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Tobias Müller, Kai Christoffel,
Falk Mazelis, Carlos Montes-Galdón

## Disciplining expectations and the forward guidance puzzle

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**Abstract**

Forward guidance operates via the expectations formation process of the agents in the economy. In standard quantitative macroeconomic models, the expectations are unobserved state variables and little scrutiny is devoted to analysing the dynamic behaviour of these expectations. We show that the introduction of survey and financial market-based forecasts in the estimation of the model disciplines the expectations formation process in DSGE models. When the model-implied expectations are matched to observed expectations, the additional information of the forecasts restrains the agents' expectations formation. We argue that the reduced volatility of the agents' expectations dampens the model reactions to forward guidance shocks and improves the out-of-sample forecast accuracy of the model. Furthermore, we evaluate the case for introducing a discount factor as a reduced form proxy for a variety of microfounded approaches, proposed to mitigate the forward guidance puzzle. Once data on expectations is considered, the empirical support to introduce a discount factor dissipates.

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## Non-technical summary

With nominal interest rates approaching the lower bound, standard monetary policy tools become less effective and forward guidance is seen as a pivotal instrument for central banks to accommodate monetary policy. By acknowledging the significant role that expectations of future developments play for monetary policy, central banks aim to engage transparently with the public to promote a better understanding of the central bank's reaction function and future actions.

New Keynesian DSGE models are particularly well equipped to study forward guidance policies as agents in the economy form rational expectations on the future evolution of the economy. Following announcements on the future path of monetary policy, they adapt their behaviour and change their consumption and investment decisions accordingly. Households and firms form their expectations not only on the path of monetary policy but also take into account the demand and inflation effects this policy is expected to have, once all agents adapt their behaviour. These feedback loops imply that standard DSGE models predicate implausibly large reactions to forward guidance. Del Negro et al. (2012) refer to this phenomenon as the *forward guidance puzzle*. Moreover, when the length of the forward guidance horizon is extended further into the future, the responses result in an explosive behaviour in standard monetary models. Drawing a quantitatively reasonable conclusion is especially crucial in models used in policy institutions. In this paper, we, therefore, choose the New Area-Wide Model (NAWM), an estimated micro-founded open-economy model of the euro area and one of the main DSGE models of the European Central Bank (see Christoffel et al. (2008)).

Recent research has focused on modifying existing models by introducing mechanisms to mitigate the forward guidance puzzle. In contrast to this, we focus on the expectations formation process in DSGE models without changing the main structure of the model. We argue that the empirical identification of expectations in quantitative macro models is weak. Adding survey and financial market-based forecasts in the estimation allows for better identification of expectations and helps to mitigate the forward guidance puzzle. The model's expectations formation process is fundamental for the way in which announced future monetary shocks have an impact on the economy. Aiming for a better fit between the expected variables in the model and actual observed forecast data, we provide the model with additional information on how market participants form their expectations and assess the macroeconomic outlook. We use information from survey

data on real GDP growth and inflation expectations as well as the term structure of interest rates. The estimation of the model parameters based on measured macroeconomic forecasts gives us model-implied expectations which are more in line with actual empirical data. The concept to mitigate the effects of forward guidance with forecast data on key macroeconomic variables in the model takes up on the idea of Campbell et al. (2016). Campbell et al. already give a hint on how to use forecast data and other theoretical extensions in an estimated general equilibrium model to make it more suitable for studying forward guidance. Our framework demonstrates that the excessive reaction of the model to forward guidance can be adjusted to more plausible levels by solely focusing on the expectations formation process.

Disciplining the model agents' expectations results in slightly modified estimates of the structural parameters of the model and a smoother, less volatile expectations formation process. As a result, the responses of the variables to forward guidance news shocks are reduced to quantitatively reasonable amounts. Furthermore, the explosive behaviour of the model after medium to long-term forward guidance announcements disappears. A major advantage of our approach comprises the absence of any modifications to key structural equations in the New Keynesian framework. Besides, we confirm previous work stating that survey expectations and yield curves also contain an informational value of the current stance of the economy, which improves the general forecast performance of the model. Finally, the paper shows that there is no empirical evidence for a discount factor in the consumption Euler equation condition for a wide range of different measurement specifications and alternative observed forecast data.

# 1 Introduction

With nominal interest rates approaching the lower bound, standard monetary policy tools become less effective and forward guidance is seen as a pivotal instrument for central banks to accommodate monetary policy. By acknowledging the significant role that expectations of future developments play for monetary policy, central banks aim to engage transparently with the public to promote a better understanding of the central bank's reaction function and future actions. For instance, Coenen et al. (2017) underline the importance of transparent communication as a non-standard monetary policy tool and highlight the central bank's capability to influence the expectations of the economic agents via precise and committed signals.

New Keynesian DSGE models are particularly well equipped to study forward guidance policies as they incorporate forward-looking agents. Forward-looking agents rationalise and anticipate statements regarding expected future policy decisions contained in monetary policy announcements, and therefore adjust their behaviour based on those expectations. By changing their consumption and investment decisions today, a credibly announced future expansionary monetary policy brings about notable reactions of macroeconomic variables in the present. However, standard DSGE models predict implausibly large reactions to forward guidance. Del Negro et al. (2012) refer to this phenomenon as the *forward guidance puzzle*. Moreover, when the length of the forward guidance horizon is extended further into the future, the responses result in an explosive behaviour in standard monetary models.

Recent research has focused on modifying existing models by introducing micro-founded or reduced-form mechanisms to mitigate the forward guidance puzzle. In contrast, in this paper our approach to moderate the forward guidance puzzle relies on an empirical method without interfering with the structural equations of the model. For that purpose, we address the core channel of the forward guidance mechanism in DSGE models – the formation of the model-implied expectations. Drawing a quantitatively reasonable conclusion is especially crucial in models used in policy institutions. We, therefore, choose the New Area-Wide Model (NAWM), an estimated micro-founded open-economy model of the euro area and one of the main DSGE models of the European Central Bank (ECB) (see Christoffel et al. (2008)).

Although researchers have developed a better understanding of the pass-through of forward guidance policies in standard monetary models, little attention has been given to the question of whether these models adequately reflect the agents' expectations. We argue that the model's expectations formation process is crucial for the way in which announced future monetary shocks have an impact on the economy. Aiming for a better fit between the expected variables in the model and actual observed forecast data, we provide the model with additional information on how market participants form their expectations and assess the macroeconomic outlook. We use information from survey data on real GDP growth and inflation expectations as well as the term structure of interest rates. The estimation of the model parameters based on measured macroeconomic forecasts gives us model-implied expectations which are more in line with actual empirical data. Disciplining the model expectations yields more sticky, less volatile smoothed variables which is reflected in the values of the estimated parameters. As a result, the responses of the variables to a forward guidance news shock are reduced to quantitatively reasonable amounts. Furthermore, the explosive behaviour of the model for extended forward guidance horizons disappears.

The concept to mitigate the effects of forward guidance with forecast data on key macroeconomic variables in the model takes up on the idea of Campbell et al. (2016). Campbell et al. already give a hint on how to use forecast data in an estimated general equilibrium model to make it more suitable for studying forward guidance. However, in their work, they trace the muted power of forward guidance back to three modifications of their benchmark model: a discount factor in the consumption Euler equation, Jaimovich-Rebelo (JR) preferences and an enriched data set in the estimation of the model including expected federal fund rates and survey expectations on inflation. Our framework demonstrates that the excessive response of the model to forward guidance can be adjusted to more plausible levels by solely focusing on the last of the three adjustments. For that purpose, we trim the model-implied expectations towards the information given by macroeconomic forecasts on expected rates of output growth, inflation and the interest rate.

It is important to stress that our approach does not rely on modifications to key structural equations in the New Keynesian model. However, besides augmenting the data set for the estimation of the model, we introduce a four quarters ahead forward guidance news shock in the Taylor rule. While the inclusion of an additional shock is not strictly necessary to enhance the expectations formation process, this formulation of the Taylor rule helps to reconcile the model expectations and the corresponding observed yield curve data. In addition, the forward guidance shock allows us to distinguish between the effects of standard monetary policy and information about future monetary policy intentions. We otherwise keep the main structure of the model unchanged as described in Christoffel et al. (2008), which we henceforth refer to as the baseline model. Following Del Negro and Eusepi (2011), we show as a further result that survey expectations and the term structure of interest rates also contain information about the economy beyond the time series used in the baseline model, which improves the general forecast performance of the model. Finally, our results indicate that there is no empirical evidence for a discount parameter in the consumption Euler equation. To underline the robustness of our results, we conduct a series of estimations using a wide range of alternative forecasting time series and specifications in the measurement equations as well as further sensitivity analyses.

