OESTERREICHISCHE NATIONALBANK
EUROSYSTEM

WORKING PAPER 148

Comparing the New Keynesian Phillips Curve with Time Series Models to Forecast Inflation

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Imprint: Responsibility according to Austrian media law: Günther Thonabauer, Secretariat of the Board of Executive Directors, Oesterreichische Nationalbank

Published and printed by Oesterreichische Nationalbank, Wien.

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Editorial

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September 30, 2008

Comparing the New Keynesian Phillips Curve with Time Series Models to Forecast Inflation[♦]

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Abstract

The New Keynesian Phillips Curve, as a structural model of inflation dynamics, has mostly been used to explain past inflation developments, but has hardly been used for forecasting purposes. We propose a method of forecasting inflation based on the present-value formulation of the hybrid New Keynesian Phillips Curve. To evaluate the forecasting performance of this model we compare it with forecasts generated from time series models at different forecast horizons. As state-of-the-art time series models used in inflation forecasting we employ a Bayesian VAR, a traditional VAR and a simple autoregressive model. We find that the New Keynesian Phillips Curve delivers relatively more accurate forecasts compared to the other models for longer forecast horizons (more than 3 months) while they are outperformed by the time series models only for the very short forecast horizon. This is consistent with the finding in the literature that structural models are able to outperform time series models only for longer horizons.

JEL Classification: E31, C32, C53

Keywords: New Keynesian Phillips Curve, Inflation Forecasting, Forecast Evaluation, Bayesian VAR

[♦] We want to thank Paul Alagidede, Markus Knell, Gabriel Moser and the participants at the International Conference on Policy Modeling (ECOMOD 2007) as well as the Annual Conference of the International Network for Economic Research (INFER 2007) for helpful comments and suggestions. The views expressed in this paper are those of the authors and do not necessarily reflect the opinion of the Oesterreichische Nationalbank or the Eurosystem.

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I. Introduction

Forecasting inflation is an important task for a central bank since the rate of inflation is commonly regarded as the most important indicator of monetary policy. Some central banks, in particular those pursuing direct inflation targeting, even attribute the inflation forecast a crucial role in their monetary policy strategy. The literature on inflation forecasting has been growing rapidly in recent years as more and more forecasting methods have been developed and applied to forecast inflation. These are mostly time series models (e.g. factor models, autoregressive models, transfer function models) as well as more structural models (such as structural VARs or traditional Phillips curve equations). This paper attempts to employ a widely used theoretical model of inflation dynamics, the New Keynesian Phillips Curve, for forecasting purposes and compares its forecasting performance with those of state-of-the-art time series models.

The New Keynesian Phillips Curve (NKPC) is currently probably the most influential theory of inflation dynamics in macroeconomics. It is derived from a New Keynesian model characterized by monopolistic competition and short-run price rigidity and represents (in its reduced-form formulation) inflation as a function of expected inflation and the firm's marginal cost. The baseline NKPC was developed in the late 1990s by Galí and Gertler (1999) and others (e.g. Sbordone, 2002).[1] Depending on the specification and the use of an appropriate empirical proxy for marginal cost, it was generally found to be successful in tracking inflation dynamics in a number of large industrial economies over the last 20 to 30 years (see Galí and Gertler, 1999, for the US, Galí et al., 2001, McAdam and Willman, 2004, for the euro area, and Jondeau and Le Bihan, 2005, for the UK and major euro area countries). Despite its empirical success to explain past inflation, it has until now never been used for forecasting purposes in a single equation approach.[2] This might be due to the fact that it contains expected future inflation which implies that a stand has to be taken on the formation of inflation expectations. If expectations are rational, the NKPC can be expressed as the discounted sum of present and future marginal costs, an expression which is hard to evaluate empirically.

[1] A survey of the literature on the New Keynesian Phillips Curve can be found in Ólafsson (2006).
[2] As a core ingredient of the New Keynesian Sticky Price Model, however, it is sometimes used as a forecasting equation in the context of DSGE models; see e.g. Adolfson et al. (2005) and Kilponen and Ripatti (2006).

In this paper we develop a method of forecasting inflation that is based on the present-value formulation of the NKPC inspired by Galí and Gertler (1999) and Galí et al. (2001). We use the hybrid version of the NKPC, i.e. one including also lagged inflation, because for most countries this has turned out to fit the data better than the purely forward-looking version. Starting from their concept of fundamental inflation we extend this methodology by expressing current fundamental inflation only with lagged variables. Iteratively we construct a series of multi-step forecasts of fundamental inflation which we interpret as the inflation forecasts implied by the NKPC. Since the NKPC is estimated for Austria which is a fairly open economy, the NKPC model is extended to include also open economy aspects that might be especially relevant for Austria. Forecasts are generated from three different specifications of the NKPC, which differ by the degree to which the open economy aspects are incorporated.

The forecasts stemming from the NKPC are compared to the forecasts of a Bayesian Vector Autoregressive model (BVAR), a traditional Vector Autoregressive model (VAR) and a univariate autoregressive (AR) model. To systematically evaluate the forecasting performance of the different models, we generate multi-step out-of-sample forecasts in a recursive procedure from which the root mean square errors (RMSE) are computed. Additionally, to test for significant differences in predictive accuracy we use the Diebold-Mariano test and perform a bootstrap to determine the significance of the results.

We find that the AR model delivers the lowest RMSE for the 1-quarter-ahead forecast horizon and the NKPC delivers the lowest RMSE for the 4-quarters and 8-quarters-ahead horizons. Although the NKPC model shows a lower RMSE than the forecasts generated from the time series models for these longer horizons, these forecasts are only significantly better than the time series models' forecasts for the 8-quarters-ahead horizon. Thus, our exercise shows that the NKPC performs significantly better than various time series models only for forecast horizons exceeding 1 year. Since longer horizons are more relevant for monetary policy than the very short run, our results suggest a large potential of NKPC models in forecasting inflation.

The remainder of the paper is structured as follows: Chapter 2 briefly introduces the specifications of the New Keynesian Phillips Curve model which are estimated for Austria and presents the forecasts generated from these specifications. In chapter 3 the forecasts of the

Bayesian VAR, the traditional VAR and the AR model are presented and chapter 4 contains the evaluation and comparison of the forecasting performance of the different models. Chapter 5 concludes the paper.

II. Forecasts from the New Keynesian Phillips Curve

II.1 The open economy New Keynesian Phillips Curve

The version of the NKPC which is estimated and used to derive the forecasts in this paper is an open economy extension of the hybrid New Keynesian Phillips Curve. The hybrid NKPC was introduced by Galí and Gertler (1999) and it is hybrid in the sense that it contains past inflation as well as future inflation and marginal cost as explanatory variables. Thus, it displays features of the traditional as well as of the New Keynesian Phillips Curve.

The open economy extension we are going to use was introduced and is discussed at length in Rumler (2007). The baseline closed economy NKPC is extended by introducing international trade as well as intermediate inputs in the production function. Specifically, two factors of production in addition to domestic labor are assumed to enter the production function of the representative firm: imported and domestic intermediate inputs. This allows import prices and the prices of intermediate inputs to affect the firm's marginal cost and ultimately, inflation. Thus, the resulting form of the hybrid NKPC for this open economy model can be written as:

$$\pi_t = E_t \frac{\theta\beta}{\Delta}\pi_{t+1} + \frac{\omega}{\Delta}\pi_{t-1} + \frac{(1-\theta)(1-\omega)(1-\theta\beta)}{[\varepsilon(\phi-1)+1]\Delta}[mc_t], \qquad (1)$$

where θ represents the Calvo probability that a firm adjusts its price in a given period, β is the steady-state discount factor, ω is the fraction of firms following a backward-looking rule of thumb in price setting, ε is the elasticity of demand, and $\Delta = \theta + \omega[1-\theta(1-\beta)]$. So far, the expression in (1) looks like the standard NKPC in structural form, which is extensively used in the literature. The only difference between the open economy NKPC and the standard model is the marginal cost expression (in square brackets), which now contains a number of additional variables:

