This draft: 12 February,
1998

Uncertainty and the Taylor rule in a simple model of the euro-area economy*

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Abstract

This paper explores the Taylor rule – defined as an instrument rule linking the central bank's policy rate to the current inflation rate and the output gap – as a benchmark for analysing monetary policy in the euro area. First, it presents evidence that interest rates in Germany and the euro area can be described by a Taylor rule with interest rate smoothing. Second, it analyses the stabilisation properties of the Taylor rule in a closed economy model of the euro area, estimated using aggregate data from five EU countries. An optimised Taylor rule performs quite well compared to the unconstrained optimal feedback rule. Finally, the robustness of these results to estimation error in the output gap and model uncertainty is examined.

* A previous version of this paper was circulated under the title "The Taylor rule: a useful monetary policy guide for the ECB?". We thank Lars Svensson, John Taylor, Shamik Dhar, Giorgia Giovanetti and participants at the workshop on "Monetary policy of the ESCB: Strategic and implementation issues", held in Milan on 6-7 July 1998, the CEPR/CREi/DGXII/EUI Conference on "The political economy of fiscal and monetary policy in EMU" held in Barcelona on 17/19 December 1998 and seminars at the BIS and the IIES in Stockholm for very useful comments. We thank Gert Schnabel for superb assistance with the data. The paper was written while the second author was at the BIS. The views expressed are solely our own and not necessarily those of the BIS or the ECB.

1. Introduction

In this paper we explore the usefulness of the Taylor rule -- defined loosely as an instrument rule linking the central bank's instrument (the short-term interest rate) to the current inflation rate and the output gap -- as a benchmark for analysing monetary policy in the euro area. Such instrument rules have the advantage that they are simple and transparent as they explicitly relate the policy instrument to current economic conditions. They have, however, two important disadvantages. First, they may be too restrictive as the number of variables in the feedback list is typically limited. Second, they may not be robust to changes in the structure of the economy. For these two reasons, central banks, including the ECB, would never want to commit to such simple instrument rules. The need to be able to change policies flexibly in response to new information and/or structural changes in the economy puts a premium on central bank discretion.[1] Nevertheless, simple instrument rules like the Taylor rule could be a useful benchmark, provided that their stabilisation properties prove to be reasonably robust to changes in the underlying economy.

To bring some evidence to bear on whether this is the case, we develop three sections. In Section 2, we first review some evidence on recent interest rate behaviour in Europe. In particular, following Clarida, Galí and Gertler (1998) (CGG), we analyse whether a Taylor rule can reasonably describe the Bundesbank's interest rate policy in the last two decades. More speculatively, we also analyse whether average interest rates in the euro zone can be described by such a rule. Such an historical analysis is of interest for two reasons. First, the Bundesbank arguably is a model central bank for the ECB. If the Taylor rule is a good description of Bundesbank policy, then it may also be an appropriate benchmark for the ECB. Second, if in the recent past average interest rates in the euro area can be described by a Taylor rule, then using such a rule as a benchmark has the advantage of continuity. By and large we confirm the results of CGG that a forward-looking version of the Taylor rule with interest rate smoothing is able to track German and European short-term interest rates quite well since 1979.

While a historical analysis of interest rate behaviour in Europe may suggest the usefulness of the Taylor rule, it does not answer the normative question whether the Taylor rule is a good benchmark to discuss policy in the newly established single currency area. To make progress on this question, we need to analyse the stabilisation properties of the Taylor rule in a model of the euro area economy. Obviously it is difficult to come up with a

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[1] In December 1998 the ECB Council announced a stability-oriented monetary policy strategy. It consists of a quantitative definition of the price stability objective as "an increase of the area-wide harmonised index of consumer prices of below 2%". In addition, a two-pillar strategy -- a reference value for the growth of a broad money aggregate and a broad-based assessment of the outlook for inflation -- was announced to explain monetary policy decisions. This strategy was designed to communicate the long-run commitment to price stability, while allowing for enough short-run flexibility to face the many uncertainties related to the establishment of the new currency.

convincing aggregate model of the euro area economy when the single currency has just been created. Nevertheless, in Section 3.1. we estimate a version of the closed-economy model presented in Rudebusch and Svensson (1998) using a weighted average of output and inflation in five euro countries as a measure of aggregate output and inflation and the real German policy rate as a measure of the common monetary policy.

We argue that this model may approximate the working of monetary policy in the euro area. Part of this justification is given in Appendix 1. There we show that once one controls for changes in bilateral exchange rates and interest rate differentials, a rise in the German real interest rate has similar effects on output in each of the five countries. Moreover, the external transmission channel through the DM-dollar exchange rate does not appear to be significant. While these results need to be taken with more than the usual degree of caution, we consider them as supporting the view that, overall, the euro area will function as a relatively closed economy. Moreover, to the extent that differences in the impact effect of the common monetary policy on the other countries are mitigated by the cross-border effects, the effects will be relatively uniform across the whole euro area.

We then use the EU5 model to compare the performance of a simple Taylor rule with various other instrument rules and the optimal feedback rule in Section 3.2. Our measure of comparison is a standard loss function which captures the fact that the central bank dislikes output, inflation and interest rate variability. Our results are similar to the ones obtained by Rudebusch and Svensson (1998). We find that a Taylor rule performs quite well compared to the optimal feedback rule, although the feedback on the output gap is larger than suggested by Taylor (1993).

Finally, in section 4 we analyse the robustness of the results to various forms of uncertainty. Given the importance of the output gap in the Taylor rule and the fact that typically the confidence band around estimates of the output gap is quite large, we first analyse the impact of estimation error in the output gap on the Taylor rule's stabilisation properties (Section 4.1). Consistent with recent research by Aoki (1998), Orphanides (1998), Rudebusch (1998) and Smets (1998), we find that estimation error reduces the optimal feedback coefficient on output in a simple Taylor rule. However, it does not affect its relative performance. In Section 4.2 we ask how sensitive the Taylor rule is to model uncertainty. As in Estrella and Mishkin (1998) and Rudebusch (1998), we find that the estimated parameter uncertainty has only negligible effects on the efficient feedback parameters. Moreover, the stabilisation properties of a simple Taylor rule with coefficients of 1.5 on inflation and 1.0 on output as recently proposed by Taylor (1998a) appear quite robust to changes in the parameters of the estimated economy as long as the basic closed economy structure is maintained.

2. Taylor rules from the past

In this section we first briefly review the work of CGG. They argue that the Bundesbank's monetary policy reaction function can be cast in terms of a forward-looking Taylor rule with interest rate smoothing. In addition, we look more broadly at interest rates in the eleven euro zone countries.

CGG argue that central bank behaviour in the G3 countries can be described by a forward-looking version of the Taylor rule with interest rate smoothing as in the following equation:

$$(1) \qquad i_t = (1-\rho)\left[\bar{i} + \beta_1\left(E\left[\pi^a_{t+n} \mid I_t\right] - \bar{\pi}\right) + \beta_2 E\left[z_t \mid I_t\right]\right] + \rho\, \mathrm{i}_{t-1} + \mu_t \,,$$

where i_t is the central bank's policy rate, $\bar{i}$ is the equilibrium nominal interest rate, $\bar{\pi}$ is the inflation target, π^a_{t+n} is the annual inflation rate at time t+n, z_t is the output gap (the log difference between actual and potential output), and μ_t is an i.i.d. disturbance representing exogenous shocks to the short rate. E is the expectation operator and I_t is the information available to the central bank at the time it sets the policy interest rate.

The term in square brackets captures the target interest rate of the central bank. In this simple Taylor-like specification the target rate is solely a function of current or expected inflation and the current output gap. For this instrument rule to lead to an effective stabilisation of the inflation rate β_1 needs to be greater than one and β_2 positive, so that the real policy rate rises whenever inflation is above target and/or output is above potential. The parameter ρ captures the degree of interest rate smoothing or the speed with which the actual policy rate adjusts to the target rate.

To estimate the parameters of equation (1), we rewrite the policy rule in terms of realised variables as follows:

$$(2) \qquad i_t = (1-\rho)\beta_0 + (1-\rho)\beta_1\pi^a_{t+n} + (1-\rho)\beta_2 z_t + \rho\, i_{t-1} + \varepsilon_t$$

where $\beta_0 = \bar{i} - \beta_1\bar{\pi}$ and $\varepsilon_t = -(1-\rho)\left[\beta_1\left(\pi^a_{t+n} - E\left[\pi^a_{t+n} \mid I_t\right]\right) + \beta_1\left(z_t - E\left[z_t \mid I_t\right]\right)\right] + \mu_t$. Suppose u_t is a vector of variables within the central bank's information set ($u_t \in I_t$), then $E\left[\varepsilon_t \mid u_t\right] = 0$. These moment conditions can be used to estimate the parameters in (2).

Table 1 presents the estimation results using monthly data covering the period 1979:1-1997:12. For the baseline specification the horizon of the inflation forecast is one year ahead ($n = 12$). Several results are worth mentioning. First, although our sample period is somewhat longer and the instrument set larger, our baseline results are close to the baseline results in CGG. The parameters on expected inflation and output are significantly greater than respectively one and zero, but significantly lower than the values of 1.5 and 0.5 postulated by

Taylor (1993). The latter result is, however, not robust and depends, for example, on the method used for detrending industrial production (see specification 8 and 9 of Table 1).[2]

Second, in contrast to the closed economy Taylor rule in which there is no explicit policy feedback on the exchange rate, the results of the second and third specification in Table 1 show that over the sample period the German policy rate rose significantly in response to a depreciation of the trade-weighted exchange rate.[3] This is consistent with previous findings using different methodologies (e.g. Clarida and Gertler (1996) and Bernanke and Mihov (1997)), as well as with a careful reading of the Monthly Reports of the Bundesbank (see, for example, Tsatsaronis (1994)). It is also consistent with the simple theoretical analysis in Gerlach and Smets (1998) and Ball (1998) who emphasise the importance of the exchange rate channel in open economies and its implications for the optimal monetary policy rule.