The remainder of the paper is structured as follows. In Section 2, we demonstrate the forward guidance puzzle in the NAWM and outline our approach to target the expectations formation process of the model. Section 3 provides information about the model while focusing on the adjustments to append the forecast observables in the estimation, the forward guidance news shock in the Taylor rule and the discount parameter in the Euler equation. Section 4 presents the employed Bayesian estimation techniques, summarises the estimation results and describes the model selection process for our preferred specification. Also, we present the estimation results for the discount factor in the consumption Euler condition. Section 5 illustrates the disciplined expectations formation process and the advancements in the study of forward guidance. In Section 6, we evaluate the model performance of our preferred specification and assess the forecast accuracy using cross-validation on empirical results. We end with robustness checks and sensitivity analyses. Section 7 concludes.

## 2 Monetary policy and expectations

### 2.1 The forward guidance puzzle

Over the last decades, central banks have developed and analysed their communication strategies. Central bank communication has transformed the nature of monetary policy, increasingly guiding the expectations of the market participants about the central bank's understanding of the state and trajectory of the economy. This became particularly evident after the financial crisis when the central banks' space for easing using the conventional rate instrument was reduced. As rates were approaching a lower bound, central banks turned to non-standard measures, including forward guidance on interest rates. To better understand the impact of such measures on the economy, economic research has devoted increasing efforts to introducing non-standard monetary tools into macroeconomic models. DSGE models are widely used in monetary policy research and central banks since they explain macroeconomic transmission mechanisms in a structural manner, are able to adequately fit the data and provide reasonable forecasts. Furthermore, DSGE models are of particular interest to policymakers as they allow to conduct counterfactual scenarios and risk analyses around baseline projections. The ECB is no exception, as the NAWM is one of the workhorse models within the institution, brought to bear on key monetary policy issues. To study the channels of forward guidance and examine the consequences of post-crisis policy actions, the paper contributes to the literature by providing an empirical approach to moderate the forward guidance puzzle and enhancing the applicability of standard monetary DSGE models for the policy analysis.

When addressing the effectiveness of forward guidance, standard DSGE models usually face two constraints which put into question their usefulness for providing monetary policy advice. First, even small forward guidance shocks about monetary policy in the near future lead to large reactions in the model. Second, extending the forward guidance stimulus further to longer horizons results in an explosive behaviour of key variables in the model. The NAWM is subject to both phenomena, as Figure 1 indicates. In Figure 1, the plots show the impulse responses of output growth, inflation, the real exchange rate and the ex-ante annualised real interest rate to credibly announced interest rate pegs. In these simulations, the central bank announces today to keep the interest rate at 20 basis points (bp) below the steady-state for 1 to 10 quarters before reverting to follow the Taylor rule. In this respect, forward guidance on future rates can be seen as a calendar-based monetary policy regime. To solve the model under the peg, we use the algorithm in Kulish and Pagan (2017), which allows for temporary deviations of the interest rate from the Taylor rule in the model. The peak response of a one quarter ahead forward guidance announcement amounts to 0.18 percentage points after three quarters for annual output growth and 0.08 percentage points after five quarters for annual inflation. However, as the figure points out, the responses increase disproportionately when the interest rate pegs are kept for longer. In case of the longest interest rate peg that can be sustained with solvable outcomes by the baseline model, the central bank announces today to keep the policy rate lower for ten quarters. This culminates in a peak response of output growth of 69.08 percentage points after four quarters and a peak inflation response of 32.72 percentage points after five quarters. Due to the explosive behaviour of the model variables to forward guidance shocks, the further extension of the interest rate peg to 11 or more quarters leads to an unstable solution preventing the use of the NAWM from this simulation analysis.

Already some years before the financial crisis, numerous papers studied the effectiveness of monetary accommodation in an environment of low policy rates and offered alternative formulations in the standard New Keynesian model to assess the implausible large reactions of the model variables to committed future monetary policy signals. Coenen and Wieland (2004) discuss the consequences of an exchange-rate peg and price-level targeting in a deflationary environment with nominal interest rates constrained by the lower bound. The authors show that the impact of monetary policy on the economy diminishes when only a fraction of agents expects adjustments in the future policy stance. Caballero and Farhi (2014) find that the influence of forward guidance on economic activity is less pronounced if the driving force behind the zero lower bound on interest rates is the shortage of safe assets in the economy which gives rise to a deflationary safety trap.

A new wave of contributions to the literature seeks to resolve the explosive behaviour of the variables in the New Keynesian model by implementing some type of discounting in the consumption Euler equation. Del Negro et al. (2012) incorporate discounting using an overlapping-generation model similar to Blanchard (1985). By setting a finite time horizon for the agents in the model, the authors yield contained effects of future consumption plans on consumption today. In a similar vein, McKay et al. (2016) modify the agents' intertemporal consumption decisions and expose them to insurable income risks and borrowing constraints. Alternatively, Michaillat and Saez (2018) incorporate wealth in the utility function in the household's side of the DSGE model. Angeletos and Lian (2017) show that a model with incomplete information and uncertainty among the agents dampens the strong reactions to future monetary policy signals. Another way to deal with the implausible responses of current outcomes to forward guidance shocks in the general equilibrium framework is obtained by incorporating bounded rationality and heterogeneous agents. While Gertler (2017) proposes a hybrid adaptive belief mechanism about trend inflation as an alternative to rational expectations, Beqiraj et al. (2019) allow for heterogeneity in the expectations formation to temper the power of forward guidance. Similarly, Gabaix (2016) includes partially myopic, not fully rational, agents in the New Keynesian framework.

Finally, several papers search for an economic rationale to resolve the forward guidance puzzle by adjusting the price dynamics of the New Keynesian Phillips curve. Studying the effects of an interest rate peg in a sticky information model of Mankiw and Reis (2002), Carlstrom et al. (2015) argue that the forward guidance puzzle is attenuated if sticky prices are replaced by sticky information. Kiley (2016) reveals that large parts of the forward guidance multiplier are based on the price rigidity á la Calvo (1983). Incorporating a sticky information price-setting into the New Keynesian model offsets these strong dynamics. Taking into account the importance of the Calvo parameter in DSGE models, we, therefore, conduct a sensitivity analysis in Section 6.3 to shed more light on the dynamics of our model when varying this key parameter.

### 2.2 Model expectations vs. forecast data

In the past years, macroeconomic research has been increasingly more open to the use of real-time macro forecast data to test the model-implied expectations with micro-level evidence from survey expectations. This paper takes on the work of Manski (2004) who was proposing to integrate information about the expectations formation gained by surveys into economic models to understand and predict the individual choice behaviour better. The importance of expectations and anticipated shocks to macroeconomic fundamentals in business cycles was described by Schmitt-Grohé and Uribe (2012). Schmitt-Grohé and Uribe identify the role of expectations by introducing different sources of anticipation into their model. Through the differentiation between an anticipated and an unanticipated component of each structural shock, they show that about half of the dynamics of the growth rates of output, consumption, investment and hours can be assigned to anticipated changes in the economy.

Our work builds on the prominent strand of literature using survey expectations to capture the forward-looking behaviour of the New Keynesian model. Adam and Padula (2003) estimate the New Keynesian Phillips curve making use of data from the Survey of Professional Forecasters (SPF) as a proxy for inflation expectations. Analysing the reaction of the household's intertemporal consumption decisions to changes in future real rates, Crump et al. (2015) exploit forecast data of the Survey of Consumer Expectations (SEC) to estimate the Euler equation. Building on these findings, Coibion et al. (2017) show that employing survey expectations of inflation in the Phillips curve improves the out-of-sample forecasting performance of inflation dynamics and helps to explain the missing deflation puzzle in the aftermath of the financial crisis.

The present paper is strongly related to the work of Del Negro and Eusepi (2011) and Campbell et al. (2016). While Del Negro and Eusepi (2011) show how survey data can be used to align the model-implied expectations with forecast data, Campbell et al. (2016) touch on the finding that models estimated with this kind of data are no longer subject to the forward guidance puzzle. Following Del Negro and Eusepi (2011), Figure 2 displays a comparison between the model-implied expectations of the baseline NAWM and the observed forecast data. The purple lines depict the smoothed series of 4 quarters ahead model-implied expectations of real GDP growth, consumer price inflation and the nominal interest rates over the full estimation sample length 1985Q1 to 2014Q4. The dark blue lines represent the available macro forecasts on output growth and inflation as reported in survey data, and interest rates for the euro area as captured in the market data. In Section 4.1, we provide a more detailed description of the forecast data on which we rely in the estimation. As shown in the figure, there is a notable mismatch between how agents build their expectations in the model and how individuals report their expectations in surveys or form their expectations in the market. On the one hand, the model seems to capture the expected decline in real GDP growth following the financial crisis quite well. The model is, on the other hand, underestimating expected real GDP growth prior to the crisis and is also not able to explain the agents' expectations at the end of the sample. In addition, the model-implied inflation expectations are more volatile than the actual expectations reflected by the data. A prominent example demonstrates the sharp decline in inflation expectations insinuated by the model during the financial crisis, which cannot be seen in the survey data. In case of the nominal interest rate, the figure reveals that the baseline model almost systematically overestimates the expected four quarters ahead policy rate in each period.