$$mc_t = \begin{bmatrix} \hat{s}_{nt} - (\phi - 1)\dfrac{\bar{s}_{m^d} + \bar{s}_{m^f}}{1 + (1-\phi)(\bar{s}_{m^d} + \bar{s}_{m^f})}\hat{y}_t + \dfrac{\bar{s}_{m^f}}{1 + (1-\phi)(\bar{s}_{m^d} + \bar{s}_{m^f})}\left(\hat{p}_t^d - \hat{p}_t^f\right) - \\ \left[(1-\rho)\dfrac{\bar{s}_{m^d}}{\bar{s}_n + \bar{s}_{m^d} + \bar{s}_{m^f}} + \rho\dfrac{\bar{s}_{m^d}}{1 + (1-\phi)(\bar{s}_{m^d} + \bar{s}_{m^f})}\dfrac{\bar{s}_n}{\bar{s}_n + \bar{s}_{m^d} + \bar{s}_{m^f}}\right]\left(\hat{w}_t - \hat{p}_t^d\right) - \\ \left[(1-\rho)\dfrac{\bar{s}_{m^f}}{\bar{s}_n + \bar{s}_{m^d} + \bar{s}_{m^f}} + \rho\dfrac{\bar{s}_{m^f}}{1 + (1-\phi)(\bar{s}_{m^d} + \bar{s}_{m^f})}\dfrac{\bar{s}_n}{\bar{s}_n + \bar{s}_{m^d} + \bar{s}_{m^f}}\right]\left(\hat{w}_t - \hat{p}_t^f\right) \end{bmatrix}, \tag{2}$$

where s_n, s_{m^d} and s_{m^f} represent the shares of: labor (n), domestic intermediate inputs (m^d) and imported intermediate inputs (m^f) in total domestic production; ρ represents the elasticity of substitution between the input factors; and $\phi = \dfrac{(\varepsilon - 1)(1 + \bar{s}_{m^d} + \bar{s}_{m^f})}{\varepsilon(\bar{s}_n + \bar{s}_{m^d} + \bar{s}_{m^f})}$. The variables w, p^d and p^f, represent the prices of the input factors: labor (wages), domestic and imported intermediate inputs. Hatted variables denote deviations from the steady state, and barred variables represent steady-state values.

Equation (2) shows that, unlike in the standard model, marginal cost in the extended model is not only a function of real unit labor cost, s_n, but also of the relative prices of the three production factors:

- the relative price of domestic labor to domestic intermediate inputs (the real wage), $w - p^d$,
- of domestic labor to imported intermediate inputs, $w - p^f$,
- and of domestic to imported intermediate inputs (the terms of trade at the intermediate products' level), $p^d - p^f$.

The weights with which the relative prices enter the marginal cost term are determined by a combination of the steady-state shares of the three factors of production (the hatted variables), the elasticity of demand (ε) and by the elasticity of substitution between them (ρ). The second term in equation (2) reflects the assumption of decreasing returns to scale of the variable factors of production making marginal cost increase with output.[3]

[3] For the derivation of equations (1) and (2) see Appendix B; for more discussion on the open economy NKPC see Rumler (2007).

Hence, this general formulation of the open economy NKPC nests the existing formulations of the New Keynesian Phillips Curve model for the closed economy and for the open economy without domestic intermediate inputs. If the share of domestic intermediate inputs in production is set at $s_{m^d} = 0$, we obtain the open economy Phillips curve model of Leith and Malley (2007); if we additionally set the share of imported intermediate inputs at $s_{m^f} = 0$, the model collapses to the standard closed economy NKPC.

II.2 Estimation Results

Our empirical strategy to generate forecasts from the NKPC starts with the estimation of the structural parameters of the NKPC presented in equations (1) and (2) using Austrian data from 1980Q1 to 1999Q4. The period 2000Q1 to 2006Q4 is reserved for the evaluation of the out-of-sample forecasts. As the model contains expected inflation as an explanatory variable, we estimate the equation with GMM, which is frequently used in the literature for this type of model (Galí et al., 2005). Since we do not know a priori which of the nested versions of the NKPC outlined above performs best in forecasting Austrian inflation, the model is estimated for all three specifications: the specification for the closed economy (SP1), for the open economy without domestic intermediate inputs (SP2) and for the general open economy specification shown in equation 2 (SP3).[4] Because our focus is on forecasting inflation, we use the year-on-year change of the Austrian quarterly HICP as the dependent variable in the regressions to be comparable with the forecasting literature; see the data description in Appendix A for the definitions of the other variables.

Table 1 summarizes the estimation results of the structural parameters of the extended NKPC in equations (1) and (2) for the specifications SP1, SP2 and SP3. The columns contain the estimated coefficients for the share of firms that keep prices fixed in a given period (which can be interpreted as the degree of structural price rigidity), $\hat{\theta}$, for the firms' discount factor, $\hat{\beta}$, for the share of firms that follow a backward-looking rule of thumb (indicating the degree of intrinsic

[4] SP1 assumes $s_{m^d} = 0$ and $s_{m^f} = 0$, SP2 assumes $s_{m^d} = 0$ and SP3 is the unrestricted model as given in equation (2).

inflation persistence), $\hat{\omega}$, and for the elasticity of substitution between input factors, $\hat{\rho}$. The (Newey-West corrected) standard errors of the coefficient estimators are given in parentheses.

Table 1: Estimation of the structural parameters of model specifications SP1, SP2 and SP3 for the extended NKPC for Austria

Dependent variable: yoy rate of inflation according to the quarterly HICP

	$\hat{\theta}$	$\hat{\beta}$	$\hat{\omega}$	$\hat{\rho}$
SP1	0.47 (0.05)	0.99 (0.01)	0.17 (0.07)	–
SP2	0.47 (0.05)	0.98 (0.01)	0.32 (0.06)	3.35 (0.98)
SP3	0.50 (0.04)	0.96 (0.01)	0.35 (0.06)	4.05 (0.92)

Instrumental variables: inflation rate lags 2-6, wage inflation lags 1-4, commodity price inflation lags 1-4, real unit labor costs lags 1-4, ratio of wages to import prices lags 1-4.

Notes: Estimation method is GMM. Estimation period is 1980Q1-1999Q4.

All parameters look very reasonable: Under all specifications around 50% of the Austrian firms leave their prices unchanged during a given quarter. This implies an average duration of a price spell of about 6 months, which is substantially lower than the median price duration of 11 months derived from micro CPI data (see Baumgartner et al., 2005). The steady-state discount factor of firms' profits shows a value lower but close to 1 as expected from theory. The share of firms following a backward-looking rule of thumb differs according to the specification and varies between 17% and 35%. The share of backward-looking firms is related the persistence of the inflation process. The observed difference in the share of backward-looking firms between the closed economy specification SP1 on the one hand, and the open economy specifications SP2 and SP3 on the other hand, implies (by equation 1) that inflation persistence is estimated almost twice as high for the open economy specifications than for the closed economy specification. A comparison of the parameters for Austria to other euro area countries can be found in Rumler (2007).[5]

[5] The parameters in table 1 cannot be directly compared to the results for other countries in Rumler (2007) or in other papers because they are based on changes in the HICP as opposed to the GDP deflator as the dependent variable. From Rumler (2007) it emerges that the degree of price rigidity in Austria estimated from the NKPC roughly corresponds to the average of the euro area countries.

II.3 Generating Forecasts from the NKPC

II.3.1 Method

Based on these estimations we construct a forecast for each of the three specifications. Theoretically, there are at least two ways of deriving a forecast from the NKPC. The most natural way would be to directly use equation (1) to generate a forecast. However, this requires data on expected inflation or an assumption on a suitable proxy for expected inflation. In our case this is not feasible because there are no appropriate data (in terms of quality and length of time series) on expected inflation in Austria. Thus, we propose an “indirect” method to generate a forecast making use of the present-value formulation of the NKPC, which to our knowledge is the first attempt in the literature to use the NKPC for inflation forecasting. The starting point is the concept of the fundamental rate of inflation as introduced by Galí and Gertler (1999) which ultimately goes back to Campbell and Shiller (1987).

