main scenarios are eventually covered in this text.

Proposals for the conduct of monetary policy have a very long history. To give some context and background on monetary policy rules, a short summary of the history of monetary rules is provided that draws mainly from the account of Asso et al. (2007). The idea of monetary rules, like various other concepts in economics, can be traced at least back to Adam Smith, who wrote about how a well-regulated paper money would be preferable to commodity money, such as metal coins. During the 19th century, many classical economists advocated rules of conduct to regulate the money supply in the hopes of ending intermittently occurring crises. The gold standard itself can be thought of as a sometimes stable monetary rule. A notable policy rule of the time is Walter Bagehot's rule for mitigating financial crises. The rule calls for a central bank to provide liquidity to financial institutions against collateral and at a penalty rate, essentially making the central bank a lender of last resort. This prescription is still quite relevant even today, as shown by recent events. Around the turn of the 20th century Irving Fisher and Knut Wicksell, both important monetary theorists, proposed their own monetary rules. Wicksell's rule was an early version of an interest-rate rule that recommended adjusting interest rates solely in response to fluctuations in prices. Fisher advocated a compensated dollar rule, where the gold content of a dollar would be changed whenever price stability would require it.

A more recent famous policy rule is Milton Friedman's constant money growth rule. The rule can be derived from a logarithmic version (as seen in Orphanides 2007) of the equation of exchange

$$\Delta m + \Delta v = \Delta p + \Delta y , \qquad (1)$$

where $\Delta p = \pi$ is inflation, Δm is the growth rate of money, Δv is the growth rate of the velocity of money, and Δy is the growth rate of real output. Assuming that the velocity (circulation speed) of money is stable and fixing the growth rate of money at *k* percent ensures that nominal GDP will also grow at a stable rate of *k* percent. So, stable money growth also leads to economic stability. One motivation for this rule was Friedman's suspicion of activist policy-making. Particularly when money velocity is stable enough this rule will be extremely robust and simple to implement (Orphanides 2007). However, a money aggregate rule is problematic when money demand is unstable, and could lead to high interest rate volatility (Clarida et al. 1999, 52). In practice, it has become increasingly difficult to define monetary targets that are linked tightly enough with the ultimate policy goals. Therefore, their value for monetary policy has been questioned (Bean et al. 2010). Nowadays, a short-term interest rate is more often treated as the the main policy instrument to achieve policy objectives and the role of monetary aggregates has somewhat diminished, with the ECB perhaps being a partial exception. While earlier monetary theory did tend to describe monetary policy in terms of setting the money supply, this is not how central banks typically operate (Goodhart 2007). Of course, recent events have also lead to untypical policy operations that have not been limited to traditional interest rate policy.

2.2 Classification of policy rules

2.2.1 Targeting rules

It is possible to divide modern policy rules into two classes that can both be used to characterize monetary policy. An alternative to instrument rules are targeting rules (see Svensson 1999; Svensson 2003), where the behavior of a central bank is determined by the objective function of an optimizing central bank that follows some specified target, while being constrained by the structural model of the economy. Those frameworks where a central bank has an intertemporal optimization problem can be considered the optimal control approach to decision-making, although targeting rules as advocated by Svensson (2003) are perhaps somewhat distinct in the sense that there is an emphasis on an announced target, as well as the allowance for the evolution of policy judgment. Monetary policy is therefore discretionary, although targeting rules with commitment are also possible. In fact, they may be preferable because discretionary optimization can be suboptimal with forward-looking behavior. The target variable could be an inflation target, but there can be other targets, or multiple targets for that matter so that policy can be characterized as flexible inflation targeting in the terminology of Svensson (1999). The objective function that contains the relevant targets is the general targeting rule, or alternatively the targeting regime. After adding a structural model of the economy, the constrained optimization problem can be solved for the first-order conditions. A specific optimal targeting rule can then be derived from the first-order conditions that will give the relationship between the target variables. It should also be noted that any reaction function implied by a targeting rule is subject to change whenever the model is updated. Svensson (2003) has advocated these types of rules as being a more realistic depiction of how inflation-targeting central banks actually conduct monetary policy. There is some debate on the relative merits of instrument and targeting rules that cannot be properly covered here (for a view that contrasts with Svensson 2003 see McCallum and Nelson 2005). One of the main issues with this framework is that the optimality property is quite sensitive to the model specifications (Giannoni and Woodford 2005). There are also practical difficulties with communicating such rules, since they can become very complicated. Woodford (2010) recommends searching for relatively simple and robust target criteria that would still be approximately optimal in more complex models. Optimal policy is thus generally any policy that is optimally derived from the objectives of monetary policy for a given model of the economy, although optimality can also sometimes be determined from the direction of the policy rule to the policy objectives.

In addition to a central bank's discretionary policy regime, if the policymaker should be able to commit by some method, there will be a difference between commitment and discretion when forward-looking expectations are important (Woodford 2003). Discretionary policy will then cause a stabilization bias. This is because the ability to directly affect expectations, which can improve the outcome of policy, is not available when the policy is discretionary.

To illustrate these differing policy frameworks in model form, the model of the economy first needs to be specified. This will be the basic New Keynesian model, which is the baseline model for many of the more complicated model frameworks used in monetary analysis. Since the New Keynesian model is highly prevalent in monetary policy and will appear in this paper with regularity, some of its main features will be described here. A characteristic feature of the New Keynesian framework is the presence of some form of price rigidity. Sticky prices or wages are what create the necessary friction for the short-term fluctuations that an economy exhibits. Typically, only a fraction of firms can adjust prices at any given period, which is known as a Calvo (1983) price-setting scheme, though there can be different kinds of rigidities as well. The real interest rate can be affected by the central bank because prices are sticky. Price stickiness also means that output can deviate from a “natural” level. Other characteristic features are monopolistic competition among firms and a macroeconomic model that is derived from the optimizing behavior of individual actors, so that the model has microfoundations. Expectations about the future are also extremely important as the basic framework is entirely forward-looking. This means that inflation has no inertial component, though modified versions often add backward-looking components that result in a sort of hybrid model. The main channels, or transmission mechanisms, of monetary policy are a short-term real interest rate, and potentially expectational channels as well. The interest rate channel works through aggregate demand, and a short-term interest rate may feed through to long-term rates. Inflation expectations are the other standard channel of monetary policy.

Instead of showing in detail how the equations of the macroeconomic model are derived from consumer and firm behavior, here they are merely presented in log-linearized form (details can be found in e.g., Galí 2002). The New Keynesian Phillips curve represents the aggregate supply of the economy. Inflation is a function of expected inflation and the output gap. The Phillips curve is derived from the pricing decisions of firms when they are faced with the possibility of prices being fixed for some time. Firms thus set prices as a mark-up over current and expected marginal costs. The output gap, which in a New Keynesian model is the deviation of output from its flexible price equilibrium, appears due to its relationship with real marginal cost. Expressed as an equation the New Keynesian Phillips curve is given by

$$\pi_t = \beta E_t \pi_{t+1} + \kappa x_t + e_t, \qquad (2)$$

where, π_t is inflation, x_t is the output gap, β is a discount term, κ is a coefficient that is closely linked to price rigidity and *t* denotes the time index. The cost shock term e_t makes policy more complicated as it forces a trade-off between the policy goals of inflation stabilization and output stabilization. Otherwise the central bank could achieve both at the same time.

Aggregate demand is given by a forward-looking IS curve that is derived from an Euler equation condition for the household. It relates the output gap positively to the expected output gap and negatively to the the real interest rate. Sometimes, though not in this case, the brackets will also contain a term for the natural rate of interest so that the deviation of the real interest rate from the natural rate (an equilibrium rate) is important, as emphasized by Woodford (2003). The equation for aggregate demand is given by

$$x_t = E_t x_{t+1} - \sigma (i_t - E_t \pi_{t+1}) + u_t, \qquad (3)$$

where σ is a coefficient related to the intertemporal substitution of consumption, i_t is the nominal interest rate and u_t is a demand shock term.

Finally, the framework for the model is completed with a specification of monetary policy. In cases when it is not a postulated instrument rule, the optimal response is found by first solving the constrained optimization problem. Examples of the optimal frameworks under both commitment and discretion are shown to better illuminate these approaches. The example for discretionary policy is taken from Clarida et al. (1999). The intertemporal loss function of the central bank is given by

$$W = -\left(\frac{1}{2}\right) E_t \left[\sum_{i=0}^{\infty} \beta^i L_t \right]. \tag{4}$$

The intertemporal loss function implies that the central bank wishes to minimize (in this case by maximizing (4) because of the negative sign) the expected discounted sum of period losses. The loss function for a single period is given by

$$L_t = [\pi_t^2 + \alpha x_t^2], \tag{5}$$

where $\alpha > 0$, which gives the relative weight placed on the output gap. This quadratic loss function implies that the central bank aims to minimize the squared deviations of inflation and output. Typically, something like (5) is the standard way to define the policy objectives of monetary policy, though the output gap here is specifically a deviation from a flexible price equilibrium. The literature on monetary policy has generally treated these policy objectives as pragmatic assumptions about policy preferences, but Woodford (2003) has also shown that a quadratic intertemporal loss function is an approximation of the welfare of a representative agent.

Under discretion a central bank cannot affect private sector expectations about future inflation. In the case of (4) the central bank attempts to maximize this function by choosing (x_t, i_t, π_t) while taking expectations as given. The optimization problem can be solved by forming a Lagrangian function with the macroeconomic constraints of (2) and (3). Aggregate demand does not actually matter as a constraint as long as the non-negativity condition of the nominal interest rate never plays a constraining role. The optimization problem proceeds in two stages. In the first stage, solving the first-order optimality condition for this set-up will lead to

$$\alpha x_t = -\lambda \pi_{t.} \tag{6}$$

This is the optimal targeting rule. What this condition says is that demand is contracted when inflation is above target and vice versa when it is below target. The aggressiveness of this response depends inversely on α and positively on λ. The interest rate plays a role in that it is chosen to achieve the optimal values of inflation and output. With the optimality condition of (6) and the Phillips curve in (2) the equilibrium values of the target variables can then be solved. The optimal feedback rule for the interest rate is found by inserting the appropriate value of x_t into the demand curve in (3).

The assumption in the above model has been that the central bank reacts immediately to the state of the economy. If the central bank needs to rely on forecasts for its decisions, as it generally probably does, the model needs to be amended with the central bank's forecasts of the future. Policy will then depend on those forecasts.

Instead of practicing discretionary policy, the central bank might be able to credibly commit its policy in some manner. This will have implications about the conduct of policy. With commitment the policymaker chooses its optimal plan and then promises to stick with it. Starting once more with the central bank's objective function and stating it this time as in Giannoni and Woodford (2005)

$$W = E_{t_0}\left[\sum_{t=t_0}^{\infty} \beta^{t-t_0} L_t\right], \tag{7}$$

where t_0 is some initial period. The period loss now takes the form

$$L_t = \pi_t^2 + \lambda x_t^2. \tag{8}$$

Now it is $\lambda > 0$ that gives the relative weight of output. The decision problem involves finding the paths of (x_t, π_t) to minimize the loss function while subject to the constraint of the supply curve in (2). Since the interest rate still has no relevant constraint it can be ignored as before. The solution proceeds in the same way as with discretion by forming a Lagrangian and solving for the first-order conditions. These can be stated as

$$\pi_t + \varphi_t + \varphi_{t-1} = 0, \tag{9}$$

$$\lambda x_t - \kappa \varphi_t = 0, \tag{10}$$

where φ_t is the Lagrange multiplier. These conditions hold for every period, except the initial one. In the first period the multiplier $\varphi_{t-1} = 0$ since there is no commitment requirement for the first period. The path of the Lagrange multipliers can also be solved. After that the evolution of output, inflation and the interest rate can be solved for as well. Unlike in the case of discretionary policy, commitment leads to the history dependence of policy. One way to see this is by the targeting rule found after eliminating the multiplier from the first-order conditions in (9) and (10)

$$\pi_t + \frac{\lambda}{\kappa}(x_t - x_{t-1}) = 0. \tag{11}$$

The optimal trade-off between the variables now depends also on the output gap of the previous period. This is the key difference between discretion and commitment; the discretionary policymaker will find that it is optimal to ignore what has happened before. It will find the condition in (6) every time it re-optimizes. This makes optimal policy time-inconsistent, and the lack of history dependence can lead to a stabilization bias from discretionary policy. This bias is caused by discretionary policy lacking the stabilizing effect on expectations that commitment would have. The significance of the welfare gain from commitment is discussed and quantified by Dennis and Söderström (2006). There are also timelessly optimal rules (Woodford 2003), which imply a slightly different form of commitment. In timelessly optimal rules the conditions of (9) and (10) hold for the initial period as well, with an implied commitment made in the past.

What allows an optimal rule to improve on a simple rule? One reason is that the optimal rule is specifically designed to achieve an optimal trade-off between the objectives of monetary policy in the applicable macroeconomic model. Whether this advantage will actually lead to significant welfare gains is not entirely clear (Taylor and Williams 2010). Comparative results between simple and optimal rules will usually be rather model-dependent. An example of simple rules performing more or less optimally is in Schmitt-Grohe and Uribe (2007). An additional advantage of the simple rules considered by Schmitt-Grohe and Uribe (2007) is the minimal amount of information that is needed for actually implementing them, as the required macroeconomic indicators are mostly readily available. An example of a study where optimal policy can lead to some improvement is the Area Wide Model for the euro area (Dieppe et al. 2004).

