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Forecast robustness in macroeconometric models*

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Abstract

The paper investigates explanations for forecasting invariance to structural breaks. After highlighting the role of policy, we isolate possible structural invariance in a simplified dynamic macro model that nevertheless has features in common with the standard model of aggregate demand and aggregate supply. We find, as expected, that structural breaks in growth rates and in the means of cointegrating relationships will always damage some of the variables. But we also find examples of "insulation" from shocks. The results about partial robustness is a property of the economy itself (here represented by the DGP) and not of the forecasts.

"A trend is a trend, is a trend, but the question is, will it bend? Will it alter its course, through some unforeseen force and come to a premature end?"

Sir Alec Cairncross

1 Introduction

The motivation for this paper is best conveyed by Figure 1. It shows real-time forecasts from March 2007 for some key macroeconomic variables in an econometric model documented in Bårdsen and Nymoen (2009a). The forecasts are compared with outcomes until the end of 2011[1]. Some forecasts fail after the outbreak of the financial crisis, but most variables are well forecasted after the initial shocks at the end of 2008 and in 2009. The most interesting information is in the behaviour of the actual data series. While the interest rate drops dramatically (lower middle panel), corresponding to a post-forecast structural break, the outcomes for inflation and the unemployment rate (upper left and right panel, respectively) are mostly unaffected, while wage inflation, GDP-growth, the real exchange rate, depreciation, and real credit growth all converge back toward their pre-break predicted paths. Variables in this set of forecasts seem to be more immune to post-forecast breaks than what is taken to be typical, see e.g. Clements and Hendry (2008). There are, of course, many possible explanations for such seemingly partial robustness to breaks.

For example, macroeconomic relationships in the Norwegian economy could be different from what standard macroeconomic theories prescribe, that the nominal and real interest rates are primary drivers of inflation and unemployment. In the standard case one would expect an interest rate forecast failure to go together with large forecast errors for unemployment for example, but this is not confirmed by the graph. The lack of response

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[1]The model used is NAM. See http://www.svt.ntnu.no/iso/gunnar.bardsen/nam/evaluation/index.html for a full evaluation of all forecasts made from 2006-2011.

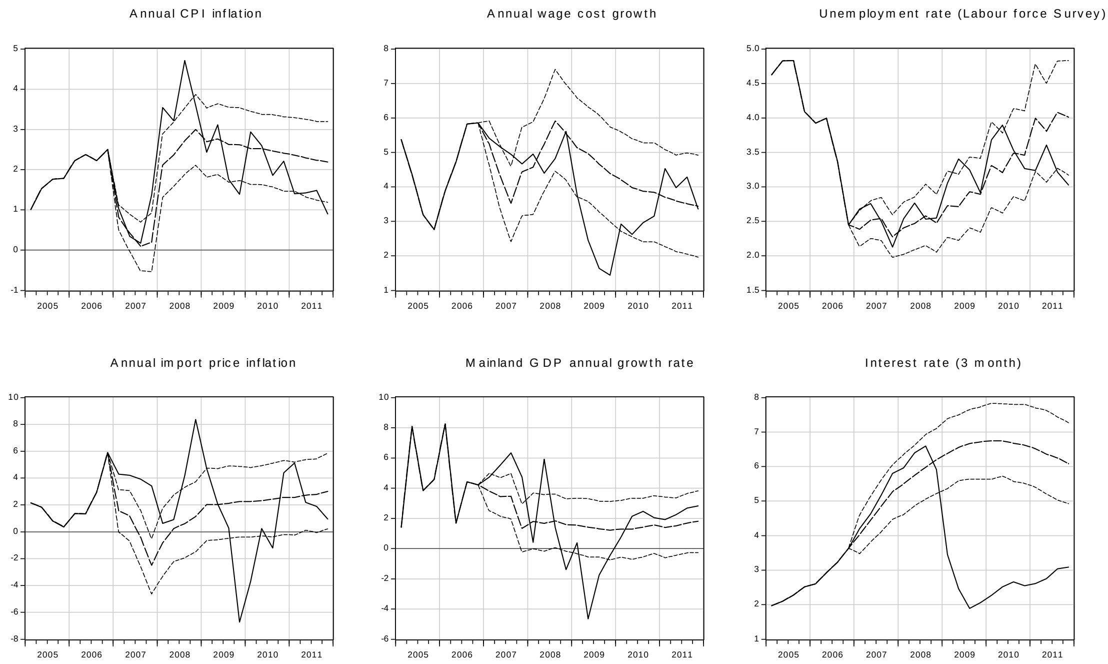

Figure 1: Forecasts, with 70% confidence bands, from March 2007 and actual values of some key macroeconomic variables of the Norwegian economy.

of certain variables of the Norwegian economy to the financial crisis could be due to structural features: the size of public and private wealth compared to most other countries, the size of the public sector, and the country's role as oil exporter being amongst the obvious candidates.

However, it is tempting to contemplate whether such seemingly partial robustness to breaks could be a more general phenomenon. And if so, whether it is possible to exploit such invariance properties of economies in modelling and forecasting more generally? The question can be framed more specifically: can we explain and replicate the phenomena in Figure 1 in smaller and more tractable models?

2 A general result using a simple example

A simple, stripped-down, model that can replicate the observed forecasts consists of inflation $\Delta p_t \equiv p_t - p_{t-1}$, output gap y_t, and the interest rate R_t:

$$\begin{aligned} \Delta p_t &= \Delta p^* + \gamma\, y_t + \varepsilon_{p,t}, \\ y_t &= -\alpha\,(R_t - \Delta p_t - \theta) + \varepsilon_{y,t}, \\ R_t &= \theta + \Delta p^* + \mu\,(\Delta p_t - \Delta p^*) + \nu\, y_t + \varepsilon_{R,t}. \end{aligned}$$

where the εs are zero mean innovations with a constant covariance matrix. The solutions for inflation and the output gap are

$$\begin{aligned} \Delta p_t &= \Delta p^* + \frac{(1+\alpha\,\nu)\,\varepsilon_{p,t} + \gamma\,(\varepsilon_{y,t} - \alpha\,\varepsilon_{R,t})}{1+\alpha\,(\nu+\gamma\,\mu) - \alpha\,\gamma}, \\ y_t &= \frac{\alpha\,(1-\mu)\,\varepsilon_{p,t} + (\varepsilon_{y,t} - \alpha\,\varepsilon_{R,t})}{1+\alpha\,(\nu+\gamma\,\mu) - \alpha\,\gamma}. \end{aligned}$$

On average, inflation Δp is equal to the target Δp^* and the output gap y is zero. Now, consider forecasting with this model when the model suffers permanent structural breaks in forecasting period $T+1$, for example because of the omission of credit variables. Accordingly, the εs contain mean shifts in the forecasting period. However, if there is no break in the structural equation for inflation, so that $E_T(\varepsilon_{p,T+1})=0$, there are no forecast biases in inflation and the output gap *if* the mean shifts in the remaining model are proportional:

$$\varepsilon_{y,T+1} = \alpha\,\varepsilon_{R,T+1}.$$

One interpretation of $\varepsilon_{R,T+1}$ is therefore as the discretionary part of monetary policy.

More formally, the *1-step ahead* forecast errors are

$$\begin{aligned}
\widehat{\Delta p}_{T+1|T} - \Delta p_{T+1} &= -\left\{(1+\alpha\,\nu)\varepsilon_{p,T+1} + \gamma(\varepsilon_{y,T+1} - \alpha\,\varepsilon_{R,T+1})\right\}/\Theta, \\
\widehat{y}_{T+1|T} - y_{T+1} &= -\left\{\alpha\,(1-\mu)\,\varepsilon_{p,T+1} + (\varepsilon_{y,T+1} - \alpha\,\varepsilon_{R,T+1})\right\}/\Theta,
\end{aligned}$$

where the constant $\Theta = 1+\alpha[\nu-\gamma\,(1-\mu)]$.

Now, consider a post-forecast structural break in $\varepsilon_{y,t}$ that changes the expectation $E\varepsilon_{y,t}$ from 0 to $m_y \neq 0$ in period $T+1$. What are the consequences for the forecasts that are produced in period T? If the discretionary policy is set as

$$\varepsilon_{R,T+1} = m_y/\alpha,$$

the inflation and GDP forecasts are unbiased:

$$E\left(\widehat{\Delta p}_{T+1|T} - \Delta p_{T+1}\right) = E\left(\widehat{y}_{T+1|T} - y_{T+1}\right) = 0. \tag{1}$$

The structural break ("a flock of black swans") does not lead to a forecast failure for inflation and GDP, only for the interest rate.

This is a very intuitive result and explains the role of policy in forecasting: to correctly forecast targets, wrong forecasts of instruments might be necessary. The result is of course quite general, but for the sake of illustration let us also consider a more dynamically sophisticated version of the model. Consider, for example, the same model with forward-looking expectations, usually labelled the New Keynesian Canonical model:

$$\begin{aligned}
\Delta p_t &= (1-\beta)\,\Delta p^* + \beta\,E_t\Delta p_{t+1} + \gamma\,y_t + \varepsilon_{p,t}, \\
y_t &= E_t y_{t+1} - \alpha\,(R_t - E_t\Delta p_{t+1} - \theta) + \varepsilon_{y,t}, \\
R_t &= \theta + \Delta p^* + \mu\,(\Delta p_t - \Delta p^*) + \nu\,y_t + \varepsilon_{R,t}.
\end{aligned}$$

If $0<\beta/\Psi<1$, where $\Psi = 1+\alpha\,(\nu+\mu\gamma)$, the solutions for inflation and output gap are

$$\begin{aligned}
\Delta p_t &= \Delta p^* + \left[(1+\alpha\,\nu)\,\varepsilon_{p,t} + \gamma\,(\varepsilon_{y,t} - \alpha\,\varepsilon_{R,t})\right]/\Psi, \\
y_t &= -\left[\alpha\,\mu\,\varepsilon_{p,t} + (\varepsilon_{y,t} - \alpha\,\varepsilon_{R,t})\right]/\Psi.
\end{aligned}$$

Provided $E_T(\varepsilon_{\Delta p,T+1}) = 0$ and $\varepsilon_{y,T+1} = \alpha\,\varepsilon_{R,T+1}$, as before, the same invariance result holds.

In terms of forecast evaluations, the 1-step forecast errors are

$$\begin{aligned}
\widehat{\Delta p}_{T+1|T} - \Delta p_{T+1} &= -\left\{(1+\alpha\,v)\varepsilon_{p,T+1} + \gamma(\varepsilon_{y,T+1} - \alpha\,\varepsilon_{R,T+1})\right\}/\Psi, \\
\widehat{y}_{T+1|T} - y_{T+1} &= \left\{\alpha\,\mu\,\varepsilon_{p,T+1} + (\varepsilon_{y,T+1} - \alpha\,\varepsilon_{R,T+1})\right\}/\Psi.
\end{aligned}$$

So for this model, (1) holds if the monetary policy shock is $\varepsilon_{R,T+1} = m_y/\alpha$, as before.

To reiterate: these results simply state that a demand shock might be mitigated by a shock to monetary policy. However, in a forecasting setting, the examples are more interesting. Forecasts are, in general, made under the assumption of no large shocks or breaks — no policy change. So in case there is a shock to target variables, the policy response must try to nullify the shocks in order for forecasts of target variables to be correct. This entails that there will be breaks in the policy rules that are used to stabilize the economy in times of no large shocks, for example in a Taylor rule for interest rate setting. The examples illustrate therefore the complication of forecasting a full system in the social sciences in general and in economics in particular. Since policy variables affect target variables, in the case of shocks policy forecasts must miss for target forecasts to hit. As an aside, this also adds to the list of reasons why policy variables like interest rates and exchange rates are so hard to forecast[2].