Similar to our paper, Campbell et al. (2016) briefly discuss that their re-estimated model with an augmented data set, including expected federal fund rates and survey expectations on inflation, is no longer subject to the forward guidance puzzle. However, we depart from their approach to dampen forward guidance shocks as we do not combine additional observed data with modifications to the model, such as a discount factor in the consumption Euler equation and JR type preferences augmented by habit consumption. We argue that disciplining the model expectations of key structural blocks in the New Keynesian model is the main channel with which the outcome of forward guidance on future rates can be reduced to reasonable levels. Most importantly, within our framework, we can refrain from arbitrary departures from the baseline model and solely rely on the information given by additional observables. Indeed, we show in Section 4.4 that estimating a discount factor using forecast data yields a parameter value close to 1. We argue that there is no empirical evidence for a discount factor in our model and no need to resort to this modification to find an economic rationale for the forward guidance puzzle in the New Keynesian framework.

Given the importance of the macroeconomic forecast data in the paper, we outline in Section 3 an extensive palette of variations in the utilised data and the corresponding measurement specifications to find the adequate and best representation of expectations in the NAWM. For that purpose, we further expand our data set on interest rate forecasts and examine two different approaches. First, we append additional bond yields of different maturities, and second we replace the yield curve with survey data on policy rate expectations. Also, in Section 6.2, we allow for auto-correlated measurement errors in the survey data and for measurement errors in the forecast data on interest rates instead of a forward guidance shock. It is noteworthy that regardless of the data and the applied measurement equation, the outcomes of the forward guidance simulations remain valid. However, we will select our preferred model version, which we will then refer to as NAWM X, via a forecast performance test in Section 4.5. Examining a series of different estimations also provides us with further evidence that the results are robust among different specifications.

## 3 Model

The NAWM is an estimated micro-founded open-economy model of the euro area and one of the main DSGE models at the ECB. The model is particularly designed for the analysis of key monetary policy issues and for the use in the macroeconomic projections (see Warne et al. (2010)). As common in the New Keynesian framework, forward-looking expectations play an essential role in the model. While households maximise their lifetime utility by optimally adjusting their consumption bundle, firms calculate the profit-maximising price scheme of their products. As in Smets and Wouters (2003) and Adolfson et al. (2007), the NAWM employs a large variety of nominal and real frictions, such as sticky prices and wages, habit persistence in consumption, adjustment costs in investment, an imperfect exchange-rate pass-through and costs of adjusting trade flows. These frictions drive the dynamics in the short run enabling the NAWM to match the data adequately and provide reasonable forecasts. A more detailed description of the model can be found in Christoffel et al. (2008). Since we refrain from modifications to the original specification of the NAWM, we focus in the subsequent section on the steps taken to estimate our model with macro forecast data as observables. First, we provide the measurement equations for the forecast data. Second, the incorporation of the forward guidance news shock in the Taylor rule is described. Finally, the section introduces the ad hoc discount parameter in the Euler equation of the model.

**Measurement specification**

To make the model fit for the estimation with forecast data as observables, we define the model agents' expectations formation and the measurement choice. The focus of the paper lies on the expectations formation in the three key structural blocks of the New Keynesian model: inflation, output growth and the nominal interest rate. As the measure of inflation expectations, we use 4 quarters ahead HICP expectations from the ECB's Survey of Professional Forecasters (SPF). The same approach holds for the case of the measurement of output growth expectations where we take 4 quarters ahead expectations of real GDP growth from the SPF database. The application of survey expectations with one year ahead forecasts corresponds with the work of Del Negro and Eusepi (2011) and is already discussed as an adequate length of the forecast horizon in Erceg and Levin (2003). Consequently, we define the agents' beliefs about the future path of inflation in average annual rates as:

$$\pi_{C,4,t} = \mathbb{E}_t(\pi_{C,t+1} + \pi_{C,t+2} + \pi_{C,t+3} + \pi_{C,t+4}). \tag{1}$$

The measurement equation for SPF forecast data on expected inflation 4 quarters ahead is then given by:

$$PIC_t^{SPF} = \pi_{C,4,t} + p + \sigma_\pi \times \eta_t^\pi, \tag{2}$$

where $p = (\bar{\pi} - 1) \times 400$ is the steady-state value of inflation. $\eta_t^\pi$ denotes the measurement error in the forecast data of inflation and $\sigma_\pi$ the corresponding standard deviation. Similar, the agents' beliefs about the future path of average annual output growth is denoted with:

$$\Delta y_{4,t} = \mathbb{E}_t(\Delta y_{t+1} + \Delta y_{t+2} + \Delta y_{t+3} + \Delta y_{t+4}), \tag{3}$$

which yields a measurement equation for SPF forecast data on expected output growth 4 quarters ahead:

$$DYA_t^{SPF} = \Delta y_{4,t} + g + \sigma_{\Delta y} \times \eta_t^{\Delta y}. \tag{4}$$

The equation contains a steady state value of output growth $g = ((\bar{g_E} - 1) + (\bar{g_z} - 1)) \times 400$, where $\bar{g_E}$ denotes the steady state growth rate of the labour force and $\bar{g_z}$ the steady state growth rate of labour productivity. $\eta_t^{\Delta y}$ represents a measurement error in the forecast data of output growth and $\sigma_{\Delta y}$ the standard deviation on the measurement error.

For the case of expectations about the future development of the policy rate, we adopt several different approaches and achieve identification via the information from the yield curve of 1 year maturity, a set of yield curves of 6 months, 9 months, 1 year and 2 years maturity, or alternatively 4 quarters ahead interest rate expectations from the SPF database. Concerning the incorporation of bond yields as observable variables, we rely on the previous work of De Graeve et al. (2009) and Kulish et al. (2017). In their work, the path of the bond yields is determined by the expectations hypothesis implying that the long-term bond yield is the average of current and expected short term bond rates. In addition, a term premium $c_j$ captures the risks of holding long-term bonds which we assume to be constant over time. Following Kulish et al. (2017), the agents' beliefs about the future path of the policy rate is constructed as:

$$r_{j,t} = \frac{1}{j}\mathbb{E}_t(r_t + r_{t+1} + ... + r_{t+j-1}), \tag{5}$$

where $r_{j,t}$ describes the log deviation of the j-period bond yield from steady-state. This results in a measurement specification for bond yields of 1 year maturity:

$$yc^{1Y} = r_{4,t} + r + c_4, \tag{6}$$

where $r = (\bar{r} - 1) \times 400$ is the steady state of the nominal interest rate and $c_4$ denotes the 1 year bond term premium, which we assume to be constant.[1] As an alternative formulation of the agents' interest rate expectations, we replace the term structure with SPF point forecast data on expected interest rates 4 quarters ahead. The agents' beliefs about the policy rate 4 quarters ahead are then expressed by:

$$r_{4,t} = 4 \times \mathbb{E}_t(r_{t+4}). \tag{7}$$

[1] In the same way, the measurement specification is constructed for euro area bond yields of 6 months, 9 months and 2 years maturity.

Thus, the measurement equation for SPF forecast data on the interest rate 4 quarters ahead is defined by the equation:

$$R_t^{SPF} = r_{4,t} + r, \tag{8}$$

where $r = (\bar{r} - 1) \times 400$ denotes again the steady-state value of the nominal interest rate.

**Forward guidance news shock**

We enrich the Taylor rule with a forward guidance news shock mainly for two reasons. The forward guidance news shock allows us not only to disentangle the effects of current and future monetary policy shocks on macroeconomic variables in the model. It also turns out that the direct mapping of the forward guidance shock in the Taylor rule helps to better identify the information from the forecast data refining the interest rate expectations generated by the model. The explicit incorporation of an additional shock results in model-implied interest rate expectations closer to the real-time macro forecast data compared to the case where we replace the shock with a measurement error in the measurement equation. However, we emphasise that all our results are still valid when we leave the monetary policy rule unchanged to the baseline version of the NAWM.

We consider two alternatives of the policy rule based on the number of additional time series of interest rate expectations applied in the estimation. For the case of the yield curve of 1 year maturity, as well as the SPF survey data on interest rates 4 quarters ahead, we introduce a single 4 quarters ahead forward guidance shock in the Taylor rule:

$$\begin{aligned} r_t = \phi_R r_{t-1} + (1 - \phi_R)(\bar{\pi} + \phi_\Pi(\pi_{C,t-1} - \bar{\pi}) + \phi_Y y_t) \\ + \phi_{\Delta\Pi}(\pi_C - \pi_{C,t-1}) + \phi_{\Delta Y}(y - y_{t-1}) + \epsilon_t^R + \epsilon_{t-4}^{4,FG}. \end{aligned} \tag{9}$$

Alternatively, for the case of four separate term structure on interest rates of 6 months to 2 years maturity, we incorporate a series of announced future policy shocks which denotes the Taylor rule as:

$$\begin{aligned} r_t = \phi_R r_{t-1} + (1 - \phi_R)(\bar{\pi} + \phi_\Pi(\pi_{C,t-1} - \bar{\pi}) + \phi_Y y_t) \\ + \phi_{\Delta\Pi}(\pi_C - \pi_{C,t-1}) + \phi_{\Delta Y}(y - y_{t-1}) + \epsilon_t^R + \epsilon_{t-1}^{1,FG} + \epsilon_{t-2}^{2,FG} + \epsilon_{t-3}^{3,FG} + \epsilon_{t-4}^{4,FG}. \end{aligned} \tag{10}$$

In either monetary policy rule, $\epsilon_t^R$ is the shock to the nominal interest rate and $\epsilon_{t-i}^{FG}$ are uncorrelated forward guidance news shocks. We assume that both, the monetary policy shock and the forward guidance shock, follow an AR(1) process: $\epsilon_t^R = \rho_R \, \epsilon_{t-1}^R + \sigma_R \, \eta_t^R$. However, we assume no autoregressive components in the forward guidance shocks and therefore set $\rho_{FG}$ to 0.