2.2.2 Instrument rules

Instrument rules commonly take a more direct approach to decision-making and are not necessarily derived from optimum conditions. One possible reason that fully optimal instrument rules are not considered that often is that they may be impracticable (Svensson 2003), at least when the complexity of the model increases significantly, so that a more feasible alternative would be some simple instrument rule. However, deriving optimal instrument rules is a viable enough approach, and such an approach is used in this study. It is also worth mentioning that distinctions between targeting and instrument rules are not necessarily always that important since a targeting rule implies an instrument rule. In any case, various Taylor-type rules are the most common class of simple rules with numerous variations. The word *simple* refers here to rules that only make use of some of the available information. Their simplicity, robustness, popularity, and empirical track record make them a practical choice for the purposes of this study. Because of the multiple variations that exist of the original rule, it is not always clear what exactly qualifies as a Taylor rule. Still, any simple interest-rate rule that adjusts to deviations from both an inflation and output target can probably be labeled a Taylor rule, or a Taylor-type rule to distinguish it from the original rule. One of the main reasons to use such a formula is that it is likely to be a good approximation for optimal policy (Galí 2002).

Some of the other advantages of these rules come from their simplicity and intuitiveness, although the simplicity has its drawbacks as well. It should not be expected that such simple formulations could be truly optimal policies for a central bank as emphasized by Svensson (2003), although they can be shown to be optimal instrument rules in some simple models, of which examples are shown later. One argument for using simple rules is that they may perform nearly as well as optimal rules (Taylor and Williams 2010; Schmitt-Grohe and Uribe 2007; Galí 2002). Another justification is that a useful policy rule should be quite robust across a wide range of models (Orphanides 2007). This means that a rule should perform well in a variety of macroeconomic models and not just one specific model; Taylor rules are typically viewed as quite robust in this way (Taylor and Williams 2010). The robustness can be tested by simulating rules in different models to find the rules that minimize output and inflation variation in multiple settings (Taylor and Williams 2010). The need for a robust rule comes from the uncertainty about how the economy actually works and hence the “correct” model, which makes robustness an inherently valuable property. Even though the rules are simple, they can often track actual policy closely and can provide a fairly readily available benchmark for monetary policy. On the other hand, a reliance on imprecisely measured concepts like potential output can be problematic.

3 Taylor-type rules

3.1 The original Taylor rule

John Taylor (1993) proposed a hypothetical monetary policy rule that became subsequently known as the Taylor rule. Taylor's now famous contribution sprang from research that had found that a promising policy rule responded to deviations from targets of both inflation and output. Taylor's rule has become widely used as a simple way to describe and evaluate monetary policy, though quite often in some modified way in an attempt to be more realistic. The original rule can be expressed by a simple equation

$$i = 2 + \pi + \frac{1}{2}(\pi - 2) + \frac{1}{2}(y - y^{*}), \tag{12}$$

Where i is the short-term policy rate (in Taylor's paper the US Federal funds rate), π is the rate of inflation (here a GDP deflator over the previous four quarters) and $y - y^*$ is the output gap, or the percentage deviation of real output y from potential real output y^*. Potential output is the long-run trend of an economy (or a flexible price equilibrium in New Keynesian models), so the output gap is a measure of slack in the economy. Taylor claimed that his rule was a good description of Federal Reserve policy between 1987-92.

It should be noted that Taylor's rule was not econometrically estimated. The parameters were chosen with plausible and rounded values in mind. The inflation target was assumed to be equal to 2, as was the equilibrium real interest rate (sometimes known as the natural rate). The coefficients for the inflation and output gaps were both 0.5. However, the logic of the rule does not require these particular values, and other values have also been considered (e.g., Taylor and Williams 2010). As well, there are many versions of Taylor-type rules with a better statistical fit than the original rule. Adding interest-rate lag tends to improve the fit of a Taylor rule sizably, as can forecast-based inflation measures (for a statistical comparison of different rules in the case of the US Fed, see Fernandez and Nikolsko-Rzhevskyy 2007). Generalized Taylor rules offer a potentially useful framework for econometric evaluation (Orphanides 2007).

In addition to being a good description of policy, Taylor also claimed that his rule could also be a good prescription for policy. This was mainly justified by model simulations and the good performance of monetary policy during this period. Taylor stressed, however, that a policymaker couldn't and shouldn't follow a rule mechanically. A simple algebraic rule cannot capture all the relevant information that a decision-maker can use when setting policy and the inevitable need for judgment. Rather, following a rule as a guideline implies a systematic and coherent approach to policy-making.

Deviations from such a rule can be justified as reactions to special factors. A plausible reason for such discretion could be, for instance, a financial shock. Taylor himself gives the 1987 stock market crash as an example. A note of caution is appropriate here, though. As Svensson (2003, 28) states, there are no rules for when to deviate from a rule. The issue of discretionary policy has resurfaced again in the context of the recent financial crisis and the Fed's conduct before it. Taylor (2007) has argued that Fed policy was too loose before the crisis. This possibility will be briefly considered later in this paper.

A critical take on both Taylor rules and optimal rules as normative policy tools from a central bank's point of view can be found in ECB (2001). On the other hand, the description “rule-based, but not rule-bound” has been occasionally evoked by the ECB. In any case, no normative claims are made with the rules used in this paper.

3.2 Estimating a Taylor rule

Instead of assuming parameters, they can be estimated from data. A Taylor rule with unspecified parameters is given by

$$i_t = r^* + \pi_t + a(\pi_t - \pi^*) + \beta_y(y_t - y^*), \tag{13}$$

where r^* is the equilibrium real interest rate, π^* is the inflation target. The weight a measures the sensitivity of the policy rate to the inflation gap, while β_y measures the sensitivity of policy to the output gap. Manipulating this equation slightly leads to equation

$$i_t = r^* + \pi^* + (1 + a)(\pi_t - \pi^*) + \beta_y(y_t - y^*). \tag{14}$$

Plugging Taylor's suggestion of a=0.5 into equation (4) yields

$$i_t = r^* + \pi^* + 1.5(\pi_t - \pi^*) + \beta_y(y_t - y^*). \tag{15}$$

This implies that the nominal policy rate should adjust strongly (more than one-for-one) to deviations from the inflation target. This is in accordance with the Taylor principle. Defining $\beta_\pi = 1 + a$ changes (14) into

$$i_t = r^* + \pi^* + \beta_\pi(\pi_t - \pi^*) + \beta_y(y_t - y^*). \tag{16}$$

The Taylor principle requires that $\beta_\pi > 1$. The principle implies that the real interest rate is adjusted in response to inflation. This is important because it is the real interest rate that should have an effect on economic decisions.

To get a regression to estimate (16) can be reformulated as

$$i_t = \alpha + \beta_\pi \pi_t + \beta_y (y_t - y^*) + \epsilon_t \tag{17}$$

Where $\alpha = r^* + (1 - \beta_\pi)\pi^*$ is a constant and ϵ_t is an error term. Notably, because both r^* and π^* are embedded inside the constant term, it is not possible to separately identify them without making some further assumptions.

3.3 Theoretical properties of the Taylor rule

Woodford (2001) has considered some of the theoretical properties of the original Taylor rule. One of the key points is that appropriate coefficients, like the ones chosen by Taylor, are sufficient to determine a rational expectations equilibrium price level. A rule that fulfills the Taylor principle can ensure that there is a unique stationary solution for output and inflation. The Taylor principle can also ensure that there are no inflationary spirals. These spirals could be driven by inflationary shocks that result in a lower real interest rate, which leads to higher expected inflation and in turn leads to a lower interest rate, and so forth. Since determinacy is quite important for interest-rate rules, and to make this determinacy condition more concrete, an example of a stabilizing rule will be shown for the canonical New Keynesian model.

The first equation is the linearized forward-looking IS equation restated in a slightly different form as

$$x_t = E_t x_{t+1} - \sigma (i_t - E_t \pi_{t+1} - r_t^n), \tag{18}$$

where r_t^n is the natural rate of interest. This emphasizes that monetary effects on output work through the gap between the prevailing interest rate and the equilibrium rate. There is also no shock term in the IS curve this time. Aggregate supply is given by the New Keynesian Phillips curve, and it is written once more as

$$\pi_t = \beta E_t \pi_{t+1} + \kappa x_t + e_t \tag{19}$$

where β is a discount rate representing time preference, κ is a coefficient, and e_t is a cost shock term. Monetary policy is set according to the rule

$$i_t = r_t^n + \phi_\pi \pi_t + \phi_x x_t \tag{20}$$

Adding the policy rule into equation (18) yields an equation of the form

$$x_t = E_t x_{t+1} - \sigma(\phi_\pi \pi_t + \phi_x x_t - E_t \pi_{t+1}) \tag{21}$$

This system that consists of equations (19) and (21) can then be written in matrix notation as

$$\begin{bmatrix} 1 & \sigma \\ 0 & \beta \end{bmatrix} \begin{bmatrix} E_t x_{t+1} \\ E_t \pi_{t+1} \end{bmatrix} = \begin{bmatrix} 1+\sigma\phi_x & \sigma\phi_\pi \\ -\kappa & 1 \end{bmatrix} \begin{bmatrix} x_t \\ \pi_t \end{bmatrix} + \begin{bmatrix} 0 \\ -e_t \end{bmatrix}. \tag{22}$$

Multiplying both sides with the inverse of the matrix on the left while also using a more compact notation of (22) will lead to

$$E_t z_{t+1} = A z_t + A_1^{-1} e_t, \tag{23}$$

where A_1^{-1} is the inverted matrix and

$$A=\begin{bmatrix} 1+\sigma\phi_x+\kappa\frac{\sigma}{\beta} & \sigma\phi_\pi-\frac{\sigma}{\beta} \\ \frac{-\kappa}{\beta} & \frac{1}{\beta} \end{bmatrix},$$

is a matrix consisting of the coefficients of the model. This system is stable if and only if the number of eigenvalues of the matrix A that are outside the unit circle is equal to the number of forward-looking variables, which is two in this case. This is equivalent to a condition that the characteristic roots λ of the characteristic equation of the matrix A are outside the unit circle. The characteristic roots can be found from

$$det(A-\lambda I)=0,$$

where *I* is an identity matrix. Omitting some calculations, the stability condition will apply when

$$\phi_\pi+\frac{\phi_x(1-\beta)}{\kappa}>1. \tag{24}$$

Taylor's suggested values satisfy this condition. Additionally, assuming that β is approximately equal to one means that then the inflation coefficient has to be more than one for the system to be stable. The stability condition of (24) will in this case reduce to approximately $\phi_\pi>1$, which is just the Taylor principle once more. The stability conditions of various linear policy rules are considered more fully in Bullard and Mitra (2002). The stabilizing property of the Taylor principle in these theoretical models has made it of interest in empirical studies, as well.

Generally speaking, determinacy is not assured in the case of interest-rate policy, so it is quite a crucial issue. For instance, for purely forward-looking rules determinacy is not assured (Svensson and Woodford 2005). Even the standard result of the determinacy property of the Taylor principle has a number of qualifications. In particular, when steady state inflation is positive, the Taylor principle is not enough to ensure determinacy. Determinacy in the New Keynesian model can still be recovered with an additional response to output growth (Coibion and Gorodnichenko 2009).

Finally, in Woodford's analysis the goals of inflation and output stability are also appropriate goals of monetary policy when they're correctly understood. Here, since this is analysis based on a New Keynesian framework, output stabilization means stabilization around a potential output corresponding to a flexible price equilibrium, which may not be equivalent with an empirical counterpart. Inflation is undesirable since it causes a dispersion of prices between goods, which in turn leads to a reduction in household welfare, as inflation will cause inefficient reallocation. Output fluctuations are undesirable because there is a preference for smoothed consumption. As mentioned earlier, an intertemporal loss function containing these policy goals has been shown by Woodford (2003) to be an approximation of household welfare. Also, Svensson (1999) has argued that inflation and output gaps are widely recognized as the proper targets of monetary policy by both researchers and policymakers.

3.4 Optimal simple rules

Assuming that a central bank commits to a simple interest-rate rule, what would this rule be like? The optimally derived simple instrument rules presented in this section are from Svensson (2003). The central bank has an intertemporal loss function, where the loss function consists of the expected sum of discounted losses given by

$$E\left[(1-\delta)\sum_{n=0}^{\infty}\delta^{\tau}L_{t+\tau}|I_t, z^t\right] \quad . \tag{25}$$

Here $E\left[\cdot|I_t, z^t\right]$ denotes rational expectations about the economy given the central bank's information set I_t, as well as the bank's judgment term z^t, while δ is the discount factor and $(1-\delta)$ is a scaling term for the discount factors.

The loss function for a single period is given by

.

$$L_t=\frac{1}{2}[(\pi_t-\pi^*)^2+\lambda x_t^2] \tag{26}$$

Where λ is the weight of output stabilization relative to inflation stabilization. As before, when $\lambda>0$ it means that the central bank has a flexible inflation target and places some weight on the output gap as well. The policy problem is to set the policy instrument, a short-term interest rate, in each period so that it minimizes the intertemporal loss function given the central bank's information set and its “judgment” .

The solutions for both a backward-looking model and a forward-looking model are showcased. These will lead to somewhat different results with different implications. In the backward-looking model expectations are modeled as adaptive expectations where aggregate supply is given by

$$\pi_{t+1} = \pi_t + \alpha_x x_t + \alpha_z z_{t+1} + \epsilon_{t+1}, \tag{27}$$

where α_x is a positive coefficient, z_{t+1} is a vector of exogenous variables, α_z is a vector of coefficients and ε is a cost shock term. The exogenous variables are additional determinants of the target variables that are unknown in period t. The idea is that they are additional information not present in a model that a central bank could still find useful when implementing policy.