These overly simple models replicate qualitatively the results shown in Figure 1. In the underlying structural model equations there are no breaks in inflation, but clear breaks in the interest rate setting and quite possibly in the aggregate demand equation. Nevertheless there is no forecast failure in inflation and only a temporary forecast failure for output. It therefore seems to be possible for mean breaks to have limited effects on forecasts in some instances.

However, the models considered so far are way too simplistic to be relevant for serious forecasting. We therefore need to consider more realistic structures, while still keeping the overall model small to keep the results tractable. In the following we try to investigate more thoroughly the possible explanations for the invariance of inflation and GDP growth to structural breaks.

3 Partial invariance to structural breaks

The idea of breaks cancelling is probably best captured by the theory of co-breaking, see Clements and Hendry (1999, Ch 9). However, in this paper we demonstrate another and dynamic mechanism than can neutralize effects of breaks on data and thus on forecasts. In the following we show, with the aid of a tractable macro model, that partial robustness to post-forecast breaks can occur in forecasting models that are built on sound and empirically non-rejected economic theory. First, there is a tendency that a lack of short-term, or dynamic, price homogeneity matters. Below, we show that dynamic homogeneity can mitigate completely the effects of breaks in exogenous nominal growth rates (like in a foreign price index) on the forecasts for real variables (for example the real exchange rate).[3]

Second, for some variables, robustness can be a result of general equilibrium. The best example below is probably the case of a structural break in the mean of the long-run wage equation. In a partial analysis, a post-forecast break of his type will damage wage forecasts. Nevertheless, the solution of the model has the property that the forecast bias for the wage-share is diminishing in the length of the forecast horizon, and the long-term forecasts are unaffected by the break (there is no co-breaking involved here). Another way to look at this property is that forecasts from an equilibrium-correction model can sometimes error-correct to the correct post-break mean (although in most cases this is not the case). The interpretation is not that the economic decisions makers in the model (or the forecaster that uses the model) "see the break coming" in period $T + h$, despite the fact that the forecasts/expectations are conditional on the period T dated information that is summarized by the model's equations. This would imply a different (and stronger) type of rationality than conventional rational expectations, or that the information set is regarded as "temporarily increased". Instead, we will consider cases where the partial

[2] An alternative explanation would be the Lucas critique, in which case target forecasts could be correct because anticipated policy changes induce parameter change.

[3] This does not imply that a model with (full) dynamic price homogenity is "better", or "more structural", than a model where there are departures from homogeneity. These questions must be answered by theoretical arguments and by econometric analysis. The point is only that if a (structural) macro model departs from dynamic homogeneity, its forecasts are more damaged by structural breaks than the forecasts of a model with homogenity.

invariance is due to the economy not changing to a new long-run mean, despite the change in one of the structural cointegrating equations.

In this paper, we maintain the assumption that the model corresponds to the data generating process (DGP) within sample[4]. Model assessment and validation are very important. If the model implies that the (general) equilibrium solution is invariant to a break, but this turns out to be false, then forecasts are wrong because the model is wrong. Forecast assessments should be more important when evaluating models, also for the evaluation of policy models. Good models need not avoid forecast failure, but reasonably good forecasts are an important indicator of the overall quality of a macro model.

Below we restrict the attention to post-forecast breaks, but in the conclusion we incorporate some remarks about the possible benefits of using a model to interpret breaks and to aid the adaptation of macroeconomic forecasts to pre-forecast breaks.

4 The model

The model we use is an adaptation and simplification of the econometric models developed for Norway, USA and Sweden (Bårdsen et al., 2005; Bårdsen and Nymoen, 2009a; Akram and Nymoen, 2009; Bårdsen and Nymoen, 2009b; Bårdsen et al., 2012). In brief, the theory of wage and price setting defines the implicit aggregate supply function, while the modelling of aggregate demand is a semi-reduced form relationship.[5] Both relationships are conditioned by the degree of openness in the economy, as well as by how fiscal and monetary policy are operated. In the simplified model we analyze here, we cut the amount of (often relevant) modelling details to a minimum, while retaining enough to make the solution representative of macroeconometric models that can have practical interest.

We want to forecast with a model for the open economy where p_t is the (log of the) price level of domestic products and w_t is wage compensation per hour.[6] Both variables are assumed to be integrated of order one, denoted as $I(1)$. The equations for p_t and w_t define the supply side of this medium term macro-model. Since p_t and w_t are $I(1)$ by assumption, domestic inflation Δp_t and wage growth Δw_t can be modelled (without loss of generality) as equilibrium-correction equations, for example:

$$\Delta p_t = c_p + \psi_{pw}\Delta w_t + \psi_{ppm}\Delta pm_t - \theta_p ecm_{p,t-1} + \varepsilon_{p,t}, \tag{2}$$
$$\Delta w_t = c_w + \psi_{wp}\Delta p_t + \psi_{wpc}\Delta pc_t - \theta_w ecm_{w,t-1} + \varepsilon_{w,t}, \tag{3}$$

with ψ_{pw}, ψ_{ppm}, θ_p, ψ_{wp}, ψ_{wpc}, $\theta_w > 0$, $\varepsilon_{p,t} \sim IID(0, \sigma_p^2)$, and $\varepsilon_{w,t} \sim IID(0, \sigma_w^2)$. The import price index pm_t and the consumer price index pc_t will be explained below. The steady-state $I(0)$ relationships we make use of here are consistent the idea that collective bargaining plays a central role in nominal wage formation and that firms set nominal prices:

$$ecm_{p,t} = -m_p + p_t - w_t + z_t - \vartheta\, y_t, \tag{4}$$
$$ecm_{w,t} = -m_w + w_t - p_t - z_t - \omega(pc - p)_t, \tag{5}$$

with ϑ, $\omega > 0$, see Bårdsen et al. (2005) and Bårdsen and Nymoen (2009a). A mark-up coefficient is denoted by $m_p > 0$ for firms and m_w for wage setting. Demand y_t and productivity z_t will be explained below. It is the relationships (4) and (5) that define the equilibrium-correction dynamics toward a well-defined steady state.

[4]The consequences of misspecification are non-trivial also in this context, and we plan to cover that aspect in future work.

[5]This is similar to the short-term macro model set out in many modern text-books, see e.g. Sørensen and Whitta-Jacobsen (2010)

[6]Logs of variables are denoted by lower-case letters.

The demand side usually consists of real GDP, transformed to an $I(0)$ variable, and the rate of unemployment, which may be non-stationary due to regime shifts, but $I(0)$ within regimes. In the short run, employment and $I(0)$-transformed GDP are highly correlated, as captured by 'Okun's law'. For simplicity, we therefore use a single aggregate-demand variable which we dub y_t. It is assumed to be $I(0)$ after transformation from $I(1)$, for example in the form of an output gap (with frictions) or excess demand, that is relative to capacity. We specify the 'demand' y_t to depend upon the real exchange rate $x_t \equiv pm_t - p_t$:

$$\Delta y_t = c_y - \theta_y \left(y - \varpi\, x\right)_{t-1} + \varepsilon_{y,t}. \tag{6}$$

with $\varepsilon_{p,t} \sim IID(0, \sigma_y^2)$. The model also contains exogenous variables that need to be forecasted. Typically, both nominal and real trend variables belong to this category. In the illustrative model we will use the import price index pm_t as the nominal exogenous variable and productivity z_t as the real exogenous variable. The equations for these two variables are assumed to be random walks with a positive drift:

$$\Delta pm_t = g_{pm} + \varepsilon_{pm,t} \quad \text{and} \quad \Delta z_t = g_z + \varepsilon_{z,t}, \tag{7}$$

with g_{pm}, $g_z > 0$ and $\varepsilon_{pm,t} \sim IID(0, \sigma_{pm}^2)$ and $\varepsilon_{z,t} \sim IID(0, \sigma_z^2)$. We define the consumer price index pc_t as a weighted sum of domestic prices and import prices:

$$pc_t = \phi\, p_t + (1-\phi) pm_t, \tag{8}$$

where $0 < \phi < 1$ reflects how closed the economy is. Since $p_t = pm_t - x_t$ we have the consumer rate of inflation $\Delta pc_t = \Delta pm_t - \phi \Delta x_t$. Using (8), the equilibrium-correction terms (4) and (5) can be written in terms of the wage share $ws_t \equiv w_t - p_t - z_t$ and the real exchange rate x_t as $ecm_{p,t} = -m_p - ws_t - \vartheta\, y_t$ and $ecm_{w,t} = -m_w + ws_t - \omega(1-\phi)x_t$.

Since pm and z are strongly exogenous variables, we investigate the system conditional on these two variables. The structural specifications of the model (2)-(6) can be written in explicit matrix form as

$$\underbrace{\begin{pmatrix} 0 & -\psi_{pw} & 0 \\ -\psi_{wp} - \psi_{wpc}\phi & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathbf{A}} \underbrace{\begin{pmatrix} \Delta p_t \\ \Delta w_t \\ \Delta y_t \end{pmatrix}}_{\Delta \mathbf{y}_t} = \underbrace{\begin{pmatrix} -\theta_p & \theta_p - \psi_{pw} & \theta_p \vartheta \\ \theta_w \left(1 - \omega(1-\phi)\right) & -\theta_w & 0 \\ -\theta_y \varpi & 0 & -\theta_y \end{pmatrix}}_{\mathbf{B}} \underbrace{\begin{pmatrix} p_{t-1} \\ w_{t-1} \\ y_{t-1} \end{pmatrix}}_{\mathbf{y}_{t-1}}$$

$$+ \underbrace{\begin{pmatrix} \psi_{ppm} & 0 & -\theta_p & c_p + \theta_p m_{p,t-1} \\ \psi_{wpc}(1-\phi) & \theta_w \omega (1-\phi) & \theta_w & c_w + \theta_w m_{w,t-1} \\ 0 & \theta_y \varpi & 0 & c_{y,t} \end{pmatrix}}_{\mathbf{C}} \underbrace{\begin{pmatrix} \Delta pm_t \\ pm_{t-1} \\ z_{t-1} \\ 1 \end{pmatrix}}_{\mathbf{x}_t} + \underbrace{\begin{pmatrix} \varepsilon_{p,t} \\ \varepsilon_{w,t} \\ \varepsilon_{y,t} \end{pmatrix}}_{\varepsilon_t}, \tag{9}$$

where we have substituted (8) for pc_t. We have dated the break-constants in the last column of $\mathbf{C}$ to make it explicit that a change in mark-ups m_p,and m_w first affects Δp and Δw with a lag. That is because the changes to the mark-ups affect the wage and price growth through the lagged equilibrium-correction terms (4) and (5) in (2)-(3). The effects of these breaks are analysed in section 5-7. In order to prepare the ground for that analysis we need to solve the model for the constant-parameter case.