### Discount factor

Drawing on the work of McKay et al. (2016), we aim to shed light on the value of the discount parameter in the Euler equation condition, which recently has been discussed extensively in the literature. Therefore, we conduct a second series of estimations introducing an ad hoc discount factor $\psi$ in the Euler equation of the model. The discount parameter arises from the idea to reduce the impact of future monetary policy shocks on real macroeconomic variables in the model. In this respect, the discount parameter in our model can be thought of as a reduced-form representation of other modelling approaches, such as finite-lived agents or agents who have assets in their utility function. The log-linearised first-order condition in the model that relates to the marginal utility of consumption with discounting is then described by:

$$\lambda_t = \psi \, \lambda_{t+1} - g_{z,t+1} + r_t - \pi_{C,t+1} + \epsilon_t^{RP}, \tag{11}$$

where $\psi$ represents the discount parameter. By introducing the discounting parameter in the marginal utility of consumption equation, we will reduce the impact of future consumption and investment decisions on current consumption and investment for values of $\psi$ below one.

## 4 Bayesian estimation

In this section, we first discuss the Bayesian techniques for the estimation of the model. We then provide information about the data, the calibrated parameters, prior and posterior distributions. Finally, we analyse the estimation of the discount factor in the consumption Euler equation and evaluate the forecasting performance of the competing models to select the preferred specification and measurement choice.

The estimation is performed with Bayesian methods as in Schorfheide (2000), and An and Schorfheide (2007). The posterior mode is computed with Chris Sims's optimiser *csminwel* and the Monte-Carlo Markov-Chain(MCMC) algorithm is used for the posterior distribution. To simulate the distribution of the parameter vector, we discard the burn-in of the first 90% of the posterior simulations as the fraction of initially generated parameter vectors to be dropped. Accounting for a large number of estimated parameters in the model, we adopt two parallel chains for the Metropolis-Hastings algorithm with 2,000,000 replications to obtain convergence of the posterior sampling.[2]

### 4.1 Data

Apart from the macroeconomic forecast data, the choice of the time series used in the estimation follow Christoffel et al. (2008) and Coenen et al. (2018). We adopt the same 18 time series as in Christoffel et al. (2008) and apply the data construction described in Coenen et al. (2018) to get consistency with the model properties of the NAWM. We explicitly decide to restrict the sample length for the observed variables to the periods prior to the zero lower bound in the euro area to impede to incur in the inaccuracy of linearised solutions which would arise in that case (see Fernandez-Villaverde et al. (2015)). Accordingly, the full sample period of the data set ranges from 1985Q1 to 2014Q4.

To moderate the forward guidance puzzle in the NAWM, the paper pursues the approach to guide the expectations formation process of the forward-looking variables in the key blocks of the model: the consumption Euler equation, the New Keynesian Phillips curve and the Taylor rule. To this end, we augment the already rich data set with three to five additional forecast time series on output growth, inflation and interest rate expectations. In Figure 3, we present the forecast data on the expected rates of inflation, real GDP growth and the nominal interest rate. Concerning the macroeconomic expectations for the rates of inflation and real GDP growth, we resort to the ECB Survey of Professional Forecasters (SPF), which is a quarterly issued survey in the euro area for several horizons. The SPF data is constructed as the average of the point forecasts of experts affiliated with financial or non-financial institutions based within the European Union.[3] To measure interest rate expectations, we either take euro area yield curves, which can be interpreted as the market expectations of the future development of the monetary policy, or SPF data on expected 4 quarters ahead nominal interest rates. While the yield curves

[2] Dynare, a software platform running on top of the programming language Matlab, is used for all computations to solve and estimate our model (see Adjemian et al. (2018)). More information about Dynare can be found here: `http://www.dynare.org`.

[3] The data and a detailed documentation are available at the ECB Statistical Data Warehouse: `https://sdw.ecb.europa.eu/`.

for the euro area are available in quarterly frequency since 2004Q3, the survey data is taken from the SPF database beginning in 2002Q1.

### 4.2 Calibration and prior distributions

Calibrated parameters are based on the description in Christoffel et al. (2008). In the measurement specification of the forecast observables, we impose a balanced-growth path on the real side of the economy with all variables considered to grow at a rate of 2.0 percent per year. The steady-state growth rate of 2.0 percent can be broken down into two components: a steady-state growth rate of 1.2 percent for labour productivity $\bar{g_z}$, and a steady-state growth rate of 0.8 percent for the labour force $\bar{g_E}$, representing a proxy for the growth rate of the population. On the nominal side, we assume a steady-state annual inflation rate $\bar{\pi}$ of 1.9 percent, in line with the policy mandate of the ECB.

Also, the prior information does not significantly deviate from the baseline specification and is taken as in Christoffel et al. (2008).[4] The third column in Table 1 reports a detailed description of the adopted prior distributions. Emphasising the additional parameters introduced for the estimation based on interest rate expectations represented by yields of 1 year maturity, we implement a term premium with prior mean of 0.1 and a standard deviation of 0.25. Further, the prior information for the standard deviation of the forward guidance shock follows the specification of all the remaining shock standard deviations (see Parameter Group I in Table 1). Finally, we have chosen a rather tight specification regarding the measurement errors on expected inflation and output growth with a prior mean of 0.07 and a standard deviation of 0.3 modelled as inverse gamma distributions.[5]

### 4.3 Estimation results

In Table 1, the prior and posterior distributions of the estimated parameters are listed. The estimation results are related to the measurement specification of the model with euro area yields of 1 year maturity as a proxy for interest rate expectations. In the following sections,

[4] There is only one minor modification in the prior specification compared to the description in Christoffel et al. (2008). In the estimation with bond yields of 1 year maturity, the prior mean of $\mu^\star$ is reduced to 1.0. In addition, the prior standard deviation of $\mu^\star$ is chosen to be 0.1 in the estimation with SPF data on expected 4 quarters ahead interest rates and increased to 0.5 in the estimation with a set of yield curves at maturities of 6 months, 9 months, 1 year and 2 years. These minor modifications were necessary to get to run Sims's optimiser *csminwel* for the computation of the posterior mode.

[5] In the case of the estimation with four euro area yield curves, we reduce the prior mean to 0.05. In case of SPF data on the expected interest rate, we assume a prior mean of 0.01 and a prior standard deviation of 0.25.

this model specification will be referred to as NAWM X. Later in Section 4.5, we show that this model choice dominates the prediction accuracy among our competing models in the forecasting exercise. Besides the prior mean, the prior standard deviation and the shape of the prior density in the third column, the table contains the posterior mean estimates as well as the 10% and 90% percentiles of the posterior distribution in the right-hand columns. In addition, Table 2 summarises the posterior mean of the baseline NAWM as well as the posterior distributions of the NAWM X and the two alternative estimations with SPF forecast data on 4 quarters ahead interest rate expectations and the set of yields of 6 months to 2 years maturity.

In comparison to the baseline model, the parameters driving the dynamics of domestic demand are slightly higher. For instance, the parameter $\kappa$, describing the degree of habit formation in consumption, denotes 0.67 in the NAWM X instead of 0.57 in the baseline. Similarly, the adjustment costs of investment $\gamma_I$ increase to 5.84 in the NAWM X, the import content of consumption $\gamma_{IM^C}$ to 7.86 and the import content of investment $\gamma_{IM^I}$ to 0.62. Those estimates are broadly in line with the values reported in Coenen et al. (2018). In contrast, the export market share $\gamma^\star$ falls to 0.32. Remarkably, the estimated value of the export market share $\gamma^\star$ falls out of line in the estimation with SPF data on interest rate expectations resulting in a posterior mean value of around 8.20. In block D, summarising the parameters of the final-good production, the increase in the substitution elasticity for consumption $\mu_C$ to 2.32 is also stated in Coenen et al. (2018). However, the estimation of the NAWM X comes along with a sharp decline in the value of the price elasticity on exports $\mu^\star$.