Aggregate demand is defined as

$$x_t = \beta_x x_t + \beta_z z_{t+1} - \beta_r (r_t - \bar{r}) + \eta_{t+1}. \tag{28}$$

Where $\bar{r}$ is the average real interest rate, $r = i_t - \pi_{t+1 \vee t}$ is the short real interest rate and η is a demand shock.

For the forward-looking model, which is a variation of the basic New Keynesian model presented earlier, aggregate supply is given by

$$\pi_{t+1} - \pi = \delta (\pi_{t+2|t} - \pi) + \alpha_x x_{t+1|t} + \alpha_z z_{t+1} + \epsilon_{t+1}. \tag{29}$$

Here $\pi = E(\pi_t)$ is average inflation and z_{t+1} again gives the additional information unknown at time t. Aggregate demand in the forward-looking model is given by

$$x_{t+1} = x_{t+2|t} - \beta_r (i_{t+1|t} - \pi_{t+2|t} - r^*_{t+1}) + \eta_{t+1}, \tag{30}$$

in which r^*_t is the Wicksellian natural rate.

Simplifying this potentially complicated framework so that the response to the judgment term is ignored, Svensson (2003) shows that the optimal decision rule for the backward-looking model is

$$i_t = r^* + \pi^* + (1 + \frac{1-c}{\alpha_x \beta_r})(\pi_t - \pi^*) + (\alpha_x + \frac{1-c}{\beta_r} + \frac{\beta_x}{\beta_r}) x_t . \tag{31}$$

The inflation gap is contemporary in (31) because the forecast for inflation in the next period is predetermined. The rule itself is a Taylor rule where the coefficients are derived from model parameters.

The optimal decision for the forward-looking model is, when expressed in the same way as Gorter et al. (2008),

$$i_{t+1} = r^*_{t+1,t} + \pi^* + (\pi_{t+2,t} - \pi^*) + \frac{\alpha_x}{\psi \beta_t}(\pi_{t+1,t} - \pi^*) + \frac{1}{\beta_r}(x_{t+2,t}) . \tag{32}$$

The rule implies that in a forward-looking model forecasts are important for the current interest rate decision (or rather the announcement of the interest rate for the next period) of the central bank, so that policy decisions are based on the forecasts. Also, the rule is no longer necessarily that simple because of the forward-looking terms.

4 Extensions and issues

4.1 Interest rate smoothing

When estimating policy rules, the rules are usually modified to take into account gradual adjustment of the policy rate. Empirical estimates find that a lagged interest rate is statistically significant and improves fit. In literature, this is a phenomenon that is variously called gradualism, inertia or interest rate smoothing. The gradual adjustment is typically modeled by

$$i_t=(1-\rho)i_t^*+\rho i_{t-1}, \tag{33}$$

where i_t^* is a target rate given by the policy rule and ρ is the smoothing parameter. It is possible to have more complicated lag structures, but a single lag is the most common specification.

Adding the rule from (16) into (33) will give

$$i_t=(1-\rho)(r^*+\pi^*)+(1-\rho)\beta_\pi(\pi_t-\pi^*)+(1-\rho)\beta_y(y_t-y^*)+\rho i_{t-1}. \tag{34}$$

To get an estimable function from (34) it is rewritten as

$$i_t=(1-\rho)\alpha+(1-\rho)\beta_\pi\pi_t+(1-\rho)\beta_y(y_t-y^*)+\rho i_{t-1}+\epsilon_t, \tag{35}$$

with $\alpha=r^*+(1-\beta_\pi)\pi^*$ being a constant term.

Rudebusch (2006) states that for quarterly data the smoothing parameter ρ is typically estimated to be around 0.8, which implies very slow adjustment. The case for the significance of ρ is strong, but explanations for it vary. Sack and Wieland (2000) look at a number of possible reasons for such behavior. First, forward-looking behavior implies that a small adjustment will be expected to be followed by later adjustments, which reduces the need for a large change in policy and decreases interest rate volatility. This means that smoothing can be advantageous in a forward-looking model (see also Woodford 2001). Second, data uncertainty may lead to cautious behavior by a policymaker, as data is likely to be revised later on. A third reason is parameter uncertainty, which involves uncertainty about the structure of the economy and the transmission mechanism of monetary policy. This uncertainty could induce policymakers to moderate their actions by gradual policymaking. Sack and Wieland (2000) argue that these issues can make central bank gradualism a sensible policy. Another possible justification for changing interest rates only gradually is a desire to reduce the volatility in financial markets that might be caused by policy actions.

Rudebusch (2006), however, is critical of the idea that central banks actually practice gradualism over several quarters (but not of gradualism within a quarter). Rudebusch (2006) argues that the appearance of gradualism may be due to serially correlated shocks. That is, discretionary policy reacts to persistent economic shocks (omitted variables) that create an illusion of gradualism. Rudebusch (2006) also argues that if central bank policy is very inertial, it implies that policy should also be predictable. However, the yield curve, which relates interest rates to bond maturities, of interest rates shows little sign of such predictability. Financial markets apparently cannot predict future interest rates accurately enough given the gradualism of central banks. It is also possible that using revised data to explain real-time policy decisions accounts for the spurious gradualism (Lansing 2002). Another possibility is that the methods commonly used to estimate policy rules are flawed in the sense of containing weak instruments that cause gradualism to seem stronger than it actually is (Consolo and Favero 2009). This is tested by performing reverse regressions that yield different results because of the weak instruments.

It is possible to model serial correlation by

$$i_t = (1-\rho)\, i_t^* + \epsilon_t \tag{36}$$

where $e_t = \Phi e_{t-1} + \varepsilon_t$ is an AR(1) error term that represents episodic shocks and Φ is a serial correlation parameter. English et al. (2003) combined the partial adjustment and serial correlation models to get a nested model that can be formulated as

$$\Delta i_t = (1-\rho)\Delta i_t^* + (1-\lambda)(1-\rho)(i_{t-1}^* - i_{t-1}) + \lambda\rho\, \Delta i_{t-1} + \epsilon_{t.} \tag{37}$$

This model was also used to test between the two hypotheses and to find evidence of both partial adjustment and serial correlation in US data. This testing approach means manipulating the serial correlation and partial adjustment mechanisms in first differences so that it is possible to isolate a coefficient that can be used to test the null hypothesis of no partial adjustment. The rejection of the null implies that partial adjustment is also present. Castelnuovo (2007) has studied this issue with data for the euro area and finds a significant role for gradualism. While this can be used to test between the possible reasons for gradualism, Welz and Österholm (2005) note that the test may not be able to properly distinguish between them if there are relevant omitted variables.

4.2 Forward-looking rules

A forward-looking Taylor rule was popularized by Clarida et al. (1998). The results of their study will be summarized later in this paper, but the forward-looking rule they utilized is introduced in this section. Because it may take several quarters for monetary policy to have its full effect on the economy, and because it is probably a better representation of actual policy, forward-looking rules have become quite widely used in estimations of ECB reaction functions (e.g., Sauer and Sturm 2003; Fendel and Frenkel 2006), as well as other central banks. The rule in this case will be given by

$$i_t = r^* + \pi^* + \beta_\pi E_t(\pi_{t+n} - \pi^*) + \beta_y E_t(y_{t+k} - y^*_{t+k}) \quad (38)$$

where E_t denotes the expected deviation (based on the information set at time period t) of inflation n periods ahead, and the expected deviation of the output gap k periods ahead. K may also equal zero, corresponding then to the expected output gap of the current period. The data used in this study implies a slightly different treatment of what the central bank knows in the current period, however. Since the data that is used is specifically designed to be part of the data that the policymakers had access to during monthly meetings, the contemporary values are treated as known values. Otherwise the treatment is similar to Clarida et al.(1998). The inflation target is constant. There is no clear consensus on what the appropriate forecast horizons are, though quite often the inflation forecast horizon is from six months to a year or more and the output horizon has similar or clearly shorter forecast horizon. It is assumed that there are no systematic forecast errors, which means that equation (38) can be rewritten in terms of realized variables. This kind of formulation is generally estimated with the two-stage least squares method or with the generalized method of moments because of the endogeneity of the realized variables. The estimation methods require choosing appropriate instrument variables so that the error term will be orthogonal to the instruments from the information set.

Typical candidates for instruments are the lags of inflation and output gaps, as well as the lags of other explanatory variables, as these are some likely sources for valid instruments.

Adding the forward-looking rule from (38) into the partial adjustment of (33) gives

$$i_t = \rho i_{t-1} + (1-\rho)(r^* + \pi^*) + (1-\rho)[\beta_\pi E_t(\pi_{t+n} - \pi^*) + \beta_y E_t(y_{t+k} - y^*_{t+k})]. \tag{39}$$

To get an equation that can be estimated from (39), it is rewritten in terms of realized variables as

$$i_t = \rho i_{t-1} + (1-\rho)\alpha + \beta_\pi (1-\rho)(\pi_{t+n}) + \beta_y (1-\rho)(y_{t+k} - y^*_{t+k}) + \epsilon_t \tag{40}$$

and where $\alpha = r^* + (1-\beta_\pi)\pi^*$. The error term consists of

$$\epsilon_t = -(1-\rho)[\beta_\pi(\pi_{t+n} - E_t(\pi_{t+n})) + \beta_y(y_{t+k} - E_t(y_{t+k}))], \tag{41}$$

so that it is a linear combination of forecast errors and is therefore orthogonal to variables in the instrument set. This yields the orthogonality conditions that can be used in GMM estimation.

Alternatively, using real-time forecast data, for example the central bank's own projections or possibly some survey as a proxy forecast, means that this framework is no longer necessary. However, central bank forecasts are only sometimes made publicly available, which is presumably why estimations based on forecasts have not been as common. The ECB does publish the Eurosystem staff forecasts biannually in its Monthly Bulletins, and in addition to those forecasts it also publishes complementary ECB staff forecasts. Yet another approach would involve replicating the central bank's forecasts as closely as possible by constructing forecasts from a real-time database. An example of this kind of method for a variety of countries is Nikolsko-Rhzevskyy (2008). If no forecasts are available, then this could be a plausible alternative. On a final note, forecasts can be expected to have the advantage of containing far more information, as such forecasts are often likely to make use of a wide range of sources, perhaps also including central bank “judgment”.

4.3 Measurement issues and speed limit rules

The implementation of a policy rule as a policy or research tool requires specific knowledge about what is happening in the economy. Such data may not always be easily obtainable and can be subject to both measurement errors and revision. These problems can be weakness of policy rules as the various issues with inputs weaken the empirical robustness of these rules. For instance, Kozicki (1999) finds that Taylor rules are not very robust when using alternative measures.

There are alternative ways of measuring inflation and the best measure is subject to some debate. It's possible to focus on either headline inflation or on core inflation that excludes some particularly volatile components in an index. It's also possible to use inflation forecasts to get a forward-looking rule. There is sometimes uncertainty about the actual inflation target.

An especially acute problem is the measurement of the output gap that requires estimating potential output, which is not actually known. Methods for estimating potential output include, but are not limited to, fitting a linear trend to data, using a Hodrick-Prescott filter to obtain a smoothed trend, or using a structural model to get a measure of the output gap. It is also possible to use unemployment measures instead of production measures. Orphanides (2001) has argued that a reliance on imprecise real-time data of the output gap was a major cause of economic problems in the 1970s. Interest rates were kept too low by the Fed because of a systematically misjudged output gap. These measurement problems still exist to this day. Additionally, analysis that relies on revised data may misrepresent actual policy by not taking into account the information that the decision-makers actually had in real-time. Unfortunately, real-time data is often difficult to acquire. This study, however, uses real-time data that is specifically designed to account for this problem, as well as real-time forecasts.

The equilibrium real interest rate also needs to be estimated and it may change over time (Woodford 2001). Such changes could lead to policy mistakes, as a change in the equilibrium real rate implies an equal change to the nominal policy rate. The values of all parameters in general could be expected to change over longer time periods. Some studies (e.g., Boivin 2006) try to take this kind of time variation into account by allowing the different coefficients to change over time.

The uncertainty about the level of the output gap provides an argument for responding to it with caution (Walsh 2004). Responding to a change in the output gap may be preferable to responding to its level. Although there are a few different versions of these types of rules, one general variant form Orphanides (2007) can be expressed as

$$i_t = r^* + \pi^* + \beta_\pi (\pi_t - \pi^*) + \beta_y (y_t - y_t^*) + \beta_{\Delta y} (\Delta y_t - \Delta y_t^*), \tag{42}$$

where $\beta_{\Delta y}$ denotes the parameter of the growth difference, Δy_t is output growth, and Δy_t is trend growth. Sometimes β_y can equal zero so that the output gap drops out of (42). This rule can be augmented with smoothing and forward-looking behavior in a similar manner as with the earlier examples. Adding a partial adjustment mechanism and defining parameters appropriately would mean that (42) collapses into a formula stated entirely in first differences, which would avoid the problems with unobserved variables such as the natural interest rate (see Orphanides 2007). The variants that are based on output growth are sometimes called “speed limit” rules and they are a fairly popular alternative, particularly since forecasts usually only report projections for GDP growth.

