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FORECASTING WITH A BAYESIAN DSGE MODEL: AN APPLICATION TO THE EURO AREA

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Abstract

In monetary policy strategies geared towards maintaining price stability conditional and unconditional forecasts of inflation and output play an important role. In this paper we illustrate how modern sticky-price dynamic stochastic general equilibrium (DSGE) models, estimated using Bayesian techniques, can become an additional useful tool in the forecasting kit of central banks. First, we show that the forecasting performance of such models compares well with a-theoretical vector autoregressions. Moreover, we illustrate how the posterior distribution of the model can be used to calculate the complete distribution of the forecast, as well as various inflation risk measures that have been proposed in the literature. Finally, the structural nature of the model allows computing forecasts conditional on a policy path. It also allows examining the structural sources of the forecast errors and their implications for monetary policy. Using those tools, we analyse macroeconomic developments in the euro area since the start of EMU.

Key words: Forecasting; DSGE models; monetary policy, euro area
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1. Introduction

Due to the lags with which changes in monetary policy affect the economy, projections of inflation and economic activity play an important role in monetary policy strategies geared towards maintaining price stability, practised in most industrial countries. At inflation targeting central banks such as the Bank of England, the Reserve Bank of New Zealand and the Sveriges Riksbank, the inflation forecast is a central tool for communicating the outlook for price stability and the associated monetary policy decisions.[1] While less prominent, projections of inflation and real GDP also play an important role at the European Central Bank and the Federal Reserve Board.[2] Traditionally, those forecasts are derived using a combination of relatively large-scale macro-econometric models and a good deal of judgement.[3] As discussed in Sims (2002), the macro-econometric models typically used at central banks for forecasting are estimated using single-equation methods and often lack a theoretically consistent model structure and treatment of expectations. While smaller-scale models with micro-foundations are frequently used for policy analysis, they are not used as forecasting tools on the basis of the arguments that they are often too simple and perform poorly in forecasting.

In a recent set of papers (Smets and Wouters, 2003a,b), we have shown that modern micro-founded dynamic stochastic general equilibrium (DSGE) models with sticky prices and wages along the lines developed by Christiano, Eichenbaum and Evans (2001) are sufficiently rich to capture most of the statistical features of the main macro-economic time series. Moreover, applying Bayesian estimation techniques, we show in those papers that even relatively large models can be estimated as a system. Not only does the system-wide estimation procedure deliver a more efficient estimate of the structural model parameters, it also provides a consistent estimate of the structural shock processes driving recent economic developments. Understanding the contribution of the various structural shocks to recent economic developments is an important input in the monetary policy decision process. Finally, our recent papers have also demonstrated that the estimated DSGE models perform quite well in forecasting compared to standard and Bayesian vector autoregressions (VARs and BVARs).

The combination of a sound micro-founded and theoretically consistent model structure and good forecasting performance suggests that these models could be further developed as an important tool for both policy analysis and forecasting in central banking. The micro foundations imply that the structural parameters are more likely to be invariant to various policy interventions the policy makers may want to consider. As such, one can more easily justify considering projections under different hypothetical monetary policies using those models.[4] The probabilistic nature of the estimated model implies that those models can also easily be used to assess forecast uncertainty and to perform a

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[1] See, for example, Bernanke et al (1999).

[2] For the role of macro-economic projections in the ECB's strategy, see, for example, ECB (2001).

[3] Sims (2002) and Pagan (2003) have recently discussed and criticised the models traditionally used at central banks.

[4] See Leeper and Zha (2002) for a discussion of modest policy interventions in the context of Bayesian VARs.

model and data consistent risk analysis. Since the introduction of the inflation targeting regimes in the late 1980s and early 1990s, the focus in the assessment of the inflation outlook has shifted from its central tendency to an analysis of the full forecast distribution and the associated risks.[5] The Bayesian estimation methodology provides an easy-to-use set of tools that can be used to perform such a risk analysis.

Following our earlier work (Smets and Wouters, 2003a,b), this paper further illustrates how Bayesian DSGE models can become a useful tool for projection and analysis in central banking. Following a brief description of the estimated euro area model in Section 2, Section 3 starts with a comparison of the forecasting performance of the DSGE model with that of VARs and BVARs. We then illustrate how the empirical posterior distribution of the model can be used to calculate the complete distribution of the forecast, as well as various risk measures that have been proposed in the literature. Moreover, we use the model to compute forecasts conditional on a policy path and show how the outlook for price stability and the associated risks may be affected by alternative monetary policy scenarios. An important assumption underlying this exercise concerns the response of private sector's expectations to changes in the future path of interest rates. In Section 4, we then analyse economic and monetary policy developments in the euro area since the start of EMU through the lens of the estimated DSGE model. The structural nature of the estimated model allows us to examine the structural sources of the forecast errors and their implications for monetary policy. Overall, the messages that come from this exercise appear to compare well with the policy assessment made by the ECB over the past years.

2. A brief description of the estimated euro area model

2.1. The Smets-Wouters DSGE model

For this paper, we re-estimate the model developed and estimated for the euro area in Smets and Wouters (2003b,c) over an extended sample period (1980:1-2002:4).[6] The DSGE model contains a large number of nominal and real frictions and various structural shocks. We refer to Smets and Wouters (2003b) for the detailed derivation. The appendix contains a list of the linearised model equations.

Households maximise a non-separable utility function in consumption and labour effort over an infinite life horizon. Consumption appears in the utility function relative to a time-varying external

[5] The introduction of fan charts is one example of this shift in focus. See also the discussion in Svensson (2001) on inflation forecast distribution targeting. The importance of risk assessment by central bankers is also underlined in Greenspan (2003).

[6] One difference with Smets and Wouters (2003a) is that we allow for a non-separable utility function in consumption and labour. In Smets and Wouters (2003b,c) we introduced this feature to allow for a balanced growth path.

habit variable that depends on past aggregate consumption. Each household provides differentiated labour inputs. Monopoly power in the labour market results in an explicit wage equation and allows for the introduction of sticky nominal wages as in the Calvo model (households are allowed to reset their wage each period with an exogenous probability). Households rent capital services to firms and decide how much capital to accumulate given certain costs of adjusting the capital stock. The introduction of variable capital utilisation implies that as the rental price of capital changes, the capital stock can be used more or less intensively according to some cost schedule. Firms produce differentiated goods, decide on labour and capital inputs, and set prices according to the Calvo model. The Calvo model in both wage and price setting is augmented by the assumption that prices that are not re-optimised in a given period are partially indexed to past inflation rates and the central bank's inflation target. Prices are therefore set in function of current and expected marginal costs, but are also determined by the past inflation rate. The marginal cost of production depends on the wage and the rental rate of capital. Similarly, wages also depend on past and expected future wages and inflation.[7] Finally, the model is closed with a generalised Taylor rule, where the interest rate is set in function of the deviation of inflation from a time-varying inflation objective and the theoretically consistent output-gap (output in deviation from the efficient flexible-price level of output).

The model contains ten identified exogenous driving forces, which are assumed to be orthogonal to each other. Six of these processes are modelled as autoregressive processes of order one: total factor productivity, the investment-specific technology process, the intertemporal preference process, the labour supply process, government spending and the inflation objective of the monetary authorities. The first five of these exogenous processes are assumed to affect the flexible-price level of output that enters the central bank's reaction function as its target level for output. The rationale for this assumption is that those shocks derive from technology and preferences and should therefore be accommodated from a welfare perspective. The remaining four shocks are assumed to be white noise: a price and wage mark-up shock, an equity premium shock and a traditional interest rate (or monetary policy) shock. Because these shocks are assumed to create inefficient temporary disturbances to the economy, they do not enter the calculation of the flexible-price output level used in the central bank's reaction function. As a result these shocks are more likely to create a trade-off between inflation and output gap stabilisation.