On the wage and price-setting side, we can see that the indexation parameters for domestic prices and import prices have decreased substantially. More importantly, however, the Calvo parameter on domestic prices has increased further starting from an already high level of 0.92 to around 0.95 in the estimations with macro forecast data. Due to the forecast data on inflation expectations, the model-implied inflation expectations are getting more sticky. Not surprisingly, the model translates the less volatile inflation dynamics into a higher value for the domestic Calvo parameter. This is why in the forward guidance simulations in Section 5.1 and in the sensitivity analysis in Section 6.3 the importance of the Calvo parameter for the model dynamics is discussed in more detail.

Newly adopted in the NAWM X, the bond risk premium parameter takes a value of 0.05 for yields of 1 year maturity. Unfortunately, in the second case with a set of yield curves, the values of the estimated risk premia do not involve a rising pattern with an extended duration of the bonds. With respect to the parameters guiding the monetary policy, the table reports a more persistent interest rate smoothing parameter $\phi_R$ and a lower Taylor rule response to a change in output growth $\phi_{\Delta Y}$. Even though all Taylor rule parameters play a crucial role in how the model reacts to forward guidance shocks, particularly the parameter $\phi_{\Delta Y}$ is a critical driver for the moderation of the forward guidance puzzle, as we describe in Section 5.1.

The properties of the structural shocks are in general closely aligned to the baseline model with the prominent exception of the standard deviation and autoregressive coefficient of the permanent technology shock $g_{z,t}$, the wage markup shock $\varphi_t^W$ and the import demand shock $\epsilon_t^{IM}$, which are all significantly stronger on impact, but less persistent over time. One interesting case is the export preference shock whose standard deviation is far smaller in the estimations with yield curves than in the estimation with SPF data on interest rate expectations. It is noteworthy that the standard deviation of the forward guidance shock takes a similar value as the standard deviation of the monetary policy shock. Yet, in the estimation with a set of term structure of interest rates the standard deviations of both monetary shocks more than double leading to a decrease in the forecasting performance in the short run and enticing us to exclude this measurement specification from our preferred model choice. The posterior mean of the standard deviation of the measurement error is estimated to be 0.43 for inflation and 0.57 for output growth.

Finally, Figure 4 to 6 indicate how much information the observables contribute to the estimation of the structural parameters. With the exception of the Calvo parameter on wages $\xi_W$, the figures hint that the data is rather informative for most of the parameters.

### 4.4 Estimating the discount parameter

We capitalise on the use of forecast data as observables and aim to identify the discount parameter in our models through the additional data outlined in 4.1. As discussed in Section 3, we introduce a discount factor $\psi$ in the consumption Euler equation condition in our previously described models. The discount parameter has been chosen to be modelled as beta distribution with prior mean of 0.9 and prior standard deviation of 0.05. The prior and posterior distributions of the discount factor are summarised for all models in Table 3. The estimation results give a strong indication for concluding that a discount factor cannot be supported in the NAWM. In all cases, the discount parameter leans towards a border solution and takes a value of close to one.

Interestingly, we can find the same result when implementing the discount factor in the baseline model and estimating the model without real-time macro forecasts. Given the low discounting in the Euler equation, the parameter has only negligible effects on the forecasting accuracy, the expectations formation process and the forward guidance simulations. For that reason, we discard the incorporation of a discount factor in the subsequent sections.

### 4.5 Model selection

In this section, we evaluate the forecast accuracy of the competing models by analysing the out-of-sample forecasting performance for a one- to eight-quarters ahead forecast horizon. To compare the forecasting performance and select the preferred model specification, we compute the root-mean-square errors (RMSE) forecast for output growth, inflation, wage inflation as well as the nominal interest rate, relative to the baseline NAWM. However, we re-estimate the baseline model and take the same sample length as specified for the competing models to ensure that the forecast evaluation is not biased solely due to additional information extracted by the extension of the estimation sample. Therefore, we also adjust the prior information in our baseline model for the parameter $\mu^{\star}$ described in Section 4.2 and once again estimate the baseline model employing the Bayesian estimation techniques stated in Section 4.

Figure 7 reports the RMSE forecast as a ratio to the benchmark model for one- to eight-quarters ahead forecasts over the evaluation period 2000Q1 to 2016Q4. The purple horizontal lines represent the benchmark values for the baseline NAWM. The orange lines denote the preferred model estimated with euro area yields of 1 year maturity as a proxy for interest rate expectations (NAWM X), whereas the green and the blue lines indicate the forecast accuracy for the models with an alternative choice for the measurement of interest rate expectations. Overall, the estimated models with forecast observables are competitive against the NAWM baseline and dominate along most dimensions. In line with Del Negro and Eusepi (2011), Figure 7 shows that adding forecast data to the estimation data set improves the predictive ability of the model. This is particularly true for the out-of-sample forecast accuracy of consumption deflator inflation, wage inflation and the nominal interest rate. In contrast, the effect on real GDP growth is not particularly noticeable.

As shown in Figure 7, the RMSE forecast of the competing models are lower for consumption deflator inflation as well as wage inflation in the short run and align with the prediction accuracy of the benchmark model in the medium-term forecast. It is noteworthy that the RMSE forecast for consumption deflator inflation is reduced by around 20% for a forecast horizon of up to five quarters ahead by all competing models. In the case of wage inflation forecasts, the two models estimated with yield curves have an approximately 40% lower RMSE forecast for two quarters ahead and still a 20% lower RMSE forecast for five quarters ahead forecasts. These results confirm Coibion et al. (2017) who state that employing survey inflation expectations in a Phillips curve improves the ability to rationalise and forecast inflation dynamics. Also, the RMSE forecast for the nominal interest rate is reduced by around 10% in the short horizon and 40% in the medium horizon with the notable exception of the one quarter ahead forecast of the model with interest rate expectations conditioned on yield curves at maturities of 6 months to 2 years. We trace this outcome back to an overfitting of interest rate expectations in the short run and hence refrain from this measurement choice as the preferred one. Taking all these results into account, we select as the preferred specification the model estimated with interest rate expectations identified by the informational content of the yield curve of 1 year maturity. In the Appendix A, the absolute values of the forecast RMSE are provided in Table A.1.

Figure 8 shows the one- to eight-quarters ahead mean out-of-sample forecasts of the NAWM X for real GDP growth, consumption deflator inflation, wage inflation and the nominal interest rate for the periods 2000Q1 to 2018Q4. The figure reveals that the NAWM X provides quite reasonable forecasts for real GDP growth and inflation. Especially the use of real-time forecasts on inflation contributes to an enhancement of inflation forecasts, which are in general stated to be difficult to predict. For example, the gradual downward trend in inflation expectations since the financial crisis is reflected in the forecasts for inflation. Not surprisingly, however, the NAWM X is not able to provide sound forecasts for the periods around the financial crisis since it does not incorporate a financial sector.

## 5 Disciplining expectations in the model

Section 5 takes on the discussion of Section 2.2 and addresses the question of whether the model-implied expectations adequately represent the expectations observed in the data. For that purpose, we are once again interested in the comparison of the four quarters ahead smoothed variables for expected output growth, inflation and the nominal interest rate. As in Figure 2, we plot the model expectations against the observed forecast data and analyse if the model variables, computed based on the available information given for all observations, are able to track the time series data. In Figure 9, the dark blue lines show the observed four quarters ahead SPF forecast data on expected rates of real GDP growth and inflation as well as the euro area yield curve of 1 year maturity. The purple lines mark the model-implied expectations of the baseline NAWM and the orange lines depict the smoothed series of the NAWM X.

The figure points out that the NAWM X better captures the dynamics of the four quarters ahead expectations of key macroeconomic variables over the whole horizon of the forecast data. Thanks to the implementation of the additional time series in the estimation, the deviation of the model expectations from the data can be diminished. In case of real GDP growth expectations, the RMSE between SPF data and baseline NAWM is 1.43, whereas the RMSE is 0.56 between SPF data and NAWM X. Also in case of inflation expectations, the deviation between SPF data and NAWM X is remarkably lower. More concretely, the RMSE is 1.27 between SPF data and the baseline model, whereas it is only 0.42 between SPF data and NAWM X. Finally, the RMSE of nominal interest rate expectations is reduced from 1.36 to 0.73 in the NAWM X.

When we examine the expectations formation of the pre-crisis period, the figure reveals that the NAWM X offsets the underestimation of output growth expectations and the overestimation of inflation expectations. Interestingly, both models capture the drop in real GDP growth expectations during the Great Recession very precisely. However, only the NAWM X predicts the relatively stable development of inflation expectations during that period correctly. Also, the second decline of real GDP growth expectations in the wake of the European debt crisis is only anticipated by the NAWM X.