The reasoning for estimating speed limit rules is two-fold. First, output growth is more readily known than the output gap. Second, a response to output growth can also help recover determinacy (a unique rational expectations equilibrium for a New Keynesian macroeconomic model as shown earlier) with positive trend inflation. The usual Taylor principle result no longer ensures determinacy with a positive steady state inflation rate, but determinacy can be recovered with an additional response to output growth (Coibion and Gorodnichenko 2009).

4.4 The zero nominal bound

Since the zero bound on interest rates has become a more pressing issue lately, its implications are also briefly covered. Monetary policy can be constrained because nominal interest rates can't fall below zero since cash will always offer a guaranteed return of zero. While monetary policy may or may not be rendered ineffective in such a situation, the usual tool of interest rate adjustment is no longer available. Central banks may still wish to lower real interest rates further, but they can no longer achieve this by lowering nominal rates, and are therefore in a liquidity trap. This dilemma has become a more acute concern after Japan's experience of prolonged deflation and the near-zero rates in the United States and elsewhere have turned the bound into a relevant issue. In fact, many of the major central banks are as of this writing near the zero bound. As an example of the zero bound problem, Rudebusch (2009) used an estimated rule to forecast the Fed funds rate during the worst period of the economic crisis. The forecast implied that rates as low as negative 5 % would be needed. The inadequacy of interest rate policy has led to experimentation with policies such as quantitative easing and credit easing. The Fed and other central banks have engaged in a massive expansion of their balance sheets to enable the supply of liquidity (echoes of the Bagehot rule) and to bring down credit spreads. At the same time such a situation may require monetary policy to function mostly through expectational channels, perhaps by promising an extended period of low rates. In practice policy has also consisted of unusual and sometimes experimental actions.

The constraint has implications for policy as well, in that models now contain an explicit constraint where the interest rate cannot take negative values. There are various proposals to modify policy rules so as to avoid the zero bound situation. One way of handling this problem would be adjusting rules to avoid hitting the lower bound (Taylor and Williams 2010). One solution could be to respond more aggressively to output gaps. Another possibility is more aggressive policy in the vicinity of the zero bound. The interest-rate cuts that happened during the recent crisis could be understood in this way (Walsh 2009). Also, for theoretical reasons a price-level target might be desirable to lessen the impact of the zero bound (Walsh 2009). A price level target can be advantageous when expectations are forward-looking, as it can have an automatically stabilizing effect. Finally, a higher inflation target could give monetary policy more room to maneuver before reaching the zero bound, though this would lead to a trade-off with the costs of higher inflation. It should also be remarked that Benhabib et al. (2001) have pointed out that the Taylor principle that was earlier shown to avert inflationary spirals may not stop an economy from falling into a liquidity trap. In this scenario the economy can end up in a deflationary steady state at the zero nominal bound. Nakov (2008) has looked at the welfare effects of the zero bound on different monetary policy rules in a stochastic general equilibrium model. To summarize this study, a central bank with optimal commitment can credibly promise low rates in the future, while a discretionary policymaker cannot. In fact, discretionary policy now has a deflationary bias, which implies average inflation that is below its target value and that is caused by the inability to affect expectations when the zero bound constraint is binding. Simple Taylor rules lead to higher welfare losses from both the zero bound and their sub-optimality, but the zero bound will be met only very rarely under such a rule.

5 Empirical research and discussion

5.1 General research

The studies mentioned in this chapter constitute only a very small part of an extensive literature that has involved the estimation of policy rules for most of the central banks that have operated in the recent past. Even though the studies that estimate the parameters for an entire dynamic stochastic general equilibrium model are ignored in this chapter, the coverage of literature is still not even close to comprehensive. To begin with, Carare and Tchaidze (2005) offer a very useful critique of the practice of estimating policy rules and draw attention to many of the issues involved in their estimation. They also use simulations to study the effects of the incorrect specification of policy rules.

Judd and Rudebusch (1997) estimated separate reaction functions for three of the four Fed Chairmen that served during 1970–1997. The Chairmen were Arthur Burns (1970–1978), Paul Volcker (1979–1987) and Alan Greenspan (1987–1997). Judd and Rudebusch hypothesized that a change in Chairman was a likely source of a change in the Fed's reaction function.

The study initially compared Taylor's own specifications with actual policy and found that the Greenspan era conformed quite well with the original rule, while the Burns period and the Volcker period seemed to consistently deviate from the specified rule. During the Burns period the Fed funds rate tended to be lower than the recommended rule, and during the Volcker period the funds rate tended to be higher than recommended by the rule. This may highlight differing attitudes to inflation during these periods.

The estimations were divided into three sub-samples and allowed for the gradual adjustment of policy. The estimation for the Greenspan period had a fairly good statistical fit. However, the coefficient for the output gap was twice the size of Taylor's recommendation. Policy also seems to have been marked by gradual adjustment.

The regression for the Volcker period implies a response to a change in the output gap that cannot be statistically rejected. The coefficient of the inflation gap is close to Taylor's assumption. The estimation is less precise than the Greenspan version. This may be due to the high inflation at the time, or due to experimentation with operating procedures. The Burns period has a coefficient for the inflation gap that is not statistically significant. The implication is that the Taylor principle did not hold during this time. Policy appears to have responded gradually to economic activity and may have overestimated potential output.

Clarida et al. (1998) estimated reaction functions for several major central banks in an attempt to characterize monetary policy since 1979. They used a forward-looking Taylor rule with smoothing for this purpose and studied the central banks of Japan, the US, the UK, Germany, France, and Italy. Summarizing the results, there seemed to be a lot of consistency in the policies of the central banks. A workable policy responds strongly to inflation with some room for output stabilization. Inflation targeting is another key component in this period of policy-making. It is these kinds of studies that suggest that the Great Moderation (a time of globally reduced economic volatility that began in the 1980s) may have been partly due to better monetary policy since the early 1980s. Clarida et al. (2000) concentrate solely on Fed policy and divide it into two sub-samples of 1960–1979 and 1980–1996, and they find similar results to the earlier studies. The Fed's response to inflation is weak before Volcker's period, and a higher inflation target doesn't seem to account for the differences in policy between these two periods.

One caveat of note is that these studies made use of current data instead of the original data that policymakers had. As has been mentioned earlier, this can have an effect on results. Orphanides (2001) has argued that instead of having an overly lax response to inflation policymakers misjudged the capacity of the economy at the time. The potential for misleading inference from revised data is a reason to rely on real-time data when it is possible. That is why real-time data is used in this thesis at all times.

Boivin (2006) also analyzes the question of historical changes in the monetary policy of US monetary policy. Notably, all parameters are allowed to be time-varying. This allows finding gradual changes in policy not necessarily captured by a split sample approach. This study again suggests that the response to inflation was weak in the late 1970s while strong otherwise with significant overall shifts in conduct by the early 1980s. The results suggest that changes in monetary policy coincided with improvements in economic performance and therefore may have been one reason for this improvement.

There are many other studies for other central banks. To mention just a few, for the UK there is a study by Nelson (2003) and for Sweden a paper by Berg et al. (2004). Dolado et al. (2005) study the the possibility of central banks having asymmetric preferences, where the nonlinearity is derived from a nonlinear Phillips curve. They find some evidence for asymmetry for European central banks before the time of the monetary union, but there is less evidence of this for the US Fed. An explanation for this finding may be greater labor market rigidities in Europe. A different example of non-linearity is considered by Taylor and Davradakis (2006), where the reaction function can switch to another form depending on the state of the economy. A slightly different approach is taken by Boinet and Martin (2008). Here the reaction function is nonlinear to take into account the potentially zone-like preferences and asymmetrical responses of the central bank. Boinet and Martin find that a nonlinear rule does better than a standard Taylor rule for the UK. An estimated monetary rule for South Africa (Naraidoo 2010) also makes use of this model. The model is of particular interest because it is used in this study as well.

5.2 Estimated reaction functions for the ECB

Gerlach and Schnabel (2000) estimated a standard Taylor rule and a forward-looking rule over the period 1990–1998 for countries that decided to join the European monetary union. They found that average interest rates in the EMU area closely followed a Taylor rule, except during the exchange rate turmoil in 1992–93. The purpose of the study was to see how much the ECB, if it employed a Taylor rule, would deviate from the average behavior of member states. They concluded that policy would not change by much, though the constructed “central bank” is rather artificial.

Sauer and Sturm (2003) have done an extensive study to estimate rules for the ECB. They note that some of the early studies on this subject found that the Taylor principle didn't seem to apply for the ECB. Using a standard rule they find similar evidence. Adding forward-looking behavior to the regressions changes the results so that the Taylor principle seems to hold. This could mean that the ECB focuses on near-term projections of the economy. There is also evidence of partial adjustment. Using real-time data as opposed to revised data does not seem to make much difference here.

Ullrich (2003) compares the Fed and the ECB with Taylor-type reaction functions. One finding is that ECB policy seems to be affected by the decisions of the Fed, but not vice versa. The coefficient for inflation is below one for the ECB.

Gerdesmeier and Roffia (2003) have done a fairly extensive set of estimations for the period lasting from 1985 to 2002. The inflation coefficient generally in a range between 1.5-2 in most estimations. This is true for contemporary, backward-looking and forward-looking variants. They also note that when using industrial production the output coefficient is slightly lower than with GDP. Gerdesmeier and Roffia (2004) have an additional study, but this time also utilizing real-time data and forecasts from the Survey of Professional Forecasters. They find that the forecasts seem to provide the most accurate estimates for real-time data. Also, real-time estimates differ from those with revised data.

Hayo and Hofmann (2005) have done a comparison of the ECB and the German Bundesbank to find out how similarly the two central banks have conducted monetary policy. There is a common perception of the ECB broadly inheriting the legacy of the Bundesbank and particularly the Bundesbank's emphasis on price stability. They find that the ECB and the Bundesbank respond in similar ways to expected inflation, but the ECB responds more strongly to the output gap, though this may be due to structural differences.

Fendel and Frenkel (2006) took stock of the first five years of the ECB by estimating forward-looking rules. They find the general result that smoothing is significant and improves fit. The Taylor principle seems to hold and the parameter for the output gap is significant for a variety of different slack measures. The model fit is quite good, though the sample is short. They estimate the inflation target, which is consistent with the stated target. They find no clear link with money growth and interest-rate setting, though the ECB uses a monetary aggregate as a reference value.

One caveat that should be mentioned about most of these early studies is the shortness of the sample period, as the time frame is not much more than a few years at most. Sometimes the short time frame has meant employing a synthetic central bank for the years prior to 1999 to achieve a longer time period. Considering the potential changes in monetary policy and the differing preferences of policymakers, such estimates may not be entirely reliable.

A study by Surico (2007) is an example of nonlinear reaction function estimated for the ECB. Here, the nonlinear rule is due to an asymmetric response by the central bank to fluctuations above and below the targets. The main results are that the response to output is asymmetric, in that responses to downturns are stronger than responses to upturns, and that the response to inflation is symmetrical. Additionally, the money aggregate does not seem to be an actual target variable for the ECB when added to the nonlinear model.

Gorter et al. (2008) is a study that is of some interest because it employs data constructed from Consensus Economics forecasts. This means that the study has results that offer a fairly close comparison to the forecast-based estimations in this study. They find that the forecasts seem to be useful for analyzing ECB policy and are superior to contemporary estimates. They also employ a more complicated error structure by incorporating serially correlated shocks.

One of the most recent studies is by Gerlach and Lewis (2010), who consider the possibility that the crisis has affected the policy of the ECB. This study argues that there is evidence for a change in the ECB's reaction function so that the policy response has been more aggressive than usual, though there are other interpretations for this as well, such as a potentially nonlinear reaction function.

Forte (2010) estimates Taylor rules for the ECB, the US Fed and the Bank of England. This study is an example of rules estimated in first differences, and the results and methods are fairly similar to another recent study by Aastrup and Jensen (2010). These studies are of interest because they share a similar time frame with the estimations in this paper. The results of the studies are also broadly speaking similar to some of the results found later with the forward-looking rules despite some other differences in the estimation approach. Both Aastrup and Jensen (2010) and Forte (2010) find that output and unemployment measures seem to most clearly account for the interest-rate policy of the ECB.

5.3 The recent financial crisis

While there is no shortage of explanations for the crisis that began in 2007, John Taylor has argued that loose monetary policy was an important precipitating factor in the crisis (e.g. Taylor 2007). Taylor (2007) claims that the Fed's policy between 2001-2006 was a major deviation from usual practice, as shown by the Taylor rule. This was an unusually significant period of discretion in both the length of time and size. The discretionary period partly coincided with a housing boom. With higher interest rates the boom might have been significantly weaker (based on a simulated housing model by Taylor) and the eventual financial fallout would have been less severe. Fed Chairman Bernanke (2010) has responded to this criticism and argued that monetary policy was not a significant factor in causing the crisis. Policy was motivated by a weak recovery and a fear of imminent deflation. Bernanke points rather to global imbalances, regulatory failures and distorted incentives in the financial sector as some of the main factors leading to the build-up of the crisis. Also, a study by Orphanides and Wieland (2008) suggests that the actual discretionary period and its significance depends quite a lot on the inflation measure that is used as well as how the yardstick rule is formulated.

6 ECB policy

This chapter briefly covers some of the general features and principles of the operation of the ECB. The ECB was established in 1998 and took responsibility of monetary policy in the beginning of the following year; this was the culmination of the second stage of the convergence process for member states that decided to join a monetary union. After expanding over time, most recently with the inclusion of Estonia, the euro area now consists of 17 member states. The main objective of the ECB as defined in EU treaties is the maintenance of price stability, with high employment and stable growth being secondary goals that cannot take precedence over its main objective. To carry out this task unhindered the ECB has been granted a great amount of independence for greater credibility in accomplishing its main objective. The ECB originally defined price stability as an annual change in the HICP of below two percent over the medium term. In 2003 price stability was further clarified as meaning a below, but close to, two percent inflation rate. A comprehensive, if perhaps no longer completely up-to-date, description of the policy framework can be found in ECB (2004).