2.2. Posterior parameter estimates

As in Smets and Wouters (2003a,b,c), the model is estimated using Bayesian estimation techniques on seven key macro-economic time series for the euro area: real GDP, consumption, investment, employment, real wages, inflation in the GDP-deflator and the short run interest rate. These data are taken from the Area Wide Model database (Fagan et al, 2000) and updated for the most recent period

[7] As in Smets and Wouters (2003a), an ad-hoc calvo-type employment adjustment equation is used to translate the labour concept in the model (hours worked) into the observed employment series.

using the ECB Monthly Bulletin. Before estimation, all data are demeaned and the real variables are linearly detrended.

[Insert Table 1]

Table 1 presents the 5, 50 and 95 percentiles of the posterior distribution of the model parameters for two estimation periods (1980:1-2002:4 and 1980:1-1998:4).[8] The latter sample period will be used for the out-of-sample forecasting exercises performed in Section 3. In this case, the forecast sample starts with the introduction of the euro in January 1999.

Overall, the estimates seem to be very similar in both samples and broadly in line with our previous estimates. The total factor productivity and labour supply processes are estimated to be the most persistent with a median first-order autoregressive coefficient of about 0.95. The three "demand" shocks have lower persistence.[9] As a result, the two "supply" shocks, productivity and labour supply, will tend to explain most of the forecast error variance for the real variables at the medium to long-term horizon. The non-stationary inflation objective shock has a relatively high standard error of 0.10%, which corresponds to a change in the inflation objective of 0.4% on a yearly basis. The estimated inflation target follows a downward trend over the whole estimation sample with an interruption around 1990. The interest rate shock has a standard error around 0.14% (or 56 basis points on a yearly basis).

Also the estimates of the behavioural parameters are generally reasonable and close to those estimated in Smets and Wouters (2003a,c). As in our previous paper, the Calvo parameter for price setting (0.89) implies a very high degree of price stickiness with prices on average remaining fixed for more than two years. Nevertheless, our estimate of the elasticity of inflation with respect to the marginal cost is very similar to those obtained by Gali, Gertler and Lopez-Salido (2002). The results for the hypothetical historical policy rule are relatively standard. The long run reaction on inflation is exactly equal to the one assumed in the original Taylor rule (1.5). The long run reaction coefficient on the output-gap is smaller than in the prototype Taylor rule (0.2). The policy reaction function exhibits a high degree of persistence with a coefficient on the lagged interest rate of 0.88. While policy-controlled interest rates do not react strongly to the level of the output gap, they do to changes in the output gap. The reaction coefficient to current changes in inflation is somewhat higher in the shorter sample, indicating that the recent mild reaction to the price mark-up shocks has lowered this parameter estimate.

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[8] The data from 1970:2 till 1979:4 were used to evaluate the unobserved state variables, so that the starting values at time 1980:1 are based on these historical realisations.

[9] The investment-specific technology shock, the government spending shock and the intertemporal preference shock can be labelled "demand" shocks in the sense that under the estimated reaction function they lead to a positive correlation between output and the output gap. The total factor productivity and labour supply shock are "supply" shocks in the sense that they give rise to an opposite response of output and the output gap.

3. The Smets-Wouters model as a projection model: some illustrations.

3.1. Out-of-sample forecast performance

To illustrate the good prediction performance of the DSGE model, in this Section we perform a traditional out-of-sample prediction exercise over the post-EMU period 1999:1 - 2002:4. As the forecasting period is relatively short, these results are only indicative. We compare the root mean squared errors (RMSEs) of the forecasts from the DSGE model with those from standard VARs and BVARS of order 1 to 3 in Table 2. Starting from the pre-EMU sample, the VAR and BVAR models are re-estimated quarterly, while the DSGE model is re-estimated only yearly. Given the relatively short sample, Table 2 reports the RMSEs for horizons of 1 to 4 quarters only.

[Insert Table 2]

Overall, this exercise confirms the good forecasting performance of the DSGE model, highlighted in Smets and Wouters (2003a,b). The RMSEs are quite a bit lower than those obtained for the VAR models. This is true for each of the macro-economic time series (with the partial exception of the nominal interest rate) and at all horizons considered. Moreover, there is some evidence that the forecast performance improves as the horizon lengthens.

3.2. Forecast uncertainty and confidence bands

As discussed in the introduction, the Bayesian estimation methodology provides a useful set of tools for calculating the full probability distribution around the central forecast. Graph 1 illustrates the uncertainty surrounding the projections of each of the seven macro-economic variables at the beginning of 1999. A comparison of the actual time series with the 5-95 percentile forecast interval suggests that there is no clear evidence of instability in the estimated model following the introduction of the euro in 1999. The bounds appear to be realistic measures of the forecast uncertainty in the sense that there are only a few exceptions in which actual developments touch the 5% tails of the forecast distribution.

[Insert Graph 1]

The calculation of the forecast bounds in Graph 1 takes into account that, for a given model, there are typically two sources of forecast uncertainty: the uncertainty coming from unexpected future shocks and the uncertainty associated with the parameters of the model. Both sources of uncertainty typically contribute to large uncertainty bounds around standard VAR-based forecasts. Due to the relatively tight parameterisation of our estimated DSGE model, the main source of forecast uncertainty as illustrated in Graph 1 comes from the shock uncertainty. Indeed, the forecast distribution generated by the estimated parameter uncertainty is very limited. While the highly restricted DSGE model strongly reduces parameter uncertainty, one should take into account that this probably leads to an

underestimation of the degree of uncertainty. It is likely that the parameter uncertainty is partly replaced by model uncertainty, which could only be assessed by estimating alternative theoretical models and evaluating their influence on the forecast.[10]

3.3. Measures of risks to price stability

While the inflation forecast uncertainty can be summarised in fan charts, as, for example, produced by the Bank of England and the Sveriges Riksbank in their Inflation Reports, such forecast distributions are often quite difficult to interpret. In a recent paper, Kilian and Manganelli (2003) propose simple risk measures that quantify the relative uncertainty in the forecasts produced by a statistical model. In their view, central bankers can be regarded as risk managers who aim at containing inflation within specified bounds. They develop simple formal tools that are useful to quantify and forecast the risks that central bankers will fail to obtain the stated objectives. Kilian and Manganelli (2003) propose the following measures to summarise the risks that inflation will move outside pre-specified bounds. [11]

(1) $$EIR_t = Prob(\pi_{t+1} > \pi_u) * E\left[(\pi_{t+1} - \pi_u)^{\beta} \middle| \pi_{t+1} > \pi_u\right]$$

(2) $$DR_t = -Prob(\pi_{t+1} < \pi_l) * E\left[(\pi_l - \pi_{t+1})^{\beta} \middle| \pi_{t+1} < \pi_l\right]$$

The first measure is a measure of excess inflation risk. It is the expected inflation for next period in excess of an upper bound where the power reflects the relative risk aversion in the central bankers' preferences multiplied by the probability (prob) that the inflation realisation is above the limit. The second measure is a measure of deflation risk. In line with the ECB's definition of price stability, we calculate these measures for an upper bound (π_u) of 2% and a lower bound (π_l) of 0% for the average inflation rate over the next four quarters[12]. In line with Kilian and Manganelli (2003) and most of the literature on optimal monetary policy, we assume a coefficient of risk aversion (β) equal to two. The sum of the projected excess inflation and deflation risk measures can be seen as a measure of the projected one-year ahead balance of risks to price stability:

(3) $$BR_t = EIR_t + DR_t$$

The posterior distribution of the DSGE model can easily be used to calculate the risk measure proposed by Kilian and Manganelli (2003). Graph 4 illustrates the development of those risk measures since the start of EMU. For example, at the start of 1999 the balance of inflation risks dropped quite considerably following the fall-out from the Russian crisis. In section 4 we will use these measures to interpret economic and monetary policy developments in the euro area since 1998.