Turning to the analysis of the volatility of the model-implied expectations, we can see that the expectations data enables the model to form less fluctuating expectation forecasts. While in the baseline NAWM the standard deviation of real GDP growth expectations is 1.36 and the standard deviation of consumption deflator inflation expectations is 1.33, the model expectations of the NAWM X exhibit a standard deviation of 1.31 for real GDP growth and a standard deviation of 0.90 for consumption deflator inflation. Further, given that the interest rate development resembles a unit-root process over the sample time horizon, we study the volatility of "interest rate growth" expectations. The NAWM X is found to have a reduced standard deviation of 0.51 in contrast to a standard deviation of 0.92 in the baseline. In sum, the inclusion of expectations data materialises in a new parametrisation leading to more sticky, less volatile model-based expectations. In that way, the information contributes to avoiding erratic fluctuations of the expected variables in the model which are not seen in the data. In the next section, we argue that this channel has a crucial impact on the forward guidance puzzle in the NAWM.

### 5.1 Tackling the forward guidance puzzle

Drawing on the findings in Section 2.1, we replicate the forward guidance exercises with the NAWM X. Equivalent to the exercise shown in Figure 1, the monetary authority credibly announces today to peg the interest rate at 20 bp below steady-state for a specific time horizon before the Taylor rule takes over again. Figure 10 reports the results of 20 different forward guidance simulations with a varying length of the interest peg for key macroeconomic variables in the NAWM X. On the right upper panel of the figure, the graph shows the curves of the nominal interest rates which are stuck at the peg for 1 to 20 quarters. The remaining plots depict the model responses for real GDP growth, consumption deflator inflation, the real exchange rate and the ex-ante real rate in annual terms.

Compared to Figure 1, the graph illustrates the considerable improvement of the simulation outcomes as well as the more plausible development of the economy following forward guidance, notably the absence of any explosive behaviour. While the peak response of a one quarter ahead forward guidance shock is roughly the same in both models for output growth and inflation, the outcome for an announced interest rate peg for four quarters is already reduced by around 40% for output growth and by around 75% for inflation. A substantial difference is then seen in case of an interest rate peg for 10 quarters. Contrasting with the peak response of output growth of 69.08 percentage points and of inflation of 32.72 percentage points in the baseline NAWM, the reactions are respectively as sizeable as 0.98 percentage points for output growth and 0.24 percentage points for inflation in the NAWM X.

Thanks to the new parametrisation and the capacity to discipline the model-implied expectations, the NAWM X is eminently better equipped to study the effects of forward guidance announcements. As a result of the exploitation of the informational content given by the forecast data, the model-based expectations are better aligned to survey and marked-based expectations and the model is more resilient to explosive dynamics in the face of credibly announced long-lasting interest rate pegs. The moderation of the forward guidance puzzle also entails the welcoming side effect that the model refrains from an overshooting of the policy rate as soon as the central bank leaves the interest rate peg. Instead, the policy rate converts smoothly back to the steady-state, suggesting a reasonable path for the nominal interest rate in the aftermath of the forward guidance policy. Moreover, the figure accentuates that the conditioning of the model expectations to real observed forecast data allows the NAWM X to extend the monetary accommodation to more than 10 quarters while maintaining plausible results. Opposed to the baseline, the NAWM X converges to a stable solution path for long-lasting forward guidance policies due to the absence of any explosive behaviour.

Consequently, the marginal increase of holding the policy rate pegged for one additional quarter presents a contrasting picture between the two models. In Figure 11, we compare the marginal impact of real GDP growth and consumption deflator inflation to an additional quarter of forward guidance between the NAWM and the NAWM X. Whereas in the NAWM forward guidance becomes disproportionately more effective the longer the interest rate is stuck at the lower bound, the marginal impact in the NAWM X seems to stay constant over time. Zooming on the exact values of the orange line, Table 4 reports the marginal impact of extending the interest rate peg for one additional quarter at a given time period on real GDP growth and inflation.

To isolate the parameters responsible for the mitigation of the forward guidance puzzle, we replace step-wise the new parametrisation with the original parameter values of the baseline. A more in-depth analysis, aimed at pinning down the parameters which bear the responsibility for the dampened forward guidance simulations, exposes the importance of the domestic Calvo parameter $\xi_H$ and the Taylor rule parameter responding to changes in output growth $\phi_{\Delta Y}$. Calibrating either of the two parameters back to the baseline NAWM value ends up again in implausibly large model responses, explosive behaviour and an unstable solution path for long-lasting forward guidance policies. However, this implies, on the other hand, that if we calibrate the remaining estimated parameters back to the baseline values, the outcome of the forward guidance simulations remains roughly unchanged compared to the NAWM X. It is important to note that the value of the parameter $\phi_{\Delta Y}$ is a necessary, but not sufficient condition to moderate the forward guidance puzzle. In fact, if we take the baseline NAWM and reduce the parameter $\phi_{\Delta Y}$ to the value of the NAWM X, the model is still subject to the forward guidance puzzle. Modest, but noticeable, effects can also be seen if the values of the indexation parameter $\chi_H$, the import content of consumption $\gamma_{IM^C}$ and the substitution elasticity between distinct bundles of domestic and foreign intermediate goods $\mu_C$ are re-calibrated to the baseline. Yet, even changing the value of these three parameters together back to the baseline increases the model response to a forward guidance shock only by a marginal amount. In sum, the main driving forces behind the dynamics of the DSGE model after medium to long-term forward guidance announcements are linked to the price-setting behaviour in the New Keynesian Phillips curve and the Taylor rule.

In addition, the incorporation of all three additional forecast time series is crucial to discipline the model expectations and control for reasonable outcomes in the forward guidance exercises. Even though the exclusion of the survey data on either real GDP growth or inflation expectations still does not offset the resolution to the explosive behaviour, the peak responses of the key variables in the model increase substantially. In case of the exclusion of both survey-based observables, the dynamics of the model start to become again implausible and unstable.

## 6 Model performance

In Section 6, we evaluate the model performance of the NAWM X to ensure that the preferred specification is still suitable to assess a wide range of macroeconomic policies and projections. First, this section studies the historical decomposition and the forecast-error-variance decomposition telling us how the model attributes the contributions of the structural shocks to the fluctuations of the observed variables. To this end, the introduction of a forward guidance shock in the Taylor rule allows us to disentangle the effects of monetary policy communication from standard monetary policy shocks in the model. The section also provides insights into the model dynamics and transmission channels of the interest rate shock and the forward guidance shock. We further verify the impulse response functions by comparing the model properties of the NAWM X with the baseline model.[6] The second part of this section compares the impulse responses of the NAWM X with empirical evidence in the literature, analyses the robustness of our results and conducts a sensitivity analysis varying one key parameter of the forward guidance simulations.

### Historical decomposition

As a first application, we briefly discuss the historical shock decomposition through the lens of the NAWM X in Figure 12 and 13. The observed variable decomposition disentangles the historical dynamics of real GDP growth and inflation as an interpretation of the structural shocks in the model. Due to their relatively large number, the shocks are grouped into six categories: technology, demand, markups, monetary policy, forward guidance and foreign shocks. As a

[6] In the Appendix A, the impulse response functions to further structural shocks are shown.

modification to the baseline model, the introduction of a forward guidance news shock allows us to distinguish between the effects of interest rate adjustments in the present and news on the future path of monetary policy.

In Figure 12, the shock decomposition is provided for the year-on-year rates of real GDP growth for the periods 2000Q1 to 2018Q4. The figure shows that forward guidance played an important role during the economic slowdown in the early 2000s, the Great Recession, the European debt crisis and in recent years. In this analysis, we make use of the term *forward guidance* in a broader way and follow the line of Gürkaynak et al. (2005). Forward guidance in this sense implies all statements of the ECB which contain information about the future path of monetary policy and goes beyond the concept of *forward guidance* as an explicit tool of unconventional monetary policy. The figure highlights the importance of central bank communication as a driving force behind the fluctuations of economic activity. However, the impact of forward guidance has steadily grown over the time horizon signalling reinforced monetary accommodation. Notably in Figure 13, the NAWM X attributes large parts of the positive stimuli for inflation between 2000Q1 and 2018Q4 to forward guidance news shocks. In that way, the figure discloses the rising importance of forward guidance for inflation dynamics over the last two decades. Therefore, this finding uncovers that central bank communication makes a difference in moving inflation expectations in times of interest rates close to or at the effective lower bound. For comparative purposes, the historical shock decomposition of the baseline NAWM is also provided in the Appendix A.

**Forecast-error-variance decomposition**

In Table 5, we report the contributions of the structural shock groups to the forecast-error variances of real GDP growth, consumption deflator inflation and the nominal interest rate in the NAWM X. To facilitate the presentation, we again bundle the structural shocks together into six shock groups: technology, demand, markups, monetary policy, forward guidance and foreign. The table provides a detailed summary of the forecast-error variances at the 1 quarter, 4 quarters, 16 quarters and 40 quarters horizon, as well as the unconditional variance decomposition. In case of real GDP growth, the model attributes most of the variability in the short run to the domestic risk premium shock and the permanent technology shock. While technology-driven fluctuations are slightly decreasing over time, the share of the demand factors, markups and forward guidance gains prominence. However, the overall shock contributions by group are relatively stable and do not vary substantially over different time horizons.