4.1 The system

In compact notation the model (9) is $\mathbf{A}\, \Delta\mathbf{y}_t = \mathbf{B}\, \mathbf{y}_{t-1} + \mathbf{C}\, \mathbf{x}_t + \varepsilon_t$, while the solved out system—the so-called reduced form—is a partial vector autoregression (VAR), $\Delta\mathbf{y}_t =$

$\mathbf{A^{-1}\,B'}\mathbf{y}_{t-1} + \mathbf{A^{-1}\,C\,x}_t + \mathbf{A^{-1}}\,\varepsilon_t$, or written out:

$$\underset{\Delta\mathbf{y}_t}{\begin{pmatrix}\Delta p_t\\ \Delta w_t\\ \Delta y_t\end{pmatrix}} = \underset{\mathbf{A}^{-1}\mathbf{B}}{\begin{pmatrix} a_{pp} & a_{pw} & n\\ a_{wp} & a_{ww} & \alpha\\ -\theta_y\,\varpi & 0 & -\theta_y\end{pmatrix}} \underset{\mathbf{y}_{t-1}}{\begin{pmatrix}p_{t-1}\\ w_{t-1}\\ y_{t-1}\end{pmatrix}}$$

$$+ \underset{\mathbf{A}^{-1}\mathbf{C}}{\begin{pmatrix} 1-e & s_{ppm} & -k & d\\ 1-e+\xi & s_{wpm} & s & b\\ 0 & \theta_y\varpi & 0 & c_y\end{pmatrix}} \underset{\mathbf{x}_t}{\begin{pmatrix}\Delta pm_t\\ pm_{t-1}\\ z_{t-1}\\ 1\end{pmatrix}} + \underset{\mathbf{A}^{-1}\varepsilon_t}{\begin{pmatrix}\varepsilon'_{p,t}\\ \varepsilon'_{w,t}\\ \varepsilon'_{y,t}\end{pmatrix}}. \tag{10}$$

In the analyses of breaks below, we shall need explicit expressions for two coefficients in the matrix $\mathbf{A}^{-1}\mathbf{B}$:

$$n = \theta_p\vartheta/\chi \quad \text{and} \quad \alpha = \theta_p\vartheta\left(\phi\psi_{wpc}+\psi_{wp}\right)/\chi, \tag{11}$$

where the denominator is $\chi = 1 - \psi_{pw}(\phi\psi_{wpc} + \psi_{wp}) > 0$. We shall also need explicit expressions for the following coefficients in the matrix $\mathbf{A}^{-1}\mathbf{C}$:

$$1-e = \left[\psi_{ppm} + \psi_{pw}\psi_{wpc}\left(1-\phi\right)\right]/\chi, \tag{12}$$
$$1-e+\xi = \left[\psi_{ppm}\left(\phi\psi_{wpc}+\psi_{wp}\right) + \left(1-\phi\right)\psi_{wpc}\right]/\chi, \tag{13}$$
$$-k = \left(\theta_w\psi_{pw} - \theta_p\right)/\chi \tag{14}$$
$$s = \left[\theta_w - \theta_p\left(\phi\psi_{wpc}+\psi_{wp}\right)\right]/\chi \tag{15}$$
$$d = \left[c_p + \theta_p m_{p,t-1} + \psi_{pw}\left(c_w + \theta_w m_{w,t-1}\right)\right]/\chi, \tag{16}$$
$$b = \left[\left(\phi\psi_{wpc}+\psi_{wp}\right)c_p + c_w + \theta_p\left(\phi\psi_{wpc}+\psi_{wp}\right)m_{p,t-1} + \theta_w m_{w,t-1}\right]/\chi. \tag{17}$$

We transform prices p and wages w, which are trending, to the real exchange rate $x_t \equiv (pm-p)_t$ and the wage share $ws_t \equiv (w-p-z)_t$, which are stationary in the stable case that we are interested in. The conditional system can then be written as the first order system

$$\begin{pmatrix}x_t\\ ws_t\\ y_t\end{pmatrix} = \begin{pmatrix} l & -k & -n\\ \lambda & \kappa & -\eta\\ \theta_y\varpi & 0 & 1-\theta_y\end{pmatrix}\begin{pmatrix}x_{t-1}\\ ws_{t-1}\\ y_{t-1}\end{pmatrix} + \begin{pmatrix} e & 0 & -d\\ \xi & -1 & \delta\\ 0 & 0 & c_y\end{pmatrix}\begin{pmatrix}\Delta pm_t\\ \Delta z_t\\ 1\end{pmatrix} + \begin{pmatrix}\epsilon_{x,t}\\ \epsilon_{ws,t}\\ \varepsilon_{y,t}\end{pmatrix}, \tag{18}$$

where the system innovations $\epsilon_{x,t}$ and $\epsilon_{ws,t}$ are linear combinations of the structural model disturbances. The conditional representation (18) is in terms of real variables, even though the underlying model is a combination of real and nominal variables. This is an implication of the long-run (or static) nominal homogeneity of degree 1 property of the model.[7] Moreover, there is no loss of usefulness in terms of forecasting nominal variables since $p_t = pm_t - x_t$, $w_t = ws_t + p_t + z_t$, and pc_t is given by (8).

Because of the block recursiveness of the model, the coefficients in the third row of (18) are the same as in the structural model, while the other system coefficients in (18) are functions of the parameters of the structural model. We are interested in the stable solutions within a constant parameterization ('regime'), see Sydsæter et al. (2008, p 417). These conditions are given in detail by Kolsrud and Nymoen (2010) for this model. In the analyses of breaks, we shall need explicit expressions for three coefficients in the first matrix in (18):

$$\eta = \theta_p\vartheta(1-\psi_{wp}-\phi\,\psi_{wpc})/\chi,$$

[7] This is seen from (4), (5), (6) and (8).

while n and k is given by (11) and (14), and four coefficients in the second matrix in (18):

$$e = 1 - [\psi_{ppm} + \psi_{pw}\,\psi_{wpc}\,(1-\phi)]\,/\chi, \tag{19}$$

$$\xi = [\psi_{wpc}\,(1-\psi_{pw})(1-\phi) - \psi_{ppm}\,(1-\psi_{wp}-\phi\,\psi_{wpc})]\,/\chi, \tag{20}$$

$$\delta = [(m_w\,\theta_w+c_w)(1-\psi_{pw}) - (m_p\,\theta_p+c_p)(1-\psi_{wp}-\phi\,\psi_{wpc})]\,/\chi, \tag{21}$$

and d is given by (16). Note that e, ξ, d, k and n are the same coefficients in the model (10) and in the system (18).

Relevant economic theory often suggests restrictions on the parameters that will affect the solution, and simplify these expressions. One example of this is *dynamic price and wage homogeneity,* which apply to the equations for Δp_t and Δw_t. The restrictions are

$$\psi_{pw} + \psi_{ppm} = \psi_{wp} + \psi_{wpc} = 1. \tag{22}$$

The dynamic consequence of the restrictions is that an exogenous change in Δpm_t is transferred in its entirety to *both* Δw_t and Δp_t in the same period due to simultaneity in (2) and (3). Then, per definition, x_t and ws_t are both unaffected by foreign inflation pm_t. It follows from (22), (19) and (20) that in the case of dynamic homogeneity $e = \xi = 0$.

4.2 Steady state

Forecasts for the long run are the steady-state solutions of (18):

$$x_{ss} = e_{ss}\,g_{pm} + b_{ss}\,g_z - d_{ss}, \tag{23}$$

$$ws_{ss} = \xi_{ss}\,g_{pm} - \beta_{ss}\,g_z - \delta_{ss}, \tag{24}$$

$$y_{ss} = \mathfrak{e}_{ss}\,g_{pm} + \mathfrak{b}_{ss}\,g_z\; + \mathfrak{d}_{ss}. \tag{25}$$

The coefficients for the steady-state real exchange rate x_{ss} are

$$\begin{aligned} e_{ss} &= \theta_y[\theta_p(1-\psi_{wp}-\psi_{wpc}) + \theta_w(1-\psi_{pw}-\psi_{ppm})]/(\theta_p\,\theta_w\,\Omega),\\ b_{ss} &= \theta_y(\theta_p - \theta_w\,\psi_{pw})/(\theta_p\,\theta_w\,\Omega),\\ d_{ss} &= [c_y\,\vartheta + \theta_y\,(m_w + m_p + c_w/\theta_w + c_p/\theta_p)]\,/\Omega, \end{aligned} \tag{26}$$

with $\Omega = \theta_y\,[\omega(1-\phi)+\varpi\vartheta]$. A higher mark-up or higher excess demand implies higher wage and price growth (2)-(5), which — as seen from (23) and (26) — cause a real depreciation.

The coefficients for the steady-state wage-share ws_{ss} are

$$\begin{aligned} \xi_{ss} &= \theta_y[\theta_w(1-\psi_{pw}-\psi_{ppm})\omega\,(1-\phi) + \varpi\,\vartheta\,\theta_p(1-\psi_{wp}-\psi_{wpc})]/(\theta_p\,\theta_w\,\Omega),\\ \beta_{ss} &= \theta_y[\theta_w\,\psi_{pw}\,\omega\,(1-\phi) + \varpi\,\vartheta\,\theta_p]/(\theta_p\,\theta_w\,\Omega),\\ \delta_{ss} &= [\theta_y\omega\,(1-\phi)(m_p+c_p/\theta_p) + c_y\vartheta\,\omega(1-\phi) - \vartheta\,\theta_y\varpi(m_w+c_w/\theta_w)]/\Omega. \end{aligned} \tag{27}$$

A higher price mark-up implies higher inflation and a smaller wage share, as (24) and (27) show. A higher wage mark-up implies higher wage growth, and thus a larger wage share. Higher excess demand (higher activity level and lower unemployment) stimulates price growth more than wage growth, which implies a smaller wage share in the long run.

Finally, the coefficients for the steady-state demand y_{ss} are

$$\begin{aligned} \mathfrak{e}_{ss} &= \theta_y\,\varpi\;[\theta_p(1-\psi_{wp}-\psi_{wpc}) + \theta_w(1-\psi_{pw}-\psi_{ppm})]\,/(\theta_p\,\theta_w\,\Omega),\\ \mathfrak{b}_{ss} &= \theta_y\,\varpi(\theta_p - \theta_w\,\psi_{pw})/(\theta_p\,\theta_w\,\Omega),\\ \mathfrak{d}_{ss} &= [c_y\,\omega\,(1-\phi) - \theta_y\,\varpi\,(m_w + m_p + c_w/\theta_w + c_p/\theta_p)]/\Omega. \end{aligned} \tag{28}$$

Higher mark-ups imply higher wage and price growth, higher costs, reduced activity, increased unemployment and consequently, as (25) and (28) show, lower excess demand.

Generally, the steady-state "variables" x_{ss}, ws_{ss} and y_{ss} in (23)-(25) all depend upon the exogenous growth rates of import prices (g_{pm}) and productivity (g_z). As mentioned above, dynamic price and wage homogeneity insulate all three variables from import price inflation, both in the short and long run since (22) implies that also $e_{ss} = \xi_{ss} = \mathfrak{e}_{ss} = 0$. Similarly, if $\theta_p = \theta_w \psi_{pw}$ (numerically) then productivity growth does not matter to the real exchange rate and the demand, since then $b_{ss} = \mathfrak{b}_{ss} = 0$.

From the definitions of the real exchange rate x and the wage share ws, it follows that the steady-state nominal growth rates are $E\Delta p = E\Delta pc = g_{pm}$ and $E\Delta w = g_{pm} + g_z$.

4.3 Structural breaks

In order to discuss forecast properties theoretically, we need to assume something about the relationship between the model and the data generating process (DGP). In the following, we assume that the model is correctly specified up to a set of structural breaks. This means that the DGP has the same equations as the model. We consider the effects of several single unknown structural breaks that occur in the forecast period $T+1$, after the forecasts have been made. Hence, each single break — one at a time — occurs post forecasts, while all forecasts are made before the break happens.