Some of the general principles of ECB's monetary strategy include: the importance of anchoring inflation expectations, the need for forward-looking policy, focusing on the medium run, and a broad-based appraisal of the economy. In addition, the ECB has a two-pillar strategy for achieving price stability. The first pillar involves economic analysis to evaluate price developments. The second pillar is monetary analysis, where a broad money aggregate M3 is used as a reference value. The emphasis on the role of a monetary aggregate makes the ECB stand out somewhat from other central banks.

The ECB employs a corridor system of policy rates within which market rates, in particular the Euro Overnight Index Average (EONIA) rate, tend to move. This corridor consists of deposit and lending facilities that determine the floor and the ceiling, and between them is the Main Refinancing Operation (MRO) rate. This is the main policy rate that the market rates usually closely track. The MRO rate is determined by open market operations, which may sometimes involve the outright purchase and sale of assets, but which most often involve temporary repo and reverse repo agreements to adjust the amount of liquidity as needed.

Since the recent crisis has been the biggest test for the ECB so far, its policy actions for that time are also briefly sketched. The financial crisis that began in 2007 and the following economic contraction have induced central banks to react with unusual force and with unorthodox methods, even including coordinated policy actions. It is quite likely that some reappraisal of the monetary framework will result from these events, particularly in respect to the role of financial markets and the transmission mechanisms of monetary policy (e.g., Bean et al. 2010). In any case, the ECB has engaged in the provision of liquidity in addition to the more typical interest rate policy to counter the weakened connection between policy and market rates and to end the dysfunction in loan markets. While the policy rates have been reduced to a historically low level, there have also been various programs started under the moniker of “enhanced credit support”. The MRO rate has become a fixed rate and the refinancing operations offer essentially unlimited liquidity to a bidder with adequate collateral. Longer-term loan operations have also been increased and a wider range of assets are accepted as collateral. The Eurosystem's balance sheet has grown significantly to facilitate these liquidity programs. The stated intention with these measures is that they are temporary and will be phased out in time. More recently it has been bond markets, and in particular those dealing with government bonds, that have been under great strain. This has resulted in the ECB playing a role in debt security markets.

7 Data

This section presents details of the data that has been used for this paper. Most of the time series data has been collected from a real-time database for the euro area, which has data in monthly, quarterly, and annual intervals. The database has been constructed from data published in ECB Monthly Bulletins and is available in the ECB Statistical Warehouse, as well as in the Euro Area Business Cycle Network website. This database is a very useful source of data because it is the information, although only a part of it, that the Governing Council receives in time for its first monthly meeting, and before actual policy decisions are made for the month (Giannone et al. 2010). As has been stressed by Orphanides (2001) in particular, real-time data can be quite important in this kind of analysis.

For the forecast-based estimations there were two main possibilities. The ECB website has a Survey of Professional Forecasters, which could be used as a proxy forecast; it has been used for this purpose by Gerdesmeier and Roffia (2004). The Survey could have been one source for forecasts, but the forecasts that are used here are the semi-annual economic projections produced by the Eurosystem staff. These forecasts are made available to the Governing Council before it meets in June and December, and they are published in ECB Monthly Bulletins during these months. They have the appealing feature of being information that is directly available to the Governing Council. A clear problem with these projections is the very limited number of observations that are available, as there are just 20 periods of data in total since December 2000. Keeping this limitation in mind, the forecasts could still be helpful in uncovering the inflation strategy of the ECB. To try to counteract the paucity of forecasts the ECB staff forecasts are employed as additional data. They are based on a similar method, though their role in policy decisions is unclear. The forecasts report projections of average annual HICP inflation and real GDP growth. There are projections for the current year and the next year, and the forecasts are reported in a range due to uncertainty involving such forecasts. The mid-point values of the forecast range are used in the estimations. The staff forecasts may also have the advantage of outperforming outside forecasts, as a central bank can be expected to have access to a lot of information.

The sample period for the estimations runs from January 1999 to June 2009, with some additional data that accounts for lag terms, forward-looking terms as well as an extended sample for industrial production. An artificial central bank created by weighted averages of data before the time of the monetary union would allow for a longer sample period, but this approach, while used in multiple early studies, is somewhat questionable. This kind of consistency in reaction functions may not be warranted, and with over ten years of data it is not quite so necessary anymore. The forecasts, on the other hand, run from December 2000 to June 2010 in six month intervals. Adding the ECB staff forecasts means that a quarterly frequency is possible after June 2004.

The interest rate that is used as the policy variable is the EONIA rate, as it is a market rate that the ECB has a close influence on, and it is also comparable to the Fed funds rate in the United States. The official ECB policy rates can be problematic as they exhibit minimal variation over time. A short-term EURIBOR rate would also be a possible alternative, but the turmoil in financial markets since 2007 may have made these rates unreliable. The drastic increase in the EURIBOR-OIS spread (the OIS rate is an overnight indexed swap rate and is a nearly risk-free rate) during the worst moments of the crisis weakened the connection of market rates to official policy rates. The persistent spread may be a problem since it disengages the connection between policy rates and market rates. The EONIA rate, while volatile, has stayed mostly in line with the policy rates during the crisis, so it will be the only interest rate that will be utilized. The EONIA rate is also the most widely employed choice of interest rate in the literature.

The inflation index is the Harmonised Index of Consumer Prices (HICP), which is the official target index for the ECB. However, a HICP that excludes food and energy is also used. This can be considered a rough measure of core inflation, which could make it more useful for a medium-term focus. The general idea with core measures is that volatile components subject to temporary price shocks are stripped away to get a better idea of the underlying trend. It is not clear if core measures play any large role for the ECB, but they are employed here as an additional check. The overall HICP is already directly available in annual percentage changes, but the “core” HICP measure is calculated as a year-to-year percentage change in the index. Neither measure is seasonally adjusted.

The output gap is somewhat problematic and it could be measured in several ways, but options are rather limited for monthly data. The conventional choice is a Hodrick-Prescott (HP) filter is that is applied to an Industrial Production Index as a smoothing method. This method is used to separate the trend component from the cyclical component. The output gap is calculated as a percentage deviation of output from the trend. The chosen Industrial Production Index excludes construction and is seasonally adjusted. The smoothing parameter that is used is λ=14400, as is standard for monthly data. There is, as is sometimes noted (Mise 2005), a so-called end-point problem with using the HP filter that leads to an exaggerated role for the end-points of the series. To account for this, a forecast has been made with an ARIMA model for twelve additional months of industrial production and the beginning date for the Index is stretched all the way to January 1994 before the HP filter is applied to it.

Since the models as they are formulated leave out potentially useful indicator or even target variables that might have explanatory power, various plausible candidates have sometimes been proposed and explored. Some of these have included: M3 (a broad money aggregate), a stock index variable and an exchange rate variable. A risk spread variable could be potentially interesting as well, but most of these additional variables will not be considered any further in this thesis. Aastrup and Jensen (2010) is an example of a study that employs a far more comprehensive set of variables in their estimations. The growth in M3 has been perhaps the most consistently, though still only intermittently, statistically significant additional variable for the ECB, and certainly the most often studied additional variable. Therefore, it is the one additional variable considered in this study. The variable is constructed by taking the monthly M3 growth and subtracting from that rate an announced reference value of 4.5%. Most of the literature argues for and maintains the assumption of the stationarity of the relevant variables (e.g., Clarida et al. 2000; Dolado et al. 2005), though a few studies (Aastrup and Jensen 2010; Forte 2010) do use variables in first differences.

8 Estimation

8.1 Estimation method

There are a number of considerations in choosing the estimation method. Instead of the standard ordinary least squares (OLS) estimation method the estimations in this paper are mostly carried out with the generalized method of moments estimator originally proposed by Hansen (1982). The discussion of the properties of GMM in this section is based on Baum et al. (2003), Hamilton (1994) and Hayashi (2000).

GMM can be considered a generalization of some other common estimation methods, such as OLS, and can be used to estimate both linear and nonlinear models. It is frequently employed as a means of handling potentially endogenous variables. When estimating a regression with OLS it is assumed that any independent variables are uncorrelated with the error term. GMM or some other method is called for whenever there is a situation where the error term is not independent of the regressors, but instead varies with them. The failure of the regressors to be exogenous variables will make OLS estimates biased. The endogeneity problem often arises in a simultaneous system of multiple equations. A classic example of this are models of supply and demand. A regression containing price and quantity as variables will not be able estimate either a demand curve or a supply curve because the variables are jointly determined by both supply and demand. The forward-looking rules that rely on rational expectations also exemplify the endogeneity issue, since they include future realized economic variables that determine the current policy rate, while these economic variables are in turn affected by past policy decisions, and are therefore endogenous. Since almost all of the regressions that are carried out are forward-looking, it becomes necessary to account for the endogenous variables.

One way of handling this so-called simultaneity bias is by using an appropriate set of instruments. These instruments need to be exogenous and at the same time need to be correlated with the explanatory variables. An estimation method with instruments is called two-stage least squares, or sometimes the instrumental variables (IV) method. GMM also makes use of instruments that provide the necessary moment conditions, but it has the advantage of being efficient in comparison to IV estimation when the errors are heteroskedastic, though the advantage is lost if there is in fact no heteroskedasticity. Still, even under homoskedasticity GMM is asymptotically no worse than the IV estimator. The small-sample performance of GMM may sometimes be poor, however.

Either linear or nonlinear least squares estimation should be sufficient, if contemporary regressors can be treated as exogenous, but this is a rather ambiguous call to make. For example Gerdesmeier and Roffia (2003) found that OLS estimates seem to have been biased in the case of contemporary estimations, and it is not the only such study to reach this conclusion (also Surico 2007). This may be because of the data used in those particular studies. The data used in this paper should allow treating contemporary variables as exogenous. Therefore, estimations containing only current-period regressors are treated as exogenous and estimated with OLS, but also by the GMM methodology as a precaution. Still, in most cases the information set of the central bank is allowed to contain current period inflation, output gaps and other explanatory variables. However, to try to minimize issues with serially correlated errors, the instrument sets generally begin from *t-2* or later. This is a similar to the approach taken by Surico (2007). All the GMM and OLS estimations are also carried out with a Newey-West standard error correction for heteroskedasticity and autocorrelation (HAC) of unknown form as suggested by Newey and West (1987). These choices follow the approach taken by the majority of previous studies since both heteroskedasticity and autocorrelation are a concern in most of these studies.

Central to GMM estimation is the (L x 1) moment function for a set of observed variables v_t given in the most general form by

$$E(g(v_t, \beta)) = Eg_t(\beta) = 0,$$

where these moment conditions, or orthogonality conditions, are fulfilled at the true value of β, which is a vector of K unknown parameters. Additionally, identification requires that L ≥ K. The variables need to satisfy ergodicity and stationarity assumptions with some additional technical assumptions for the moments (see Hayashi 2000, chapter six). The general principle in estimating forward-looking reaction functions is that the error term ϵ_t is a linear combination of forecast errors so that it is orthogonal to variables in the central bank's information set at the time when (rational) expectations are formed. A vector of L observable instruments Z_t from the information set have orthogonality conditions of the following form

$$E(\epsilon_t Z_t) = 0,$$

where the expected crossproducts of the errors and the instruments are zero. It should also be noted that

$$\epsilon_t = y_t - f(x_t; \beta),$$

where f(.) is a linear or nonlinear model.

GMM chooses the estimator for the model parameters so that the sample moment conditions, which are based on population moment conditions, are fulfilled as closely as possible. This is done by minimizing an objective function based on the moment conditions. Generally this is achieved by a weighting matrix that determines how the individual moment conditions are weighted to best achieve the moment conditions, as it is not usually possible to fulfill the sample moment conditions exactly. The sample equivalent of the population moment conditions is given by

$$\bar{g}(\beta)=\frac{1}{n}\sum_{t=1}^{n} g_t(\beta),$$

which in this case implies

$$\bar{g}(\beta)=\frac{1}{n}\sum_{t=1}^{n} \epsilon_t Z_t,$$

where n is the number of observations. The task is to select a $\hat{\beta}$ of β that sets the moment conditions close to zero by minimizing a quadratic objective function.

The GMM objective function that is minimized is

$$min\, J(\beta)=\bar{g}(\beta)'\, W\, \bar{g}(\beta), \tag{43}$$

where W is a L x L symmetric positive definite weighting matrix. While W could be chosen from any number of weighting matrices, efficiency requires the use of an optimal weighting matrix. In practice the weighting matrix is an asymptotically consistent estimate of an optimal weighting matrix so that $\hat{W} \rightarrow_p W$ as n tends to infinity. Sometimes the sample size n is also added to (43) as a multiplier, as it will later be used to test the overidentifying restrictions and the minimization problem itself is not affected by a constant term. Regardless, a GMM estimator of the true parameter vector β is the $\hat{\beta}$ that minimizes $J(\beta)$, which can be found from the first order conditions

$$\frac{\partial J(\beta)}{\partial \beta}=0.$$

The GMM estimator is asymptotically normally distributed. Under certain conditions the GMM estimator will be the same as the OLS estimator, or the same as the IV estimator, or a number of other estimators. As an example of this generality, the connection between OLS and GMM has been made use of for the OLS estimations in this paper. When the instruments for GMM estimation are defined as just the explanatory variables (and that are therefore treated as exogenous variables) of the model, then OLS is an exactly identified GMM estimator. The key condition in this case is that

$$E(\epsilon_t Z_t)=E(\epsilon_t x_t)=E[(y_t-x_t{}'\beta)x_t]=0,$$

where x_t is a vector of K explanatory variables so that K=L. It is possible to derive the OLS estimator as a special case of GMM under these conditions. This connection is utilized to get a standard error correction for OLS that accounts for both autocorrelation and heteroskedasticity.