To arrive at fundamental inflation, the NKPC (which is a difference equation) is solved forward for current inflation. The solution yields inflation as a function of the discounted sum of present and future marginal costs. Thus, fundamental inflation is the rate of inflation implied from the present-value formulation of the NKPC. In the case of the hybrid NKPC the present-value representation is given by:

$$\pi_t = \delta_1 \pi_{t-1} + \left(\frac{\lambda}{\delta_2 \gamma_f} \right) \sum_{s=0}^{\infty} \left(\frac{1}{\delta_2} \right)^s E_t \left[mc_{t+s} \right], \tag{3}$$

where $\delta_1 = \dfrac{1-\sqrt{1-4\gamma_f \gamma_b}}{2\gamma_f}$ and $\delta_2 = \dfrac{1+\sqrt{1-4\gamma_f \gamma_b}}{2\gamma_f}$ are the stable and unstable roots of the above difference equation. The parameters γ_f, γ_b and λ are the coefficients of the reduced-form hybrid NKPC

$$\pi_t = \gamma_f E_t(\pi_{t+1}) + \gamma_b \pi_{t-1} + \lambda(mc_t), \tag{4}$$

which are calculated from the estimated structural parameters. Computing fundamental inflation according to equation (3) requires multi-period forecasts of marginal cost. Campbell and Shiller (1987) propose to generate them from a bivariate VAR containing inflation and marginal cost. Note that the multi-period forecast of a VAR for the vector Z is given by $\hat{Z}_{t+h} = A^h Z_t$ where A

is the companion matrix of a VAR(p) system with $Z_t = [mc_t, mc_{t-1}, ..., mc_{t-p+1}, \pi_t, \pi_{t-1} ... \pi_{t-p+1}]'$. Applying the summation formula to (3), fundamental inflation, π^*, can then be calculated as:

$$\pi_t^* = \delta_1 \pi_{t-1} + \left(\frac{\lambda}{\delta_2 \gamma_f}\right) e_1' \left(1 - \frac{1}{\delta_2} A\right)^{-1} Z_t \tag{5}$$

where e_1' is a selection vector that singles out the forecast of marginal cost.

In Galí and Gertler (1999) and in a number of successive papers in this field, fundamental inflation has been mainly used to assess the empirical fit of the NKPC by comparing it to actual inflation. In this paper, we propose to extend this methodology to generate a forecast of fundamental inflation which we interpret as the inflation forecast implied by the (present-value formulation of the) NKPC. This requires only a small additional step: We lead expression (5) by one period and make use of the fact, which was used in the construction of (5), that the one-period-ahead forecast of Z is $\hat{Z}_{t+1} = AZ_t$. Thus, we can express the next-period fundamental inflation using only current variables. This forecast of fundamental inflation for *t+1* based on information up to period *t* can be used to calculate a forecast for the next period *t+2* and so on, iteratively for *t+3*, … *t+h*. The generalization of this principle yields an *h*-step forecast of fundamental inflation:

$$\hat{\pi}_{t+h}^* = \delta_1 \pi_{t+h-1}^* + \left(\frac{\lambda}{\delta_2 \gamma_f}\right) e_1' \left(1 - \frac{1}{\delta_2} A\right)^{-1} A^h Z_t . \tag{6}$$

Our forecasts are generated from this equation, where A is estimated from a VAR(1) which includes marginal cost and inflation. In the choice of the variables and the specification of the VAR we follow Galí and Gertler (1999) and successive papers, e.g. Kurmann (2005) and Tillmann (2005), who used this specification to construct fundamental inflation.[6]

[6] It is obvious that the quality of the final inflation forecast depends crucially on the quality of the auxiliary forecast for marginal cost. To see how these auxiliary forecasts perfom, we evaluated them against a naïve forecast (assuming no change over the respective forecast horizon) of marginal cost. It turns out that the forecasting performance of the VAR(1) for marginal cost is reasonably good: In all cases, i.e. for all three specifications (SP1, SP2 and SP3) and all horizons, the VAR(1) forecast resulted in a lower RMSE than the naïve forecast. Specifically, the RMSE was on average over the three specifications 5% lower than that of the naïve forecast for the 1-quarter horizon, 13% lower for the 4-quarter horizon and 22% lower for the 8-quarter horizon. To check how this performance compares with other possible specifications of the VAR, we considered VARs with a lag length up to 4. We find that the VAR(1) delivers the best forecast for marginal cost of all the lag specifications considered. However, its forecasting performance is only slightly better than that of the VAR(2), while the VAR(3) and the VAR(4) are clearly

However, in our application it could be argued that assuming a model for the auxiliary forecast of marginal cost which implies a different process for inflation than the NKPC itself is inherently inconsistent. In order to avoid this possible inconsistency, we construct an alternative set of forecasts assuming a univariate model for the auxiliary forecast of marginal cost. Specifically, as we deal with quarterly data, we generate the auxiliary forecast with an AR(4) model for marginal cost. In this case $Z_t = [mc_t, mc_{t-1}, mc_{t-2}, mc_{t-3}]'$.[7]

II.3.2 Results

In order to evaluate the forecasting performance of the NKPC model over different horizons we generate forecasts for 1-quarter, 4-quarters and 8-quarters-ahead over the period 2000Q1 to 2006Q4. Figures A1 to A3 in the Appendix show the forecasts derived from the three specifications of the NKPC based on the VAR specification for the auxiliary forecast of marginal cost for each horizon along with actual inflation and figures A4 to A6 show the forecasts based on the AR specification for the auxiliary forecast also for each horizon.

An interesting observation out of these graphs is that the forecasts of all six models are quite similar to each other, which suggests the necessity to carry out a formal evaluation of the forecasting performance based on statistical tests to determine whether the differences in the forecasting performance are significant. The results of this evaluation are presented in section IV. In general, we observe that all six models tend to overestimate or underestimate inflation at the same time. Second, we see that the forecast values vary much less than actual inflation, especially for the NKPC model based on the AR auxiliary forecast.

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outperfomed by the former two models. Thus, we continue with the VAR(1) as our standard specification for the auxiliary forecast.

[7] To check the robustness of this choice, also here we experimented with AR(1), AR(2) and AR(3) models for the univariate auxiliary forecast of marginal cost, but none of these models performed better than the AR(4) in forecasting marginal cost. All results are available upon request.

III. Forecasts from Time Series Models

In this part we describe the three different time series models used to forecast inflation in Austria – a univariate AR model, a traditional VAR and a VAR estimated with Bayesian techniques (BVAR) – which will be used in the next section as competing models to assess the forecasting performance of the NKPC model.

AR and VAR models are the most straightforward and most widely used time series techniques to forecast inflation which also yield reasonable good results. Bayesian techniques have the advantage over an AR or a traditional VAR that the problem of over-fitting is avoided by imposing priors that assign a probability distribution to each coefficient. This reduces the amount of information required to estimate the model. In other words, Bayesian VARs allow for more degrees of freedom by incorporating prior beliefs to the initial estimation.[8] Although, there is a rather long tradition of using this type of model in forecasting inflation, it has never been used to forecast inflation in Austria.[9]

Using a similar data set as in the first part of the paper (quarterly data up to 1999) we estimate the three models listed above. In the multivariate cases (BVAR and VAR) we assume that inflation is driven by aggregate demand and supply shocks. Thus, we include the HICP, a measure of economic activity (real GDP) and two variables that represent supply shocks (wages, proxied by compensation per employee, and the oil price).

In the case of the VAR and the AR, we need to decide on the number of lags that enter the regression. In the case of the BVAR we additionally have to decide on the priors. The most commonly used type of priors proposed by Litterman (1980) assumes that each variable in the system follows a random walk. In other words, the prior mean of the coefficient on the own first lag of each variable is one and the coefficients on the cross lags are close to zero. When estimating a BVAR, the assumption of a random walk is summarized in a set of hyperparameters: tightness, decay and weight. The role of these hyperparameters is to control for the overall prior

[8] See Robertson and Tallmann (1999) for a very intuitive explanation of BVAR models.
[9] See Kenny et al. (1998) and the references therein, for examples of inflation forecasts using BVAR models or more recent papers such as Lack (2006) and Nobili (2005).

tightness, that is, the degree of uncertainty about the prior; the rate of lag-decay in the prior variance; and by how much we change the overall tightness for each lag.

In order to determine which combination of hyperparameters and lags delivers the best forecast, i.e. yields the lowest root mean square error (RMSE), we do a grid search over all possible combinations of hyperparameters (from 0.1 to 1.0, with increments of 0.1) and lag specifications from 1 to 6, which gives a total of 6,000 estimations. The exact specification of the models in terms of hyperparameters and number of lags which yield the lowest RMSE for inflation out of the 6,000 models are given in table 2. These are the specifications used to generate the forecasts for the subsequent analysis.

Table 2: Number of lags and hyperparameters of the time series models

		Number of lags	Tightness	Decay	Weight
AR		4			
VAR	1-step ahead	4			
	4-step ahead	3			
	8-step ahead	3			
BVAR	1-step ahead	5	0.1	0.7	0.8
	4-step ahead	1	0.1	0.1	0.1
	8-step ahead	2	0.1	1.0	0.2

As the third model type that is used in the forecast comparison we employ a univariate time series model. Univariate autoregressive models have been widely and successfully used to forecast macroeconomic variables that are characterized by a high degree of persistence, such as inflation. Therefore, the forecast based on the AR model serves as a benchmark against which the forecasting performance of the other models is evaluated. Equivalently to the NKPC model, we estimate the BVAR, VAR and the AR(4) model for quarterly Austrian HICP inflation for the period 1981Q1-1999Q4 and construct 1-step, 4-steps and 8-steps-ahead forecasts for the period 2000Q1-2006Q4.