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[10] See, for example, the discussion in Brock, Durlauf and West (2003) and Sims (2003).

[11] As the fan charts in the Inflation Reports of the Bank of England and the Sveriges Riksbank are not based on statistically generated distribution functions, but rather reflect the subjective uncertainty around the inflation and output forecasts of the policy makers, it is much more difficult to calculate such risk measures based on the fan charts.

[12] This exercise reflects the ECB's broad definition of price stability but is not meant to reproduce in detail the actual strategy of the ECB, which has been refined in the course of 2003.

3.4. Projections under alternative monetary policy scenarios

The projection exercises presented in the previous sections were performed under the assumption that the European Central Bank followed the interest rate reaction function estimated over the pre-EMU period. Often such projections are called unconditional forecasts. Typically, however, monetary policy makers prefer to use constant nominal-interest-rate forecasts.[13] Such conditional projections provide a natural benchmark for assessing whether interest rates need to be changed given the central bank's goal of maintaining price stability. They also avoid the need to specify the central bank's reaction function, which may not be very easy to do in particular following a regime change such as the introduction of the euro. However, producing such conditional projections using rational expectations models raises two issues. First, it is well known that rational expectations models will typically not solve under a constant nominal interest rate path because nominal interest rate pegging often leads to an explosive path for the ex-ante real interest rate, output and inflation. One solution to this problem is to assume that the nominal interest rate is kept constant for a limited period of time, say three years, after which a policy reaction function kicks in putting the economy again on an equilibrium path.

A second issue raised by a constant interest rate projection concerns how to implement the constant interest rate path in a forward-looking model. At least two options are available. One option, applied in this section, is to calculate the monetary policy shocks that are necessary to keep the interest rate on a constant path relative to the historically estimated reaction function. The advantage of this option is that current economic variables that depend on expectations of future interest rates (such as various asset prices, but also consumption and investment) will only gradually respond to the constant interest rate scenario. This option is also closest to the analysis of modest policy interventions using Bayesian VARs in Leeper and Zha (2002)[14]. Of course, as emphasised by Leeper and Zha (2002), this assumption only makes sense if the required unexpected policy shocks are relatively small and comparable in size to the historically estimated policy shocks. A second option is to assume that the private sector has perfect foresight of the constant interest rate path and adjusts its decisions in line with this change in expected policy. This approach is fully compatible with the rational expectations assumption embedded in our estimated DSGE model. However, it will typically lead to relatively large jumps in all the forward-looking variables including consumption and investment, which in some circumstances may be perceived as implausible.

[Insert Graph 2]

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[13] Also at the European Central Bank the macro-economic projection of the Eurosystem staff are based on the assumption of constant nominal short-term interest rates.

[14] Cogley, Morozov and Sargent (2003) suggest an alternative approach to generate a posterior distribution around the forecast that is conditional on a specific interest rate path: by restricting the interest rate path, the distribution around the baseline scenario is shifted according to a minimum entropy method. This approach is applicable in BVAR models that do not provide a structural interpretation of the shocks.

Graph 2 plots the forecast distribution of the seven macroeconomic variables at the end of 1998 (similar to Graph 1) under the assumption that the nominal interest rate is kept constant for three consecutive years (after which the estimated reaction function kicks in). The private sector continues to think that the central bank follows the estimated reaction function and treats the deviations of actual interest rates from the expected interest rates as policy shocks. The graph shows that because the monetary authorities keep nominal interest rates persistently below their expected path (see Graph 1), the median forecast for output and inflation is much higher than projected in Graph 1. It is also clear from comparing Graphs 1 and 2 that the uncertainty surrounding the median forecast is much higher under the constant interest rate path. As monetary policy is passive the effects of future shocks are projected to be much larger.

Table 3 summarises the effects of the constant interest rate assumption on the inflation and output growth forecast and the various risk measures at two points in time: 1998:4 and 2000:4. These two dates correspond to the start of the two sub-periods that will be discussed below in Section 4. In 1998:4, the unconditional median forecast for inflation over the next year and growth over the next two quarters was 1.5 percent and 1.63 percent respectively. According to this forecast, the balance of inflation risks was slightly tilted upwards and the probability of a recession (defined as two consecutive quarters of negative growth) was negligible at 0.01. Under this scenario, short-term interest rates were expected to increase gradually to their long-run neutral level of about 5.5%. The third line in Table 3 shows the impact of a constant interest rate path for three years. The inflation and growth projection increase by respectively 0.35 and 0.61% compared to the baseline scenario. The excess inflation risk increases reflecting the increase in uncertainty, and the balance of risks also clearly increases suggesting that upward inflation risks would have dominated under this scenario. The series of unexpected shocks that are necessary to keep the interest rate path constant for three years starting in 1998:4 are negative and growing over the three-year period. As such, they can not be catalogued as a modest intervention.[15]

[Insert Table 3]

The effects of an alternative and more realistic scenario, in which the interest rate is decreased by 50 basis points for two consecutive quarters starting in 1999:1 (compared to the baseline scenario) is given in the second line of Table 3. In this case, the median inflation forecast increases with 0.17 percentage points and the growth rate is revised upward by 0.42 percentage points. Also in this case, the balance of inflation risks would have shifted upward. As discussed below in Section 4, the euro area faced significant negative demand shocks in the first two quarters of 1999 (partly following the fall-out of the Russian crisis in 1998) shifting the balance of inflation risks downward. Scenarios such as the one reported in the second line of Table 3 may be quite informative about the policy choices

[15] Leeper and Zha (2002) show very similar results for the mean forecast under a constant interest rate assumption using their VAR model for the US starting in October 1990.

that policymakers where faced with at the time. The actual decline in the interest rate that occurred in April 1999 can be partly seen as an attempt to restore the balance of risks.

The lower part of Table 3 performs a similar exercise around the baseline unconditional forecast of inflation and growth in 2000:4. At that time, the outlook for inflation over the next year and the associated risks were very similar to the outlook at the beginning of 1999. However, the outlook for output growth was less favourable with a 7 percent probability of a recession. The bottom two lines of Table 3 illustrate the effect of two alternative scenarios: a reduction and an increase in interest rates of 100 basis points in total. A reduction in interest rates would have supported growth considerably reducing the probability of a recession, but at a cost of increased inflation by about 17 percentage points. In contrast, the interest rate increase would have increased the probability of a recession quite considerably to 15%.

The exercises performed in this section illustrate the potential usefulness of our Bayesian DSGE model in assessing the impact of alternative monetary policy scenarios on the outlook for price stability and the associated risks. It is, however, important to re-emphasise that the reported results crucially depend on the assumptions made about how expectations of private agents adjust to the alternative interest rate paths. In the exercises reported above, we implemented alternative interest rate paths by shocking the estimated interest rate reaction function. As discussed in Leeper and Zha (2001), this makes sense if the shocks are relatively modest. However, identical interest rate paths could also be implemented under the assumption of perfect foresight or with alternative systematic monetary policy reaction functions and their associated shocks. The impact of these alternative assumptions may very well be non-negligible. This is an important question for future research.

4. Euro area economic and monetary policy developments since 1999

One advantage of the structural nature of the estimated DSGE model is that the model can be used to analyse the structural sources of the shocks that have affected the euro area economy during the first four years of EMU. As is clear from Graph 1, the first four years of EMU (1999:1-2002:4) can be roughly divided into two equal sub-periods. The first sub-period (1999:1-2000:4) was characterised by relatively strong output, employment and real wage growth. In contrast, the second sub-period (2001:1-2002:4) is characterised by a slowdown in economic activity, a stabilisation of real wages and a temporary surge in inflation. In what follows, we interpret each of those periods through the lens of the estimated DSGE model.