Third, in contrast to CGG we find that current inflation remains significant when we add it to the baseline specification (specification 6). Instead, two-year-ahead annual inflation is not (specification 7). This sheds some doubt on CGG's interpretation of (2) as an inflation-forecast rule from which the relative weights on inflation versus output stabilisation in the central bank's preferences can be deduced.[4] As most estimates suggest that central banks affect inflation with a lag that is longer than one year, the forecast horizon should more likely be 2 years ahead.[5] In fact, specification 6 suggests that the policy rate responds to a measure of current trend inflation, with the trend being calculated as a 24-month centred moving average of inflation. This is consistent with the importance many central banks attach to measuring core inflation. Its purpose is to purge purely temporary factors from the current inflation rate as these cannot be influenced anyway.

Finally, Graph 1 examines the stability of the Bundesbank's policy reaction function during the whole post-Bretton Woods period by estimating the parameters of (2) with a moving window of 10 years. Although the Bundesbank regained its monetary policy independence and started announcing monetary growth targets immediately following the breakdown of the Bretton Woods system in 1974, there is evidence of instability in the estimated equation between most of the 1970s and the period following 1979. The wide

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[2] The magnitude of the parameters also changes when we estimate the reaction function using quarterly data of GDP instead of industrial production (see specification 10 in Table 1).

[3] In this specification the target rate includes a fourth term, $\beta_3 \Delta e_t$, where Δe_t is the log difference of a nominal (real) trade-weighted exchange rate in percentage points.

[4] See, for example, Svensson (1997) for a derivation of such a rule in a simple theoretical model. CGG argue that the significance of the output gap in the reaction function in spite of the inclusion of the inflation forecast proves that the Bundesbank cares about output stabilisation.

[5] See, for example, Black, Macklem and Rose (1997) and Battini and Haldane (1998) for a numerical analysis of the optimal forecast horizon in inflation forecast targeting rules.

confidence bands during the 1970s suggest a misspecification of the equation. In particular the coefficient on inflation is very volatile and even negative in the early period.

With the adoption of the Maastricht Treaty in the early 1990s the process of monetary convergence in the EU countries accelerated. It may thus make sense to look at average interest rate behaviour in the EU countries in the 1990s as an indicator of the European monetary policy stance. Gerlach and Schnabel (1998) show that a simple Taylor rule applied to a weighted average of the output gap and the inflation rate in the eleven euro countries can explain the fall in the average 3-month interest rate over the period 1990-97 quite well.[6] One exception is the period of exchange market turmoil in late 1992 and early 1993 when interest rates rose quite dramatically in a number of ERM countries to defend the fixed exchange rate parity.

The lower panel of Table 1 reports the results of estimating equation (2) on quarterly weighted average data for the eleven euro-area countries. Somewhat surprisingly the results are very similar to the results obtained for Germany. Graph 2 plots the average three-month interest rate together with the forward-looking target rule.

In sum, the evidence presented in this Section suggests that a Taylor rule with interest rate interest rate smoothing can track short-term interest rates in Germany and the euro area as a whole quite well. While this evidence complements similar evidence for the United States and other relatively large economies, the analysis remains ex post and does not necessarily say much about how well a Taylor rule may work for the future ECB. To this we turn in the next section.

3. The Taylor rule in an aggregate model for the EU5.

One of the obvious problems with analysing optimal monetary policy in the euro area is that it is difficult to predict how the economy and the transmission mechanism will work under the new monetary regime. Nevertheless, the establishment of the ESCB is not a completely new policy environment as a gradual process of monetary convergence has preceded it. In particular, France and Germany and some of their smaller neighbours have had fixed exchange rates with occasional parity adjustments since the end of the Bretton Woods system. In this section we use a simple model of the transmission process in these countries to analyse more formally the performance of a simple Taylor rule. The model is similar to that estimated by Rudebusch and Svensson (1998) for the United States. As our measures of output and inflation we take a weighted average of real GDP and the CPI in Germany, France, Austria, Belgium and the Netherlands. The monetary policy indicator used to estimate the

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[6] To calculate the interest rate that is consistent with a Taylor rule, they assume coefficients of 1.5 and 0.5 on respectively inflation and the output gap, a constant inflation target of 2 percent and a constant equilibrium real interest rate of 3.55%. The latter is derived from a cross-country regression which filters out the effect of changes in the real exchange rate.

effects of a change in the common monetary policy stance is the real German day-to-day rate.[7]

This aggregate EU5 model may be a useful approximation of the working of the euro economy as a whole in a number of respects. First, while two large euro countries, Italy and Spain, are excluded from the aggregate model, the five countries included still account for almost two thirds of GDP in the EMU area. Second, the countries included have had a history of fixed bilateral exchange rates, with the German Bundesbank de facto playing the anchor role.[8] As a result, the transmission of the German interest rate on aggregate output and inflation under a fixed exchange rate regime may be as close as one can get to a historical description of the effects of a common monetary policy in EMU.

Third, the model takes into account that in terms of openness the euro area as a whole will be more like the United States than like any of its individual members. The ratio of exports of goods to euro area-wide GDP is about 14% and by and large comparable to that of the United States and Japan. The disaggregated analysis of the transmission mechanism in Appendix 1 confirms this hypothesis. Two results from this analysis need to be highlighted. First, we find that once one controls for changes in bilateral exchange rates and interest rate differentials the output effects of a rise in the German real rate are similar in the five countries (with the possible exception of Belgium). Second, the external exchange rate approximated by the DM/USdollar exchange rate has only negligible effects on aggregate output. Thus, in contrast to recent estimation results in Dornbusch et al. (1998) we find that the coefficient on the external exchange rate in an implicit Monetary Conditions Index (MCI) for the ECB would be close to zero.

It is nevertheless obvious that the aggregate EU5 model can only be a rough approximation of the transmission process in the euro area. First, while we argue in Appendix 1 that the output effects of monetary policy in these five countries are similar, this may not be the case for the other euro area countries. Indeed, in Appendix 1 we find some evidence that the impact of a common monetary policy shock on Italian output may be significantly larger than in these countries. Second, the bilateral exchange rates were not completely fixed during the estimation period. The omission of changes in bilateral exchange rates or interest rate differentials may bias the estimation of the aggregate model. Third, it is hard to predict how inflation will respond to the output gap under the new policy regime. Implicitly we assume that the euro area-wide Phillips curve will resemble the one in the EU5 countries over the last two decades. Finally, not only is the monetary regime changing, at the same time many other

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7 Also Italy has been a long-standing member of the ERM. We decided against including Italy in the estimation of the aggregate model because its inflation behaviour over the estimation period was very different. Other countries participating in EMU are excluded either because of problems with data availability (Ireland) or because they started participating in the ERM only recently (Spain, Portugal, Finland). See also Taylor (1998).

8 See, for example, the references in Gros and Thygesen (1992) and De Grauwe (1997).

structural changes are taking place which may have an impact on the transmission process. For all these reasons, the results of this section need to be treated very cautiously.

The rest of this section is structured as follows. In Section 3.1 we estimate a simple aggregate model for the EU5 based on Rudebusch and Svensson (1998). In Section 3.2 we analyse the performance of various optimal instrument rules in the estimated model.

3.1. An estimated aggregate model for the EU5

In this section we estimate a simple aggregate model for the EU5 along the lines of Rudebusch and Svensson (1998). The main difference with the latter paper is that we simultaneously estimate the model and the output gap using unobservable component techniques.[9]

The estimated model has the following form:

(3) $$\pi_{t+1} = \alpha(L)\pi_t + \beta z_t + \varepsilon^{\pi}_{t+1}$$

(4) $$z_{t+1} = \varphi_1 z_t + \varphi_2 z_{t-1} + \lambda(i_t - \overline{\pi}_t) + \varepsilon^{z}_{t+1}$$

(5) $$y^{p}_{t+1} = \mu + y^{p}_t + \varepsilon^{y}_{t+1}$$

(6) $$y_t = y^{p}_t + z_t ,$$

where π_t is an EU5 weighted average of quarterly inflation in percentage points at an annual rate; $\overline{\pi}_t$ is four-quarter inflation in Germany; i_t is the quarterly average German day-to-day rate in percentage points at an annual rate; y^{p}_t is a weighted average of the log of unobserved potential GDP in percentage points and z_t is the unobserved output gap, i.e. the log difference between actual real GDP (y_t) and potential GDP in percentage points.

Equation (3) can be interpreted as a Phillips-curve which relates inflation to the lagged output gap and to lags in inflation. The second equation is the reduced form of an aggregate demand equation which relates the output gap to its own lags and to a lagged real interest rate, which is approximated by the difference between the nominal day-to-day rate and average inflation over the previous four quarters. Equation (5) assumes that potential output follows a random walk process with constant drift. Finally, equation (6) is an identity that defines the output gap.

In Appendix 2 we show how this model can be written in state space form and estimated using the Kalman filter and maximum likelihood methods. Table 2 reports the

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9 See Smets (1998). This estimation methodology extends the work by Kuttner (1994) and Gerlach and Smets (1997).

estimation results with quarterly data over the period 1975:1-1997:4. For comparison we also add the estimation results for the same model estimated for the United States over the same period. As can be seen all the parameters have the expected sign and are significant. It is useful to compare the EU5 estimates with the US ones. While the effect of the real policy rate on the output gap is almost the same in both cases (λ=-0.10), we estimate the slope of the Phillips-curve to be steeper in EU5 than in the US (β=0.33 instead of 0.11).