The results of the forecast-error variances for inflation depict a different picture. Even though the domestic price markup shock is responsible for most of the variability in the short run, its contribution decreases to less than 40% in the 20 and 40 quarters horizon. Conversely, technology, demand and foreign driven factors represent a significant share of the forecast-error variances in the long run. More precisely, the domestic risk premium shock accounts for around 35% and the foreign risk premium shock for approximately 10% of the long-term dynamics of inflation. Also, the monetary shock and the forward guidance shock become increasingly more important in explaining the inflation dynamics over time.

The shock contributions for the decomposition of the forecast-error variances of nominal interest rates follow the prevailing view that monetary policy shocks dominate the variability in the short run and that demand-driven factors kick in in the long term. In addition, technology shocks, the domestic price markup shock, the forward guidance shock and the foreign risk premium shock trigger noticeable variability in the interest rate.

**Impulse responses**

From the forward guidance exercise, we might infer that the effects of monetary shocks tend to be dampened in the NAWM X. Figure 14 and Figure 15 give more insights into how the model reacts to a standard monetary policy shock and to the newly introduced forward guidance shock. Both figures report the model responses to a negative shock by the size of one standard deviation implying an expansionary monetary policy stance. In Figure 14, the impulse responses to a monetary policy shock are qualitatively in line with the baseline model and follow the general understanding of a loosening monetary policy. While the model reaction of inflation is slightly milder relative to the baseline, real GDP, consumption, investment as well as wages respond more strongly to a monetary shock.

Figure 15 shows the typical pattern of a forward guidance shock in DSGE models. The signal of the monetary authority to decrease the interest rate in the future leads to adjustments in the agents' consumption and investment plans today. As a consequence, the central bank attempts to counteract the positive developments with an interest rate increase in the present. In sum, a negative four quarters ahead forward guidance shock triggers the same qualitative model responses as the interest rate shock even though the order of magnitude differs. Even if the model reactions to forward guidance are mitigated in the NAWM X, the figures underline that the impulse responses to a standard monetary shock are only marginally influenced by the new parametrisation and cannot explain the muted power of forward guidance.[7]

### 6.1 Comparison with empirical evidence

Having acknowledged the capacity of the model to temper the responses to forward guidance shocks, a comparison with other evidence from the literature is provided. In the NAWM X, the four quarters ahead announcement of rate easing that reduces the annual interest rate by about 35 bp in one year's time, see Figure 15, results in a peak effect in annual inflation and GDP growth of about 17 bp and 69 bp, respectively. Christoffel et al. (2019) develop a Bayesian vector autoregression (BVAR) model that identifies forward guidance shocks separately from unanticipated monetary shocks by using sign and zero restrictions. They show that a forward guidance shock of the same magnitude increases annual inflation and GDP growth by 11 bp and 62 bp, respectively. Using intraday data, Andrade and Ferroni (2018) find a peak reaction of 19 bp in reaction to a 35 bp widening in 12-months and 3-months EONIA swaps. In a sign and zero restrictions BVAR that features identification similar to that in Christoffel et al. (2019), Zlobins (2019) conducts a six-variable structural vector autoregression (SVAR) with monthly euro area data. He finds slightly higher reactions of inflation and GDP growth at 25 bp and 77 bp for a 4 quarters ahead forward guidance announcement that moves the 1 year forward rate by 35 bp. The more pronounced reaction may be explained by the different sample horizons: Zlobins (2019) focuses on the most recent period that includes asset purchases, sub-zero rates and explicit forward guidance announcements. As shown in Coenen et al. (2017), forward guidance announcements became more credible with the introduction of asset purchases. This enhanced credibility may have been translated into a stronger response of macro variables.

Moreover, contrasting the dynamics of a forward guidance shock with that from an unexpected monetary policy shock, the above papers all find that forward guidance shocks result in more pronounced dynamics than unanticipated monetary policy shocks of the same magnitude. Figure 14 shows the reaction of the NAWM X in response to an unanticipated easing of 38 bp: annual inflation and real GDP growth increase by 11 bp and 45 bp at their peak. The BVAR by Christoffel et al. (2019) arrives at a maximum reaction of 8 bp in inflation and 20 bp in GDP

[7] We provide additional impulse responses of the NAWM X in the Appendix A.

growth. Andrade and Ferroni (2018) report a 13 bp increase in annual inflation following a 38 bp unanticipated tightening.

The dynamics of the NAWM X in response to monetary policy shocks therefore firmly fit into evidence from other sources. This is remarkable enough, given the very different techniques in the empirical methods compared to our DSGE approach. In addition, all studies employ data on expectations from various sources and at different frequencies. This analysis is therefore an important cross-validation of all these papers.

### 6.2 Robustness

To control for the robustness of our results and to take into account alternative formulations of the measurement equation for the forecast observables, we consider four different variations of the NAWM X. First, we allow for autoregressive parameters in the measurement error of the measurement equations of the real-time forecast observables. Second, we include a weight parameter in the measurement equation and let the model decide to what extent the information from the forecast observables are exploited in the estimation. Also, we estimate a model in which we combine the first two alternatives. Last, we replace the forward guidance shock by a measurement error in the measurement equation to verify to which amount this modification is causal for the moderation of the forward guidance puzzle. To validate the robustness test, we compute the out-of-sample forecast accuracy and apply the model selection process outlined in Section 4.5.

The first robustness test is motivated by the conjecture that the survey participants report systematically biased forecasts, meaning that the observed forecasts display correlated errors. Under the hypothesis of correlated errors, the inclusion of an autoregressive component $\rho_\pi$ in the measurement error of the measurement equation for the SPF forecast data on expected inflation 4 quarters ahead results in:

$$PIC_t^{SPF} = \pi_{C,4,t} + p + \epsilon_t^\pi, \tag{12}$$

with $\epsilon_t^\pi = \rho_\pi \times \epsilon_{t-1}^\pi + \sigma_\pi \times \eta_t^\pi$. In a same manner, the incorporation of an autoregressive component $\rho_{\Delta y}$ in the measurement error of the measurement equation for the SPF forecast data on expected output growth 4 quarters ahead gives:

$$DYA_t^{SPF} = \Delta y_{4,t} + g + \epsilon_t^{\Delta y}, \tag{13}$$

where $\epsilon_t^{\Delta y} = \rho_{\Delta y} \times \epsilon_{t-1}^{\Delta y} + \sigma_{\Delta y} \times \eta_t^{\Delta y}$. Applying Bayesian inference techniques, the estimation yields with 0.87 for $\rho_\pi$ and 0.79 for $\rho_{\Delta y}$ relative high values for the autoregressive parameters. Calculating the prediction accuracy reveals that the inclusion of auto-correlated components deteriorates the model performance significantly.

Second, we conduct the experiment to incorporate a weight parameter $\omega$ in the measurement equation to test whether the model actually chooses to use the additional information from the forecast times series. The measurement equations then adjust to:

$$PIC_t^{SPF} = \omega_\pi \left(\pi_{C,4,t} + p\right) + \left(1 - \omega_\pi\right) \sigma_\pi \times \eta_t^\pi, \tag{14}$$

$$DYA_t^{SPF} = \omega_{\Delta y} \left(\Delta y_{4,t} + g\right) + \left(1 - \omega_{\Delta y}\right) \sigma_{\Delta y} \times \eta_t^{\Delta y}, \tag{15}$$

and

$$yc^{1Y} = \omega_r \left(r_{4,t} + r + c_4\right) + \left(1 - \omega_r\right) \sigma_{ME,r} \times \eta_t^{ME,r}. \tag{16}$$

Here, $\omega_\pi$ represents the weight parameter in the measurement equation for inflation expectations, $\omega_{\Delta y}$ the weight parameter for output growth expectations and $\omega_r$ for interest rate expectations. For the estimation of the weight parameters, we assume non-informative priors. The estimates are found to be 0.72 for $\omega_\pi$, 0.76 for $\omega_{\Delta y}$ and 0.89 for $\omega_r$. Yet, the forecasting performance for real GDP growth, inflation, wage inflation and the nominal interest rate falls off in accuracy.

As a third alternative, we combine, both the autoregressive component and the weight parameter in the measurement equations for expected output growth, inflation and interest rates. However, this specification again leads to a worse prediction accuracy compared to the NAWM X.

As a final exercise, we replace the forward guidance shock with a measurement error in the measurement equation:

$$yc^{1Y} = r_{4,t} + r + c_4 + \sigma_{ME,r} \times \eta_t^{ME,r}. \tag{17}$$

The standard deviation of the measurement error $\sigma_{ME,r}$ is estimated to be 0.58. With respect to the model-implied expectations formation process, there is almost no change to the NAWM X in how the model tracks observed output growth and inflation expectations. In contrast, the model's interest rate expectations are less aligned to the yield curve than in the preferred specification. These results are also reflected in the forecasting exercise where the RMSE forecast for real GDP growth, inflation and wage inflation are similar to the ones of the NAWM X, albeit higher for the nominal interest rate. Using this model for the forward guidance simulations, we see a marginal shift in the reaction to forward guidance shocks. Even though the overall outcome stays the same and the power of forward guidance is still mitigated, the responses slightly increase for real GDP growth while they decrease for inflation.