The first two years of EMU

Graph 1 shows that, at the end of 1998, the baseline projection as captured by the median forecast of our model was for the economy to gradually return to its deterministic growth path following a slightly negative output gap at the end of 1998[16]. As a result, the model predicts as a median scenario

[16] See Smets and Wouters (2003a) for a discussion and estimation of the output gap concept in this model.

relatively stable growth of the economy, with a slightly above average growth for investment and employment in the first years of the forecast exercise. Inflation is expected to increase slightly towards the implicit inflation target of monetary policy that is estimated to be somewhat below 2 % at the end of 1998. As part of this move to equilibrium, the nominal interest rate is forecast to return relatively quickly to its equilibrium level.

Graph 1 also shows that by the end of 2000, most of the actual time series were close to their projected values. One exception is employment, which grew much stronger than expected. Moreover, this end-of-2000 snapshot masks some volatility in economic developments during the first two years of EMU. Graph 3 presents the estimated structural shocks during this period together with a one-standard-error band. Graphs 4 and 5 show the resulting evolution of the balance of inflation risks and its components over the period.

[Insert Graph 3]

Starting from a slightly positive balance of risks in the fourth quarter of 1998, our estimated model suggests that deflation risks rose while excess inflation risks fell during the first half of 1999 (Graph 4). As a result, the risks were quite balanced in the second quarter of 1999. This is mainly a result of the negative spending shock in the first quarter of 1999 (mostly reflecting a fall in the demand for net exports following the fall-out from the Russian financial crisis at the end of 1998) and the subsequent negative preference shock in the second quarter of 1999. As a result, in contrast to what was forecast by the model, nominal interest rates fell during the first half of 1999. However, the interest rate appears to have fallen by more than predicted by the estimated policy reaction function, thereby supporting output and investment in the following year. Subsequently, deflation risks fell, while excess inflation risks rose towards the end of 1999 and in 2000. This led to a reversal and gradual rise in policy-controlled interest rates, which approach the forecast level towards the end of 2000. The most striking development in the first sub-period is the stronger than expected development of employment, which contributed to a stabilisation of real wages in the second half of 2000. The positive effects on output are, however, partly offset by a series of negative productivity shocks over the same period[17].

[Insert Graph 4]

A reading of the Editorials of the ECB's Monthly Bulletin suggests that the changing balance of risks as captured by our model in the first two-years of EMU more or less corresponds to the ECB's interpretation of events. In the beginning of 1999, HICP inflation was *lower than previously expected* and was explained by subdued growth of unit labour costs in 1998 and by the downward risk following the Asian crisis. The March 1999 Monthly Bulletin read: "*In the light of recent developments in real economy indicators, and taking into account the current level of HICP inflation*

[17] Overall the identification of the structural shocks by our DSGE model produces results that are in line with results of SVAR models. Typically, SVAR exercises identify supply, demand, policy and inflation (or oil) shocks. See Peersman (2004) for a recent application on similar data.

rates, it appears that there is no risk of HICP inflation exceeding the 2% ceiling in the near future. At the same time, the pattern of upward and downward risks to price stability has remained broadly unchanged on balance." The reduction of official interest rates from 3% to 2.5% in April 1999, was motivated in the April 1999 Monthly Bulletin by increased downward inflation risks: "*This picture is also reflected in recent downward revisions to real GDP forecasts for the euro area in 1999 and 2000 by major international organisations. ... the downward revisions in the growth forecasts and uncertainty concerning these forecasts have reinforced expectations of somewhat lower inflationary pressure arising from economic activity this year.*"

Also the favourable developments in the labour market were clearly identified as unexpected surprises in the following quote from the September 2000 Monthly Bulletin. "*Euro area employment growth has recently been revised upwards, in particular for the past two years, and is now estimated to have reached a remarkable annual rate of growth of close to 2% in the first half of 2000. This dynamism reflects robust economic growth and wage moderation, and may also point to some progress in labour market flexibility. Continued moderate wage increases would contribute to maintaining the favourable trends in labour market developments in the context of still high unemployment.*" However, the fall in total factor productivity identified by our model was not commented upon.

Finally, the series of interest rate increases that started in December 1999 and continued during the course of 2000 were largely based on a rise in the upward risks to price stability due to strong output and employment growth in a favourable international environment and the delayed pass-through of the depreciation of the euro and the rise in energy prices. Due to the use of the GDP deflator rather than the HICP, these cost-push shocks only show up with a delay in our model's forecasts.[18] For instance, in the April 2000 Monthly Bulletin, the official interest increase from 3.25% to 3.5% dated 17 March was commented upon as follows: "*This picture of continuing strong domestic demand supports the favourable outlook for economic growth in the euro area as shown in recent forecasts. The positive prospects for euro area activity are also benefiting from the cyclical upswing in the world economy, which has become broadly based across industrial and emerging economies and which is expected to continue in coming years. ... Against this background, monetary policy must remain vigilant in assessing upside risks to price stability and take appropriate action if and when*

[18] From the comparison with the policy discussions in the Monthly Bulletin, it is clear that the DSGE model misses some information because the HICP is not included in the data set. The pass-through of energy prices, the exchange rate and volatile food prices into the GDP deflator is much slower than into the HICP series. However, the interpretation of these shocks was largely in line with the role of the mark-up shocks in the model as unexpected short run disturbances to inflation. Monetary policy is rather ineffective in reducing the short run inflation impulse coming from those shocks and is confronted with a clear trade-off problem if it reacts too strongly to such shocks. The price increases that were affecting the HICP already in the second half of 2000, where clearly interpreted as temporal price shocks as is clear from this quote from the November 2000 Monthly Bulletin: "*Owing to developments in energy prices and the past decline in the euro, consumer proce inflation may remain above 2% for longer than was expected just a few months ago. In the respect, in order to support the maintenance of price stability over the medium term, it is important that economic agents accurately perceive the nature of current price developments. In particular, it needs to be recognised that current upward pressures can be overcome most smoothly if economic agents see them for what they are, namely one-off or temporal price increases resulting from external factors. If, as the markets expect, oil prices do not rise further, the effects of past oil price increases will gradually drop out of the annual inflation rate*"

required. Monetary policy has to be forward-looking, since responding to risks to price stability before they materialise will avoid the need for costly process of disinflation at a later stage."

Less favourable developments than projected during the 2001 - 2002 period

Graph 5 depicts the forecast distribution based on information up to the fourth quarter of 2000 for the seven euro area macro variables in 2001 and 2002. The estimated DSGE model predicted a more modest growth of consumption, investment and output than realised growth in 2000. Employment was projected to remain constant and wages were projected to increase relatively strongly as the model expected the favourable labour supply shocks over the first two years of EMU to gradually die out over time. Inflation and the nominal interest rate were predicted to gradually return to their long run levels corresponding to a 1.5% inflation objective (estimate at 2000:4) and a 5.5% equilibrium nominal interest rate respectively.

With the exception of the labour market developments, the actual outcome in 2001 and 2002 was much less rosy than projected. Real GDP and particularly real investment turned out much lower than expected due to a series of negative investment technology, equity premium and productivity shocks (Graph 3). The impact of the drop in investment on output is somewhat offset by the mostly positive labour supply shocks over this period. In the last quarter of 2001, the negative shocks to investment are reinforced by a large negative preference shock reflecting the confidence effects of the September 11 attacks in the US on consumption. Also on the inflation side the news was predominantly negative as a series of positive price mark-up shocks pushed inflation above the projected level in spite of the favourable developments in real wages.