The EU5 output gap is somewhat more persistent than the US one, but does not exhibit the hump-shaped pattern of the US output gap. In contrast, the inflation process is much less persistent in the EU5 than in the US. The sum of the α-parameters is 0.74 in the EU5 case versus 0.92 in the US case. One interpretation for the fact that we can easily reject a unit root in the inflation process in the EU5 is that during this period agents in the EU5 put a positive weight on the constant inflation target (which equals the average inflation rate over the sample) in forming their inflation expectations. One important issue for the analysis of optimal Taylor rules is whether this weight will be different in the EMU area. This will in part depend on the reputation of the new central bank. Everything else equal lower anti-inflationary credibility will result in a higher persistence of inflation.[10] Implicitly we assume that the ECB will inherit the credibility of the EU5 central banks. If this turns out not to be the case and, for example, the weight on the ECB's inflation target is less than implicit in the EU5 model, then one implication for the optimal Taylor rule would be that the central bank will have to lean more against inflation and output (see the results of section 4.2).

Graph 3 compares the effects of a temporary one-percentage point rise in the real policy rate during 8 quarters on the output gap and inflation in the EU5 and the US. Consistent with the discussion above, one can see that the effects on EU5 output are less in magnitude, but more persistent than in the US, while the effects on inflation are stronger. This again suggests that according to these estimates the output cost of reducing inflation is less in Europe than it is in the US. Comparing these results with the results of the disaggregated analysis in Graph A.1 and A.2. of Appendix 1, it is likely that the output effects would be larger if the aggregate data had included Italy.[11]

Turning to the estimates of the variances of the shocks, we find that the variance of the inflation shocks is very similar to that in the US. However, estimated supply shocks are relatively less important, while demand shocks are more important in the EU5 compared to the US. Graph 4 plots the one-sided and two-sided estimates of the EU5 output gap together with a two standard-deviations confidence band. Consistent with the findings of Gerlach and Smets (1997) the confidence band around the estimates of the output gap is quite wide, but somewhat less so than for the US (Smets, 1998). Typically, the standard deviation of the

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[10] See, for example, the discussion in McLean (1998).

[11] In Section 3.4 we analyse the robustness of the stabilisation properties of the Taylor rule to larger output effects of a monetary policy shock.

output gap is a bit less than one percent. According to these estimates the EU5 was at the end of 1997 still facing a negative output gap of 2% which is marginally significantly different from zero.

3.2. How well does the Taylor rule perform?

Instrument rules and the loss function

In order to analyse how well an optimised Taylor rule performs in the EU5 model estimated in the previous section, we consider the following loss function, [12]

(7) $$E(L_t) = \gamma Var(\bar{\pi}_t) + (1-\gamma) Var(z_t) + \nu Var(i_t - i_{t-1}) .$$

The central bank cares about variability in the deviations of annual inflation from a constant inflation target, variations in the output gap and changes in the short-term interest rate. As all variables are demeaned before the analysis, equation (7) implies that the inflation target equals the mean inflation rate over the sample.

In this section we assume that the central bank takes the model estimated in section 3.1 as given and observes the current state of the economy, including not only current and past inflation and interest rates, but also the current and past output gap. The central bank's task is then to set its policy instrument, i_t, in such a way as to minimise the loss function (7) subject to the dynamics of the economy described by equations (3) to (6).

We consider seven instrument rules. The benchmark rule is the unrestricted optimal feedback rule. Given the linear-quadratic nature of the optimal control problem the optimal rule is linear in each of the seven state variables. In addition, we consider six restricted instrument rules. The first four of these are all variants of the popular Taylor rule. The first restricted rule is the simple Taylor rule (T), and constrains the feedback of the policy rate to the current annual inflation rate and the current output gap,

(T) $$i_t = g_\pi \bar{\pi}_t + g_z z_t .$$

The second restricted rule is a forward-looking Taylor rule (FT). In such a rule the central bank responds to an inflation forecast rather than to current inflation. Following RS, we assume the central bank responds to a constant-interest-rate inflation forecast, i.e. the inflation forecast is calculated under the assumption of a constant interest rate. The forecast horizon is assumed to be 8 quarters.

(FT) $$i_t = g_\pi \bar{\pi}_t^e + g_z z_t$$

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[12] This discussion follows Rudebusch and Svensson (1998). They show how this loss function is equivalent to a more standard intertemporal loss function with a discount rate equal to one.

The third and fourth restricted rules (TS) and (FTS) correspond to the previous two rules, but allow for interest rate smoothing by including the lagged interest rate in the feedback list, i.e.

(TS) $$i_t = g_\pi \bar{\pi}_t + g_z z_t + g_i i_{t-1}$$

(FTS) $$i_t = g_\pi \bar{\pi}_t^e + g_z z_t + g_i i_{t-1}.$$

Finally, the last two restricted rules (F) and (FS) are pure inflation-forecast rules with and without smoothing, i.e.

(F) $$i_t = g_\pi \bar{\pi}_t^e$$

(FS) $$i_t = g_\pi \bar{\pi}_t^e + g_i i_{t-1}.$$

For each of these rules the feedback parameters are optimised so as to minimise the unconditional variance of the period loss function in equation (7) (see Appendix 2). In addition, we also report the performance of the original Taylor rule (OT) and a modified Taylor rule with a somewhat larger response to output (MT), i.e.

(OT) $$i_t = 1.5\bar{\pi}_t + 0.5 z_t.$$

(MT) $$i_t = 1.5\bar{\pi}_t + 1.0 z_t.$$

Results

The upper panel of Table 3 gives the feedback parameters for each of the nine instrument rules, the corresponding standard deviations of the goal variables, the value of the loss function and the ranking among the rules considered. Following Rudebusch and Svensson (1998), we assume for the benchmark case that the central bank puts equal weight on inflation and output deviations ($\gamma = 0.5$) and a weight of 0.25 ($\nu = 0.25$) on the interest rate smoothing component.

The optimal feedback rule in the estimated EU5 model is given by

(8) $$i_t = 0.34\pi_t + 0.17\pi_{t-1} + 0.09\pi_{t-2} + 0.05\pi_{t-3} + 1.17 z_t + 0.12 z_{t-1} + 0.56 i_{t-1}.$$

This rule implies a quite strong response to the current output gap with policy rates increasing more than one for one with increases in the output gap. Not surprisingly, with a weight of 0.25 on the interest rate smoothing component, the optimal feedback rule also implies a significant feedback on the lagged interest rate.

The importance of the output gap is also obvious in the restricted instrument rules. We find that the weight on the output gap in the simple Taylor rule is as large as the weight on inflation and equals about 1.5. In other words, while the weight on inflation is close to the weight proposed by Taylor (1993), the optimal weight on the output gap is three times as large (i.e. 1.5 instead of 0.5). This result is consistent with the findings of Ball (1997) who using a small calibrated model of the US economy argued that an efficient weight on the output gap should be much larger than the 0.5 proposed by Taylor (1993). The third and fourth row in Table 3 give an indication of the cost of following a Taylor rule with lower weights on output . Using the original Taylor rule (OT) increases a typical deviation of the output gap by almost 30 percentage points and a typical deviation of inflation from target by about 20 percentage points. Using a weight of 1.0 reduces these losses considerably.[13]

Obviously, the optimal feedback coefficients in the Taylor rule will also depend on the weights in the objective function. Graph 5 plots the efficient Taylor rule parameters as a function of the weights on output relative to inflation and the weight on the interest rate smoothing component. In this graph the symbol O on the left side of the solid curves stands for strict output targeting, i.e. $\gamma = 0$, while the symbol I on the right side stands for strict inflation targeting, i.e. $\gamma = 1$.[14] The middle curve corresponds to a weight on interest rate smoothing, ν, equal to 0.25 as in the benchmark case. The upper and lower curves correspond to respectively a smaller and greater weight on interest rate smoothing in the loss function.

A couple of observations are worth making. First, for a given weight on interest rate smoothing it appears that the optimal feedback coefficient on the output gap is not much affected by the relative weight on output versus inflation stabilisation. A higher weight on inflation does increase the response to inflation considerably. Again, this reflects the crucial role of the output gap in attempts at inflation stabilisation in this model. In contrast, the weight on interest rate smoothing does affect the optimal response to output quite significantly. As interest rate smoothing becomes more important the coefficient on the output gap falls quite considerably. Over the sample period the standard deviation of changes in the German policy rate was 0.68. If this is a good indicator of the interest rate smoothing objective of a central bank, it suggests that the implicit weight on interest rate smoothing should lie between the cases of $\nu = 0.25$ and $\nu = 0.5$ depicted in Graph 5.

In view of the considerable weight on interest rate smoothing in the objective function, allowing for a response to the lagged interest rate in the restricted instrument rule, improves the performance of the Taylor rule quite considerably. While the long-run feedback on inflation is not much affected, interest rate smoothing allows for an even stronger response

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[13] In a recent paper John Taylor seems to acknowledge that his original proposal may be inefficient and considers rules with a weight on output of 1.0 (Taylor, 1998). See, for example, also McCallum and Nelson (1998).

[14] A weight in between is what Svensson (1997) calls flexible inflation targeting.

to the output gap in the medium-term. As is clear from Table 3, a Taylor rule with interest rate smoothing (TS) comes very close to the optimal feedback rule in this EU5 model.

Allowing the central bank to respond to a constant-interest rate inflation forecast rather than current inflation does not particularly improve the performance of the Taylor rule. While the optimal feedback coefficient on the output gap falls somewhat and that on the inflation forecast rises, the losses are very comparable. The crucial role of the output gap in the transmission mechanism of monetary policy is most obvious when comparing the Taylor rules with the simple inflation forecast rules. The latter perform clearly much worse than the simple Taylor rule. As there are only two shocks in the economy, it is not very surprising that in this economy, one can not improve very much upon a simple Taylor rule by using inflation forecasts rather than current inflation. Obviously, in a more realistic setting filtering out temporary shocks from more permanent ones by using a inflation forecast will be optimal given the considerable lags in the transmission process.[15]

In sum, if the model estimated for the EU5 in section 3.1. is a reasonably good approximation of the way the euro-area economy will work, then the results in this section suggest that a simple Taylor rule with a relatively strong feedback on the output gap would perform quite well in stabilising the economy in the face of macroeconomic shocks. How do these results relate to the existing literature on optimal monetary policy rules? These results on the stabilisation properties of the Taylor rule are quite similar to the findings in Rudebusch and Svensson (1998). One difference with the RS results is that they find a much stronger feedback on inflation. This can be explained by the higher persistence of inflation in the estimated US model. Lower inflation persistence which may be interpreted as higher crediblity of the inflation target implies that the central bank will need to lean relatively less against changes in inflation.