In the overidentified case of L > K the choice of weighting matrix becomes important. The optimal weighting matrix that is required for efficiency minimizes the asymptotic variance of the GMM estimator. Hansen (1982) has shown that this lower bound is achieved with a weighting matrix that is the inverse of the covariance matrix of moment conditions. That is, the optimal choice of weighting matrix converges in probability to S^{-1}. The asymptotic covariance matrix S is given by

$$S=\lim_{(N\to\infty)}\left(\frac{1}{N}\right)\sum_{t=1}^{N}\sum_{j=-\infty}^{\infty}E(\epsilon_t\epsilon_{t-j}Z_tZ_{t-j}^{'}),$$

and by setting

$$W = S^{-1},$$

gives the efficient GMM estimator. A consistent estimator $\hat{S}$ of the long-run covariance matrix S yields an asymptotically efficient GMM estimator. So while the optimal weighting matrix is not known, it can be consistently estimated. As emphasized by Hayashi (2000), to get a good estimate of the optimal weighting matrix the sample size may need to be quite large.

The estimate for the covariance matrix would simplify if the residuals were serially uncorrelated and homoskedastic. When these assumptions do not hold the estimate of the covariance matrix needs to take into account the heteroskedasticity and serial correlation in the errors. This correction is achieved by constructing a HAC estimator for S, which can be accomplished with a kernel-based approach. This entails the choice of both a kernel ω_j and a bandwidth parameter b_T.

The covariance matrix has the property that it is absolutely summable

$$S = \sum_{j=-\infty}^{\infty} \Gamma_j = \Gamma_0 + \sum_{j=1}^{\infty} (\Gamma_j + \Gamma_j'),$$

where it should be noticed that $\Gamma_{-j} = \Gamma_j'$. The j-th order autocovariance is

$$\Gamma_j = \sum_{j=-\infty}^{\infty} E(\epsilon_t \epsilon_{t-j} Z_t Z'_{t-j}).$$

The j-th sample autocovariance is given by

$$\hat{\Gamma}_j = \frac{1}{n} \sum_{t=j+1}^{n} \hat{\epsilon}_t \hat{\epsilon}_{t-j} Z_t Z'_{t-j}.$$

The HAC consistent estimate of S suggested by Newey and West (1987) is

$$\hat{S}_n = \hat{\Gamma}_0 + \sum_{j=1}^{l} \omega_j (\hat{\Gamma}_j + \hat{\Gamma}_j') = \hat{\Gamma}_0 + \sum_{j=1}^{l} (1 - j/b_T)(\hat{\Gamma}_j + \hat{\Gamma}_j').$$

with $\omega_j = 1 - j/b_T$ being the Bartlett weights, where more distant lags receive less weight. The Newey-West kernel corresponds to a Bartlett kernel with a bandwidth parameter $b_T = l + 1.$ The residuals are

$$\hat{\epsilon}_t = y_t - f(x_t; \hat{\beta}),$$

which are needed for estimating the covariance matrix. The somewhat circular implication from this is that an estimate of the parameters is needed so that the parameters might be calculated. How the residuals can be obtained in advance will be returned to later.

The kernels weight the estimated autocorrelations and the bandwidth has a role in determining how many autocorrelations are used in calculating the covariance matrix. The lag length *l* denotes how many lags of autocorrelations need to be used before the autocorrelation becomes negligible for the purpose of estimating the covariance matrix. The Newey-West kernel is a popular weighting method, though it is not the only possibility. More critical than the kernel choice may be the selection of the bandwidth. The chosen bandwidth parameter is approximately based on a guideline from Stock and Watson (2007, 607), where a suggested way of deciding on the bandwidth parameter for the Newey-West kernel is

$$b_T = 0.75 n^{\frac{1}{3}},$$

rounded to the nearest integer. This guideline is in turn based on a discussion of optimal kernel selection by Andrews (1991). This formula is used to calculate the initial bandwidth parameter for the estimations in this paper, with some variation since the bandwidth depends on the sample size. Most of the time the bandwidth parameter recommended by the guideline is four, but it has been lowered to three since results were not very much affected either way. With the forecast-based estimations the bandwidth equals two. Since there is no definitive method of choosing the bandwidth parameter, it may be a good idea to try a few values to check whether results are very sensitive.

The construction of the estimated covariance matrix requires residuals, which means that they need to somehow be obtained first. For this reason the efficient GMM estimator may be estimated by a two-step process as described by Hansen (1982). First, some consistent, though inefficient, estimator (two stage least squares in this case) is used to compute the residuals, which are used to form the optimal weighting matrix. Next, the computed weighting matrix is used to compute the efficient GMM estimator with (43). It would also be possible to use an iterative method, so that the residuals from the second stage of the two-step process are used to calculate a new weighting matrix, which is again used to re-estimate (43), and so forth. The second step can be iterated until the estimator converges.

It should be kept in mind that any approach that uses instrument variables has the problem of finding good instruments. Good instruments need to be orthogonal to the error term and at the same time need to correlate strongly enough with the regressors. Instruments that do not correlate sufficiently with the variables that are instrumented are termed weak instruments. There has been some evidence (Favero and Consolo 2009) that weak instruments could be a problem in the studies that estimate policy rules as weak instruments can make the estimations inconsistent. In general it is also probably a good idea to be parsimonious when choosing instruments. Tauchen (1986) notes that employing very many lags of the instruments leads to a trade-off off between increasingly biased estimates and a decrease in variance. The general conclusion of Tauchen is that the increased precision from longer lags is outweighed by the potentially biased results. In this study, instruments are mostly selected by the principle that there are slightly more than what is needed for identification, while the chosen instruments are conventional.

If there are more moment conditions than there are parameters to estimate so that L > K, the model is said to be overidentified, and then it becomes possible to test the overidentifying restrictions for the exogeneity of the instruments, or more generally the moment conditions. The J-statistic is a test statistic for the validity of the overidentifying restrictions. Under the null of the overidentifying restrictions being satisfied, the J-statistic, which includes a multiplier equivalent to the number of observations in (43), is asymptotically chi-square distributed with degrees of freedom equivalent to the number of overidentifying restrictions. That is, under the null hypothesis that $H_0 : Eg_t = 0$

$$nJ(\hat{\beta}) \xrightarrow{d} \chi^2_{L-K},$$

where L-K gives the degrees of freedom. If the test statistic exceeds a chi-square critical value, or has an unexpectedly low p-value, the null is rejected. The rejection of the null hypothesis is an indication of some problem with the model. This includes the possibility that at least some of the moment conditions are incorrect. It is also worth noting that in small samples the J-statistic test may end up rejecting the null too often (Hayashi 2000).

The reliance on instrument variables and the imposition of rational expectations are some of the reasons to consider other methods of estimating forward-looking rules, such as generating forecasts, as suggested by Nikolsko-Rzhevskyy (2008). Generating actual forecasts from the real-time data might have been possible, but this would also have been time-consuming and laborious, while requiring at least a tolerable replication of central bank forecasts. Since the Eurosystem and ECB staff forecasts are available those are used instead.

8.2 Estimated Taylor rules

To begin with, some simple contemporary Taylor rules are estimated. The estimations are based on (17) and (35) with results for these estimations reported in table 1. The rules are estimated with both OLS and GMM, in case the explanatory variables should happen to have an endogeneity problem. There is in fact some discrepancy between the estimates when the smoothing term is added, but this might be because of serial correlation. As can be seen from the table, the contemporary estimates lead to rather nonsensical results for the inflation coefficient, as it is always negative and rarely statistically significantly different from zero. While these estimates do not seem particularly appropriate then, it is worth mentioning that a fairly clear shift downwards in the estimate of the contemporary inflation coefficient is detectable when contrasting these results with the earlier literature. With a longer sample period of several decades the coefficient would most likely become positive and statistically significant, and possibly even strongly positive. An inflation coefficient this ambiguous for contemporary estimates seems to be a fairly recent phenomenon. One plausible explanation for this is that it is a symptom of a general shift in the practice of monetary policy towards a greater emphasis on forward-looking policy. Since these results only mirror the general conclusion of most other studies that it is necessary to employ forward-looking rules, these will be considered next.

Table 1. Results for estimated contemporary rules for 1:1999-6:2009.

Estimation method	Constant	Inflation coefficient	Output gap coefficient	Smoothing term	SSE	Adjusted R^2	J-statistic
OLS	3.23*** (0.31)	-0.08 (0.16)	0.25*** (0.04)	-	55.89	0.54	-
OLS	4.80*** (0.95)	-0.93** (0.40)	0.65*** (0.15)	0.92*** (0.03)	3.06	0.97	-
OLS with core	3.30*** (0.40)	-0.14 (0.21)	0.24*** (0.03)	-	55.55	0.54	-
OLS with core	6.11*** (0.96)	-1.85*** (0.52)	0.57*** (0.09)	0.92*** (0.02)	2.6	0.98	-
GMM	3.37*** (0.35)	-0.16 (0.17)	0.30*** (0.05)	-	58.05	0.52	0.19
GMM	3.93*** (0.45)	-0.43 (0.22)	0.37*** (0.06)	0.70*** (0.07)	5.99	0.95	0.95
GMM with core	3.50*** (0.36)	-0.29 (0.19)	0.29*** (0.04)	-	59.23	0.51	0.17
GMM with core	4.55*** (0.60)	-0.90** (0.36)	0.36*** (0.06)	0.80*** (0.07)	3.53	0.97	0.34

Notes: HAC robust standard errors in parentheses. The superscripts *, **, *** denote the rejection of the null for a true coefficient of zero at a 10%, 5% and 1% significance level, respectively. The instruments are a constant, the second, third and fourth lag of inflation and the second and third lag of the output gap. SSE denotes the sum of squared errors. Regressions with core include an inflation measure that excludes energy and unprocessed food. The J-statistic column reports the p-value for the null hypothesis of the validity of the overidentifying restrictions.

Forward-looking rules pose some difficulties. The imposition of rational expectations may not be an entirely ideal way to model policy (see Nikolsko-Rzhevskyy 2008). There is no clear consensus on what the appropriate forecast horizon should be. Impulse response analysis suggests that monetary policy has its strongest effects on GDP and inflation after three to five quarters have passed from an unexpected interest-rate shock (ECB 2010). On the other hand, the Governing Council of the ECB may not pay that much attention to future values of the output gap, since it is an imprecisely measured concept (Gerlach 2007). Theoretically, the output horizon should be shorter or no longer than the inflation forecast horizon. The forecast horizons are chosen as nine and 12 months for inflation and one month for the output gap, which are fairly standard choices. Small changes in these horizons do not really affect the results all that much. The equation that is estimated is based on (40). The results for forward-looking rules are reported in table 2.

Table 2. Results for estimated forward-looking rules for 1:1999-6:2009.

Estimation method	Constant	Inflation coefficient	Output coefficient	Smoothing term	SSE	Adjusted R^2	J-statistic
GMM [t+9, t+1]	1.86** (1.02)	0.52 (0.48)	0.34*** (0.06)	0.86*** (0.05)	3	0.97	0.65
GMM [t+12,t+1]	2.06*** (0.70)	0.43 (0.33)	0.36*** (0.06)	0.85*** (0.04)	2.95	0.98	0.62
GMM with core [t+12,t+1]	1.50 (1.92)	0.75 (1.06)	0.32*** (0.11)	0.88*** (0.04)	2.82	0.98	0.03

Notes: HAC robust standard errors in parentheses. The superscripts *, **, *** denote the rejection of the null for a true coefficient of zero at a 10%, 5% and 1% significance level, respectively. The instruments are a constant, the second, third and fourth lag of inflation and the second and third lag of the output gap. SSE denotes the sum of squared errors. Regressions with core include an inflation measure that excludes energy and unprocessed food. The square brackets term [t+n, t+k] denotes the forecast horizon for inflation and the output gap, respectively. The J-statistic column reports the p-value for the null hypothesis of the validity of the overidentifying restrictions.

Now the inflation coefficients are indeed positive, although the values are fairly low and not statistically significantly different from zero. In fact, they are far lower then what would be expected based on both theory and many earlier studies, as they do not even seem to fulfill the Taylor principle. This is seemingly true no matter what sort of forecast horizon is attempted for inflation. It is possible that either the inflation shocks so far have been mostly viewed as temporary, or inflation expectations are so strongly anchored it is not necessary to take strong measures to counter price movements, or that without actual forecast data the coefficient is misleading, which is something that will be explored later on with ECB forecasts. A general conclusion of earlier studies has been that survey data appears to work quite well, and is something the ECB Governing Council pays quite a lot of attention to (Gerlach 2007). It is also worth mentioning a study by Gorter et al. (2008) that used mostly similar methods, but had access to monthly forecasts, which resulted in far larger point estimates. Since their data is not readily available, it is not possible to check whether expectations data would yield a significantly higher inflation coefficient when using monthly data. The forecast-based estimations that are performed later make do with a sparser sample.