The forecasts obtained by all three time series models are depicted in figures A7 to A9 in the Appendix. There are also some interesting features of these forecasts. As was the case for the

NKPC specifications, there is not much variation across models in the 1-step-ahead forecast. Indeed, all three models tend to overestimate or underestimate inflation at the same time. For the longer horizons, there is much more variation across the forecasts, and this variability increases with the length of the forecast horizon. Both, the BVAR and the VAR model, do much better in forecasting the period of falling inflation rates from 2001 to 2003 than the AR(4) model, perhaps due to the fact that these are the only two models that include commodity prices in the set of explanatory variables. On the other hand, all three models fail to forecast at the 4-steps and 8-steps-ahead horizons the following increase in inflation up to mid-2004. Finally, it is worth noticing that both, the VAR and the BVAR, underestimate inflation significantly at the end of the sample period for the 8-quarters-ahead horizon.

IV. Forecast Evaluation

For the evaluation of the performance of the different models over various forecast horizons we construct series of 1-step, 4-step and 8-step-ahead pseudo out-of-sample forecasts.[10] Specifically, we estimate the models for the period 1981Q1 to 1999Q4, generate 1-period, 4-periods and 8-periods-ahead forecasts, move one quarter forward and calculate new 1-period, 4-periods and 8-periods-ahead forecasts, and so on. This procedure continues until the last 1-period, 4-periods and 8-periods-ahead forecast has reached the end of the validation period, i.e. 2006Q4. By stacking the last forecast values of each forecast we obtain series of 1-step, 4-step and 8-step-ahead forecasts which are then used to compute forecast error and test statistics.

We first assess the forecasting performance of the NKPC models, the BVAR, VAR and the AR(4) model by calculating the root mean square errors (RMSE) for the forecasts of the corresponding models and for the naïve forecast (assuming a flat forecast profile over the forecast horizon). The naïve forecast is frequently used as a benchmark in the literature on forecast evaluation because it is usually hardly outperformed by other models in the short to medium term for many macroeconomic variables. The results are shown in table 3.

[10] They are called pseudo out-of-sample forecasts because we use revised data rather than real-time data that were available at the time of the forecast.

Table 3: Root Mean Square Forecasting Error (RMSE) for inflation forecasts based on the NKPC (both, based on the VAR and AR specification for the auxiliary forecast), BVAR, VAR, AR(4) models and the naïve forecast by forecast horizon (calculated over the period 2000Q1-2006Q4)

Models	RMSE 1-quarter-ahead	RMSE 4-quarters-ahead	RMSE 8-quarters-ahead
NKPC(VAR) SP1	0.321	0.484	**0.463**
NKPC(VAR) SP2	0.376	0.621	0.525
NKPC(VAR) SP3	0.365	0.634	0.527
NKPC(AR) SP1	0.321	0.535	0.537
NKPC(AR) SP2	0.312	**0.478**	0.505
NKPC(AR) SP3	0.317	0.520	0.536
BVAR	0.314	0.585	0.468
VAR	0.318	0.600	0.591
AR(4)	**0.310**	0.537	0.605
Naïve	0.331	0.629	0.723

From the table we can see that – for the evaluation period considered (2000Q1-2006Q4) – some specifications of the NKPC outperform the time series models for the 4-quarters and 8-quarters horizons, whereas for the 1-quarter horizon the simple AR(4) shows the best forecasting performance.[11] Among the NKPC specifications that are based on the VAR model for the auxiliary forecast of marginal cost, the closed economy specification SP1 delivers the lowest RMSE for all three horizons. In contrast, for the NKPC models based on an AR auxiliary forecast the open economy specification SP2 (with imported but without domestic intermediate inputs in the production function) shows consistently the best predictive accuracy for all horizons. Among all NKPC models, the specification SP2 based on the AR auxiliary forecast (of marginal cost) delivers the best forecast for the 1-quarter and 4-quarters horizons, while specification SP1 based on a VAR for the auxiliary forecast shows the best forecasting performance for the 8-quarters horizon.

[11] This result is specific to the evaluation period considered. However, for a shorter alternative evaluation period ranging from 2003Q1 to 2006Q4 we found very similar results, which are shown in Table A1 in the Appendix. The forecast derived from the AR(4) model performs slightly better than the NKPC (SP1), the BVAR and the VAR for the 1-quarter-ahead horizon, while for the 4-quarters and 8-quarters-ahead horizons the best NKPC specification (SP1) outperforms the BVAR, VAR as well as the AR(4) forecasts.

Comparing the RMSEs of the BVAR and the VAR models, they show a quite similar forecasting performance for the 1-quarter horizon which is also in the range of the best-performing NKPC specification. In contrast, for the 4-quarters and the 8-quarters horizons the BVAR clearly outperforms the traditional VAR. This indicates that in our experiment the gain in degrees of freedom brought about by the Bayesian estimation, i.e. the imposition of prior beliefs on the estimated coefficients, clearly results in an improved predictive ability of the VAR for medium to long term horizons.

The AR(4) model delivers the lowest RMSE of all models for the 1-quarter horizon. For the 4-quarters horizon its forecasting performance is in the intermediate range compared to the other models, whereas for the 8-quarters horizon the AR(4) is outperformed by all other model types – except the naïve forecast. Finally, the naïve forecast is outperformed in terms of predictive accuracy by all other model types (considering the best-performing NKPC specification) for all three horizons.

Interestingly, while the forecast errors clearly increase with the length of the forecast horizon when moving from the 1-quarter to the 4-quarters horizon, we do not always observe higher RMSEs for the 8-quarters horizon compared to the 4-quarters horizon. This is particularly the case for some of the NKPC specifications and for both, the BVAR and VAR models. Also, the variation of the RMSEs among the different models is much larger for the 4-quarters-ahead forecast compared to the 1-quarter-ahead, but very similar between the 4-quarters and the 8-quarters-ahead forecast. This indicates that, at least when using NKPC and BVAR/VAR models, forecasting inflation 4-quarters ahead is not necessarily easier than forecasting inflation 8-quarters ahead.

In addition to the analysis of the RMSEs, we also perform a formal test to check if the differences in predictive accuracy among models are statistically significant. For this purpose, we employ the Diebold-Mariano test for non-nested models.[12] The Diebold-Mariano test is applied to test the null hypothesis of equal predictive accuracy between the best performing model according to the RMSE (the AR(4) model for 1-step ahead and the NKPC for 4- and 8-steps ahead) and the other models (except the naïve forecast). Since we are mainly interested in finding significant

[12] See Diebold and Mariano (1995).

differences in forecasting performance between the NKPC and the other models, we only consider the best-performing specification of the NKPC, i.e. SP2(AR) for 1- and 4-quarters ahead and SP1(VAR) for 8-quarters ahead. In table 4 the test statistics of the Diebold-Mariano tests are shown for the indicated pairs of models.[13] Because the power of this test may be poor due to the small sample, we use bootstrapped critical values to determine the significance of our results.[14]

Table 4: Comparing the forecasting performance of the NKPC, BVAR, VAR and AR(4) models using the Diebold-Mariano test

Forecast comparisons	DM statistic 1-quarter-ahead	DM statistic 4-quarters-ahead	DM statistic 8-quarters-ahead
NKPC vs. BVAR	0.04	0.60	0.03
NKPC vs. VAR	0.15	0.72	0.62
NKPC vs. AR(4)	0.09	0.51	1.59**
BVAR vs. VAR	0.18	0.19	1.67**
BVAR vs. AR(4)	0.11	0.36	0.63
VAR vs. AR(4)	0.28	0.48	0.07

Notes: Evaluation period is 2000Q1-2006Q4. ** indicates rejection of the null of equal predictive accuracy at the 5% significance level.

According to table 4, we only find significant differences in predictive accuracy between the forecast derived from the NKPC model and the forecast based on the AR(4) model for the 8-quarters forecast horizon (at the 5% significance level); as well as between the BVAR forecast and the VAR forecast also for the 8-quarters horizon (at the 1% level). For all other model comparisons we do not find any significant difference in the predictive performance. Thus, for the shorter horizons (4-quarters and 1-quarter-ahead) we cannot say that the NKPC – despite its relatively lower RMSE – significantly outperforms the time series models or vice versa. Only for the longest forecast horizon of 2 years, the best specification of the NKPC shows a significantly better forecasting performance than the worst performing time series model.