Specifically, in the DGP, we replace (7) by

$$\Delta pm_t = g_{pm} + D_{pm,t>T}\, dpm + \varepsilon_{pm,t} \quad \text{and} \quad \Delta z_t = g_z + D_{z,t>T}\, dz + \varepsilon_{z,t},$$

where $D_{False} = 0$ and $D_{True} = 1$ are step-dummy variables that time the breaks of size dpm and dz in the growth rates of the nominal and the real trend. We also consider the consequences of structural breaks in the other equations. For aggregate demand a break changes the level:

$$\Delta y_t = c_y + D_{y,t>T}\, dy - \theta_y\,(y - \varpi\, x)_{t-1} + \varepsilon_{y,t}.$$

Finally, we also consider breaks in the mark-up of price and wage:

$$p_t = w_t - z + \vartheta\, y_t - (m_p + D_{p,t>T}\, dp) \quad \text{and} \quad w_t = p_t + z_t + \omega(pc_t - p_t) - (m_w + D_{w,t>T}\, dw).$$

Note that since a change in a mark-up affects the price growth (2) and the wage growth (3) with a lag (through the lagged equilibrium-correction term), it will affect all variables in the model but one (y) with a lag, and y with two periods delay (through the lagged exchange rate). Likewise, an exogenous shift in demand y affects the price growth and the wage growth with a lag (through the lagged equilibrium-correction term ecm_w).

We are going to assume that at most one structural break is active at a time, so that when one of the $D_{k,t>T}$ dummies are 1, the others are zero. In order to simplify the notation, and because it is not likely to cause misunderstandings, we omit the $D_{k,t>T}$ dummies from the expressions below.

The nature of a structural change is important to diagnose once it has become a part of the information set. Then the model can be correctly adapted to the new structure and bias in the *after-break forecasts* be avoided, see Pesaran et al. (2011), Nymoen (2002) and Falch and Nymoen (2011) among others. In this paper the focus is however on the *pre-break forecasts*, and for that purpose it is relevant and simple to assume that a structural break for a given parameter happens only once in the forecast period, and that the change is permanent (a single step).

5 Biases in short-term and long-term forecasts

As just noted, we assume that the model corresponds to the real-world data generating process, DGP. With no break occurring in the forecast period, the forecasts errors of the model will be (feasible) minimum mean squared forecast errors (MMSFEs). However, in the event of after-forecast structural breaks there will in general be non-zero expectations in the errors of the model based forecasts.

Assume that in period $T+1$ a post-forecast structural break occurs in the data generating process, after the pre-break forecasts were made at the end of period T. The break is permanent, and we are interested in the forecast errors the first period(s) after the break and in the long run or steady state (after the break). We denote the 1-step ahead forecast of any variable v made at period T by $\hat{v}_{T+1|T}$. In the cases where the break affects the other variables with a lag, we have to look at the 2-steps ahead forecast $\hat{v}_{T+2|T}$ for the first possible effects. All forecasts assume zero values for all future shocks/innovations. The h-step forecast error ($h = 1, 2$ or ∞) is the difference between the forecast and the realization/observation: $e(\hat{v}) = \hat{v}_{T+h|T} - v_{T+h}$. The bias in the forecast is the expected forecast error, that is the difference between the mean forecast and the expected realization/observation:

$$bias(\hat{v}_{T+h|T}) \equiv E[e(\hat{v}_{T+h|T})] = E(\hat{v}_{T+h|T} - v_{T+h}) = E\hat{v}_{T+h|T} - Ev_{T+h}.$$

We denote the long-term forecast $E\hat{v}_{T+\infty|T}$ by $\hat{v}_{ss}$, since the infinite horizon point forecast for an endogenous variable is the the deterministic steady-state solution for the corresponding variable given in section 4.2. In steady state, the bias is the expected forecast error $bias(\hat{v}_{ss}) \equiv \hat{v}_{ss} - v_{ss}$, where $v_{ss} = Ev_{T+\infty}$. Since the model coincides with the DGP, the parameters are known, and the shocks are independent and zero-mean, the biases measure the pure effects of the breaks.[8]

We next give the algebraic results for the short-term biases, for one and two periods ahead, i.e., $bias(\hat{v}_{T+1|T})$ and $bias(\hat{v}_{T+2|T})$ since they are tractable with the use of the results above. The long term biases are also analytically tractable, and are given below. The algebra for the biases for the intermediate-term forecasts ($h = 3, 4...$) are impractical to show, and are illustrated by simulation in section 7.

5.1 Short-term forecast biases

We forecast the growth variables Δw_t, Δp_t, Δpc_t and the levels variables x_t, ws_t and y_t. We are interested in biases of forecasts of the nominal variables and real variables immediately after a break and in the long run. How soon a break affects a variable depends on the break, which variable and the dating of the variables in the transmission mechanism. To see this, it is necessary to look at the model (9), in addition to the structural equations (2)-(5) and the system (10). There is one break that affects all but one endogenous variable immediately: a break in imported inflation by g_{pm} changing to $g_{pm} + dpm$ at $T+1$ affects x_{T+1} per definition, Δw_{T+1}, Δp_{T+1}, Δpc_{T+1} due to simultaneity in the wage-price spiral, and therefore also ws_{T+1}. The break first shows in y_{T+2}, since the break affects excess demand through the lagged exchange rate x_{t-1}, see (6).

There are two breaks that affect the break variable immediately but the other variables with a lag. A break in excess demand y by c_y changing to $c_y + dc_y$ at $T+1$ affects y_{T+1}, while all other endogenous variables are affected first at $T+2$ through lagged y in the equilibrium-correction term ecm_p and simultaneity in the wage-price spiral. A break in productivity changing g_z to $g_z + dz$ at $T+1$ affects z_{T+1}, and by definition also the wage share ws_{T+1}. The other endogenous variables are affected at $T+2$ through lagged z in the equilibrium-correction terms ecm_p and ecm_w and simultaneity in the wage-price spiral. These three breaks cause biases in 1-step forecasts for some variables, and the first biases in 2-step forecasts for other variables.

[8] Given our assumption that the model corresponds to the DGP withing sample, and that the structural disturbances are not autocorrelated, the assumption about known parameters can be replaced by estimated parameters, with no consquences for the analysis of the foreast error biases. We utilize this in the simulated forecast errors in section 7.

Each of the remaining two breaks we investigate changes constants in the lagged equilibrium-correction term ecm_p in (2) and ecm_w in (3). A break in the price mark-up by m_p changing to $m_p + dp$ at $T+1$, or a break in the wage mark-up by m_w changing to $m_w + dw$ at $T+1$, affects all endogenous variables but y first at period $T+2$ since the new mark-ups influence wage and price adjustments with a time delay of one period. The break affects x_{T+2} which then affects y_{T+3}.

From (10) and (12)-(13) we see that only one of the breaks causes a bias in the 1-step forecast for inflation and wage growth, namely the break dpm in the imported inflation rate:

$$bias(\widehat{\Delta p}_{T+1|T}) = -(1-e)dpm \quad \text{and} \quad bias(\widehat{\Delta w}_{T+1|T}) = -(1-e+\xi)dpm. \tag{29}$$

It follows from (8) that

$$bias(\widehat{\Delta pc}_{T+1|T}) = \phi\, bias(\widehat{\Delta p}_{T+1|T}) + (1-\phi) bias(\widehat{\Delta pm}_{T+1|T}) = -(1-\phi e)dpm. \tag{30}$$

A break in the productivity growth rate, a mark-up or excess demand causes no bias in the 1-step forecasts due to lagged effects. We find the lagged effects of the breaks from the systems (10) and (18) and the elements in the expressions for d (16) and δ (21):

$$\begin{pmatrix} bias(\widehat{\Delta p}_{T+2|T}) \\ bias(\widehat{\Delta w}_{T+2|T}) \end{pmatrix} = \begin{pmatrix} k & -\theta_p/\chi & -\theta_w \psi_{pw}/\chi & -n \\ -s & -\theta_p\left(\phi\psi_{wpc}+\psi_{wp}\right)/\chi & -\theta_w/\chi & -\alpha \end{pmatrix} \begin{pmatrix} dz \\ dp \\ dw \\ dy \end{pmatrix}. \tag{31}$$

Note that at most one break is active at a time, as explained above. For these breaks $bias(\widehat{\Delta pc}_{T+2|T}) = \phi\, bias(\widehat{\Delta p}_{T+2|T})$.

From the reduced form (18) we get the 1-step forecast biases for the real variables:

$$\begin{pmatrix} bias(\widehat{x}_{T+1|T}) \\ bias(\widehat{ws}_{T+1|T}) \\ bias(\widehat{y}_{T+1|T}) \end{pmatrix} = \begin{pmatrix} -e & 0 & 0 \\ -\xi & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} dpm \\ dz \\ dy \end{pmatrix}. \tag{32}$$

The other breaks cause biases first in the 2-step forecast. The expressions for the biases in the 2-step forecasts follow from (18) and the reasoning in the previous section. A break dpm in the imported inflation rate affects the real exchange rate immediately and thus excess demand the next period

$$bias(\widehat{y}_{T+2|T}) = \theta_y \varpi\, bias(\widehat{x}_{T+1|T}) = -\theta_y \varpi\, e\, dpm. \tag{33}$$

A break dz in the growth rate of productivity affects the wage share immediately, and through it the real exchange rate the next period:

$$bias(\widehat{x}_{T+2|T}) = -k\, bias(\widehat{ws}_{T+1|T}) = -k\, dz. \tag{34}$$

Excess demand is first affected at $T+3$ by a break in productivity at $T+1$, through lagged $x : bias(\widehat{y}_{T+3|T}) = \theta_y \varpi\, bias(\widehat{x}_{T+2|T}) = -\theta_y \varpi\, y\, dz$.

A change in a mark-up affects wage and price adjustments through lagged equilibrium correction. We find the lagged effects on the real exchange rate and the wage share in the expressions for d (16) and δ (17). The lagged effects of a break in excess demand are found in the first matrix in (18). The 2-step forecast biases are

$$\begin{pmatrix} bias(\widehat{x}_{T+2|T}) \\ bias(\widehat{ws}_{T+2|T}) \end{pmatrix} = \begin{pmatrix} \theta_p/\chi & \theta_w \psi_{pw}/\chi & n \\ \theta_p(1-\psi_{wp}-\phi\, \psi_{wpc})/\chi & \theta_w(1-\psi_{pw})/\chi & \eta \end{pmatrix} \begin{pmatrix} dp \\ dw \\ dy \end{pmatrix}, \tag{35}$$

Excess demand is first affected by a break to a mark-up at $T+3$, through lagged x: $bias(\widehat{y}_{T+3|T}) = \theta_y \varpi\, bias(\widehat{x}_{T+2|T}) = \theta_y \varpi\, \theta_p dp/\chi$ or $\theta_w \psi_{pw} \theta_p dw/\chi$.

5.2 Biases in steady-state forecasts

In steady state $E\Delta p = E\Delta pc = g_{pm}$ and $E\Delta w = g_{pm} + g_z$. Then,

$$\begin{pmatrix} bias(\widehat{\Delta p}_{ss}) \\ bias(\widehat{\Delta w}_{ss}) \\ bias(\widehat{\Delta pc}_{ss}) \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ -1 & -1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} dpm \\ dz \end{pmatrix}. \tag{36}$$

A permanent change in a mark-up (m_p, m_w) or the mean excess demand (c_y) has no long-run effects on the growth rates of the nominal variables.