[Insert Graph 5]

The implications of the various shocks in 2001 and 2002 for the evolution of the one-year ahead projected inflation and the balance of inflation risks is again shown in Graphs 4 and 5. Despite the large positive mark-up shocks which reflect the effects of the depreciation of the euro and rising food and energy prices on inflation, the balance of risks rapidly dropped from its maximum in the first quarter of 2001 to a negative value in the third quarter of 2001, indicating the dominance of downward risks to price stability. The model sees through the temporary effects of the mark-up shocks and puts a dominant weight on the negative demand shocks when assessing the risks to price stability. Following a brief surge in the excess inflation risks due to a new series of price mark-up shocks, the downward risks clearly dominate during most of 2002. This occurred in spite of the fact that the easing of monetary policy appeared to be stronger than could be expected on the basis of the hypothetical historical reaction function as indicated by the negative monetary policy shocks throughout most of 2001 and 2002 (Graph 3).[19] In the second half of 2002 the probability of one-year ahead deflation is estimated to be relatively high at around 25%.

[19] The large negative policy shock in the first quarter of 2001 is the counterpart of the weak response of monetary policy to the strong mark-up shocks. As discussed in Section 3, the estimated short-run coefficient in the policy rule over the period 1980:1 – 2002:4 is indeed lower than the one over the shorter period that excludes these observations.

The picture drawn by the one-year ahead balance of risks indicator produced by our model again corresponds quite closely with the discussion in the ECB's Monthly Bulletins. The first sign of increased concern about the international environment appeared in the December 2000 Monthly Bulletin coinciding with the slight drop in our excess inflation risk indicator during the last quarter of 2000. While in January 2001 the risks to price stability were still predominantly seen on the upside, in February and even more clearly in March, the risks appeared to be evaluated as more balanced than in late 2000, although it was also stated that there were not yet signs that the slowdown in the US economy had significant or lasting spill-over effects on the euro area. In the April 2001 Monthly Bulletin the balance clearly tilted to the downside. This foreshadowed the policy easing that was in the pipeline and eventually happened on 10 May, mainly based on the risk analysis rather than on observed data. During this period the ECB expressed a clear satisfaction with the maintained wage moderation that has supported employment growth, while repeatedly warning for possible spill-over effects from the price shocks.

In the July 2001 Monthly Bulletin, there was a first clear recognition that growth was lower than expected: "*The first Eurostat estimate of real GDP growth in the first quarter of 2001 was 0.5%, as compared with the 0.6% in the last quarter of 2000. The slowdown appears to be related to the external environment and to the weak growth of domestic demand. The significant decline in the growth rate of domestic demand was stronger than expected, with investment being affected both by the adverse influences from the world economy and by specific domestic developments related to construction investment. At the same time, growth in consumption was weak, which may in part be explained by adverse income effects relating to the increases in energy and food prices.*" At the same time HICP inflation rose to 3.4% in May following the increase in food and energy prices. However, the ECB stressed that due to the special nature of these shocks, they were likely to only have a temporary effect on inflation.

Also in the August 2001 Bulletin the lower than expected growth rate was emphasised, eventually leading to further interest rate easing. In the November issue the November 8 decline in the policy-controlled interest from 3.75 to 3.25% was motivated as follows: "*Several economic indicators which have become available for the euro area and beyond point to weakening demand of both domestic and external origin. In line with this and taking into account expectations of further weak data in the period ahead, forecasts and projections will in all likelihood show downward revisions. The current environment of high uncertainty is likely to lead to delays in investment and, to some extent, also to negatively affect private consumption in the euro area. This has lead to expectations of weak data for the euro area real GDP growth in the second half of 2001. Real GDP growth is now expected to remain below potential for part of next year.*"

In sum, our stylised estimated DSGE model seems to perform relatively well in capturing the evolution of the perceived risks to price stability. At the same time, it allows for a structural interpretation of the sources behind the developments in the risks to price stability.

5. Conclusions

Modern sticky-price DSGE models of the type used in this paper and estimated using Bayesian techniques combine a sound, micro-founded structure necessary for policy analysis with a good probabilistic description of the observed data and forecasting performance. In this paper we illustrated how such Bayesian DSGE models can become an additional useful tool in the forecasting kit of central banks. First, we show that the forecasting performance of such models compares well with a-theoretical vector autoregressions. Moreover, we illustrate how the posterior distribution of the model can be used to calculate the complete distribution of the forecast, as well as various inflation risk measures that have been proposed in the literature. Finally, the structural nature of the model allows computing forecasts conditional on a policy path. It also allows examining the structural sources of the forecast errors and their implications for monetary policy. Using those tools, we briefly analysed and interpreted macroeconomic developments in the euro area since the start of EMU.

Of course, many challenges still lie ahead. Here it suffices to highlight three of those challenges. First, the structure of the model remains relatively simple and in many cases the micro-foundations are not very deep. Much more work is needed to both deepen and broaden the scope of the existing DSGE models. For example, the introduction of more realistic financial and labour markets is one vibrant area of current research. For practical forecasting exercises, the introduction of an open economy dimension and the HICP-inflation in addition to the inflation in the GDP-deflator might allow for a better identification of external demand and price shocks. Second, the assumption of model consistent expectations is theoretically appealing and relatively easy to implement. However, in reality constraints on information processing, pervasive model uncertainty and the associated need for perpetual learning highlight the limits of the rational expectations assumption. When forecasting in a policy context, realistic assumptions about how private sector expectations will adjust to alternative policy scenarios are of crucial importance. Finally, the linearity of the model used in this paper is an attractive feature from a computational and estimation point of view. Linear models are typically also more robust in forecasting. However, non-linearities due to shifting economic relationships, time-variation in the sources of shocks, various institutional and technical constraints and the non-monotone adjustment of expectations are important factors in the risk analysis of monetary policy makers. While it would be impossible to take into account all those sources of non-linearities in one model, an analysis of the implications of each of them is an important area of current and future research.

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Appendix: The linearised DSGE model (Smets and Wouters, 2003c).

The *consumption* equation:

$$\hat{C}_t = \frac{h}{1+h}\hat{C}_{t-1} + \frac{1}{1+h}E_t\hat{C}_{t+1} + \frac{(\sigma_c - 1)}{\sigma_c(1+\lambda_w)(1+h)}(\hat{l}_t - \hat{l}_{t+1}) - \frac{1-h}{(1+h)\sigma_c}(\hat{R}_t - E_t\hat{\pi}_{t+1}) + \frac{1-h}{(1+h)\sigma_c}(\hat{\varepsilon}_t^b) \tag{1}$$

Consumption $\hat{C}_t$ depends on a weighted average of past and expected future consumption, the ex-ante real interest rate $(\hat{R}_t - E_t\hat{\pi}_{t+1})$, expected employment growth $(\hat{l}_{t+1} - \hat{l}_t)$ and a preference shock $\hat{\varepsilon}_t^b$. h represents the habit formation coefficient and σ_c is the analogue of the intertemporal elasticity of substitution.

The *investment* equation:

$$\hat{I}_t = \frac{1}{1+\beta}\hat{I}_{t-1} + \frac{\beta}{1+\beta}E_t\hat{I}_{t+1} + \frac{1/\varphi}{1+\beta}(\hat{Q}_t + \hat{\varepsilon}_t^I) \tag{2}$$

Investment $\hat{I}_t$ depends on past and expected future investment, the value of the existing capital stock $\hat{Q}_t$ and an investment-specific technology process, $\hat{\varepsilon}_t^I$. β is the rate of time preference and φ is the parameter that summarises the investment adjustment costs.

The *Q equation* :

$$\hat{Q}_t = -(\hat{R}_t - \hat{\pi}_{t+1}) + \frac{1-\tau}{1-\tau+\bar{r}^k}E_t\hat{Q}_{t+1} + \frac{\bar{r}^k}{1-\tau+\bar{r}^k}E_t\hat{r}_{t+1}^k + \eta_t^Q \tag{3}$$

The value of the capital stock depends negatively on the ex-ante real interest rate, and positively on its expected future value, the expected rental rate $\hat{r}_{t+1}^k$ and an equity premium shock η_t^Q.