To sum up, the forecasting performance of the time series models compared to the NKPC is relatively better at the very short horizon of 1-quarter ahead, but it decreases relative to the

[13] We performed Diebold-Mariano tests between all pairs of models. The results are reported in Table A2 in the Appendix.
[14] We resample the DM-test 50,000 times and derive a distribution which we compare with our null hypothesis.

NKPC for longer horizons of 1- and 2-years ahead. Specifically for a forecast horizon of one quarter, a simple AR model delivers the best forecast of the models considered, while for the longer horizon of 1 and 2 years the best performing specification of the NKPC outperforms all other model types. The forecasts based on the BVAR clearly outperform the competing VAR forecasts for the longer horizons of 1 and 2 years, but not the forecast derived from the best NKPC specification. In terms of statistical significance, we only observe significant differences between the best and the worst performing models for the longest forecast horizon.

V. Conclusions

The New Keynesian Phillips Curve is currently the most widely used theory of inflation dynamics in macroeconomics. Until now it has been used in a number of studies to explain inflation developments and to estimate the structural parameters of the price setting process, but only rarely for forecasting purposes. The main contribution of this paper is that we develop a method of generating a forecast of inflation from the single-equation New Keynesian Phillips Curve. This is done by extending the concept of fundamental inflation such that current fundamental inflation is expressed only with lagged variables. The resulting expression is then used to iteratively construct forecasts of fundamental inflation which we interpret as the forecasts implied by the NKPC. We evaluate the performance of these forecasts by systematically comparing them to forecasts generated from a Bayesian VAR (which is also used for the first time to forecast Austrian inflation), a traditional VAR, an AR model and the naïve forecast for 1-quarter, 4-quarters and 8-quarters horizons.

The evaluation of the forecasting quality of all models shows that the NKPC beats the forecasts derived from the time series models and the naïve forecast in terms of lower RMSE only for the longer forecast horizons of 1 and 2 years. This confirms the results in the forecasting literature that forecasts based on structural models are able to outperform time series models only for forecast horizons longer than 1 year. For a shorter forecast horizon of 1 quarter all model types show a quite similar performance. However, we only find significant differences in forecasting performance between the model with the lowest and the highest RMSE for the longest forecast horizon. Among the different specifications of the NKPC, the open economy specification SP2 (with imported but without domestic intermediate inputs) delivers the relatively lowest RMSE for two (1-quarter and 8-quarters) out of the three horizons considered. This implies that not only the in-sample fit of the NKPC but also its forecasting performance can be significantly improved by using the open economy specification of the NKPC developed in Rumler (2007).

The method we propose in this paper is an indirect approach of generating a forecast from the NKPC, as it uses the concept of fundamental inflation as an intermediate step. It consists of two steps. First, the NKPC is estimated and its structural coefficients are used to construct fundamental inflation. In the construction of fundamental inflation an auxiliary forecast of marginal cost is employed. In the second step, a forecast of fundamental inflation is computed which, by the definition of fundamental inflation as the present-value formulation of the NKPC, is the inflation forecast implied by the NKPC. Thus, the quality of the final forecast depends on two distinct ingredients of the process: the GMM estimation of the NKPC and the auxiliary forecast of marginal cost. One way to improve the quality of the final forecast is therefore trying to optimize the (GMM) estimation of the structural parameters. It is well known that the performance of GMM depends crucially on the validity of the instruments. A possible future extension of our research could therefore be to choose the set of instruments based on the forecasting performance of the model. The second promising route for an improvement of our forecast would be to improve the auxiliary forecast of marginal cost by applying different, more sophisticated methods, rather than using a VAR or AR model.

The forecasting process described above appears to be quite complicated and therefore a valid question is whether it is useful and practical for regular forecasting exercises, such as those done by research institutions and central banks. The first problem is the issue of timeliness of the forecast, since our model uses quarterly data all of which are released with a delay of about half a year in the quarterly national accounts statistics. Despite the fact that inflation data are available in a more timely fashion, the lagged release of national accounts data limits the usefulness of our approach for the very short horizon of one and two quarters ahead, as by the time the data is published the forecasted events have already taken place. For longer forecast horizons, however, such a problem does not arise and the method could be used without limitations.

The second concern is related to the stability of the results over time in recurring forecasting exercises. The procedure requires two important decisions: the choice of the instruments in the

GMM estimation and the specification of the auxiliary forecast. While the specification of the auxiliary forecast is usually not expected to deliver strongly varying results for different estimation periods, the choice of the instruments is known to have a great effect on the parameter estimates in GMM. It might easily happen that the use of a specific set of instruments that works fine for a certain estimation period may cause the estimation to break down for a slightly different estimation period. In that case, a different instrument set has to be found that performs well for the new estimation period with the potential risk of delivering considerably different coefficients estimates. In general, the sensitivity of the GMM estimations to the specific instruments used requires a time-consuming search for the optimal instrument set for each estimation period, which could reduce the feasibility of our method in recurring forecasting.

Although the NKPC has certain disadvantages in terms of timeliness and stability of the forecast over time, it can still be used complementary to time series models because it is a structural model of inflation determination. The advantage of structural models in forecasting is that they allow an economic interpretation of the main factors driving the forecast. In our version of the NKPC, variations in inflation can be traced back to changes in marginal costs which are, in turn, determined by the cost of labor and the prices of domestic as well as imported intermediate inputs.

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Appendix

A Data Description

The year-on-year log change of the Austrian HICP at quarterly frequency is used as the inflation variable in all estimations. For the estimation of the NKPC real unit labor cost, s_n, is defined as the nominal total compensation to employees divided by nominal GDP, and s_{m^d} as well as s_{m^f} are the ratios of domestically produced and imported intermediate goods to nominal GDP. y denotes real GDP, domestic nominal wages per employee are used for w, and the domestic GDP deflator and the import deflator are used as proxies for p^d and p^f, respectively. HICP inflation, real GDP, nominal compensation per employee and oil prices are used in the Bayesian as well as the traditional VAR. All data (except oil prices) stem from the Austrian System of National Accounts (ESA 79 until 1988, ESA 95 from 1988 on); input/output tables available for the sample period were used to separate intermediate inputs into domestic and imported shares.

Figure A1: 1-Quarter-Ahead Inflation Forecasts based on the NKPC(VAR) and Actual Inflation

Figure A2: 4-Quarters-Ahead Inflation Forecasts based on the NKPC(VAR) and Actual Inflation

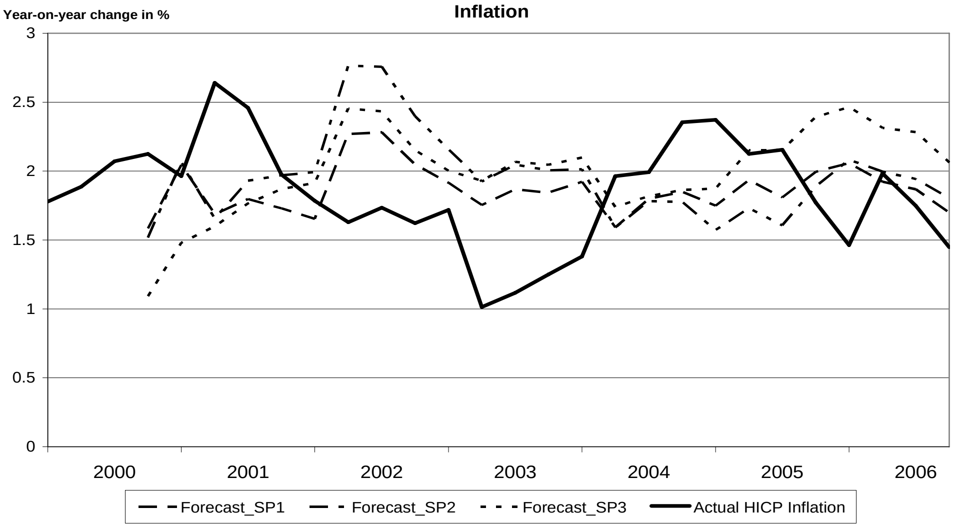

Figure A3: 8-Quarters-Ahead Inflation Forecasts based on the NKPC(VAR) and Actual Inflation