Biases in steady-state forecasts of the real variables follow directly from (23)-(25) and the expressions (26), (27) and (28) for the steady-state coefficients:

$$\begin{pmatrix} bias(\widehat{x}_{ss}) \\ bias(\widehat{ws}_{ss}) \\ bias(\widehat{y}_{ss}) \end{pmatrix} = \begin{pmatrix} -e_{ss} & -b_{ss} & \theta_y/\Omega & \theta_y/\Omega & \vartheta/\Omega \\ -\xi_{ss} & \beta_{ss} & \theta_y\omega(1-\phi)/\Omega & -\vartheta\,\theta_y\varpi/\Omega & \vartheta\,\omega(1-\phi)/\Omega \\ -\mathfrak{e}_{ss} & -\mathfrak{b}_{ss} & \theta_y\varpi/\Omega & \theta_y\varpi/\Omega & -\omega(1-\phi)/\Omega \end{pmatrix} \begin{pmatrix} dpm \\ dz \\ dp \\ dw \\ dy \end{pmatrix}. \tag{37}$$

6 Calibrated biases

In order to make the forecast biases more concrete we use the following calibration of the parameters of the deterministic part of the DGP:

$$\begin{aligned} \psi_{ppm} &= \psi_{wpc} = \phi = \theta_p = \theta_w = \theta_y = m_p = m_w = 0.5, \\ c_p &= c_w = c_y = 0, \\ g_{pm} &= g_z = 0.02, \quad \vartheta = 0.2, \; \varpi = 0.1, \quad \omega = 1, \\ \psi_{pw} &= \psi_{wp} = \begin{cases} 0.25 & \text{without dynamic homogeneity,} \\ 0.5 & \text{with dynamic homogeneity.} \end{cases} \end{aligned}$$

These structural parameters of the macroeconomic model are consistent with global asymptotic stability of the companion form representation for x_t, ws_t and y_t in (18). Note that we are interested in the biases both with dynamic homogeneity imposed, and without this restriction on the short-term parameters.

With these calibrated structural parameter values we have the following numerical values of the reduced-form and steady-state coefficients in the two cases with and without dynamic wage and price homogeneity (22):

	System coefficients							Steady-state coefficients					
hom.	α	k	s	e	ξ	n	η	e_{ss}	ξ_{ss}	$\mathfrak{e}_{ss}$	b_{ss}	β_{ss}	$\mathfrak{b}_{ss}$
no	.06	.43	.29	.36	−.07	.11	.06	1.92	.50	.19	2.88	.56	.29
yes	.12	.4	.2	0	0	.16	.04	0	0	0	1.92	1.04	.19

The three constant terms appearing in the VAR (10) and in the reduced form (18) contain the effects of breaks in the mark-ups:

$$d = \begin{cases} 0.36 - 0.06\,dp - 0.014\,dw, & \text{without,} \\ 0.6 - 0.08\,dp - 0.04\,dw & \text{with homogeneity,} \end{cases}$$

$$b = \begin{cases} 0.43 - 0.03\,dp - 0.06\,dw & \text{without,} \\ 0.7 - 0.06\,dp - 0.08\,dw & \text{with homogeneity,} \end{cases}$$

$$\delta = \begin{cases} 0.07 - 0.04\,dp + 0.03dw & \text{without,} \\ 0.1 + 0.02\,dp - 0.02\,dw & \text{with homogeneity.} \end{cases}$$

The three constant terms in the steady-state solutions also contain the effects of a break in excess demand:

$$
\begin{aligned}
d_{ss} &= 1.92 - 0.19\,dp - 0.19\,dw + 0.08\,dy, \\
\delta_{ss} &= 1.85 - 0.38\,dp + 0.015\,dw - 0.15\,dy, \\
\mathfrak{d}_{ss} &= -0.19 + 0.02\,dp + 0.02\,\delta w - 0.19\,dy.
\end{aligned}
$$

The latter three expressions are unaffected by dynamic homogeneity or by the degree of inhomogeneity. With the chosen parameterization $d_{ss} = 1.92$, $\delta_{ss} = 1.85$ and $\mathfrak{d}_{ss} = -0.19$ before a break. These values are maintained in the forecasts after the break, while the data series change. Below we shall use the numerical values $dpm = dz = dp = dw = dy = -0.1$, and that at most one break is active at a time.

6.1 A break in imported inflation

The bias of the 1-step forecast of import price inflation is $bias(\widehat{\Delta pm}_{T+1|T}) = -dpm = 0.1$, which is also the bias of the steady-state forecast $bias(\widehat{\Delta pm}_{ss|T})$. From the previous section we select other relevant results. The biases in the forecasts of the nominal variables are given by (29), (30) and (36):

bias	$\widehat{\Delta p}$	$\widehat{\Delta pc}$	$\widehat{\Delta w}$
1-step	$-(1-e)dpm = 0.064$	$-(1-\phi\, e)dpm = 0.082$	$-(1-e+\xi)dpm = 0.057$
with homogeneity	$-dpm = 0.1$	$-dpm = 0.1$	$-dpm = 0.1$
steady state	$-dpm = 0.1$	$-dpm = 0.1$	$-dpm = 0.1$

when we use the calibrated coefficients above and set $dpm = -0.1$. The biases in the forecasts of the real variables are given by (32), (33) and (37):

bias	$\widehat{x}$	$\widehat{ws}$	$\widehat{y}$
1-step	$-e\,dpm = 0.036$	$-\xi\,dpm = -0.007$	0
with homogeneity	0	0	0
2-step			$-\theta_y \varpi\, e\,dpm = 0.0036$
with homogeneity			0
steady state	$-e_{ss}dpm = 0.192$	$-\xi_{ss}dpm = 0.05$	$-\mathfrak{e}_{ss}dpm = 0.019$
with homogeneity	0	0	0

with the use of the calibrated values above. The blank entries mark that a bias first appears in the 1-step forecasts.

6.2 A break in productivity growth

We next consider the impact of a permanent change in growth rate of productivity from $g_z = 0.02$ to $g_z + dz = 0.02 - 0.1 = 0.08$ at period $T+1$, one period after the forecast was made. Here, and in the rest of the paper we only look at the case with dynamic homogeneity.

The definition of the wage share $ws_t \equiv w_t - p_t - z_t$ implies that a break in productivity causes an immediate forecast failure for the wage share ws. In the wage-price spiral a productivity break is transmitted by both lagged equilibrium-correction terms onto wage and price growth. Hence the effects of a break on the other variables are lagged at least one period. The biases in the forecasts of the nominal variables are given by (31) and

(36):

bias	$\widehat{\Delta p}$	$\widehat{\Delta pc}$	$\widehat{\Delta w}$
2-step	$k\,dz = -0.04$	$\phi\,k\,dz = -0.02$	$-s\,dz = 0.02$
steady state	0	0	$-dz = 0.1$

The biases in the forecasts of the real variables are given by (32), (34) and (37). Specifically, with the chosen parameterization we get

bias	$\widehat{x}$	$\widehat{ws}$	$\widehat{y}$
1-step	0	$dz = -0.1$	0
2-step	$-k\,dz = 0.04$		0
steady state	$-b_{ss}dz = 0.192$	$\beta_{ss}dz = -0.106$	$-\mathfrak{b}_{ss}dz = 0.019$

Depending on the parameter values, the steady-state biases can be small or large. If $\theta_p = \theta_w\,\psi_{pw}$, which could happen if the degree of equilibrium correction in wages is larger than in prices, then $b_{ss} = \mathfrak{b}_{ss} = 0$, and the biases in the forecasts of the steady-state real exchange rate, $\widehat{x}_{ss|T}$, and the steady-state demand, $\widehat{y}_{ss|T}$, both disappear.

6.3 A change in the price mark-up

The mark-up m_p can be shown (with reference to price setting theory) to depend on the elasticity of product demand, and more generally on the degree of competition in product markets. So a reduction in the mark-up can for example be associated with trade liberalization or with changes in consumer preferences.

After the forecasts are made, the price mark-up changes in the DGP from $-m_p = -0.5$ to $-(m_p+dp) = -(0.5+(-0.1)) = -0.4$. Since the mark-up affects price and wage growth through the lagged equilibrium-correction term ecm_p, we think of the mark-up as being dated the same as the variables in ecm_p. Then a break in the price mark-up at $T+1$ affects data first in period $T+2$.

We see from (2)-(5) that a break in the price mark-up at $T+1$ affects the (unlagged) equilibrium-correction term $ecm_{p,t} = -(m_p + \delta_{p,t}\,dp) - ws_t - \vartheta\,y_t$ immediately with the full size of the break. The bias in the 1-step forecast is

$$bias(\widehat{ecm}_{p,T+1|T}) = dp = -0.1.$$

The biases in the forecasts of the nominal variables are given by (31) and $bias(\widehat{\Delta pc}_{T+2|T}) = \phi\,bias(\widehat{\Delta p}_{T+2|T})$:

bias	$\widehat{\Delta p}$	$\widehat{\Delta pc}$	$\widehat{\Delta w}$
2-step	$-\theta_p dp/\chi = 0.08$	$-\phi\,\theta_p dp/\chi = 0.04$	$-\theta_p(\psi_{wp} + \phi\psi_{wpc})dp/\chi = 0.06$
steady state	0	0	0

The steady-state growth rates of nominal prices and wages are all unaffected by the break, hence there is no bias in the forecasts of steady-state inflation in wage and prices. The biases in the forecasts of the real variables are given by (35) and (37):

bias	$\widehat{x}$	$\widehat{ws}$	$\widehat{y}$
2-step	$\theta_p dp/\chi = -0.08$	$\theta_p(1 - \psi_{wp} - \phi\psi_{wpc})dp/\chi = -0.02$	0
steady state	$\theta_y dp/\Omega = -0.192$	$\theta_y\omega(1-\phi)dp/\Omega = -0.096$	$\theta_y\varpi\,dp/\Omega = -0.0192$

The bias in the forecasts of the steady-state equilibrium-correction term (4) is

$$bias(\widehat{ecm}_{p,ss}) = dp - bias(\widehat{ws}_{ss}) - \vartheta\,bias(\widehat{y}_{ss}) = dp(1 - \theta_y(\omega(1-\phi) + \vartheta\,\varpi)/\Omega) = 0. \quad (38)$$

These numerical values of the forecast biases are illustrating that the biases for the real exchange rate (x) are larger than for the wage-share (ws), and that both biases increase with the length of the forecast horizon. We have a permanent break in the mean of the long-run price equation, but the long-term biases for the nominal growth rates are nevertheless zero. The explanation is that the nominal path of the economy is unaffected by the break in price mark-up coefficient.

6.4 A change in the wage mark-up

The mark-up m_w is central in the modern macroeconomic theory of wage setting, inflation and unemployment determination, see Layard et al. (2005). The reason for interest in the wage mark-up coefficient is that a too high wage-mark up is seen as one of the main reasons for the high unemployment rates in many European countries compared with the US economy. Bårdsen and Nymoen (2009b) provides a generalized version of this model, and show that the effect of the wage mark-up on unemployment is less direct and that the generalized model is relevant for US macroeconomic data. From the perspective of forecasting, it is relevant that the long-run wage mark-up coefficient is interpreted by most researchers as a parameter which is fundamentally conditioned by labour market institutions and other socioeconomic factors, see e.g., Iversen (1999) and Barkbu et al. (2003). As such it is a parameter which is subject to intermittent shifts as a result of reform and structural changes in society.

After the forecasts are made, the wage mark-up changes from $-m_w = -0.5$ to $-(m_w + dw) = -(0.5 + (-0.1)) = -0.4$ at $T+1$. Like the price mark-up, the wage mark-up works through the lagged equilibrium-correction term, and the effects on the variables will be lagged one period.