The *capital accumulation equation*:

$$\hat{K}_t = (1-\tau)\hat{K}_{t-1} + \tau\hat{I}_{t-1} + \tau\hat{\varepsilon}_{t-1}^I \tag{4}$$

The capital stock $\hat{K}_t$ depreciates with a rate τ.

The *inflation equation*:

$$\hat{\pi}_t - \bar{\pi}_t = \frac{\beta}{1+\beta\gamma_p}(E_t\hat{\pi}_{t+1} - \bar{\pi}_t) + \frac{\gamma_p}{1+\beta\gamma_p}(\hat{\pi}_{t-1} - \bar{\pi}_t) + \frac{1}{1+\beta\gamma_p}\frac{(1-\beta\xi_p)(1-\xi_p)}{\xi_p}\left[\alpha\hat{r}_t^k + (1-\alpha)\hat{w}_t - \hat{\varepsilon}_t^a - (1-\alpha)\gamma t\right] + \eta_t^p \tag{5}$$

The deviation of inflation $\hat{\pi}_t$ from the target inflation rate $\bar{\pi}_t$ depends on past and expected future inflation deviations and on the current marginal cost, which itself is a function of the rental rate on capital, the real wage $\hat{w}_t$ and the productivity process. α determines the share of capital and labour

in the marginal cost. $(1-\xi_p)$ is the probability that prices can be reset in a given period, while γ_p is the degree of indexation of prices on past inflation. η_t^p is the i.i.d. shock in the price mark-up.

The *real wage* equation:

$$\hat{w}_t = \frac{\beta}{1+\beta}E_t\hat{w}_{t+1} + \frac{1}{1+\beta}\hat{w}_{t-1} + \frac{\beta}{1+\beta}(E_t\hat{\pi}_{t+1} - \overline{\pi}_t) - \frac{1+\beta\gamma_w}{1+\beta}(\hat{\pi}_t - \overline{\pi}_t) + \frac{\gamma_w}{1+\beta}(\hat{\pi}_{t-1} - \overline{\pi}_t)$$

(6)
$$-\frac{1}{1+\beta}\frac{(1-\beta\xi_w)(1-\xi_w)}{(1+\frac{(1+\lambda_w)\sigma_L}{\lambda_w})\xi_w}\left[\hat{w}_t - \sigma_L\hat{L}_t - \frac{1}{1-h}(\hat{C}_t - h\hat{C}_{t-1}) + \hat{\varepsilon}_t^L\right] + \eta_t^w$$

The real wage $\hat{w}_t$ is a function of expected and past real wages, the expected, current and past inflation rate and the deviation of the actual real wage from the wage that would prevail in a flexible labour market. η_t^w is the i.i.d. shock in the wage mark-up while $\hat{\varepsilon}_t^L$ is the persistent labour supply shock.

The *labour demand* equation:

(7) $$\hat{L}_t = -\hat{w}_t + (1+\psi)\hat{r}_t^k + \hat{K}_{t-1}$$

Labour demand $\hat{L}_t$ depends negatively on the real wage (with a unit elasticity) and positively on the rental rate of capital and last period's capital stock. ψ reflects the capital utilisation adjustment cost.

The *goods market equilibrium condition*:

(8)
$$\begin{aligned}\hat{Y}_t &= (1-\tau k_y - g_y)\hat{C}_t + \tau k_y\hat{I}_t + g_y\varepsilon_t^G \\ &= \phi\hat{\varepsilon}_t^a + \phi\alpha\hat{K}_{t-1} + \phi\alpha\psi\hat{r}_t^k + \phi(1-\alpha)(\hat{L}_t + \gamma t) - (\phi-1)\gamma t\end{aligned}$$

with k_y the capital-output ratio and g_y the share of public consumption in output. ϕ reflects the fixed costs in the production function.

The *monetary policy reaction* function:

(9)
$$\begin{aligned}\hat{R}_t &= \overline{\pi}_t + \rho(\hat{R}_{t-1} - \overline{\pi}_{t-1}) + (1-\rho)\{r_\pi(\hat{\pi}_{t-1} - \overline{\pi}_{t-1}) + r_Y(\hat{Y}_{t-1} - \hat{Y}_{t-1}^p)\} + \\ &\quad r_{\Delta\pi}\left[(\hat{\pi}_t - \overline{\pi}_t) - (\hat{\pi}_{t-1} - \overline{\pi}_{t-1})\right] + r_{\Delta y}\left[(\hat{Y}_t - \hat{Y}_t^p) - (\hat{Y}_{t-1} - \hat{Y}_{t-1}^p)\right] + \eta_t^R\end{aligned}$$

The interest rate $\hat{R}_t$ reacts persistently, via the parameter ρ, on both the level and the first difference of the inflation deviation from the objective and the output gap.

Table 1:

Posterior distribution of the model parameters

	Estimation period 1980:1 - 2002:4 Posterior sample based			Estimation period 1980:1 - 1998:4 Posterior sample based		
	0.05%	50%	95%	0.05%	50%	95%
Standard errors of the shocks						
σ productivity shock	0.479	0.604	0.775	0.480	0.609	0.814
σ inflation obj. shock	0.073	0.106	0.152	0.069	0.106	0.166
σ cons.pref. shock	0.176	0.285	0.498	0.185	0.306	0.707
σ gov.spending shock	0.275	0.310	0.354	0.290	0.329	0.378
σ labour supply shock	0.297	1.411	2.561	0.196	1.201	2.345
σ investment shock	0.098	0.141	0.231	0.100	0.152	0.263
σ interest rate shock	0.113	0.145	0.183	0.107	0.143	0.182
σ equity premium shock	0.361	0.468	0.575	0.406	0.533	0.658
σ price mark-up shock	0.150	0.175	0.204	0.146	0.170	0.203
σ wage mark-up shock	0.212	0.240	0.276	0.226	0.261	0.306
AR(1) persistence						
ρ productivity shock	0.897	0.953	0.987	0.754	0.857	0.937
ρ cons.pref. shock	0.696	0.783	0.847	0.635	0.774	0.847
ρ gov. spending shock	0.806	0.887	0.969	0.803	0.887	0.966
ρ labour supply shock	0.758	0.939	0.982	0.802	0.942	0.983
ρ investment shock	0.460	0.675	0.817	0.468	0.660	0.805
Behavioural parameters						
investment adj cost	4.243	5.889	7.814	3.696	5.433	7.395
σ consumption utility	0.675	0.881	1.374	0.633	0.855	1.184
h consumption habit	0.478	0.609	0.715	0.479	0.606	0.711
σ labour utility	0.738	1.570	2.667	0.839	1.763	2.858
fixed cost	1.085	1.268	1.465	1.110	1.301	1.489
capital util. adj.cost	0.112	0.226	0.344	0.098	0.213	0.335
calvo employment	0.506	0.582	0.649	0.488	0.567	0.643
calvo wages	0.679	0.798	0.888	0.635	0.792	0.885
calvo prices	0.855	0.890	0.924	0.856	0.892	0.927
indexation wages	0.218	0.411	0.618	0.220	0.428	0.657
indexation prices	0.246	0.469	0.679	0.243	0.447	0.669
Monetary policy reaction function						
r inflation	1.354	1.508	1.667	1.324	1.487	1.653
r d(inflation)	0.034	0.104	0.196	0.092	0.191	0.286
r lagged interest rate	0.832	0.880	0.917	0.811	0.867	0.909
r output	0.019	0.061	0.139	0.020	0.064	0.144
r d(output)	0.159	0.227	0.315	0.153	0.218	0.303

Table 2:

Comparing out-of-sample forecast : performance for individual variables

RMSE-statistics - for different forecast horizons over the period 1999:1 - 2002:4

DSGE-model	Y	π	R	L	w	C	I
1	0.34	0.27	0.13	0.17	0.25	0.38	1.02
2	0.57	0.29	0.20	0.32	0.39	0.57	1.93
4	1.17	0.29	0.26	0.61	0.58	1.02	4.09