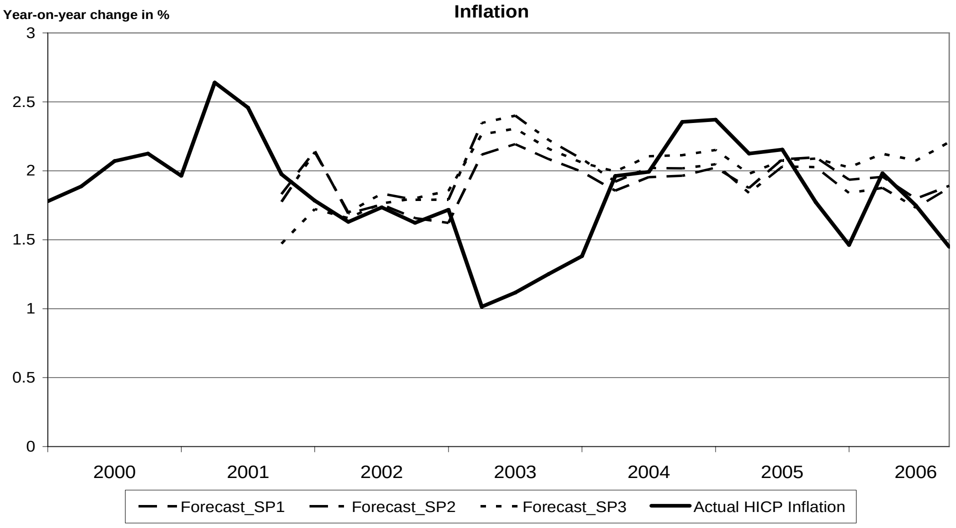

Figure A4: 1-Quarter-Ahead Inflation Forecasts based on the NKPC(AR) and Actual Inflation

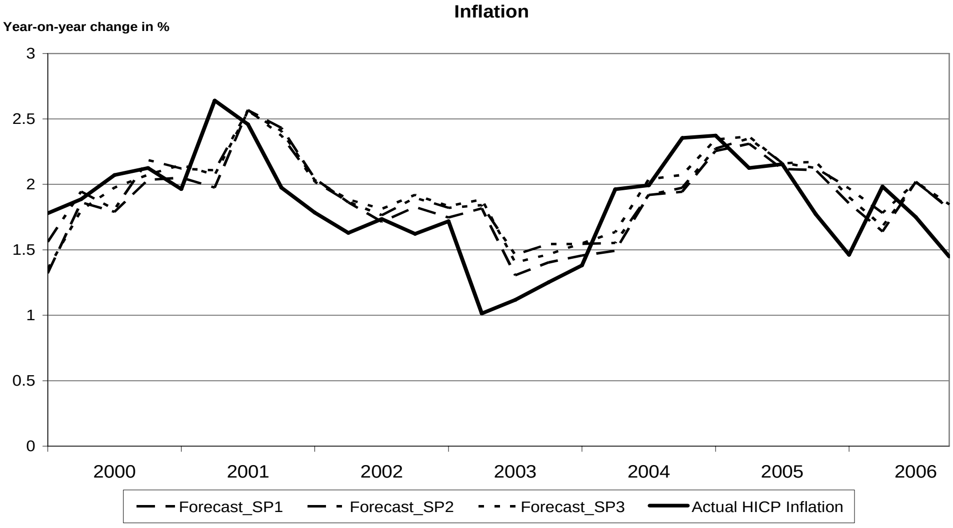

Figure A5: 4-Quarters-Ahead Inflation Forecasts based on the NKPC(AR) and Actual Inflation

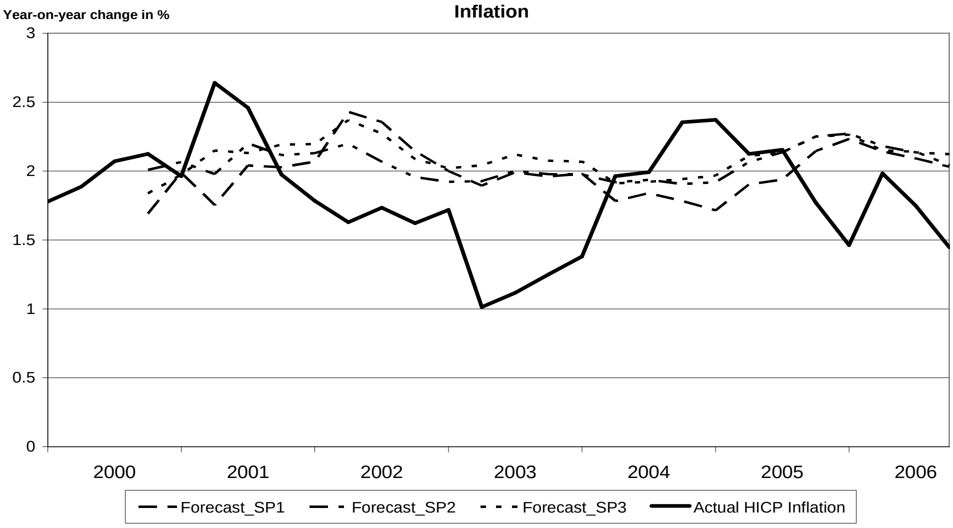

Figure A6: 8-Quarters-Ahead Inflation Forecasts based on the NKPC(AR) and Actual Inflation

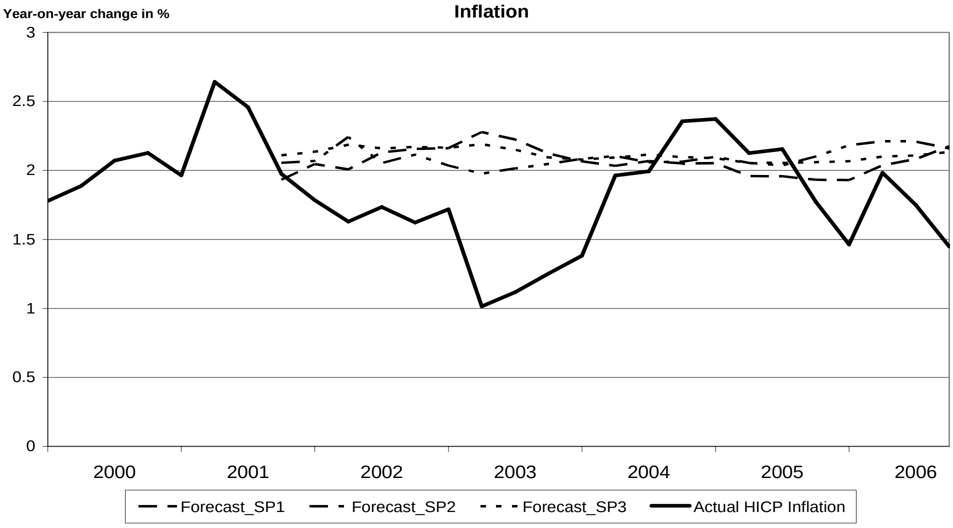

Figure A7: 1-Quarter-Ahead Inflation Forecasts from Time Series Models and Actual Inflation

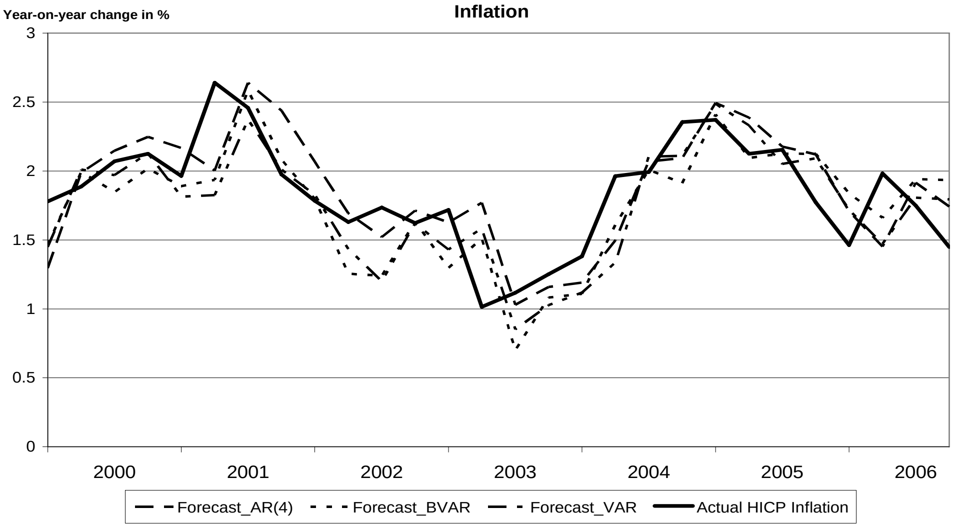

Figure A8: 4-Quarters-Ahead Inflation Forecasts from Time Series Models and Actual Inflation