There is more evidence that a simple Taylor rule with a relatively strong feedback on the output gap performs quite well in the US economy. Earlier work include the studies by Henderson and McKibbin (1993) and Levin (1996). More recently Levin et al (1998) examined the performance of a Taylor-like rule in a range of models for the US economy.[16] Similarly to our findings they find that such a rule outperforms simple inflation-forecast rules. In addition, they find that not much can be gained from including other information (such as lagged variables, foreign variables or the exchange rate) in the feedback rule. [put also reference to McCallum and Nelson (1998)].

The overall positive results that have been found for the US economy contrast with the less favourable results researchers have found for smaller, more open economies.

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[15] See Battini and Haldane (1998) on a lucid discussion of why forward-looking rules while simple in form may perform very well.

[16] One difference with the findings in this paper is that they find that a strong persistence in the policy rate is optimal. This result is in part due to the fact that it is the long-term interest rate that matters in the aggregate demand equation.

Black, Macklem and Rose (1997) and Battini and Haldane (1998), for example, find that inflation forecast rules have the ability to perform much better than simple Taylor rules in respectively the Bank of Canada's QPM-model and a calibrated model of the UK economy. Similarly, De Brouwer and O'Regan (1997) find that including the exchange rate and foreign variables improves the performance of the Taylor rule in a model for the Australian economy.

These results are not very surprising. While in closed economies the current output gap and inflation may be close to sufficient statistics to describe the state of the economy, this is unlikely to be the case for more open economies. The most important difference is probably the importance of the exchange rate channel, which is, for example, emphasised in Svensson (1997c) and Battini and Haldane (1998). Indeed, the importance of this channel in relatively open economies is reflected in a significant response to the exchange rate as, for example, illustrated in the estimated reaction function for the Bundesbank in Table 1. However, these results do not necessarily turn around the positive results concerning the Taylor rule of this section. As long as the underlying paradigm of a relatively closed economy with the main transmission channel working through the output gap is reasonable for the euro-zone economy, a Taylor rule would appear to be a useful benchmark.

4 Uncertainty and the robustness of simple Taylor rules

4.1. The effect of estimation error in the output gap

In light of the crucial role of the output gap in the efficient Taylor rules of the previous section, an important question that needs to be addressed concerns the impact of estimation error in the output gap on the efficient feedback parameters and the performance of the Taylor rule. Several authors, including Kuttner (1994), Staiger et al (1996) and Gerlach and Smets (1997) have shown that indicators of capacity utilisation such as the output gap or the NAIRU are estimated with a considerable margin of uncertainty. Given the initial aggregation problems and the lack of reliable historical data, this is likely to be even more true for the measurement of an EMU-wide output gap. One counterargument is that the variability of the EMU-wide output gap will be less than that of the individual countries because some of the idiosyncrasies will be averaged out. In this section, we analyse the effect of estimation error in the output gap on the efficient instrument rules and their performance in the estimated model of section 3.1.

To address this question we follow Smets (1998) who argues that estimation error in the output gap may in part explain why the actual central bank response to movements in the output gap is less than optimal control exercises suggest.. The loss function and the dynamics of the economy are again given by equations (3) to (7). However, now we assume, consistent with the estimated model, that output gaps are not directly observed, but need to be estimated. In other words, two of the state variables, z_t and z_{t-1} are unobserved.

Current and past growth rates of real GDP, Δy_t, are observed, but could be due to either a change in the growth of potential output or a change in the output gap, so that the central bank faces a signal extraction problem. The Kalman filter which was used in section 3.1. to estimate the model gives the optimal estimate of the output gap given the observed data and the structure of the economy.

The middle panel of Table 3 gives the results of the optimal control exercise when we take the estimated uncertainty of the output gap into account.[17] As emphasised in Estrella and Mishkin (1998) and shown by Chow (1970) estimation errors in the state variables do not affect the optimal unconstrained feedback rule in a linear-quadratic framework. As a result of this certainty equivalence theorem, the only difference between the optimal linear feedback rule in panel 1 and 2 of Table 3 is that in the latter case the feedback is on the estimated state variables rather than on the actual state variables.[18] However, the loss function is affected as the policy feedback on measurement error in the output gap will filter through into the economy and increase the variability of the goal variables. Indeed, the loss under the optimal feedback rule increases from 1.03 to 1.60.

More interesting are the results concerning the restricted feedback rules. The relative ranking of the different rules is not affected. However, comparing panel 1 and 2 of Table 3, it is obvious that in the simple Taylor rule, the weight on output falls from 1.58 to 1.41 and the weight on inflation increases from 1.53 to 1.65. The effect of measurement error is to put less weight on the variable that is measured with error and more on the variable that is perfectly observed.[19] Graph 6 plots the Taylor rule coefficients as a function of the uncertainty in the output gap. The optimal response to the output gap in a simple Taylor rule falls at an increasing rate as the standard deviation of the estimation error in the output gap increases, while the optimal response to inflation rises. In both cases the optimal feedback parameter is still relatively high at the estimated standard deviation (around 0.8 percent). However, increasing the standard deviation beyond its estimate results in a rapid drop of the feedback parameter. A standard deviation of 1.13 would in this model be consistent with a coefficient of 0.5 on output, as suggested by Taylor (1993). It becomes optimal not to respond to the output gap when its standard deviation is larger than 1.15 percent.

Graph 5 shows that the negative effect of higher estimation error on the Taylor rule coefficients is robust to various weights in the objective function. The dashed lines give the optimal Taylor rule coefficients for various weights taking the estimated output gap uncertainty into account. In almost all cases the efficient Taylor rule coefficient on output falls, but how much depends on the weights in the objective function. It is worth noting that although the effect of the estimated output gap uncertainty is to move the efficient Taylor rule

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[17] See Appendix 2 for some of the technical details.

[18] This result is sometimes called a separation theorem. See Chow (1970) for a discussion.

[19] See Staiger et al (1996).

parameters in the direction of the values suggested by Taylor (1993), it is clear that one needs either larger than estimated output gap uncertainty or a strong interest rate smoothing objective to explain why actually estimated feedback parameters on output are around 0.5. However, from the third and fourth row in the middle panel of Table 3 it is obvious that the loss of having a lower feedback parameter on output (0.5 or 1.0) is much less when one takes into account the measurement error in the output gap.

In sum, estimation error in the output gap can partly explain why central banks in practice respond less to the output gap than suggested by optimal control exercises which do not take into account this uncertainty. In the extreme, high uncertainty may result in a zero response to the output gap. With the estimated standard deviation of the EU5 output gap, a quite strong feedback is still optimal. It is an empirical question whether estimates of the EMU-wide output gap are subject to much larger confidence bands. These results correspond with other recent research that has analysed the effects of measurement error in both output gaps and inflation on the optimal feedback coefficients in a Taylor rule. Both Rudebusch (1998) and Orphanides (1998) analyse measurement error in inflation and the output gap in a very similar model for the United States. Both of them document that there are significant revisions in US estimates of inflation and the output gap and show that taking this measurement error into account reduces the efficient feedback parameters and brings them more in line with the original Taylor rule ones. Aoki (1998) performs a theoretical analysis in a simple, but optimising model of the US economy. Consistent with the previous results, he shows that noise contained in the data offers a reason for policy conservatism.

4.2. The effect of uncertainty about the transmission mechanism

In Section 3 we have argued that a simple model of the transmission mechanism for a relatively closed economy may be a useful starting point for analysing monetary policy in the euro area. However, the uncertainties remain large. In part, this is a generic problem facing central banks. In spite of decades of economic research on this issue, there is still a considerable degree of uncertainty about the precise effects on output and inflation of changes in the monetary policy stance.[20] In the case of euro area, the fact that monetary policy may impact the economy of the different nations differently, the associated aggregation problem, the absence of aggregate historical data and the potential for a structural break under the new regime make an analysis of the euro area-wide transmission mechanism even more complicated. In this section, we make a preliminary and necessarily limited attempt at assessing the impact of parameter uncertainty on the optimal policy rules considered in this paper.

[20] For an overview of some of the empirical research on the transmission mechanism in the European context, see Kieler. and Saarenheimo (1998).

Following the original work of Brainard (1967), a number of authors, including Svensson (1997b), Clarida et al (1997b), Cecchetti (1997), Estrella and Mishkin (1998) and Wieland (1997), have recently analysed the effect of parameter uncertainty on optimal monetary policy rules using simple mostly theoretical models of the transmission mechanism.[21] There is, however, little attempt to quantify the effects of parameter uncertainty in an empirical model. Such quantification is important because only in the special case where none of the parameters are correlated can one unambiguously show that higher uncertainty about the transmission mechanism will result in a more cautious response of the central bank to the economy's state variables.[22]

In this section we use two admittedly limited ways of assessing the impact of model uncertainty on optimal policy behaviour and the performance of the Taylor rule in particular. First, following the literature discussed above we analyse the optimal Taylor rule if we take into account the estimated variance-covariance matrix of the parameter estimates as a measure of model uncertainty. The lower panel of Table 2 presents the results.[23] We basically confirm the results of Estrella and Mishkin (1998) and Rudebusch (1998) who show that parameter uncertainty only marginally reduces the efficient feedback parameters in the instrument rules. This is true for both the optimal linear feedback rule and the simple Taylor rule. Moreover, even doubling the estimated standard deviations of the parameters does not significantly change this result. In sum, conventional parameter uncertainty does not seem to matter very much for the efficient instrument rules.