We see from (2)-(5) that a break in the wage mark-up at $T+1 = 181$ affects the (unlagged) equilibrium-correction term $ecm_{w,t} = -(m_w + \delta_{w,t}\, dw) + ws_t - \omega(1-\phi)\, x_t$ immediately with the full size of the break. The bias in the 1-step forecast is

$$bias(\widehat{ecm}_{w,T+1|T}) = dw = -0.1.$$

The biases in the forecasts of the nominal variables are given by (31) and $bias(\widehat{\Delta pc}_{T+2|T}) = \phi\, bias(\widehat{\Delta p}_{T+2|T})$:

bias	$\widehat{\Delta p}$	$\widehat{\Delta pc}$	$\widehat{\Delta w}$
2-step	$-\theta_w \psi_{pw} dw/\chi = 0.04$	$-\phi\, \theta_w \psi_{pw} dw/\chi = 0.02$	$-\theta_w dw/\chi = 0.08$
steady state	0	0	0

The steady-state growth rates of nominal prices and wage are all unaffected by the break, hence there is no bias in the forecasts of steady-state inflation in wage and prices. The biases in the forecasts of the real variables are given by (35) and (37):

bias	$\widehat{x}$	$\widehat{ws}$	$\widehat{y}$
2-step	$\theta_w \psi_{pw} dw/\chi = -0.04$	$-\theta_w(1-\psi_{pw})dw/\chi = 0.04$	0
steady state	$\theta_y dw/\Omega = -0.192$	$-\theta_y \vartheta\, \varpi\, dw/\Omega = 0.004$	$\theta_y \varpi\, dw/\Omega = -0.02$

It is in particular interesting to note that $bias(\widehat{ws}_{ss}) = -\theta_y \vartheta\, \varpi\, dw/\Omega$ which can be zero if $\vartheta = 0$, which is an admissible restriction. The bias in the forecasts of the steady-state equilibrium-correction term (4) is

$$\begin{aligned} bias(\widehat{ecm}_{w,ss}) &= dw + bias(\widehat{ws}_{ss}) - \omega(1-\phi) bias(\hat{x}_{ss}) \\ &= dw(1 - \theta_y(\vartheta\, \varpi + \omega(1-\phi))/\Omega) = 0. \end{aligned} \tag{39}$$

These numbers illustrate in particular that, with the calibrated values, the biases in the long-term wage-share forecasts are much smaller than in the short-term forecasts. It is opposite for the real-exchange rate forecasts. Since the forecast does not respond to the break, this result must be due to how the economy operates to mitigate the effects of a break in the sector where it occurs (wage-setting) and transmitting the effects to another variable (the real exchange rate). We return to this point when we discuss the Monte Carlo simulations in the next section.

6.5 A break in the mean of aggregate demand

At $T+1$, after the forecasts are made, $c_y = 0$ changes to $c_y + dy = 0 + (-0.1) = -0.1$. Excess demand increases at the same time and by the same amount as the shift dy in c_y. The break affects wage growth and inflation through the lagged equilibrium-correction term $ecm_{p,t-1}$ and simultaneous determination of wage and price growth. Consequently, all variables apart from y react first in period $T+2$. The biases in the forecasts of the nominal variables are given by (31) and $bias(\widehat{\Delta pc}_{T+2|T}) = \phi\, bias(\widehat{\Delta p}_{T+2|T})$:

bias	$\widehat{\Delta p}$	$\widehat{\Delta pc}$	$\widehat{\Delta w}$
2-step	$-n\, dy = 0.016$	$-\phi\, n\, dy = 0.008$	$-\alpha\, dy = 0.012$
steady state	0	0	0

The steady-state growth rates of nominal prices and wage are all unaffected by the break. There is no bias in the forecasts of steady-state inflation in wage and prices. The biases in the forecasts of the real variables are given by (35) and (37):

bias	$\widehat{x}$	$\widehat{ws}$	$\widehat{y}$
1-step	0	0	$-dy = 0.1$
2-step	$n\, dy = -0.016$	$\eta\, dy = -0.004$	
steady state	$\vartheta\, dy/\,\Omega = -0.077$	$\vartheta\, \omega(1-\phi)dy/\,\Omega = 0.038$	$-\omega(1-\phi)dy/\,\Omega = 0.192$

7 Monte Carlo simulation

In order to obtain results for the forecast errors for intermediate run horizons we use Monte Carlo simulation. In the simulations we let the structural breaks affect the DGP 11 periods after the forecasts have been made. In this way we can use the simulations both to confirm that the 10 first dynamic forecasts are unbiased (because there are no breaks), and to study how the forecasts evolve after the break. In particular we expect to find the simulated end-of-horizon biases are close to the numerical steady-state biases above.

We also use the simulations to show that the analysis does not depend on the assumption that the forecaster knows the parameters of the DGP (with the exception of the breaks), since we use the Monte Carlo to generate an estimation sample.

7.1 Experiment design

We have made experiments where the parameterized DGP (with coefficient given above) and the stochastic disturbances generate the observable“ real world” data series for 200 periods. The first part of the sample has no breaks, and this sub-sample is used to estimate the forecasting model. The estimated model is used to generate forecasts for the last part of the sample, where the structural breaks have occurred.

Specifically, the DGP is subject to five breaks: one in each of the driving exogenous variables, the import price inflation and the productivity growth, and one in each of the trending domestic price and wage levels, and one in the stationary demand. We call the numerical simulations of each break a *break experiment*. Each break experiment is simulated in the following manner. We first generate a single realization of the DGP for 200 periods, with disturbance shocks in each period. The break occurs at period $T+1 = 181$, and is permanent as in the analysis above. The generated data series are called 'observations' or 'realizations'. For the first $T = 180$ periods all generated data series are identical between the different break experiments. The only exception is a single experiment *without* dynamic homogeneity, which thus generates a slightly different series of observations before as well as after the breaks. For the 20 periods after a break, $t = 181, ..., 200$, the simulated observations may differ between experiments since they are subject to a different structural breaks. We estimate the model with the first 170 observations, and construct a multivariate normal distribution for the parameter estimates and for the residuals. The forecasts are generated by dynamic stochastic simulations with quasi-random parameter estimates and innovations drawn from their sample distributions. Like the observations, the estimated model and the distributions of the estimates and residuals are identical across all experiments. Since the forecasts are made from the same model and no breaks have yet been observed, the forecasts are identical across all experiments with dynamic homogeneity imposed. Again the only exception is the single experiment *without* dynamic homogeneity reported in Figure 2.

A single *forecast* is a dynamic stochastic simulation of the model over the periods 171 to 200. A set of parameter estimates are drawn from their distribution and held constant in the simulation through the forecast horizon of 30 periods, while new residual shocks are drawn for each variable each period. A single forecast is replicated 1000 times, and the forecasts are summarized by the mean encapsulated in a pointwise 90 percent forecast band delimited by 5 and 95 percentiles in the simulated sample.

7.2 Simulation results

The graphs in Figure 2 show the break-in-imported-inflation experiment for the case of dynamic inhomogeneity (both in the DGP and in the forecast model). At $T+1 = 181$ the drift in (real world) import price inflation Δpm_t changes from $g_{pm} = 0.02$ to $g_{pm} + dpm = 0.02 - 0.1 = -0.08$. The forecasts are conditioned on observations up to $t = 170$. The mean forecasts are therefore $E_{t=170}(\Delta pm_{t>170}) = g_{pm} = 0.02$ and not $g_{pm} + dpm = -0.08$. The bias in a forecast is the difference between the forecast and the expected realization/observation. Before the break at $T+1 = 181$ the economy, represented by the single ragged graph, fluctuates around the mean forecast, which is the central dashed line enveloped by 5 and 95 forecast percentiles. After the break the mean forecast is higher than the post-break realization, hence the bias is positive. There is of course no response in the forecasts (as indicated by the forecast bands) to the large break in Δpm (lower right panel), but the economy reacts. The lower row of panels shows the immediate reaction of the other two nominal variables: the consumer price inflation Δpc (lower left panel) and the wage inflation Δw (lower centre panel). Of the real variables in the upper row of panels, the real exchange rate x (upper left panel) reacts fast and much, while the wage share ws (upper centre panel) and aggregate demand y (upper right panel) react more slowly and less. For y, the bias is about 1/2 of the half-width of the forecast band with pointwise coverage 0.9 for a realization with no breaks. The bias is thus not very significant in light of the uncertainty in the forecasts of y. For the other five variables the breaks are much more significant.

The graphs in Figure 3 are different from the ones in Figure 2 because the DGP and the model have been made subject to dynamic homogeneity. As a result, there is no impaft of the structural break on the real exchange rate x, the wage share ws, or the aggregate demand y. The algebra has already shown this, and it is clearly demonstrated in the upper row of graphs in Figure 3. Of course there is no similar robustness to breaks

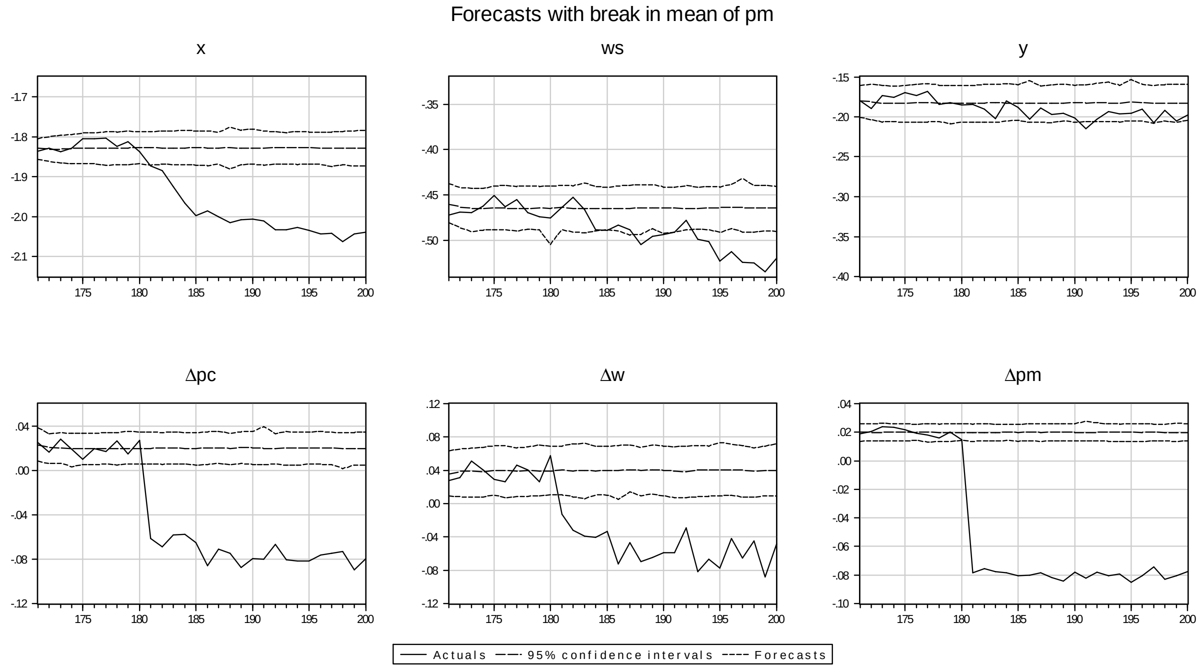

Figure 2: Pre-break forecasts and a realization subject to a change in the growth rate of import prices Δpm_t from 2% to -8% in period 180. The model is without dynamic homogeneity: $\psi_{pw} + \psi_{ppm} = \psi_{wp} + \psi_{wpc} = 0.75$.

in the nominal variables, inflation and wage growth. The lower row of graphs show that the biases for the 1-step and the steady-state forecasts of wage and price inflation are all $-dpm = 0.1$.