VAR(1)	Y	π	R	L	w	C	I
1	0.40	0.35	0.14	0.27	0.39	0.68	1.12
2	0.74	0.45	0.21	0.52	0.75	1.36	2.23
4	1.73	0.56	0.29	0.98	1.66	2.85	5.17

VAR(2)	Y	π	R	L	w	C	I
1	0.47	0.31	0.12	0.20	0.53	0.72	1.10
2	0.78	0.34	0.17	0.41	0.85	1.21	2.07
4	1.74	0.38	0.26	0.80	1.75	2.44	4.73

VAR(3)	Y	π	R	L	w	C	I
1	0.47	0.34	0.12	0.17	0.55	0.74	1.08
2	0.77	0.41	0.17	0.34	0.86	1.22	1.89
4	1.61	0.48	0.24	0.64	1.57	2.39	4.32

BVAR(1)	Y	π	R	L	w	C	I
1	0.39	0.35	0.14	0.27	0.39	0.67	1.11
2	0.74	0.45	0.21	0.52	0.74	1.34	2.21
4	1.72	0.56	0.29	0.98	1.65	2.80	5.13

BVAR(2)	Y	π	R	L	w	C	I
1	0.41	0.32	0.12	0.21	0.45	0.69	1.10
2	0.71	0.38	0.17	0.43	0.78	1.24	2.09
4	1.69	0.46	0.22	0.84	1.65	2.57	4.88

BVAR(3)	Y	π	R	L	w	C	I
1	0.42	0.32	0.12	0.20	0.47	0.70	1.09
2	0.72	0.38	0.17	0.39	0.79	1.25	2.07
4	1.67	0.45	0.22	0.76	1.59	2.52	4.82

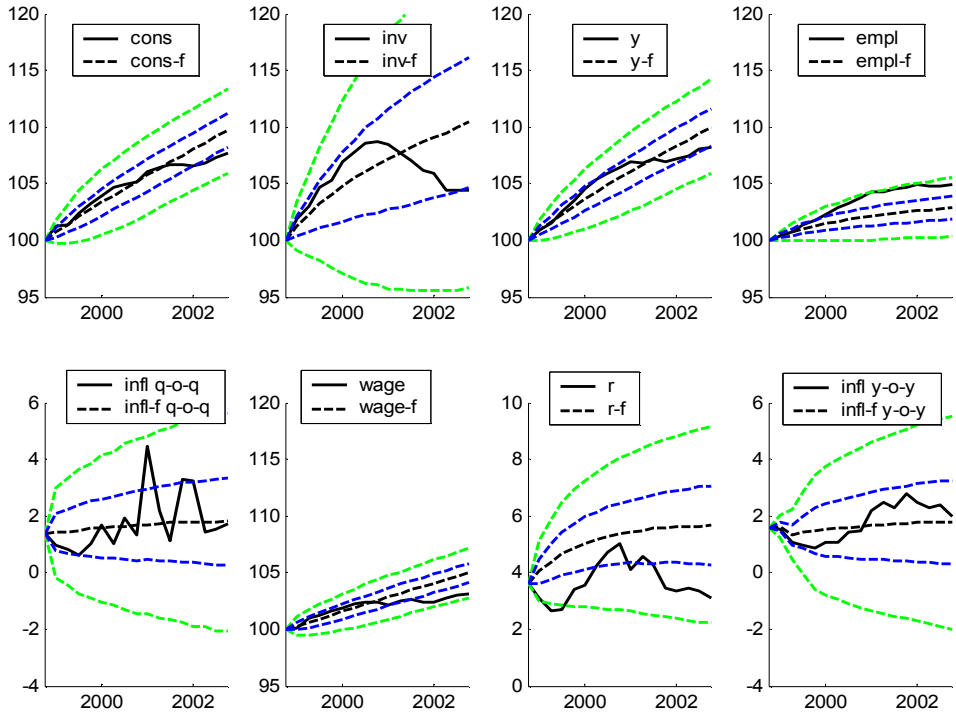
Table 3:

Impact of alternative monetary policy scenarios on the forecast outcome

Forecast starting 1999:1	Inflation forecast[1] (average over 4 q.)	Growth forecast[1] (average over 2 q.)	Excess inflation risk forecast	Deflation risk forecast	Balance of risk forecast	Probability of recession
Baseline scenario	1.50	1.63	0.16	-0.02	0.14	0.01
+ two consecutive interest shocks in 1999:1 and 1999:2 of 50 bp.	1.67	2.05	0.24	-0.01	0.23	0.00
+ series of unexpected shocks holding interest rate constant for 3 years	1.85	2.24	0.38	-0.01	0.37	0.00
Forecast starting 2001:1						
Baseline scenario	1.54	0.91	0.17	-0.02	0.16	0.07
+ two consecutive neg. interest shocks in 2001:1 and 2001:2 of 50 bp.	1.71	1.32	0.26	-0.01	0.25	0.03
+ two consecutive pos. interest shocks in 2001:1 and 2001:2 of 50 bp.	1.36	0.45	0.13	-0.03	0.10	0.15

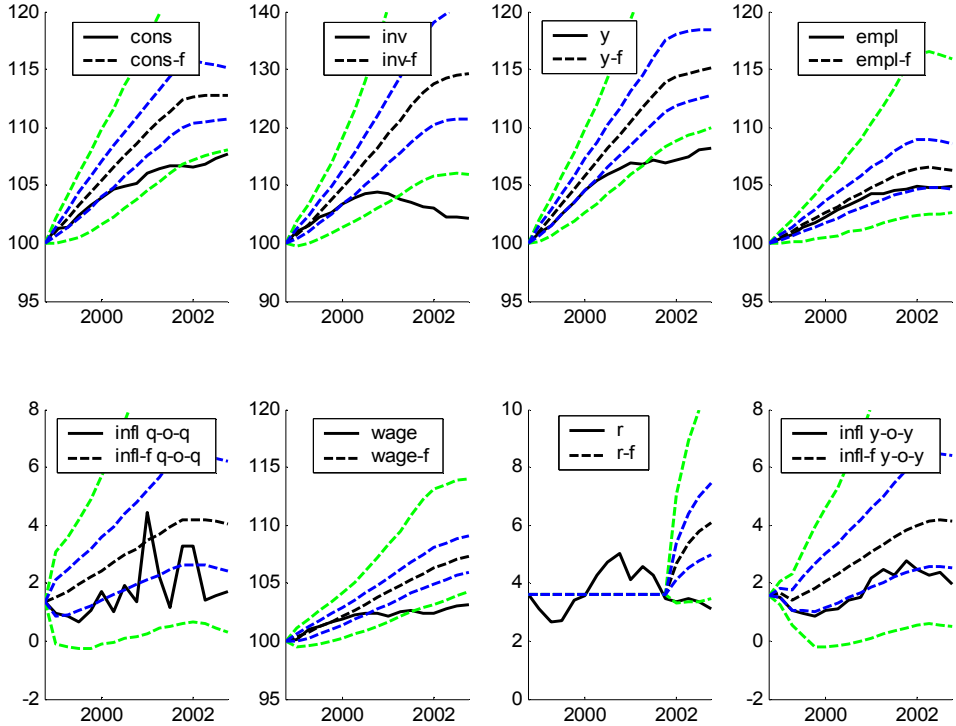
[1] Inflation and growth effects are annualised outcomes