However, the estimated parameter uncertainty of the EU5 model may not take into account the potential for model uncertainty that arises from the fact that the transmission in the other EMU countries may be different or from structural breaks due to the establishment of the new monetary regime. While a full analysis of the robustness of simple Taylor rules to such model uncertainty deserves a separate paper, Graph 7 presents some suggestive evidence. In this graph we plot the efficiency frontier of both the optimal linear feedback rule and the efficient simple Taylor rule (T) for four different versions of the EU5 model. In each case the symbol MT corresponds to the outcome of the Modified Taylor rule with a feedback coefficient of 1.5 on inflation and 1.0 on the output gap. The solid lines correspond to the estimated model.

The lines indicated by Model 1 correspond to a similar model with a reduced slope of the Phillips curve (β is 0.15 instead of 0.33). In other words, compared to the estimated model, the sacrifice ratio is higher and similar to the one estimated for the United

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21 See also Blinder (1998). A particularly innovative paper is Wieland (1997). He analyses the trade-off faced by the central bank between caution and experimentation.

22 Recent papers that contain a quantitative assessment of the effects of parameter uncertainty are Estrella and Mishkin (1998), Rudebusch (1998), Sack (1998), Shuetrim (1998) and Salmon et al (1998).

23 Some of the technical details can again be found in Appendix 2.

States. As noted in Rudebusch (1998), a steeper slope of the Phillips curve will reduce the feedback coefficient on the output gap while increasing the one on inflation. The lines indicated by Model 3 correspond to a model in which the output effects of an interest rate rise are much higher (λ is –0.15 instead of –0.10). A higher interest rate sensitivity will generally reduce the feedback coefficients on both output and inflation. Finally, the lines with short dashes (Model 2) correspond to a model in which the persistence of inflation is greater ($\alpha(1)$ is 0.85 instead of 0.74).

Except in the latter case, the results of Graph 7 seem to indicate that the modified Taylor rule does relatively well in stabilising output and inflation compared to the efficiency frontier. The gains from moving to the frontier are typically less than 10 basis points in terms of a reduced standard deviation of inflation and the output gap. More substantial gains can be achieved when inflation is much more persistent than estimated in the EU5 model. In this case an efficient Taylor rule would do much better and could potentially reduce the standard deviation of inflation by more than 20 basis points. The reason for this is that when shocks to inflation are highly persistent it pays for the central bank to be much more aggressive. In this particular case the efficient Taylor rule parameters are 1.9 on inflation and 1.8 on the output gap if the central bank cares equally about output and inflation. Most evidence seems, however, to suggest that inflation persistence has fallen as inflation has been come down.

Overall, the evidence presented here suggests that the relatively good performance of a simple Taylor rule with coefficients of 1.5 on inflation and 1.0 on output is robust to small variations in the parameters of the estimated model. This is consistent with tests of the robustness of simple Taylor rules in the US models. Levin et al (1998), for example, find that the Taylor rules they consider are quite robust across the different models of the US economy they analyse. One possible exception that we identified is when the inflation process turns out to be much more persistent than estimated in the EU5 model. In that case optimal Taylor rules are still performing quite well, but the feedback parameters need to be much higher than the ones typically suggested. Of course, the significance of these results is somewhat reduced by the fact that we did not consider radically different models of the euro area economy.

5. Conclusions

The need to be able to change policies flexibly in response to new information and/or structural changes in the economy puts a premium on central bank discretion. Nevertheless, simple policy guidelines can be useful in two respects. First, they can be used internally as a benchmark to assess policy decisions which are based on the widest information set available. The availability of a benchmark puts some discipline on the central bank's staff to explain why its analysis deviates from what the benchmark suggests. Second, when made public they can also be used as a communication device to explain policy decisions to the general public.

In this paper we have argued that it may be worth considering a simple guideline like the one suggested by Taylor (1993) as a benchmark for analysing monetary policy in the euro area. Our justification is basically threefold. First, as the rule explicitly links the current policy rate to the current state of the economy as captured by the current trend inflation rate and the current output gap, it is easy to calculate and understand. This simplicity helps the communication of the central bank. Second, there is increasing evidence that the policy behaviour of successful central banks can be usefully described by variants of the Taylor rule.[24] In Section 2 of this paper we present some evidence that also in Europe movements in short-term interest rates can be approximated by such a rule. In part, these two reasons explain why so many private sector economists use a Taylor rule to analyse policy decisions.

Third, the benefits of having a benchmark rule will, of course, depend on how robust the ability of the rule to stabilise inflation and output is to changes in the structure of the economy. Obviously, if optimal policy deviates frequently and persistently from the benchmark and/or the rule needs to be revised frequently, the advantages of having such a benchmark will quickly disappear.[25] In section 3 of the paper we argue that to a first degree the euro area economy can be modelled as a relatively closed economy along the lines of Rudebusch and Svensson (1998). Using this estimated model we show that simple Taylor rules do a rather good job in stabilising output and inflation. In Section 4 we show, in addition, that estimation error in the output gap does not significantly affect the performance of the Taylor rule, although it does reduce the optimal feedback coefficient on the output gap. We also find that the performance of the Taylor rule is robust to small changes in the parameters of the model. Overall, this is consistent with research on simple policy rules using models for the US economy.

In spite of the generally favourable results concerning the stabilisation properties of a Taylor rule in a relatively closed economy, there remain a number of issues which need to be resolved. First, questions remain about the appropriate choice of the feedback coefficients in the Taylor rule, in particular on the output gap. Second, most empirical studies of central bank behaviour reveal that central banks smooth interest rates and only gradually move towards the policy suggested by a Taylor rule. The reasons for interest rate smoothing need to be better understood. In an innovative study, Sack (1998) finds that in a situation where the central bank learns about the policy multiplier by observing the reaction of the economy to recent interest rate changes, it may be optimal to move gradually over time.

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[24] For an interesting historical analysis of US monetary policy through the lenses of the Taylor rule, see Taylor (1998).

[25] The importance of robustness in the design of monetary policy rules has often been stressed by Ben McCallum (See, e.g. McCallum (1997)).

Third, implementing the Taylor rule requires an estimate of the equilibrium real interest rate. The implications of considerable uncertainty about its level need to be examined.

Appendix 1: Some more evidence on the transmission mechanism in Europe.

In this appendix we provide some additional evidence on the monetary policy transmission mechanism in six European countries, Austria, Belgium, France, Germany, Italy, and the Netherlands. The emphasis is on the output effects of a common monetary policy shock taking into account the interaction effects among the EU countries due to their trade links. The effects of such a shock will most closely replicate the effects a common monetary policy under EMU. The immediate goal of the exercise is to provide some suggestive evidence that, first, a common monetary policy shock has quite similar effects on output in the five EU countries that we use in the aggregate model and, secondly, that the external (dollar) exchange rate has negligible effects on output.

To do so, we estimate for each country i the following output equation:[26]

$$\text{(A1.1)} \quad \begin{aligned} y_t^i = {} & \sum_{j=1}^{k} A_j^i y_{t-j}^i + \sum_{j=1}^{k} B_j^i y_{t-j}^{-i} + \sum_{j=1}^{k} C_j^i r_{t-j}^{DM} + \sum_{j=1}^{k} D_j^i (r_{t-j}^i - r_{t-j}^{DM}) \\ & + \sum_{j=1}^{k} E_j^i x_{t-j}^{US/DM} + \sum_{j=1}^{k} F_j^i x_{t-j}^{i/DM} + \varepsilon_t^i \end{aligned}$$

where y^i is output growth in country *i*, r^{DM} is the real German interest rate, r^i the real rate of country *i*, $x^{US/DM}$ the US/DM exchange rate and the exchange rate of country *i* in DM.[27] We include the German real rate and $x^{i/DM}$ the DM/dollar exchange rate as measures of the common monetary policy stance in Europe. In addition, we add the real interest rate differential and the DM exchange rate of each European currency to control for deviations of the domestic policy stance from the common monetary policy stance.

Equations (A1.1) can be seen as the output equations of a VAR, which also includes real interest rates and exchange rates. We estimate this system for the six EU-countries mentioned above using SUR estimation and quarterly data over the period 1978:1-1995:4.[28] The common lag length of two quarters was derived using a sequence of (likelihood ratio) exclusion tests. With this system, we simulate the effect of a 1 percentage point increase in the German real interest rate and the effect of a 1 percent appreciation of the DM/USdollar

[26] This partially follows the methodology used in Dornbusch, Favero and Giavazzi (1998). In contrast to that paper, we include the real German rate and deviations of real short-term interest rate from the German rate. Dornbusch et al (1998) include expected and unexpected interest rates in their equation.

[27] Real rates are defined as the corresponding nominal rate minus current annual inflation.

[28] We also estimated the system excluding Italy over the period (1975:1-1995:4) with very similar results. The six EU countries represent about 84% of PPP-adjusted real GDP of the EMU area in 1990. Without Italy this share falls to 62% of EMU GDP. While it would be interesting to include Spain and the other smaller EMU countries Ireland, Finland, Portugal and Luxembourg, data limitations prevented us from doing so.

exchange rate during 8 quarters on GDP in each of the six countries, as well as on a weighted average.