We next look at the experiment where the growth rate of productivity changes from $g_z = 0.02$ to $g_z + dz = 0.02 - 0.1 = 0.08$ in period $T + 1 = 181$ (after the forecasts are made in period 170).

Figure 4 illustrates the analytical and numerical results clearly: the wage share ws (upper centre panel) is directly and in full affected by the break in Δz (lower right panel). There is a significant bias $dz = -0.1$ in ws already in the break period 181, and it increases to almost -0.11 and persists for the length of the simulation. The forecasts of the real exchange rate x (upper left panel) become upward biased a few periods after the break because of the lasting effect of the break on the domestic price level p, which persists in accordance with the analytic result above. The forecasts of aggregate demand y (upper right panel) are affected by the shift to the new mean in the real exchange rate x. There is little sign of any significant bias in the y-forecasts until 5 or 6 periods, when a gap between the (mean) forecasts and the data series emerges ($bias \approx 0.02$).

The reduction in productivity Δz (lower right panel) affects inflation Δp and thus Δpc (lower left panel). The change is only temporary and due to the dynamic adjustment process, before consumer price inflation returns to fluctuating around the imported inflation rate ($g_{pm} = 0.02$). That is a necessary requirement for a stable exchange rate x after the break. Reduced productivity does on the other hand reduce wage growth Δw permanently and by the same amount (lower centre panel). That is a necessary requirement for a stable wage share ws after the break.

After the breaks in the growth rates of the trending exogenous processes for pm and z, we are now going to look at the immediate and long-run effects of breaks in the mean of the endogenous processes for the trending p and w, and for the stationary y. We start with the price level mark-up parameter m_p.

The graphs in Figure 5 confirm that the real exchange rate and the wage share are af-

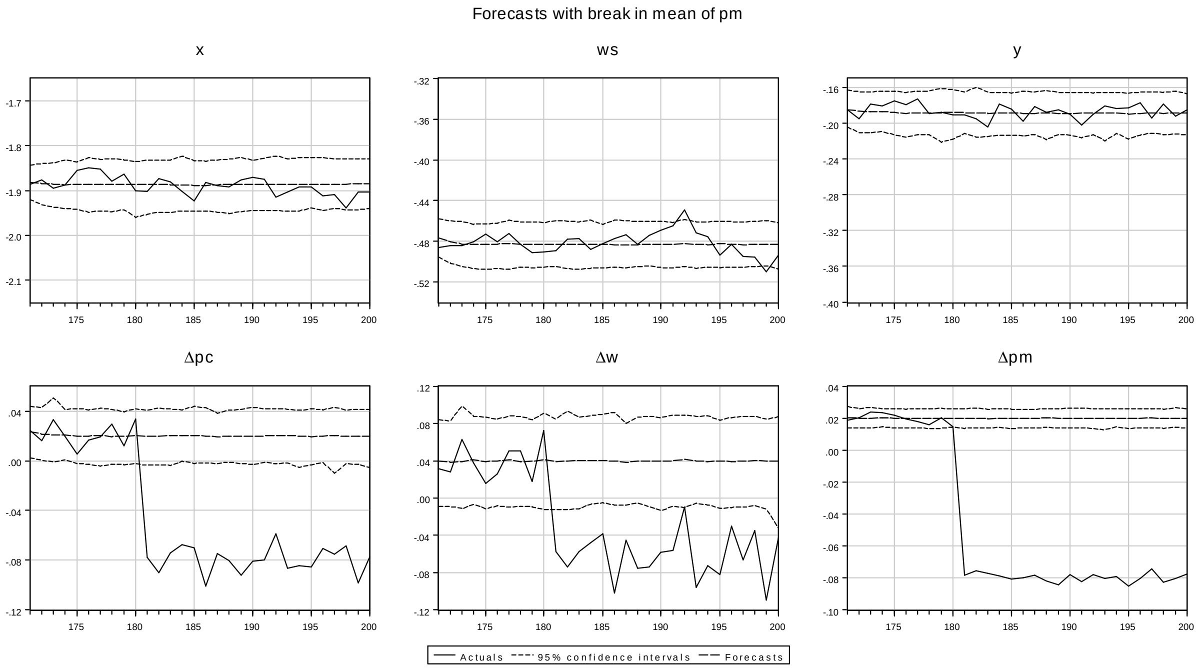

Figure 3: Pre-break forecasts and a realization subject to a change in the growth rate of import prices Δpm_t from 2% to -8% in period 180. The model is with dynamic homogeneity: $\psi_{pw} + \psi_{ppm} = \psi_{wp} + \psi_{wpc} = 1$.

fected immediately after the decrease in m_p. After 11 periods, without systematic forecast errors, before the break, there are negative *post*-break forecast failures for these variables. The same will be the case for the excess demand forecasts, but several periods after the occurrence of the break though. Price- and wage inflation are only temporarily affected for a few periods, as the economy goes through a dynamic adjustment process after the change. Even though the break occurs in the price-setting equation, there will be no fundamental forecast failure for these nominal growth-rate variables. The ecm_p is affected by the full impact of the break, but as (38) shows, there is no steady-state bias (lower right panel).

The mark-up m_w is central in modern macroeconomic theory of wage setting, inflation and unemployment determination, see Layard et al. (2005). The reason for interest in the wage mark-up coefficient is that a too high wage mark-up is seen as one of the main reasons for the high unemployment rates in many European countries compared with the US economy. Bårdsen and Nymoen (2009b) provide a generalized version of this model, and show that the effect of the wage mark-up on unemployment is less direct and that the generalized model is relevant for US macroeconomic data. From the perspective of forecasting, it is relevant that the long-run wage mark-up coefficient is interpreted by most researchers as a parameter which is fundamentally conditioned by labour market institutions and other socioeconomic factors, see e.g., Iversen (1999) and Barkbu et al. (2003). As such, it is a parameter which is subject to intermittent shifts as a result of reform and structural changes in society.

After the forecasts are made, the price mark-up changes from $-m_w = -0.5$ to $-(m_w + dw) = -(0.5 + (-0.1)) = -0.4$ at $T + 1 = 181$. Like the price mark-up, the wage mark-up works through the lagged equilibrium-correction term, and the effects on the variables will be lagged one period.

Figure 6 shows effects of the break that are in several ways similar to the effects of a break to the price mark-up seen in Figure 5. An important exception is the wage-share: True enough, the forecasts overpredict the wage-share significantly in the first quarters

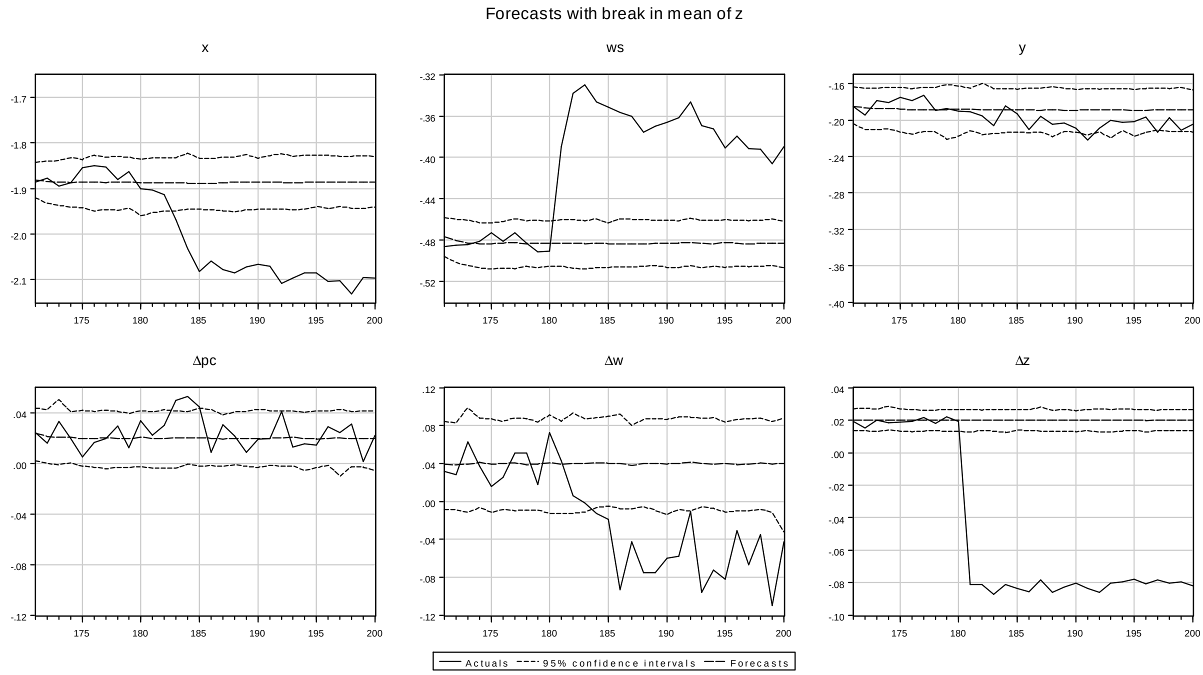

Figure 4: Pre-break forecasts and a realization subject to a change in the growth rate of productivity Δz_t from 2% to -8% in period 180. The model is with dynamic homogeneity: $\psi_{pw} + \psi_{ppm} = \psi_{wp} + \psi_{wpc} = 1$.

after the break in period 181, but soon after the forecast failure goes away! Note again (by looking at the ws forecast graph) that this fortunate outcome is not due to any error correction in the forecasts (they have settled at the pre-break equilibrium long before period 181). Instead, it is the economy that is equilibrium-correcting back to that pre-break wage-share. We therefore have the very counterintuitive result that a break in the mean of the wage cointegrating relationship (a shift in the wage-curve) has no effect on the equilibrium wage-share.

This result comes about because dynamic stability of the wage-price spiral is driving the long-run wage share to a point on the price-setting curve, see Kolsrud and Nymoen (2010), which also happens after the downward shift in the wage-setting curve occuring here. The consequence is that the steady-state bias for the wage-share is zero, as shown in (39), while the short-term bias may be substantial. Compared to the importance attributed to the wage mark-up as a determinant of unemployment, the effect on the excess demand variable (which we can think of as negatively and strongly correlated with unemployment) is very muted. Finally, in the same manner as the price mark-up simulation, we see that the effects on forecast errors for price- and wage inflation are temporary.

As discussed in Kolsrud and Nymoen (2010) these results for a mark-up break depend on the equilibrium-correction coefficients θ_p and θ_w being different from zero. If one of these parameters is zero the model becomes unstable, and other mechanisms must replace the equilibrium correction in the wage and price setting. A Phillips-curve specification is the most popular alternative, but since the dynamic behaviour of the Phillips-curve version of the model is different form the equilibrium-correction version, the implications for forecasts need to be considered separately. Other features of the simulation set-up are not of the same qualitative importance. For example, the result above still holds if we let aggregate demand affect wages instead of (or in addition to) prices only. With reference to Okun's law, the interpretation of the demand y can also be changed to be the rate of unemployment. Subject to the sign changes on the coefficients that follow from this re-interpretation, all the results above go through as before.