Graph 1: Forecast and actual euro area macro series: 1999:1 to 2002:4

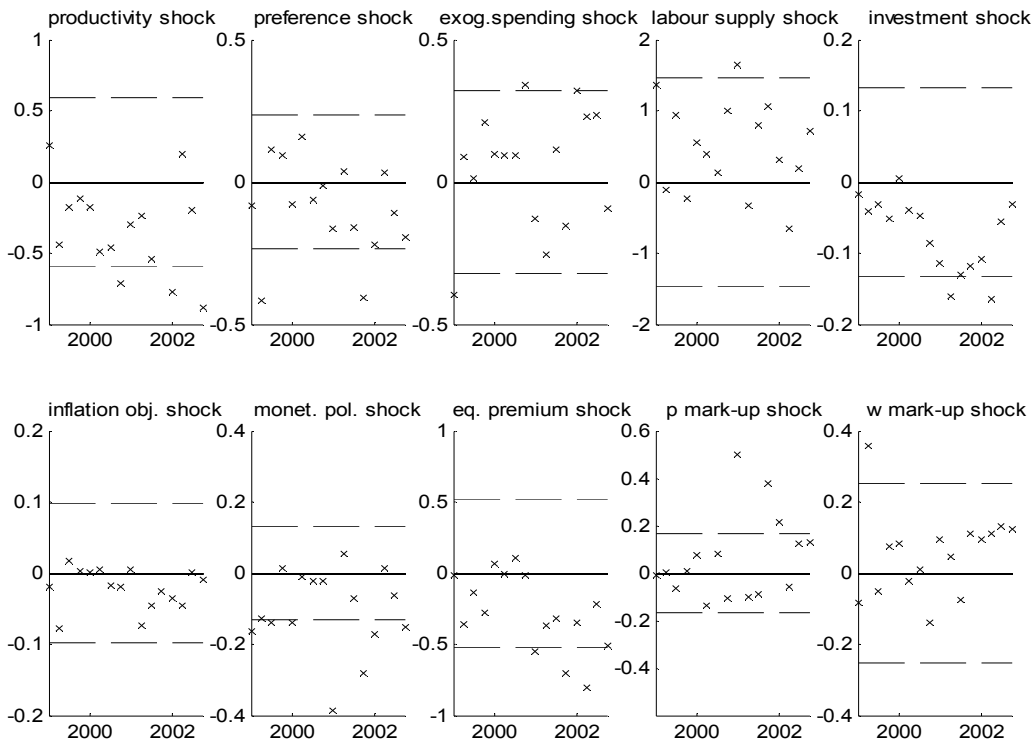


Note: The model parameters are estimated using the sample period up to 1998:4. The broken lines represent respectively the 5, 25, 50, 75 and 95 percentiles of the forecast distribution. The panel takes into account both shock and parameter uncertainty.

Graph 2: Forecast based on the constant interest rate hypothesis

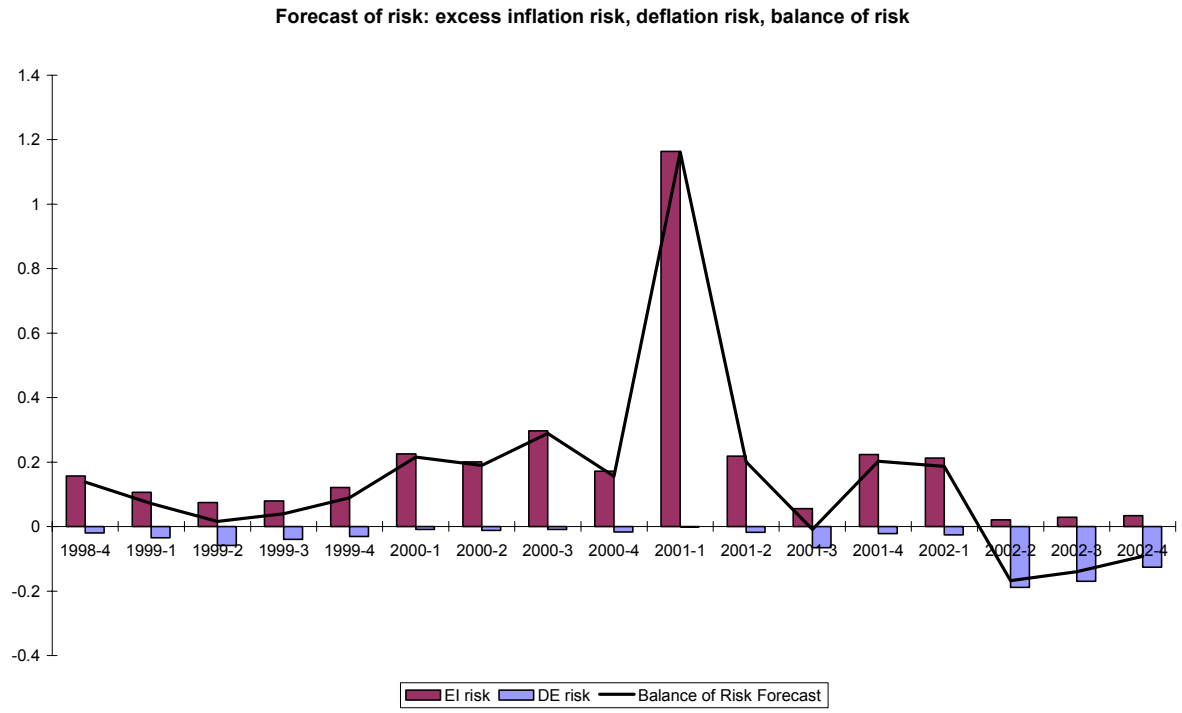
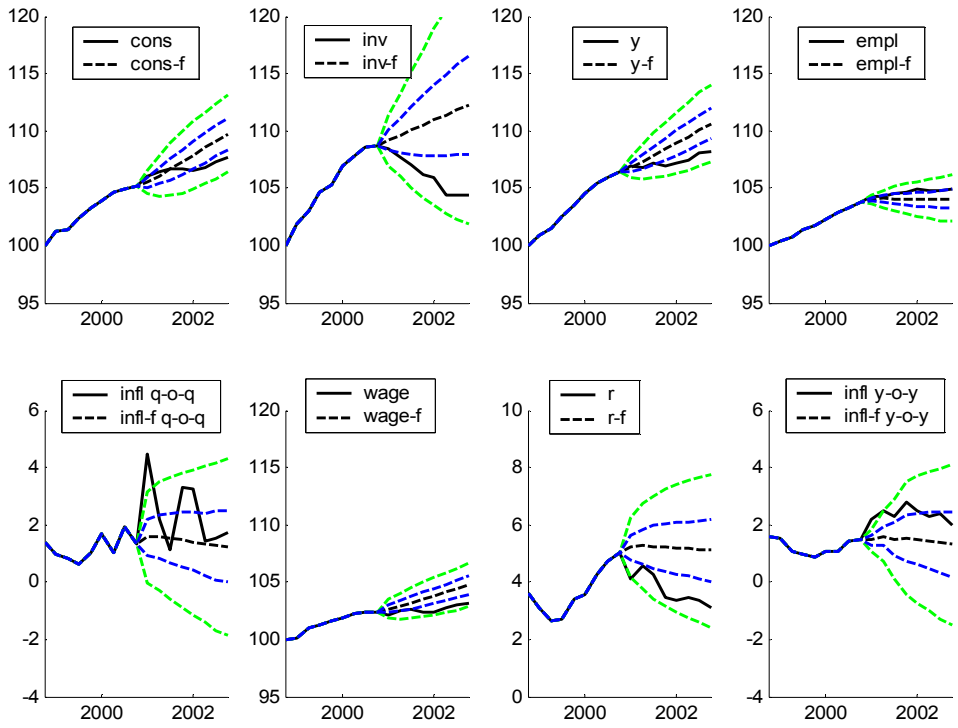


Graph 3: Structural shocks: two-sided estimates of the innovations over EMU period



Note: The dotted line indicates the one standard error magnitude of the shock estimated over the complete observation period.

Graph 4: Measures of projected one-year ahead risks to price stability (1999:1 – 2002:4)



Graph 5: Forecast and realised euro area macro series: 2001:1 to 2002:4 - parameters estimated up to 1998:4