Graphs A.1 and A.2 highlight the main results of the analysis. Graph A.1 shows the effect of a one percentage point increase in the interest rate and a one percent appreciation of the dollar exchange rate on a weighted average of GDP in the six countries together with a two standard deviations confidence band. It is immediately clear that while there is a strong interest rate channel, in contrast to Dornbusch et al (1997), we do not find a systematic negative effect of an appreciation of the dollar on output in these six countries. Only in France we find a significant negative effect (See lower panel of Graph A.2). However, even there the implicit weight on the exchange rate in a Monetary Conditions Index is small. While we find these estimates more plausible than the ones suggested by Dornbusch et al (1998), our results need to be taken with more than the usual degree of caution. In estimating the system, we assumed the real interest rate and the exchange rate to be pre-determined. While this may be a reasonable assumption for the real interest rate, it is much less clear for the real exchange rate. In particular, if the exchange rate appreciates in response to forecasts of stronger growth, a simultaneous equations bias may reduce the estimated output effects of such an appreciation. In future research we intend to address this problem by using instrumental variables in the estimation.

Graph A.2 suggests that there are significant differences in the strength of the interest rate channel across the six countries. The graph shows the difference in output effects between each country and the EU6 (i.e. a weighted average of the six EU countries) together with a 95 percent confidence band. An interest rate shock has very similar effects on output in Austria, France, Germany and the Netherlands, but considerably larger effects in Belgium and Italy. In view of the high government debt in both countries one possible explanation is that higher interest rates increase the government debt burden and lead to a procyclical tightening of fiscal policy. The fact that monetary policy may have larger effects in Italy than in the rest of the EMU area has also been noted in other studies (for example, BIS (1995) or Dornbusch et al (1998)). One explanation emphasised in these studies is that the share of the private debt incurred at adjustable interest rates is larger in Italy than in the other EMU countries. This implies that a rise in interest rates has a more direct effect on the interest rate burden of the private sector.

Appendix 2: Estimation and optimal control of the EU5 model

A2.1. Estimation of the EU5 model

In order to estimate model (3) to (6) using the Kalman filter and maximum likelihood methods, we write the model in state space form. The measurement equations are given by:

(A2.1) $$\begin{bmatrix} \Delta y_t \\ \pi_t \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 0 & \beta \end{bmatrix} \begin{bmatrix} z_t \\ z_{t-1} \end{bmatrix} + \begin{bmatrix} \mu \\ \alpha(L)\pi_{t-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_t^y \\ \varepsilon_t^\pi \end{bmatrix}$$

The corresponding state equation is:

(A2.2) $$\begin{bmatrix} z_{t+1} \\ z_t \end{bmatrix} = \begin{bmatrix} \varphi_1 & \varphi_2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} z_t \\ z_{t-1} \end{bmatrix} + \begin{bmatrix} \lambda(i_{t-1} - \overline{\pi}_{t-1}) \\ 0 \end{bmatrix} + \begin{bmatrix} \varepsilon_t^z \\ 0 \end{bmatrix}$$

Assuming that each of the three shocks are independently normally distributed with the following variance-covariance matrix,

(A2.3) $$\Sigma_\varepsilon = \begin{bmatrix} \sigma_y^2 & 0 & 0 \\ 0 & \sigma_z^2 & 0 \\ 0 & 0 & \sigma_\pi^2 \end{bmatrix},$$

one can form the likelihood function using the Kalman filter and derive the estimates of the model using maximum likelihood estimation. The results are presented in Table 1.

A2.2. Optimal control of the EU5 model

In order to derive the optimal feedback parameters of the different instrument rules, we write the EU5 model in its companion form. The state-space representation of the economy is then given by,

(A2.4) $$X_{t+1} = AX_t + Bi_t + \nu_t,$$

where the vector X_t of state variables, the matrix A, the column vector B, and the disturbance vector ν_t are given by

$$X_t = \begin{bmatrix} z_t \\ \pi_t \\ z_{t-1} \\ \pi_{t-1} \\ \pi_{t-2} \\ \pi_{t-3} \\ i_{t-1} \end{bmatrix}, A = \begin{bmatrix} \varphi_1 & -\lambda/4 & \varphi_2 & -\lambda/4 & -\lambda/4 & -\lambda/4 & 0 \\ \beta & \alpha_1 & 0 & \alpha_{21} & \alpha_3 & \alpha_4 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} \lambda \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \nu_t = \begin{bmatrix} \varepsilon_t^z \\ \varepsilon_t^\pi \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The vector Y_t of goal variables fulfils

(A2.5) $$Y_t = C_X X_t + C_i i_t,$$ where

$$Y_t = \begin{bmatrix} \bar{\pi}_t \\ z_t \\ i_t - i_{t-1} \end{bmatrix}, C_X = \begin{bmatrix} 0 & 1/4 & 0 & 1/4 & 1/4 & 1/4 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix}, \ C_i = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}.$$

The period loss function can then be written as

(A2.6) $$E[L_t] = E[Y_t{'}KY_t],$$

where K is a 3×3 diagonal matrix with (γ,1-γ,ν) on the diagonal.

The loss function when the model and the state variables are known

If one assumes that both the parameters of the model in (A2.1) and the state variables are known, then each of the restricted rules can be written as a linear function of the vector of state variables (say $i_t = gX_t$). The dynamics of the model and the goal variables for a given rule are then given by[29]

(A2.7) $$X_{t+1} = MX_t + v_{t+1},$$

(A2.8) $$Y_t = CX_t,$$

where $M = A + Bg$ and $C = C_X + C_i g$.

The optimal feedback parameters in each of the restricted instrument rules can than be calculated by minimising the unconditional loss:

(A2.9) $$E[L_t] = E[Y'_t KY_t] = trace(K\Sigma_Y),$$

where Σ_Y is the unconditional covariance matrix of the goal variables and is given by:

(A2.10) $$\Sigma_Y = C\Sigma_X C',$$

and Σ_X is the covariance matrix of the state variables and is in turn related to the covariance matrix of the disturbances by the following equation,

(A2.11) $$vec(\Sigma_X) = [I - (M \otimes M)]^{-1} vec(\Sigma_v).$$

29 See Rudebusch and Svensson (1998) for a discussion of how the constant-interest rate forecast can be calculated.

The loss function with measurement error in the output gap

In matrix notation the observation equation equivalent to equation (A2.1) is given by:

(A2.12) $$W_t = DX_t + \eta_t,$$

where the vector of observables W_t, the matrix D, and the vector η_t are given by

$$W_t = \begin{bmatrix} \Delta y_t \\ \pi_t \\ i_{t-1} \end{bmatrix},\ D = \begin{bmatrix} 1 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},\ \eta_t = \begin{bmatrix} \varepsilon_t^y \\ 0 \\ 0 \end{bmatrix}.$$

The central bank's estimate of the current state of the economy is then given by $E_t X_t = E\left[X_t \middle| W_t\right]$.

In this case the objective function is still given by equation (A2.9). However, with measurement errors in the output gap the covariance matrix of the goal variables and the state variables need to be modified to include the effect of measurement error. This results into the following expressions:

(A2.13) $$\Sigma_Y = C\Sigma_X C' + C_X \Sigma_S C_X', \text{ and}$$

(A2.14) $$vec(\Sigma_X) = \left[I - (M \otimes M)\right]^{-1}\left[vec(\Sigma_v) + \left[(A \otimes A) - I\right]vec(\Sigma_S)\right],$$

where Σ_S is the covariance matrix of the measurement errors in the vector of state variables and can be derived separately from the Kalman filter used in A2.1. (See Chow (1970))

The loss function under model uncertainty

If the state variables are observed, but the parameters of the estimated model in equation (A2.4) are subject to uncertainty, then equations (A2.9) and (A2.10) again describe the loss function and the covariance matrix of the goal variables, but in this case the covariance matrix of the state variables is given by the following equation:

(A2.15) $$vec(\Sigma_X) = \left[I - E\left[(A + Bf) \otimes (A + Bf)\right]\right]^{-1} vec(\Sigma_v).$$

In order to calculate the expectation in (A2.15) we use the estimated covariance matrix of the parameters.

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Table 1

Estimates of a forward-looking Taylor rule

	β_0	β_1	β_2	β_3	ρ
Germany (1979:1-1997:12)					
1. Baseline	2.52	1.30	0.28		0.93
	(0.32)	(0.10)	(0.05)		(0.01)
2. + nominal effective exchange rate	2.57	1.29	0.32	-0.52	0.94
	(0.36)	(0.11)	(0.06)	(0.24)	(0.01)
3. + real effective exchange rate	2.47	1.29	0.34	-0.77	0.94
	(0.37)	(0.12)	(0.06)	(0.29)	(0.01)
4. With current inflation	3.24	0.99	0.43		0.92
	(0.19)	(0.06)	(0.03)		(0.01)
5. With two year ahead inflation	1.19	1.93	0.30		0.96
	(0.99)	(0.33)	(0.09)		(0.005)
6. + current inflation	2.61	0.69	0.26	0.57	0.91
	(0.26)	(0.12)	(0.03)	(0.09)	(0.01)
7. + two year ahead inflation	2.80	1.26	0.22	-0.01	0.92
	(0.42)	(0.10)	(0.04)	(0.15)	(0.01)
8. HP-filter on output	1.74	1.59	0.43		0.93
	(0.37)	(0.11)	(0.10)		(0.01)
9. Exponential smoothing on output	1.15	1.83	0.49		0.95
	(0.39)	(0.14)	(0.09)		(0.01)
10. Quarterly data	3.50	0.96	0.54		0.84
	(0.78)	(0.27)	(0.17)		(0.02)
The euro area (1980:1-1997:4)					
11. Quarterly data	3.87	1.20	0.76		0.76
	(0.44)	(0.09)	(0.13)		(0.13)

Notes: The estimated equation is given by equation (2). The optimal weighting matrix is obtained from first step two-stage least squares parameter estimates. In the case of Germany the instrument set u_t includes lagged values of inflation, the output gap, short and long term interest rates, the exchange rate, commodity prices and the money supply. Industrial production is used to capture output developments on a monthly basis. In the baseline case a quadratic trend is used to calculate the output gap. In the case of the euro area, the instrument set includes lagged values of inflation, the output gap, short and long-term interest rates and the money supply. A linear trend is used to calculate the output gap on the basis of GDP data. GDP weights are used to aggregate the national series.