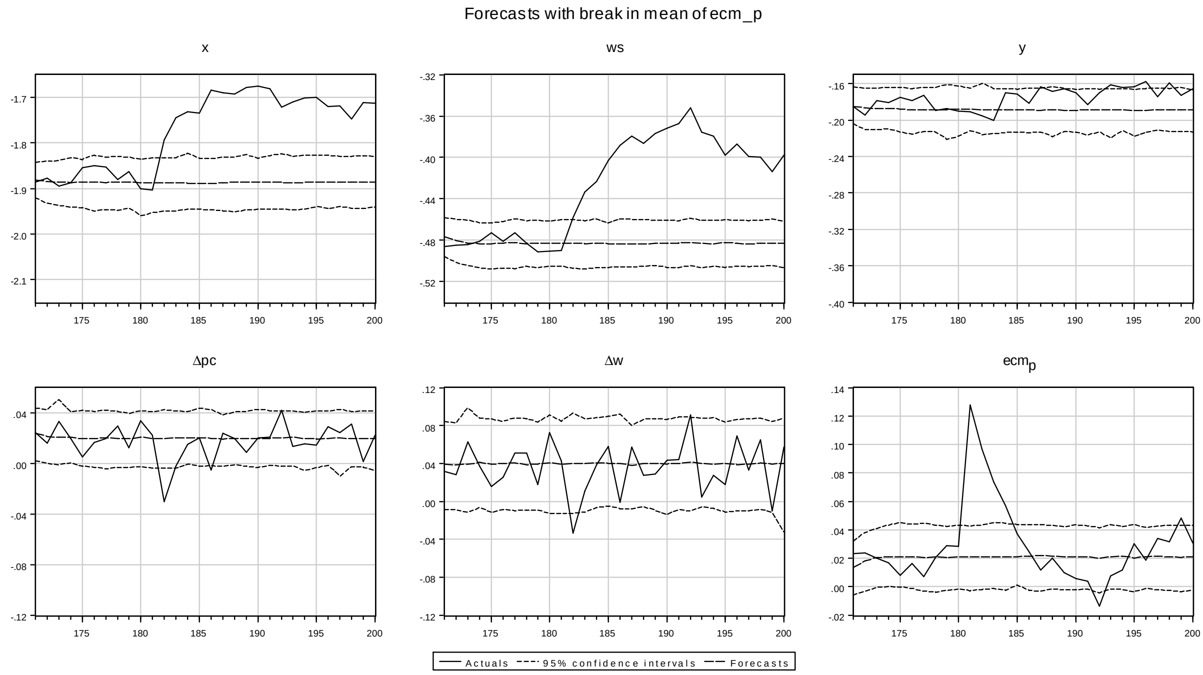

Figure 5: Pre-break forecasts and a realization subject to a change in the long-run price mark-up from -0.5 to -0.4 in period 180. The model is with dynamic homogeneity: $\psi_{pw} + \psi_{ppm} = \psi_{wp} + \psi_{wpc} = 1$.

Finally, we consider a permanent demand shock (could be increased friction). At $T+1$, after the forecasts are made, $c_y = 0$ changes to $c_y + dy = 0 + (-0.1) = -0.1$.

In Figure 7, the reduction in excess demand is seen to affect the solution for both the real exchange rate and the wage share permanently. There are no forecast failure for these two variables before 5 periods after the structural break though. Given the central role for the output gap in the standard model of inflation one would perhaps expect that a break in this variable is really damaging for the forecasting of price and wage inflation, but the impression from the second row in Figure 7 is that any induced bias is hard to detect.

8 Summary and discussion

The financial crisis has had a large impact on forecast errors in many economic models. This is also the case for some variables of a macroeconometric model for Norway but the crisis has done very little damage to the forecasts of many other variables. This is surprising since, in a solution of a dynamic macroeconomic model, "everything depends on everything else" — if not contemporaneously, then definitely after a few periods. The interpretation of the observed forecast outcomes is that a realistic model of the Norwegian economy includes both fewer really strong links between variables than custom will have us believe, see also Bårdsen et al. (2003), but also that there are balancing effects present in the economy and captured by the model.

The paper then investigates the role of mechanisms that can mitigate the effects of structural breaks in macroeconomic models along two dimensions. The first part of the paper highlights the role of policy in forecasting. The main result is that forecasting with a (correct) model is possible even with unforecasted structural change. If the forecasts include both targets for and instruments of discretionary economic policy, the forecasts of the target variables can still succeed if the policy forecasts fail—since policy will be used to counteract the breaks.

The second part investigates structural invariance is possible. We therefore exclude

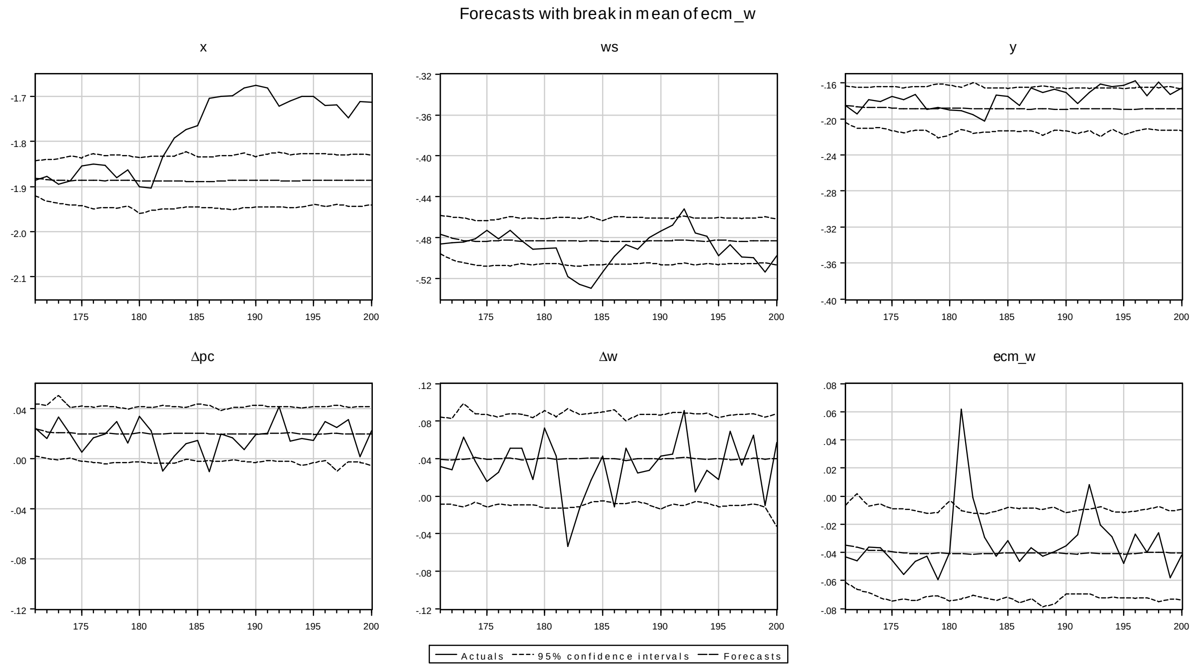

Figure 6: Pre-break forecasts and a realization subject to a change in the long-run wage mark-up from -0.5 to -0.4 in period 180. The model is with dynamic homogeneity: $\psi_{pw} + \psi_{ppm} = \psi_{wp} + \psi_{wpc} = 1$.

policy, but work within a richer model. We find, as expected, that structural breaks in growth rates and in the means of cointegrating relationships will always damage some of the variables. But we also find examples of "insulation" from shocks. It appears to have some generality that the degree of dynamic inhomogeneity plays a role for how much a break in the exogenous nominal growth rate affects the relative prices and, through them, the GDP output. We also show that a break in the mean of the long-run wage equation does not lead to bias in the forecasts of the wage-share, or for the degree of wage growth. This statement is formally only correct for long-run forecasts, but simulations show that in practice the results are a good approximation for practical forecast horizons.

The results about partial robustness is a property of the economy itself (here represented by the DGP) and not of the forecasts. Model-based forecasts themselves never error-correct to a post-forecast structural break, as made clear by Clements and Hendry in their work, so if the forecasts are robust it is because two conditions hold (at least to some extent). First, the economy must operate in such a way that the old equilibrium is re-installed even after a break has occurred and, second, this kind of structural stabilization (related to autonomy) is correctly represented in the forecasting model. Clearly, neither conditions can be assumed a priori, in advance of model specification and model assessment, including assessment of model forecasts. In this respect, our argument supports the earlier emphasis on relative (or comparative) forecast success as a sign of model quality. Good models will misforecast due to intermittent structural breaks, but we show that good models also have the property of correctly predicting invariance to breaks if it is a property of the economy.

Although we have focused on post-forecast breaks, we would think that a model of the type we have analyzed has a good chance of delivering forecasts that are adaptive to pre-forecast breaks. This is because the model represents a framework for interpreting a break. The simulations above already provide examples, which aids intercept-correction as a short-term measure to error-correct forecasts after a break, and for parameter updating as a semi-permanent solution. This is not denying that in practice, more fundamental re-

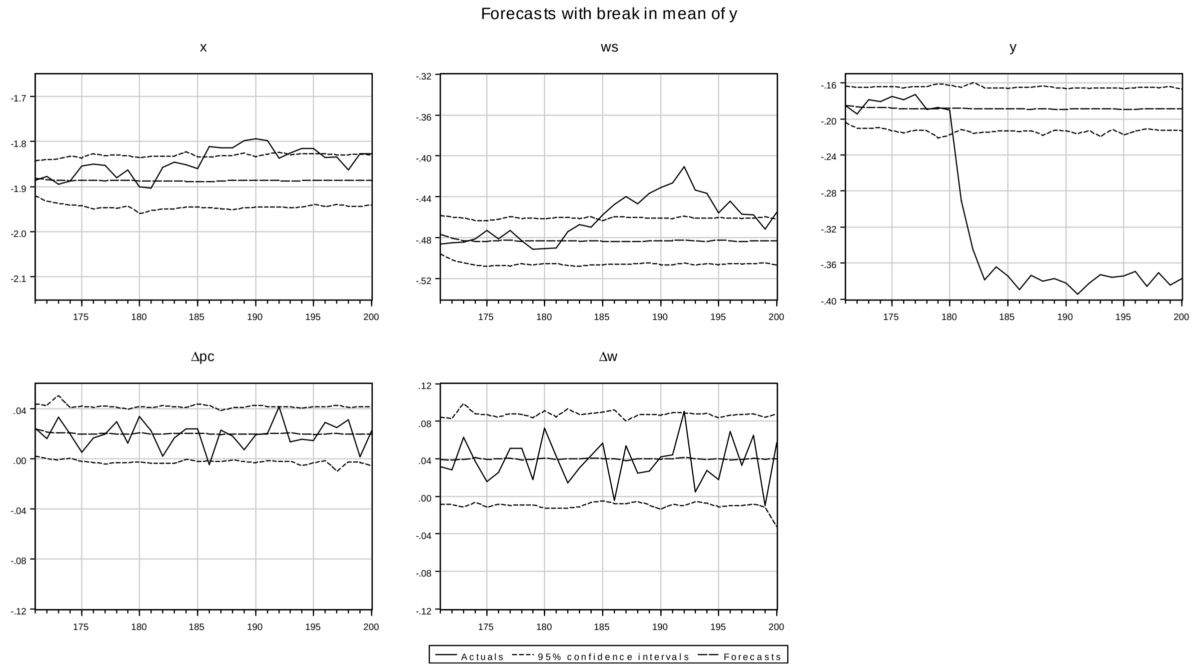

Figure 7: Pre-break forecasts and a realization subject to a change in the constant term of aggregate demand from 0 to .-0.1 in period 180. The model is with dynamic homogeneity: $\psi_{pw} + \psi_{ppm} = \psi_{wp} + \psi_{wpc} = 1$.

modelling is often the only lasting solution to a forecast failure. But again, and consistent with the analysis above, our experience is that often only parts of the model need serious re-specification after a break, and often the qualitative model properties are passed between model versions. In fact we do not see frequent re-modelling as a problem for model-based macro-forecasting, since it is one way to maintain model relevance in an changing world.

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