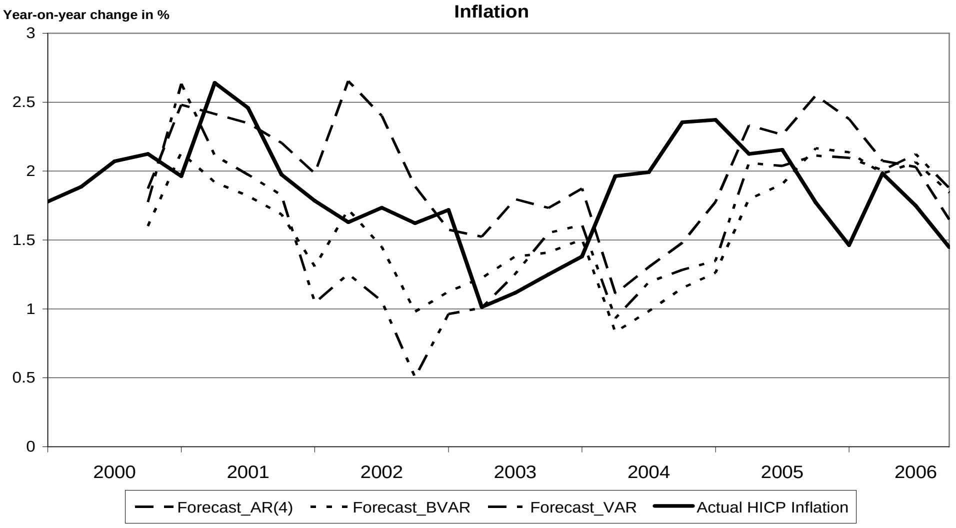

Figure A9: 8-Quarters-Ahead Inflation Forecasts from Time Series Models and Actual Inflation

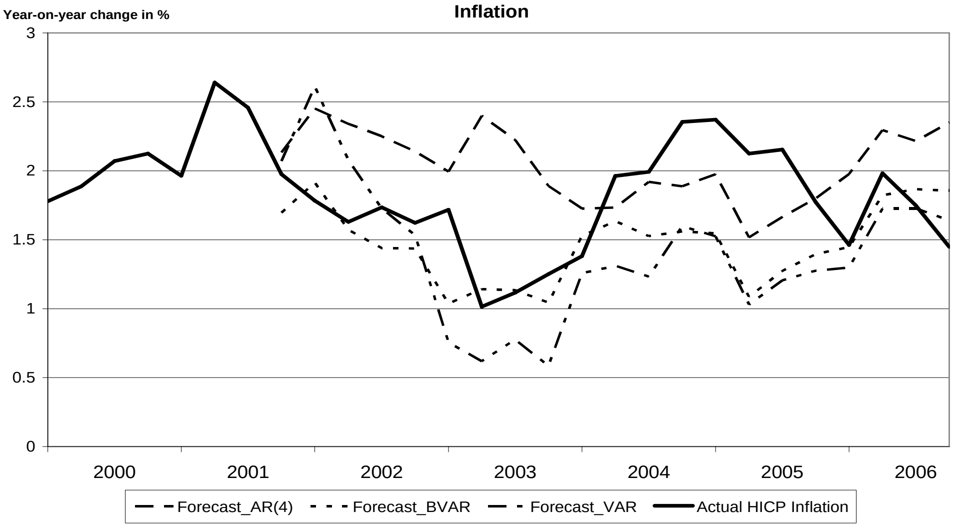

Table A1: **Alternative Evaluation Period 2003Q1-2006Q4 –** RMSEs for inflation forecasts based on the NKPC, BVAR, VAR, AR(4) models and the naïve forecast

Models	RMSE 1-quarter-ahead	RMSE 4-quarters-ahead	RMSE 8-quarters-ahead
NKPC(VAR) SP1	0.315	**0.402**	0.533
NKPC(VAR) SP2	0.368	0.557	0.597
NKPC(VAR) SP3	0.336	0.516	0.668
NKPC(AR) SP1	0.378	0.440	**0.444**
NKPC(AR) SP2	0.463	0.526	0.693
NKPC(AR) SP3	0.581	0.610	0.780
BVAR	0.317	0.614	0.620
VAR	0.324	0.614	0.647
AR(4)	**0.311**	0.541	0.454
Naïve	0.330	0.658	0.703

Table A2: Comparing the forecasting performance of all models and specifications using the Diebold-Mariano test with bootstrapped critical values

Forecast comparisons		DM statistic 1-quarter-ahead	DM statistic 4-quarters-ahead	DM statistic 8-quarters-ahead
NKPC(VAR)_SP1	NKPC(AR)_SP1	0.00	1.14 **	1.49 **
NKPC(VAR)_SP1	NKPC(VAR)_SP2	1.84	1.81 **	0.97 **
NKPC(VAR)_SP1	NKPC(AR)_SP2	0.28	0.09	0.60
NKPC(VAR)_SP1	NKPC(AR)_SP3	1.68	2.40 **	1.25 **
NKPC(VAR)_SP1	NKPC(VAR)_SP3	0.12	0.41	1.53 **
NKPC(VAR)_SP1	AR(4)	0.66	0.45	1.59 **
NKPC(VAR)_SP1	VAR	0.07	0.76	0.62
NKPC(VAR)_SP1	BVAR	0.20	0.65	0.03
NKPC(AR)_SP1	NKPC(VAR)_SP2	2.28 **	1.35 **	0.19
NKPC(AR)_SP1	NKPC(AR)_SP2	0.49	1.31 **	0.43
NKPC(AR)_SP1	NKPC(AR)_SP3	1.90 **	2.00 **	0.25
NKPC(AR)_SP1	NKPC(VAR)_SP3	0.21	0.27	0.03
NKPC(AR)_SP1	AR(4)	0.70	0.02	1.02
NKPC(AR)_SP1	VAR	0.06	0.42	0.25
NKPC(AR)_SP1	BVAR	0.20	0.31	0.30
NKPC(VAR)_SP2	NKPC(AR)_SP2	2.02 **	1.40 **	0.17
NKPC(VAR)_SP2	NKPC(AR)_SP3	0.34	0.16	0.04
NKPC(VAR)_SP2	NKPC(VAR)_SP3	1.96 **	1.07 **	0.13
NKPC(VAR)_SP2	AR(4)	2.37 **	0.71	0.84
NKPC(VAR)_SP2	VAR	1.18	0.14	0.27
NKPC(VAR)_SP2	BVAR	1.30	0.21	0.21
NKPC(AR)_SP2	NKPC(AR)_SP3	1.62 **	2.43 **	0.25
NKPC(AR)_SP2	NKPC(VAR)_SP3	0.42	1.18 **	0.65
NKPC(AR)_SP2	AR(4)	0.09	0.51	1.01
NKPC(AR)_SP2	VAR	0.15	0.72	0.44
NKPC(AR)_SP2	BVAR	0.04	0.60	0.18
NKPC(AR)_SP3	NKPC(VAR)_SP3	1.96 **	1.62 **	0.16
NKPC(AR)_SP3	AR(4)	2.12 **	0.84	0.96
NKPC(AR)_SP3	VAR	1.01	0.21	0.28
NKPC(AR)_SP3	BVAR	1.12	0.28	0.24
NKPC(VAR)_SP3	AR(4)	0.36	0.14	0.95
NKPC(VAR)_SP3	VAR	0.02	0.45	0.27
NKPC(VAR)_SP3	BVAR	0.10	0.34	0.31
AR(4)	VAR	0.28	0.48	0.07
AR(4)	BVAR	0.11	0.36	0.63
VAR	BVAR	0.18	0.19	1.67 **

Notes: Evaluation period is 2000Q1-2006Q4. ** indicates rejection of the null of equal predictive accuracy at the 5% significance level.

B Derivation of the Model

Product demand: Assume that consumers derive their utility from a consumption bundle including domestic and foreign consumption goods:

$$C_t = \left[\chi^{\frac{1}{\eta}} \left(c_t^d \right)^{\frac{\eta-1}{\eta}} + (1-\chi)^{\frac{1}{\eta}} \left(c_t^f \right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \tag{1}$$

where $c_t^d = \left[\int_0^1 c_t^d(z)^{\frac{\varepsilon-1}{\varepsilon}} dz \right]^{\frac{\varepsilon}{\varepsilon-1}}$ and $c_t^f = \left[\int_0^1 c_t^f(z)^{\frac{\varepsilon-1}{\varepsilon}} dz \right]^{\frac{\varepsilon}{\varepsilon-1}}$ are CES indices of consumption goods produced in the home and in the foreign country, respectively. ε is the elasticity of substitution of goods within one country, η is the elasticity of substitution of consumption bundles between countries and χ is the parameter representing the home bias in consumption.