Table 2

Estimation Results

	EU5 (75:1–97:4)		US (75:1–97:4)	
φ_1	0.84	(0.22)	1.41	(0.15)
φ_2	0.10	(0.22)	-0.52	(0.13)
β	0.33	(0.13)	0.11	(0.05)
λ	-0.10	(0.04)	-0.12	(0.03)
α_1	0.45	(0.09)	0.48	(0.09)
α_2	0.17	(0.11)	0.19	(0.08)
α_3	0.06	(0.10)	0.13	(0.09)
α_4	0.06	(0.09)	0.12	(0.10)
σ^2_y	0.19		0.39	
σ^2_z	0.22		0.14	
σ^2_π	0.98		0.74	
likelihood	129.3		129.5	

Note: Standard errors in parenthesis

Table 3

Results on volatility and loss ($\gamma = 0.5$, $\nu = 0.25$)

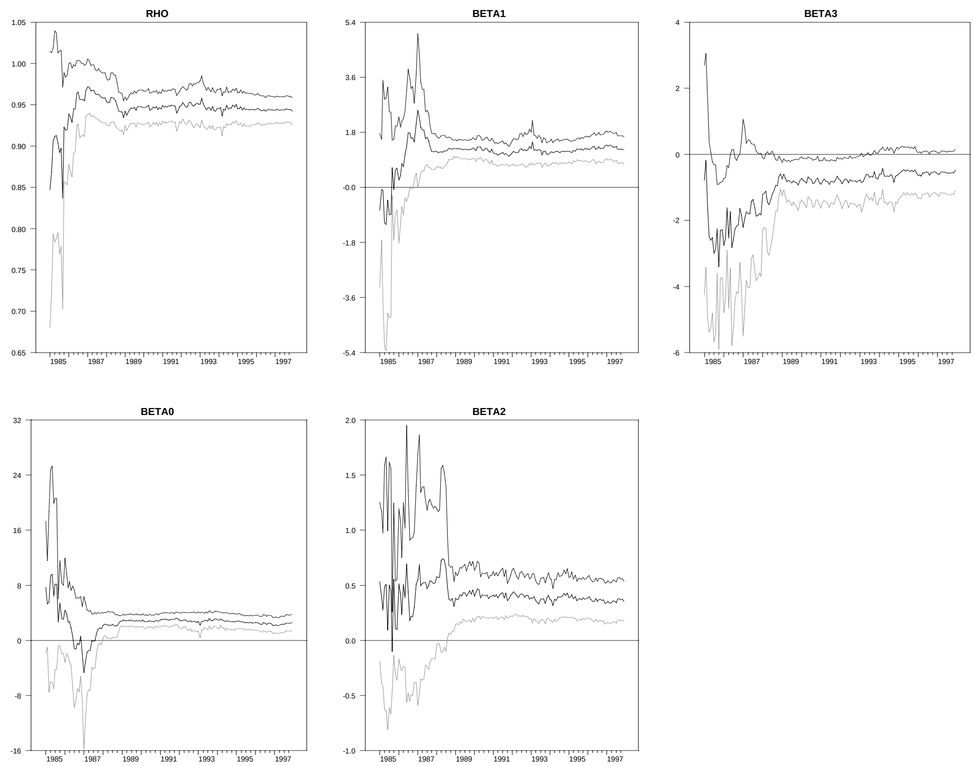
w/o output gap and parameter uncertainty

Rule	σ_{π_t}	σ_{z_t}	$\sigma_{i_t - i_{t-1}}$	Loss	Rank
Without uncertainty					
Optimal	1.12	0.69	0.82	1.03	1
T (g_π = 1.53, g_z = 1.58)	1.16	0.73	0.96	1.18	4
MT (g_π = 1.5, g_z = 1.0)	1.23	0.83	0.74	1.25	6
OT (g_π = 1.5, g_z = 0.5)	1.35	0.97	0.62	1.48	7
F (g_π = 2.39)	1.42	1.16	0.89	1.89	9
FT (g_π = 1.89, g_z = 1.54)	1.15	0.73	1.01	1.19	5
TS (g_π = 0.67, g_z = 1.33, g_i = 0.55)	1.14	0.69	0.82	1.06	3
FS (g_π = 2.47, g_i = -0.03)	1.42	1.15	0.91	1.89	8
FTS (g_π = 0.84, g_z = 1.26, g_i = 0.58)	1.13	0.69	0.82	1.05	2
With estimated output gap uncertainty					
Optimal	1.30	1.03	0.92	1.60	1
T (g_π = 1.65, g_z = 1.41)	1.32	1.04	0.99	1.67	3
MT (g_π = 1.50, g_z = 1.00)	1.39	1.07	0.81	1.70	4
OT (g_π = 1.50, g_z = 0.50)	1.46	1.11	0.69	1.81	5
TS (g_π = 0.80, g_z = 1.54, g_i = 0.48)	1.31	1.03	0.92	1.61	2
With estimated model uncertainty					
Optimal	1.15	0.72	0.83	1.11	1
T (g_π = 1.51, g_z = 1.56)	1.19	0.77	0.98	1.27	3
TS (g_π = 0.67, g_z = 1.31, g_i = 0.55)	1.17	0.72	0.84	1.13	2

Graph 1

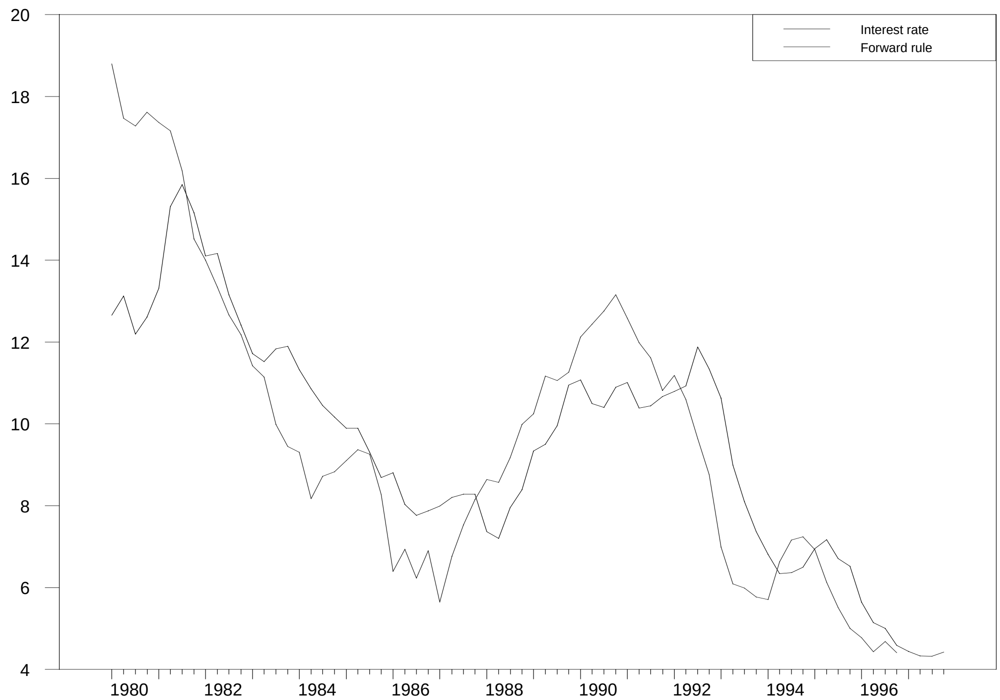
10-year moving window estimates of the Bundesbank's reaction function

(1975:1-1997:12)



Graph 2
Average interest rates in the euro area and an estimated forward-looking Taylor rule

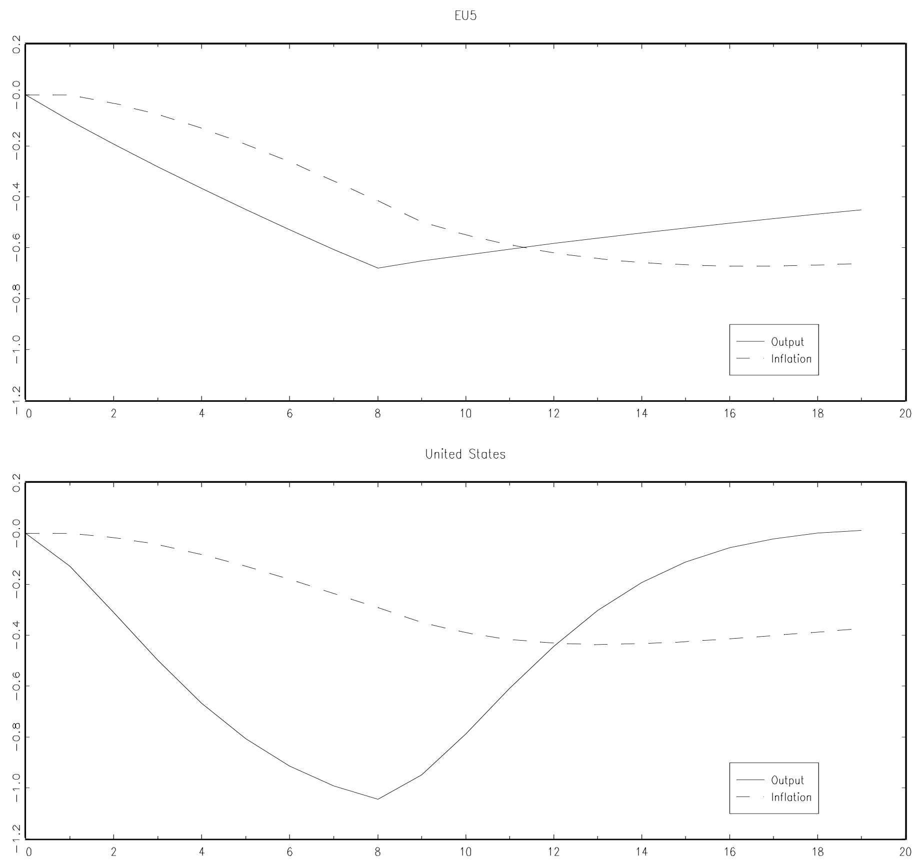
(1980:1-1997:4)