There is also an issue with the instruments and an important caveat that should be mentioned about the estimations so far. The inflation coefficient in particular seems to be highly sensitive to the choice of instruments. By trying different instruments, one thing appears fairly clear. Adding lags of the interest rate as instruments tends to strengthen the response to inflation, and sometimes makes the coefficient statistically significant. An example of this phenomenon can be seen in the estimated linear model found in table 4. However, the inflation coefficient is also highly sensitive to the exact specification of the instruments, in particular to how many interest rate lags are added, and therefore there is very little robustness to this result and the estimated coefficient is quite imprecise. This sensitivity means that it is difficult to conclude anything about the inflation coefficient except that forward-looking models tend to yield a positive coefficient and that instrument selection seems to matter a lot. The other results are not nearly as strongly affected by the choice of instruments, so for example the output measure remains significant in almost all cases. The relevance of the instruments can be tested with the R^2 of the first-stage regressions, but this test indicates that the instruments are acceptable.

Since the inflation coefficient is imprecisely estimated, it might be worth allowing the coefficient to vary over time, or to allow for a nonlinear response to inflation. Time variation in the coefficients is beyond the scope of this thesis and should be more critical for longer time periods, but non-linearity is considered later on. The estimates from table 2 may seem unlikely and surprising, but on the other hand many of the more recent studies (Gerlach 2007; Aastrup and Jensen 2010; Forte 2010) seem to have been unable to find a strong inflation response. Aastrup and Jensen (2010) provide a few possible explanations and argue particularly that both optimal discretion and commitment could manifest itself as a low estimate for the inflation coefficient, or that indicator variables may be a large component of ECB policy. Possibly these results may then reflect a central bank that has been quite successful in keeping inflation in check, and it is therefore difficult to extract a policy response from ex post data.

Another general point of the estimations so far is the far more precisely estimated and statistically significant response to the output gap. This may imply that output measures are used for gauging future inflation pressures, or that the ECB places some value on output stabilization. The partial adjustment term that can be interpreted as inertial policy is mostly estimated in a typical range of 0.8-0.9 and is always strongly significant. The core measures end up not appearing that useful as they tend to be quite inconsistent and the J-statistic test also tends to reject the validity of the overidentifying restrictions for most models with core inflation. Only one result with core inflation is therefore reported in table 2, and core measures are dropped after this point because of these problems. Before considering the possibility of a nonlinear response to inflation, table 3 reports the result for adding an M3 growth variable to the forward-looking estimations.

Table 3. Forward-looking estimate with M3 growth for 1:1999-6:2009.

Estimation method	Constant	Inflation coefficient	Output coefficient	M3 growth	Smoothing term	SSE	Adjusted R^2	J-statistic
GMM [t+12,t+1]	3.14*** (0.53)	0.20 (0.27)	0.45*** (0.06)	-0.21*** (0.07)	0.87*** (0.03)	2.37	0.98	0.56

Notes: HAC robust standard errors in parentheses. The superscripts *, **, *** denote the rejection of the null for a true coefficient of zero at a 10%, 5% and 1% significance level, respectively. The instruments are a constant, the second,third and fourth lag of inflation, the second, third lag and fourth lag of the output gap, and the M3 growth gap. SSE denotes the sum of squared errors. The square brackets term [t+n, t+k] denotes the forecast horizon for inflation and the output gap, respectively. The J-statistic column reports the p-value for rejecting the null hypothesis of the validity of the overidentifying restrictions.

The M3 growth coefficient turns out to be negative and in fact statistically significantly negative, which suggests that current fluctuations in money growth do not have an independent role in policy decisions. This finding is also not affected all that much by instrument selection; the coefficient remains consistently negative with different specifications. If money growth is important, it is presumably so over a long term perspective.

8.3 Estimated nonlinear rules

While the estimated rules up to this point have been some of the workhorse models of monetary policy, there have been several proposals that involve nonlinear forms, since a linear response would not fully capture certain plausible, though speculative, aspects of policy-making. A nonlinear monetary policy model will therefore also be estimated as an alternative to the linear rules. Recently, a number of proposals for nonlinear reaction functions have been appearing, and the possibility of nonlinear reaction functions has gained more attention in the literature. The model used here has originally been proposed by Boinet and Martin (2008), and has been employed by at least Naraidoo (2010) as well. This model can, to some extent, be considered a generalization of the model used in a study of ECB policy by Surico (2007), though that model had an additional nonlinear component resulting from a nonlinear Phillips curve, which is not present here. The non-linearity in this model arises purely from the non-quadratic preferences of the policymaker. While the objective function is nonstandard, it is on the other hand fairly flexible and allows, but does not specifically require, some additional features. The main additional feature is zone-like behavior, which means that the force of the response to deviations from targets depends on the size of the deviations. There can potentially be a zone around the target where the central bank is indifferent to minor deviations so that the the marginal loss from the deviation from target will be zero. Moving away from this “comfort” zone the response will then become increasingly forceful. The same can also be true for output. The model also allows for asymmetrical responses to target deviations, such as a stronger response to an economic downturn than an upturn. This will mean that the loss function has a different slope for negative and positive deviations, unlike in the case of a normal symmetric quadratic loss function. Zone-like behavior has been proposed by Orphanides and Wieland (2000), while an asymmetric loss function is originally a proposal by Nobay and Peel (2003).

There are a number of reasons to consider this kind of model in the case of the ECB. First, the model allows studying aspects of policy that otherwise would not be feasible with the models used so far. Second, it could be that the ECB has a muted response to inflation within some range near its inflation target. Speculatively, there could be some range around and near the official definition of price stability in which inflation can vary fairly freely, while it also seems quite realistic to expect that the response to inflation becomes more forceful when the deviation becomes larger. This kind of behavior could also potentially explain the previous ambiguities with the estimated inflation coefficient. Third, the study of Surico (2007) concluded that the ECB had an asymmetrical response to output with another kind of estimated nonlinear policy model. Fourth, it is also useful to look at how different models perform against each other. Finally, the financial crisis is a prominent example of an event where a linear response may not adequately capture the actual intricacies of policy (Gerlach 2010).

Before proceeding with the estimations, the optimal rule needs to be derived. This will involve an optimization problem for a central bank that solves the problem in each period to find the target interest rate, and that exhibits non-quadratic preferences. The framework here is more or less meant to represent the constrained discretion of policymakers. The period loss function will be of the form

$$L=\frac{e^{\alpha_\pi(\pi-\pi^*)^{\beta_\pi}}-\alpha_\pi(\pi-\pi^*)^{\beta_\pi}-1}{\beta_\pi\alpha_\pi^2}+\lambda\frac{e^{\alpha_y(y)^{\beta_y}}-\alpha_y(y)^{\beta_y}-1}{\beta_y\alpha_y^2}+\frac{\mu}{2}(i-i^*)^2, \tag{44}$$

where $\mu>0$ is a coefficient that measures the central bank's aversion to fluctuations of the interest rate around its target rate and λ is the relative weight on the output gap, which is denoted here by *y*. The parameters α_y, α_π, β_y *and* β_π define what form the central bank preferences take. β_y and β_π are integers that determine the asymmetry and zone-like properties. When β_y *and* β_π are greater than one the preferences are zone-like. The larger that β becomes, the wider the zone without loss becomes. When β is an odd value, there is asymmetry so that both the zone and the loss are asymmetric. The values of α_y and α_π determine the sign of asymmetry and the slope of the loss function. A larger α implies a more steeply rising loss function. When β is an odd value a positive value of α means that positive gaps of inflation and output are penalized more. The different values for these parameters lead to multiple different specifications of the loss function, which are elaborated on in detail in the paper of Boinet and Martin (2008). The usual quadratic loss function is embodied as a special case when β_y and β_π are equal to one and α_y and α_π approach zero. A linear exponential specification used by Surico (2007) is also nested as a special case in this loss function.

To complete the optimization problem the economic model has to be defined. This will be a standard New Keynesian model that is repeated for convenience. Aggregate demand is again given by the forward-looking IS curve

$$y_t = E_t y_{t+1} - \sigma(i_t - E_t \pi_{t+1}) + u_{t.} \qquad (45)$$

Aggregate supply in turn is given by the New Keynesian Phillips curve and it can be written as

$$\pi_t = \beta E_t \pi_{t+1} + \kappa y_t + e_t . \qquad (46)$$

The assumption here is that the basic New Keynesian model is a decent approximate model for the euro area, though it is stylized and makes no allowance for backward-looking features, in particular the persistence of inflation. Smets and Wouters (2003) is a notable example of a study that analyzes these issues. The intertemporal loss function that is minimized by choosing the interest rate in each period is written as

$$Min \;\; E_t \left[\sum_{i=0}^{\infty} \delta^i L_{t+i} \right], \qquad (47)$$

where L is the period loss function and δ is a discount term.

This study departs slightly from the approach of Boinet and Martin (2008) by considering the interest rate decision to be based on the information from the current time period. As mentioned before, this is due to the data being in real-time and constructed in such a way that it was available to the policymakers at the ECB before decisions for the month were typically made. This change should only affect the timing notation of the expectations operator and what is allowed into the information set. The solution itself proceeds normally as a discretionary optimization problem, where the central bank chooses the interest rate while it is constrained by the supply and demand equations. Under discretion the central bank cannot affect expectations directly and will choose to re-optimize in every period.

The first order condition for the decision problem is

$$\delta E_t f'(\pi_{t+1}) \frac{d\pi_{t+1}}{d y_{t+1}} \frac{d y_{t+1}}{d i_t} + \delta \lambda E_t f'(t+1) \frac{d y_{t+1}}{d i_t} + \mu (i_t - i^*) = 0, \tag{48}$$

where $f(x_t; \alpha, \beta) = (\frac{e^{\alpha x_t^\beta} - \alpha x_t^\beta - 1}{\beta \alpha^2})$ and $f'(.)$ is the derivative of this function.

Solving for the optimal reaction function from this condition leads to

$$i_t = i^* + \omega_\pi E_t g(\pi_{t+1} - \pi^*)(\pi_{t+1} - \pi^*) + \omega_y E_t g(y_{t+1})(y_{t+1}), \tag{49}$$

where $g(x_t; \alpha, \beta) = x_t^{\beta-2}(e^{\alpha x_t^\beta} - \frac{1}{\alpha})$, $\omega_\pi = (\frac{\kappa \rho \delta}{\mu})$ and $\omega_y = (\frac{\lambda \rho \delta}{\mu})$.

The identification of the parameters from nonlinear rules may in practice prove to be weak. As a solution, the rule is approximated by a second-order Taylor expansion when α_y *and* α_π tend to zero. This yields an equation that is more feasible to estimate and can be formulated as

$$\begin{aligned} i_t = i^* &+ \omega_\pi E_t ((\pi_{t+1} - \pi^*)^{2\beta_\pi - 1}(1 + \frac{\alpha_\pi}{2}(\pi_{t+1} - \pi^*)^{\beta_\pi})) \\ &+ \omega_y E_t (y_{t+1})^{2\beta_y - 1}((1 + \frac{\alpha_y}{2})(y_{t+1})^{\beta_y}). \end{aligned} \tag{50}$$

When this equation is written in terms of realized values it is defined as

$$\begin{aligned} i_t = i^* &+ \omega_\pi ((\pi_{t+1} - \pi^*)^{2\beta_\pi - 1}(1 + \frac{\alpha_\pi}{2}(\pi_{t+1} - \pi^*)^{\beta_\pi})) \\ &+ \omega_y (y_{t+1})^{2\beta_y - 1}((1 + \frac{\alpha_y}{2})(y_{t+1})^{\beta_y}). \end{aligned} \tag{51}$$

When β_y and β_π are equal to one and when α_y and α_π approach zero, this function reduces to a linear Taylor rule. Adding the partial adjustment equation to (51) results in

$$i_t=\rho i_{t-1}+(1-\rho)[\omega_0+\omega_\pi(\pi_{t+1}-\pi^*)^{2\beta_\pi-1}(1+\frac{\alpha_\pi}{2}(\pi_{t+1}-\pi^*)^{\beta_\pi})] \\ +(1-\rho)[\omega_y(y_{t+1})^{2\beta_y-1}((1+\frac{\alpha_y}{2})(y_{t+1})^{\beta_y})]+\epsilon_t, \qquad (52)$$

The equation in (52) may be more practical to estimate as

$$i_t=\rho i_{t-1}+(1-\rho)[\omega_0+\omega_\pi((\pi_{t+1}-\pi^*)^{2\beta_\pi-1}+\frac{\alpha_\pi}{2}(\pi_{t+1}-\pi^*)^{3\beta_\pi-1})] \\ +(1-\rho)[\omega_y((y_{t+1})^{2\beta_y-1}+\frac{\alpha_y}{2}(y_{t+1})^{3\beta_y-1})]+\epsilon_{t.} \qquad (53)$$

The error term contains

$$\epsilon_t=-\omega_\pi(1-\rho)((\pi_{t+1}-\pi^*)^{2\beta_\pi}-E_t(\pi_{t+1}-\pi^*)^{2\beta_\pi-1}) \\ -\omega_\pi(1-\rho)\frac{\alpha_\pi}{2}((\pi_{t+1}-\pi^*)^{3\beta_\pi-1}-E_t(\pi_{t+1}-\pi^*)^{3\beta_\pi-1}) \\ -\omega_y(1-\rho)((y_{t+1}^{2\beta_y-1}-E_t y_{t+1}^{2\beta_y-1})+\frac{\alpha_\pi}{2}(y_{t+1}^{3\beta_y-1}-E_t y_{t+1}^{3\beta_y-1})). \qquad (54)$$

The error term is a linear combination of forecast errors and is therefore orthogonal to the variables in the information set at time t, which is the requirement for using the GMM estimation method.