The associated consumption price index is given by

$$P_t = \left[\chi \left(p_t^d \right)^{1-\eta} + (1-\chi) \left(p_t^f \right)^{1-\eta} \right]^{\frac{1}{1-\eta}} \tag{2}$$

where $p_t^d = \left[\int_0^1 p_t^d(z)^{1-\varepsilon} dz \right]^{\frac{1}{1-\varepsilon}}$ and $p_t^f = e_t \left[\int_0^1 p_t^{*f}(z)^{1-\varepsilon} dz \right]^{\frac{1}{1-\varepsilon}}$ are the price indices associated with domestic and foreign production and e_t being the nominal exchange rate; foreign variables are denoted with an asterisk.

In addition to domestic and foreign consumers, the product of each individual firm is also demanded by domestic and foreign producers as intermediate input in their production. Accordingly, the bundles of domestically produced goods used in domestic and foreign production as intermediate inputs are defined by $m_t^d = \left[\int_0^1 m_t^d(z)^{\frac{\varepsilon-1}{\varepsilon}} dz \right]^{\frac{\varepsilon}{\varepsilon-1}}$ and $m_t^{*d} = \left[\int_0^1 m_t^{*d}(z)^{\frac{\varepsilon-1}{\varepsilon}} dz \right]^{\frac{\varepsilon}{\varepsilon-1}}$, where the degree of substitutability between intermediate goods is assumed to be the same as between consumption goods.

Given that domestic and foreign consumers as well as domestic and foreign producers demand the product of each individual firm and allocate their demands for consumption and intermediate goods across countries and products with the same pattern, the total demand for the output of firm z is given by

$$y_t^d(z) = \left(\frac{p_t^d(z)}{p_t^d} \right)^{-\varepsilon} \left(c_t^d + c_t^{*d} + m_t^d + m_t^{*d} \right) \tag{3}$$

Production technology: We assume each individual firm produces its output employing labor and domestic as well as foreign intermediate goods as variable factors of production and a fixed amount of capital $\overline{K}$:

$$y_t(z) = \left(\alpha_N N_t(z)^{\frac{\rho-1}{\rho}} + \alpha_d m_t^d(z)^{\frac{\rho-1}{\rho}} + \alpha_f m_t^f(z)^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{(\rho-1)\phi}} \overline{K}^{1-\frac{1}{\phi}} \tag{4}$$

where $N_t(z)$, $m_t^d(z)$ and $m_t^f(z)$ are domestic labor, domestically produced and imported intermediate inputs used in production by firm z and α_N, α_d and α_f are the weights of these factors in the production function. The inputs enter the production function as imperfect substitutes where ρ is the constant elasticity of substitution between them and $1-\frac{1}{\phi}$ represents the weight of fixed capital in the production function.

From this we can derive real marginal cost of firm z as

$$MC_t(z) = \phi\left[\frac{W_t N_t(z) + p_t^d m_t^d(z) + p_t^f m_t^f(z)}{P_t y_t(z)}\right]. \tag{5}$$

Price setting: Firms set their prices by maximizing real profits facing the constraints implied by Calvo contracts, i.e. firms are allowed to change their price with a fixed probability $1-\theta$ in a given period, while they keep their price constant with probability θ. The optimization problem of the firm in period t can be written as

$$\frac{\Pi_t(z)}{P_t} = E_t \sum_{s=0}^{\infty} \frac{\theta^s\left[\frac{x_t}{P_{t+s}}\left(\frac{x_t}{p_{t+s}^d}\right)^{-\varepsilon}\widetilde{y}_{t+s} - MC_t\left(\frac{x_t}{p_{t+s}^d}\right)^{-\varepsilon\phi}\widetilde{y}_{t+s}^{\phi}\right]}{\prod_{j=1}^{s} r_{t+j-1}} \tag{6}$$

where $\Pi_t(z)$ denotes the profit of the firm, x_t is the newly set optimal price, $\widetilde{y}_{t+s}$ summarizes total demand for domestic goods from the demand function (3), MC_t is the part of real marginal cost that is not firm specific and r_t is the time-varying discount rate.

In addition to pure Calvo pricing we assume that within the group of firms that is allowed to reset the price in a given period, a fraction of firms follow a simple rule of thumb. This deviation from optimality by part of the firms is common in the literature and can be rationalized by costs of price adjustment. With the fraction ω of firms who use the rule of thumb the average reset price in period t is given by

$$p_t^r = \omega p_t^b + (1-\omega)x_t \tag{7}$$

where p_t^b is the price set according to the rule of thumb which is assumed to be the average reset price of the previous period updated with last period's inflation rate

$$p_t^b = p_{t-1}^r\left(1+\pi_{t-1}^d\right). \tag{8}$$

The open economy NKPC: Maximizing the firm's real profits given in (6) with respect to x_t and applying the Calvo pricing assumptions and after log-linearizing the system around a zero-inflation steady state gives rise to an open economy hybrid New Keynesian Phillips Curve

$$\widehat{\pi}_t^d = E_t \frac{\theta\beta}{\Delta}\widehat{\pi}_{t+1}^d + \frac{\omega}{\Delta}\widehat{\pi}_{t-1}^d + \frac{(1-\theta)(1-\omega)(1-\theta\beta)}{[\varepsilon(\phi-1)+1]\Delta}\left[\widehat{MC}_t + \widehat{P}_t - \widehat{p}_t^d + (\phi-1)\widehat{\widetilde{y}}_t\right] \tag{9}$$

where $\widehat{\pi}_t^d = \widehat{p}_t^d - \widehat{p}_{t-1}^d$ and $\Delta = \theta + \omega[1-\theta(1-\beta)]$ and $\beta = \frac{1}{\overline{r}}$ is the steady-state discount rate of future profits. Hatted variables denote deviations from steady state and barred variables represent steady state values.

In order to transform the open economy NKPC in (9) into a form appropriate for estimation we first note that the marginal cost term that is not firm specific can be decomposed in terms of the prices of all factors of production (in log-linearized form):

$$\widehat{MC}_t = \frac{\frac{\overline{w}}{\overline{P}}\widehat{w}_t + \frac{\overline{p}^d}{\overline{P}}\left(\frac{\overline{w}}{\overline{p}^d}\frac{\alpha_d}{\alpha_N}\right)^{\rho}\widehat{p}_t^d + \frac{\overline{p}^f}{\overline{P}}\left(\frac{\overline{w}}{\overline{p}^f}\frac{\alpha_f}{\alpha_N}\right)^{\rho}\widehat{p}_t^f}{\frac{\overline{w}}{\overline{P}} + \frac{\overline{p}^d}{\overline{P}}\left(\frac{\overline{w}}{\overline{p}^d}\frac{\alpha_d}{\alpha_N}\right)^{\rho} + \frac{\overline{p}^f}{\overline{P}}\left(\frac{\overline{w}}{\overline{p}^f}\frac{\alpha_f}{\alpha_N}\right)^{\rho}} - \widehat{P}_t \tag{10}$$

Plugging this expression into (9) and after some further substitutions, the term in square brackets in equation (9) can be expressed in terms of the relative prices of the factors of production and the labor share

$$\begin{aligned}[....] = \; & \widehat{s}_{nt} - (\phi-1)\frac{\overline{s}_{md}+\overline{s}_{mf}}{1+(1-\phi)\left(\overline{s}_{md}+\overline{s}_{mf}\right)}\widehat{y}_t + \frac{\overline{s}_{mf}}{1+(1-\phi)\left(\overline{s}_{md}+\overline{s}_{mf}\right)}\left(\widehat{p}_t^d - \widehat{p}_t^f\right) - \\ & \left[(1-\rho)\frac{\overline{s}_{md}}{\overline{s}_n+\overline{s}_{md}+\overline{s}_{mf}} + \rho\frac{\overline{s}_{md}}{1+(1-\phi)\left(\overline{s}_{md}+\overline{s}_{mf}\right)}\frac{\overline{s}_n}{\overline{s}_n+\overline{s}_{md}+\overline{s}_{mf}}\right]\left(\widehat{w}_t - \widehat{p}_t^d\right) - \\ & \left[(1-\rho)\frac{\overline{s}_{mf}}{\overline{s}_n+\overline{s}_{md}+\overline{s}_{mf}} + \rho\frac{\overline{s}_{mf}}{1+(1-\phi)\left(\overline{s}_{md}+\overline{s}_{mf}\right)}\frac{\overline{s}_n}{\overline{s}_n+\overline{s}_{md}+\overline{s}_{mf}}\right]\left(\widehat{w}_t - \widehat{p}_t^f\right)\end{aligned} \tag{11}$$

Equation (9) combined with (11) corresponds to equations (1) and (2) in the main text.

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