Graph 3

The effects of a one percentage point interest rate rise

(horizon=8 quarters, estimation period is 1974:1-1997:4)

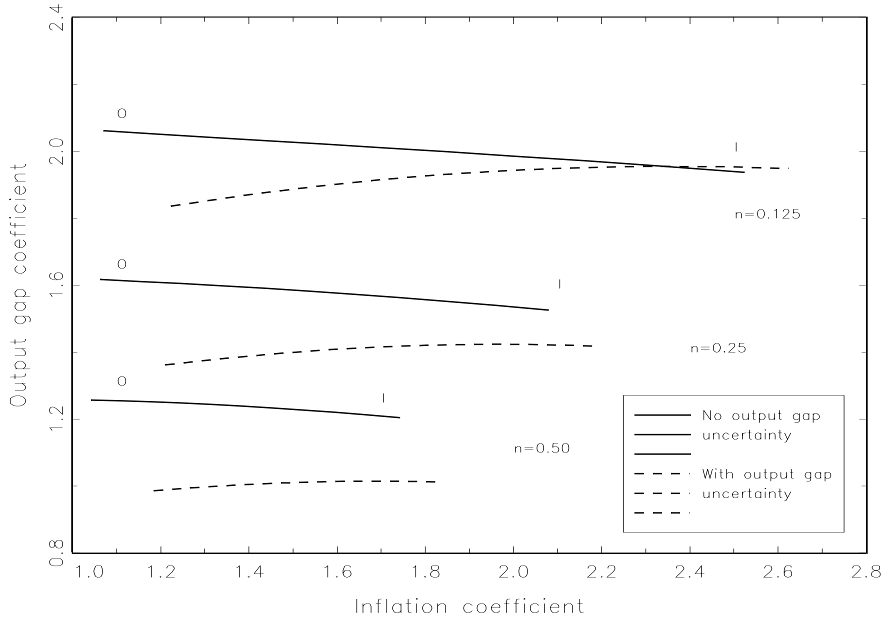


Graph 4

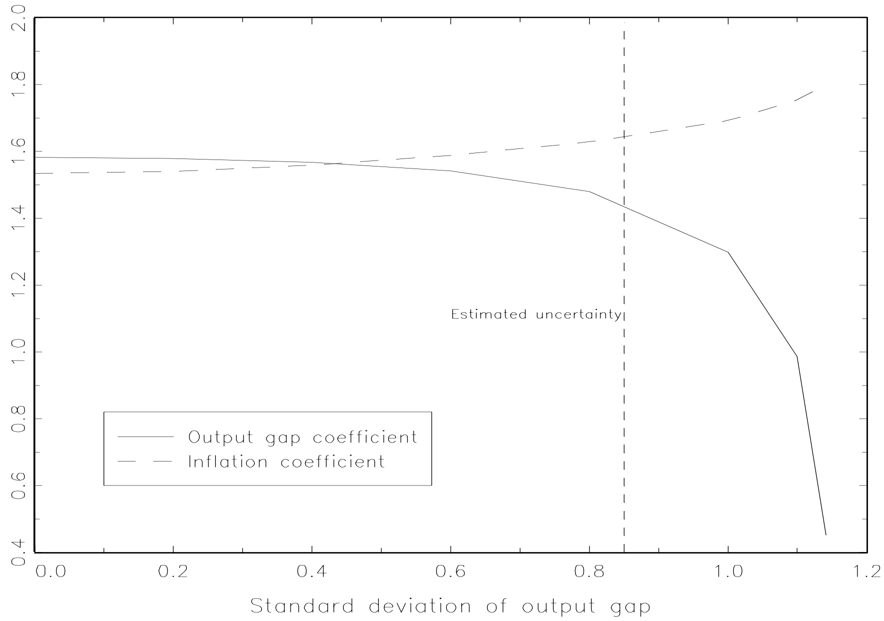
Estimated output gap for the EU5

With two SE confidence band

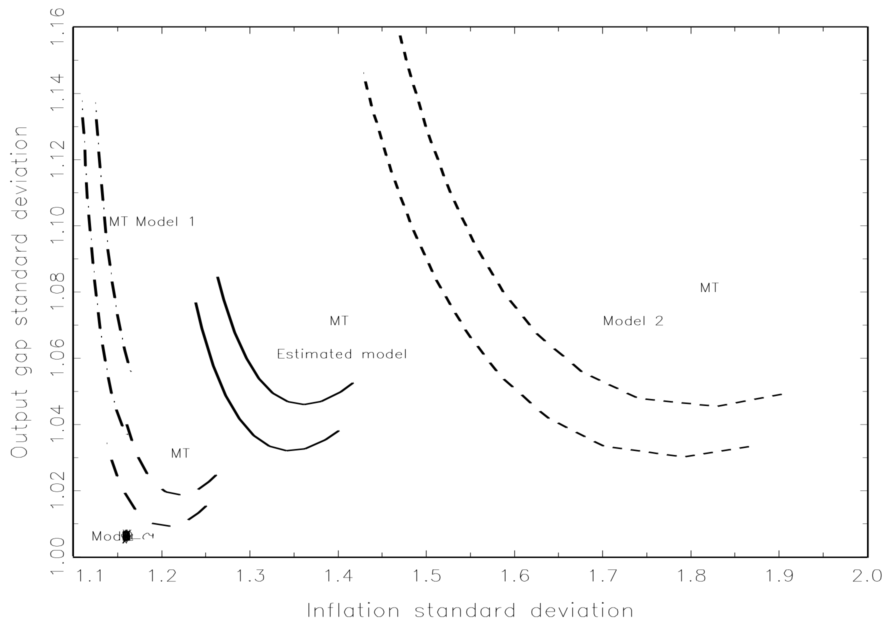
Graph 5
Efficient Taylor rule coefficients



Graph 6
Taylor rule coefficients as function of output gap uncertainty

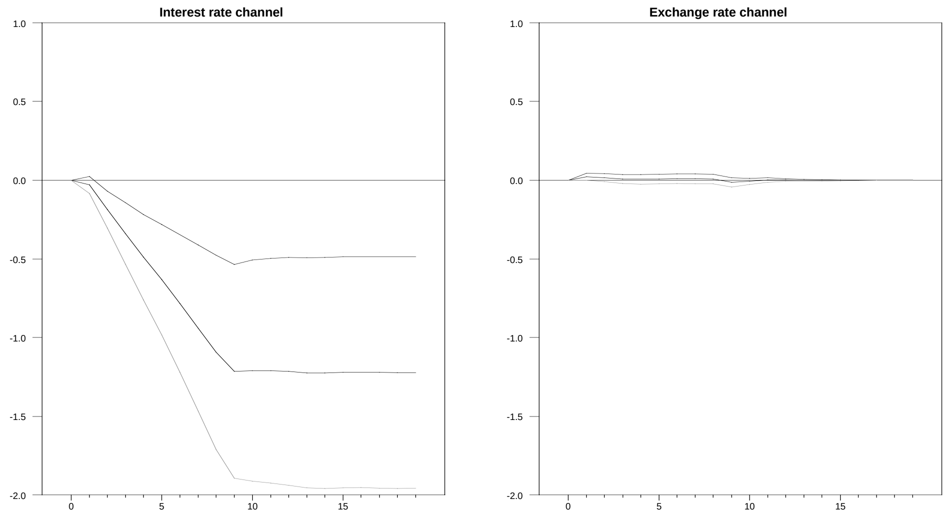


Graph 7
Efficiency frontiers



Graph A.1
Transmission channels in EU6

(Estimation period: 1978:1-1995:4)



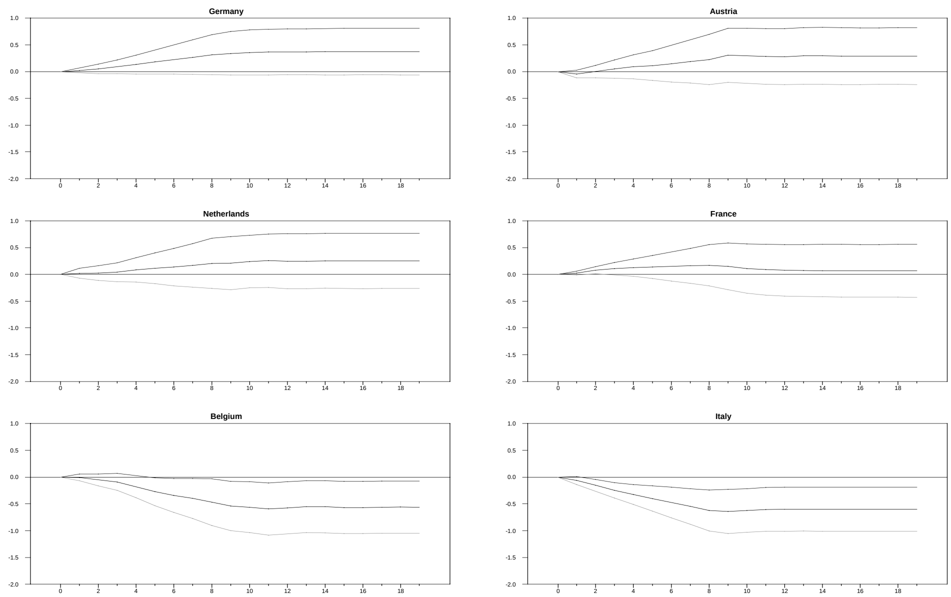
Graph A.2

Transmission channels in six EU countries:

Differences from the average output effect on EU6

(Estimation period: 1978:1-1995:4)

Interest rate channel



Exchange rate channel