Only several cases of the multiple possible combinations from different integer values are considered here. Since the inflation target of the ECB has to be defined for these regressions, it is treated as being equal to 2%. The first model is the best performing version in Boinet and Martin (2008). It has a symmetric response to inflation, an inflation zone and a linear response to output, so that α_y approaches zero, β_y=1 and β_π=2. In the second version, β_π=1, β_y=2 and α_π approaches zero for a symmetric zone of output and a linear response to inflation. The third result is for β_y=2 and β_π=2 so that both output and inflation have zones without increasing loss. The fourth result is for the Taylor rule that results from β_y=1, β_π=1 and α tending to zero. The fifth result allows for an asymmetric response to output, so that β_y=1, β_π=1 and $\alpha_y \neq 0$. The sixth model augments the fifth with an inflation zone, which means that β_π=2. To account for the lags in monetary policy, the forecast horizon is chosen as with the forward-looking Taylor rules. The results for estimating these versions of (52) can be found in table 4, where the instruments are chosen to be close to those of Boinet and Martin (2008).

The results suggest that the nonlinear models do work and seem to perform adequately, but never really seem to be superior to the linear rule. If a lower standard error of regression is used as a way to rank the performance of these models (as in Boinet and Martin 2008), it implies that the linear Taylor rule outperforms the other models. While the standard error is not reported, the same implied ranking can be seen from the column that reports the sum of squared errors since the standard error (or root mean squared error) can be derived from the sum of squared errors. Trying even higher values of β would make the model increasingly nonlinear, and judging by some trial estimations seems unlikely to lead to any real improvement in results, although $\beta_\pi=3$ still works fairly well. There is no clear suggestion of anything but a symmetric response to inflation, though it is worth noting that the last two models in table 4 do have an asymmetric response to output. In these cases $\alpha_y < 0$, which implies a greater loss from economic downturns. This result can be contrasted with the results of Surico (2007) and Dolado et al. (2005), although the coefficient is not statistically significant in this case. The models turn out not to be that helpful in characterizing the inflation response, though one notable feature is that as long as there is a positive tightening response to inflation when β_π=2, a large enough deviation from the inflation target will eventually lead to the Taylor principle holding in the nonlinear models. The real interest rate begins to change in those models when inflation is slightly over 3%, except for the first model where this happens only when inflation is slightly more than 3.5%. The same applies to low values of inflation as well in a symmetrical way (and ignoring possible concerns about the zero bound). Overall the evidence for zones and asymmetry does not appear to be all that strong. This conclusion appears to be quite robust to the choice of instruments, though the estimates do vary otherwise.

Table 4. Results from the estimated nonlinear rules 1:1999-6:2009**.**

Estimation method	ω_0	ω_π	ω_y	ρ	α_y	α_π	SSE	Adjusted R^2	J-statistic
GMM [t+12,t+1] β_y=1, β_π=2	2.96*** (0.21)	0.45 (0.74)	0.53*** (0.12)	0.93*** (0.02)	-	-0.11 (0.85)	2.95	0.98	0.21
GMM [t+12,t+1] β_y=2, β_π=1	2.99*** (0.60)	1.46 (1.49)	0.01 (0.01)	0.97*** (0.02)	-0.14 (0.60)	-	3.3	0.97	0.39
GMM [t+12,t+1] β_y=2 , β_π=2	2.99*** (0.42)	0.99 (1.38)	0,01* (0.01)	0.96*** (0.02)	0.01 (0.06)	-0.24 (0.19)	3.35	0.97	0.30
GMM [t+12,t+1] β_y=1 , β_π=1	2.79*** (0.23)	1.28* (0.77)	0.52*** (0.11)	0.93*** (0.02)	-	-	2.64	0.98	0.26
GMM [t+12,t+1] β_y=1 , β_π=1	3.16*** (0.44)	0.91 (0.91)	0.39 (0.17)	0.95*** (0.02)	-0.27 (0.32)	-	2.86	0.98	0.24
GMM [t+12,t+1] β_y=1 , β_π=2	3.18*** (0.40)	0.72 (1.06)	0.38** (0.18)	0.95*** (0.03)	-0.27 (0.36)	-0.26 (0.27)	2.87	0.98	0.18

Notes: HAC robust standard errors in parentheses. The superscripts *, **, *** denote the rejection of the null for a true coefficient of zero at a 10%, 5% and 1% significance level, respectively. The instruments are a constant, the second,third, fourth and fifth lag of inflation, the second, third, fourth and fifth lag of the output gap, and the third, fourth and fifth lag of the interest rate. SSE denotes the sum of squared errors. The square brackets term [t+n, t+k] denotes the forecast horizon for inflation and the output gap, respectively. The J-statistic column reports the p-value for rejecting the null hypothesis of the validity of the overidentifying restrictions

8.4 Forecast-based estimations

The final set of estimations includes actual forecasts as data, which could shed more light on the issue of the inflation response of the ECB. Forecasts also avoid the reliance on instruments, and could well be a more appropriate way of representing a central bank's response to economic information. The first set of estimates utilize the Eurosystem staff forecasts published biannually in ECB Monthly Bulletins. The second set of estimates utilize both Eurosystem and ECB staff forecasts; the second set of estimates will be considered separately after the first set. The estimations are based on those months for which the forecasts were available. The Eurosystem staff forecasts have been collected from the December and June issues of Monthly Bulletins beginning with the December 2000 issue and ending with the June 2010 publication. This means a sample of only 20 usable observations, and slightly more when the ECB staff forecasts are added. This could admittedly mean that the results may not be entirely credible, but they should still be suggestive. Projections for both the current year and the next year are used, though generally the projections for the next year seem to be more appropriate. Using estimates based solely on the projections for the current year lead to very unlikely results and those estimates are omitted from the tables. The near-term projections also clearly miss the rapid deterioration of the economy that happened during 2008. With the March forecasts it might be debatable whether the projections for the current year or the next year would be more appropriate.

The estimations are performed with ordinary least squares as there does not seem to be a reason to think of the projections as endogenous, which means that OLS should provide consistent estimates, though Boivin (2006) does discuss the possibility that staff forecasts could be correlated with the error term. The assumption of exogenous forecasts is maintained here, as it is also maintained in Boivin (2006), who notes that this should be a relatively safe assumption particularly when the forecasts are conditioned on no interest rate changes, which is seemingly the case for the forecasts used here. The estimates now substitute a growth gap in place of the output gap, with regressions based on the formula in (42). Gorter et al. (2008) suggest that the ECB considers trend growth to be around 2-2.5%, and they therefore define trend growth as a fixed 2.25% rate. Since the constant term is not of particular interest here, this study lets trend growth be subsumed into the constant, which is one reason for the negative coefficients of the constants in table 5 and 6. This way it is not necessary to explicitly define potential growth. To stay consistent with the information from the forecasts, they are not manipulated to get either a constant forecast horizon or more observations by the averaging of the forecasts, though Orphanides and Williams (2008) do employ such an approach for biannual data. Something similar to their approach might be worthwhile, but the additional forecasts make it less necessary. It should be remarked that some amount of variation in forecast horizons may not change results much as the horizons can be strongly correlated (Boivin 2006; Berg et al. 2004), though this does not apply for the projections for the current year. The estimates based on Eurosystem staff forecasts are reported in table 5.

Table 5. Estimations with Eurosystem staff forecasts for 12:2000-6:2010.

Estimation method	Constant	Inflation coefficient	Output growth coefficient	Smoothing term	M3 growth gap	SSE	Adjusted R^2
OLS [next, current]	-5.97* (2.86)	4.54** (1.69)	-0.05 (0.26)	0.90*** (0.03)	-	0.44	0.98
OLS [next, next]	-3.52** (1.31)	2.05** (0.73)	1.27*** (0.36)	0.89*** (0.02)	-	0.27	0.99
OLS [next, next]	-3.06* (1.55)	1.78* (0.96)	1.23** (0.30)	0.88*** (0.02)	0.05 (0.08)	0.27	0.99

Notes: HAC robust standard errors in parentheses. The superscripts *, **, *** denote the rejection of the null for a true coefficient of zero at a 10%, 5% and 1% significance level, respectively. SSE denotes the sum of squared errors. The terms in square brackets denote the forecast for inflation and output growth, respectively. The projections are for either the current year or for the next year.

Results are quite striking, though the limited sample is a reason for some caution. Next year's GDP growth projection is required to make the output growth coefficient significant. The inflation coefficient is also closer to the higher range of values of previous estimations for the ECB, and much closer to what might be expected. While the standard errors are fairly wide, the point estimate for inflation does more convincingly than before fulfill the Taylor principle. The inflation coefficient is still less precisely estimated than the output coefficient, which is something of a recurring theme in all the estimations. The model fit measures also exhibit relatively good values, suggesting that the estimates closely track actual policy. The smoothing term is still a highly necessary addition.

To achieve a slightly larger sample, the ECB staff forecasts published in March and September issues of the Monthly Bulletins are used as complementary data. These forecasts have been published since September 2004 so by adding them to the Eurosystem staff forecasts the total sample is 32 observations. It is not clear if they are also an input in policy decisions, but they should be highly useful as proxies. The frequency of the forecasts is therefore biannual until June 2004 and quarterly after that point. The results can be found in table 6.

The evidence for a strong response to inflation projections becomes even clearer with the additional forecasts, though the point estimate for inflation remains slightly noisy. In case M3 growth still might have some independent value in ECB policy, it is added to the estimates in tables 5 and 6, but results do not support any systematic role for it. Its potential usefulness as an indicator might of course already be reflected in the forecasts themselves.

Table 6. Estimations with combined ECB and Eurosystem staff forecasts for 12:2000-6:2010.

Estimation method	Constant	Inflation coefficient	Output growth coefficient	Smoothing term	M3 growth gap	SSE	Adjusted R^2
OLS [next, current]	-5.41*** (1.74)	4.25*** (1.03)	-0.01 (0.16)	0.92*** (0.03)	-	0.52	0.99
OLS [next, next]	-4.11*** (1.18)	2.52*** (0.62)	1.15*** (0.39)	0.90*** (0.02)	-	0.37	0.99
OLS [next, next]	-3.27*** (1.09)	2.06*** (0.66)	1.03*** (0.30)	0.89*** (0.02)	0.08 (0.06)	0.37	0.99

Notes: HAC robust standard errors in parentheses. The superscripts *, **, *** denote the rejection of the null for a true coefficient of zero at a 10%, 5% and 1% significance level, respectively. SSE denotes the sum of squared errors. The terms in square brackets denote the forecast for inflation and output growth, respectively. The projections are for either the current year or for the next year.

The credibility of a sample size that is quite small could be questioned, and therefore some consideration should also be given to the results of Gorter et al. (2008). Their study used Consensus Economics forecasts with a monthly frequency, but with results that are not too dissimilar to these ones. Some of the the main differences are that the estimated inflation coefficient is generally higher in this study, while the estimated output coefficient is in turn slightly lower here. The combined results from the estimates in this study and studies like Gorter et al. (2008) do suggest that the explicit use of forecasts is useful and quite possibly preferable to the alternative of the outcome-based estimations for inference on ECB policy. In this way the results presented here also mirror the results of Orphanides and Williams (2008) for the US Fed. One way to extend this analysis would be to investigate whether there are major deviations in policy from the simple formula and the possible reasons for these deviations. Other possibilities include allowing for various complicating elements such as time variation, forecast uncertainty and perhaps non-linearity as well. These could be useful extensions particularly when there is slightly more data to work with.

9 Conclusion

This thesis has estimated reaction functions using both real-time data and real-time central bank forecasts to study the recent monetary policy of the ECB and to see how different models perform at this task. A number of possibilities have been explored as the results have at times been surprising and ambivalent. Contemporary Taylor rules, forward-looking rules, nonlinear rules and forecast-based measures have all been considered, but only forecast-based estimates seem to offer very solid conclusions. Purely contemporary rules do not seem to be a reasonable characterization of ECB policy. Forward-looking rules may be more appropriate, but on the other hand the results are quite sensitive to instrument selection and also ultimately ambivalent about the response to inflation. Nonlinear models can also be used to characterize ECB policy, but do not appear to have a strong advantage over a simpler linear model. A nonlinear response to inflation and an asymmetric response to output seem to have the most merit as possible departures from linearity. For the models that utilize rational expectations, the output gap seems the most reliably significant macroeconomic variable, which is a rather curious finding. The inflation response in the rational expectations models is quite ambiguous, either not seeming to fulfill the Taylor principle or possibly fulfilling it, but mostly appearing to be weak, not statistically significant and difficult to reliably identify. The uncertainty about the inflation response is only compounded by results from several other recent studies.

Actual ECB forecasts give a rather different impression of policy. The forecasts imply that policy is to a large extent based on projections of inflation and GDP growth for the next year and the response to projected inflation does not appear weak. These projections also seem to be the most reliable and accurate basis for inference, even with the limited amount of observations, since different outcome-based estimates lead to the aforementioned uncertainty about the point estimate for inflation. The results also suggest that forecasts are a large component of ECB policy behavior and that the forecasts can be potentially highly informative about policy decisions. Forecasts therefore seem like a promising avenue for future research, particularly when more forecasts become available.

10 References

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