### 6.3 Sensitivity

As a final exercise, we vary the value of the Calvo parameter which constrains the price-setting decisions of domestic firms that are selling in home markets, $\xi_H$. To that end, we decrease the value to a parameter region which is more in line with actual micro-founded data. We set the lower bound of the parameter range to 0.7 and incrementally increase the value by 0.01 to finally end up at a value of 0.99. For that spectrum of values, we hence simulate the announced interest rate peg for a 2, 4, 6 and 8 quarters horizon.

Figure 16 illustrates the impulse response functions for real GDP growth, inflation, the nominal interest rate, the real exchange rate and the ex-ante real rate in annual terms. The black lines indicate the impulse responses taking the parametrisation of the NAWM X. Although the model reactions to forward guidance on interest rates increase with a rising tendency for lower values of $\xi_H$, the results continue to be plausible even for values in the lower end of the parameter range. Remarkably, the model responses of the NAWM X are located in the region around the minimum of the peak responses.

## 7 Conclusion

In this paper, we present an empirical approach to mitigate the forward guidance puzzle in DSGE models by disciplining the model-implied expectations formation process. We provide evidence that the model's expectations formation process is crucial for the way in which announced future monetary shocks have an impact on the economy. For that purpose, survey and financial market-based macro forecasts are used in the estimation to reach a better fit between the expected smoothed variables in the model and actual observed forecast data.

Our findings indicate that the additional information on how the market participants form their assessment about the macroeconomic outlook yields more sticky, less volatile model-implied expectations which is reflected in the values of the estimated parameters. As a result, we manage to reduce the responses of the structural variables to a forward guidance news shock.

Furthermore, the explosive behaviour of the model disappears for extended forward guidance horizons. A major advantage of our approach comprises the absence of any modifications to key structural equations in the New Keynesian framework. Besides, we confirm previous work stating that survey expectations and yield curves also contain an informational value of the current stance of the economy, which improves the general forecast performance of the model. Finally, the paper shows that there is no empirical evidence for a discount factor in the consumption Euler equation condition for a wide range of different measurement specifications and alternative observed forecast data.

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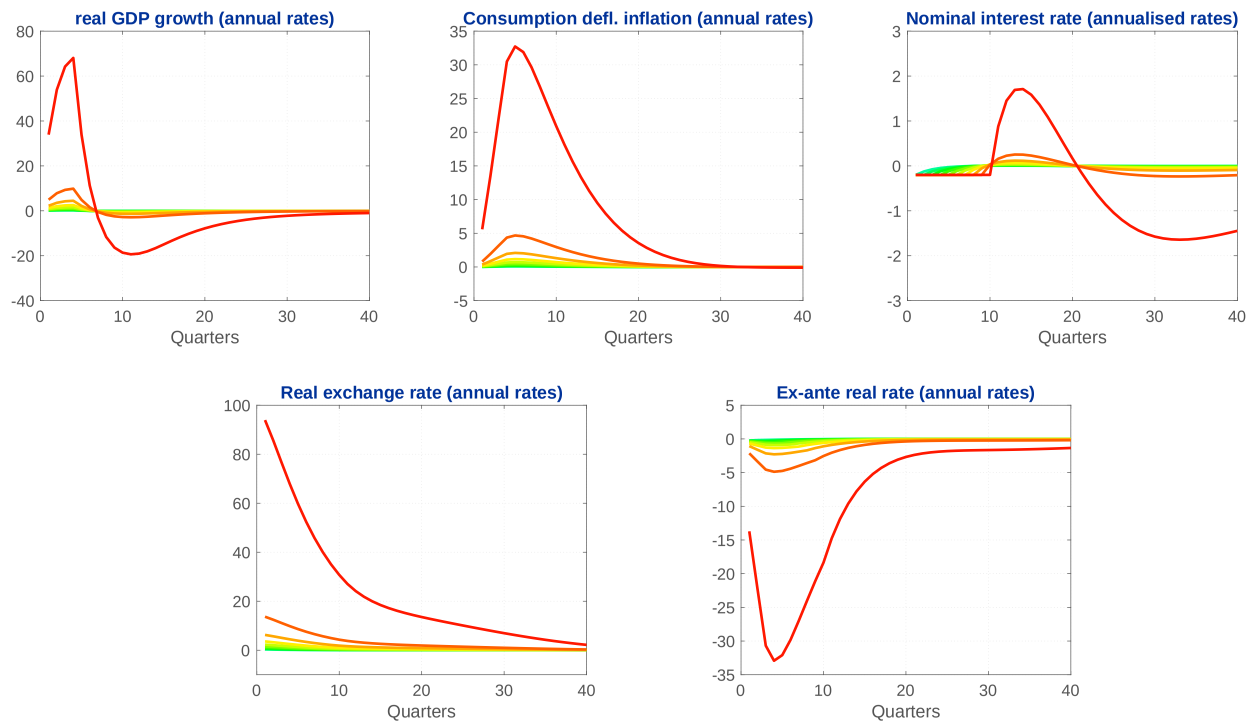
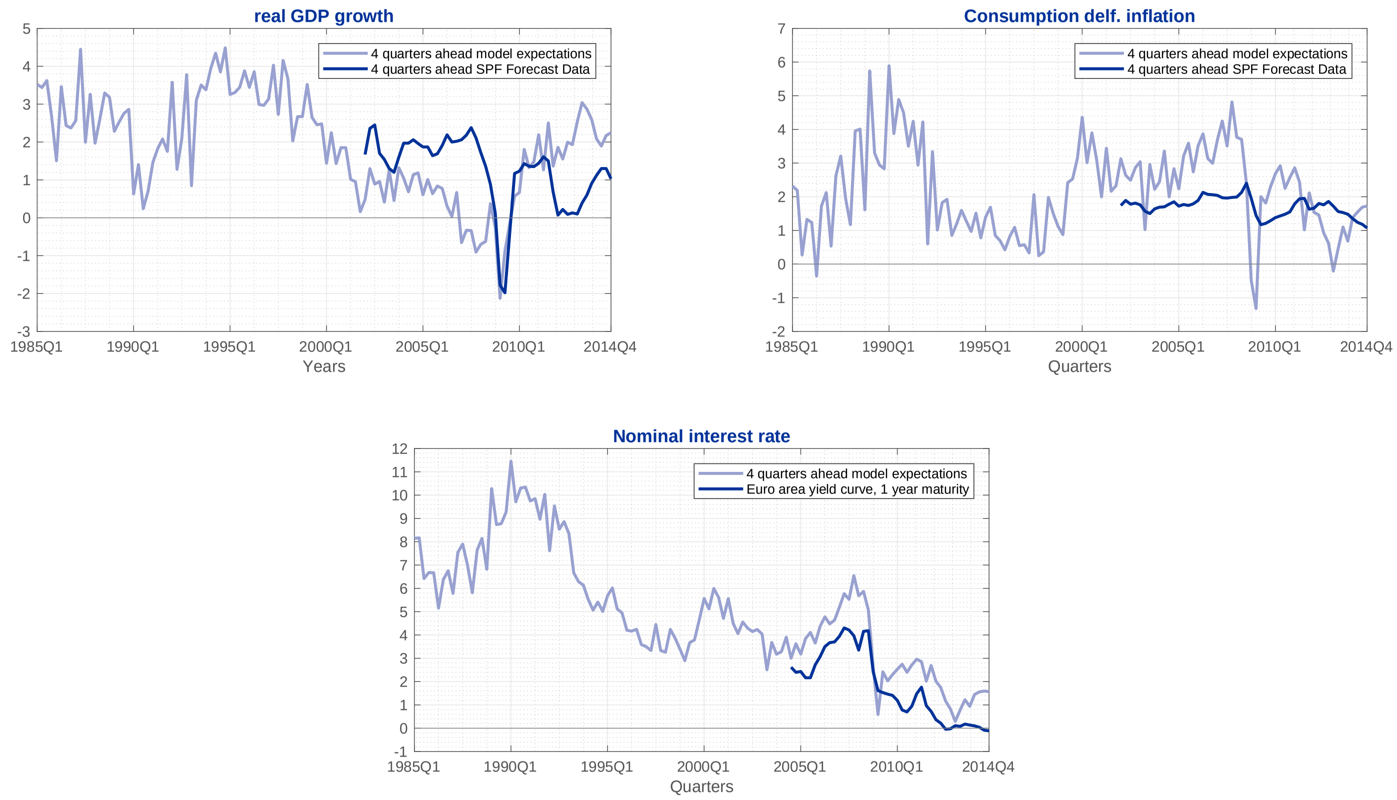
**Figure 1:** Forward guidance puzzle in the NAWM



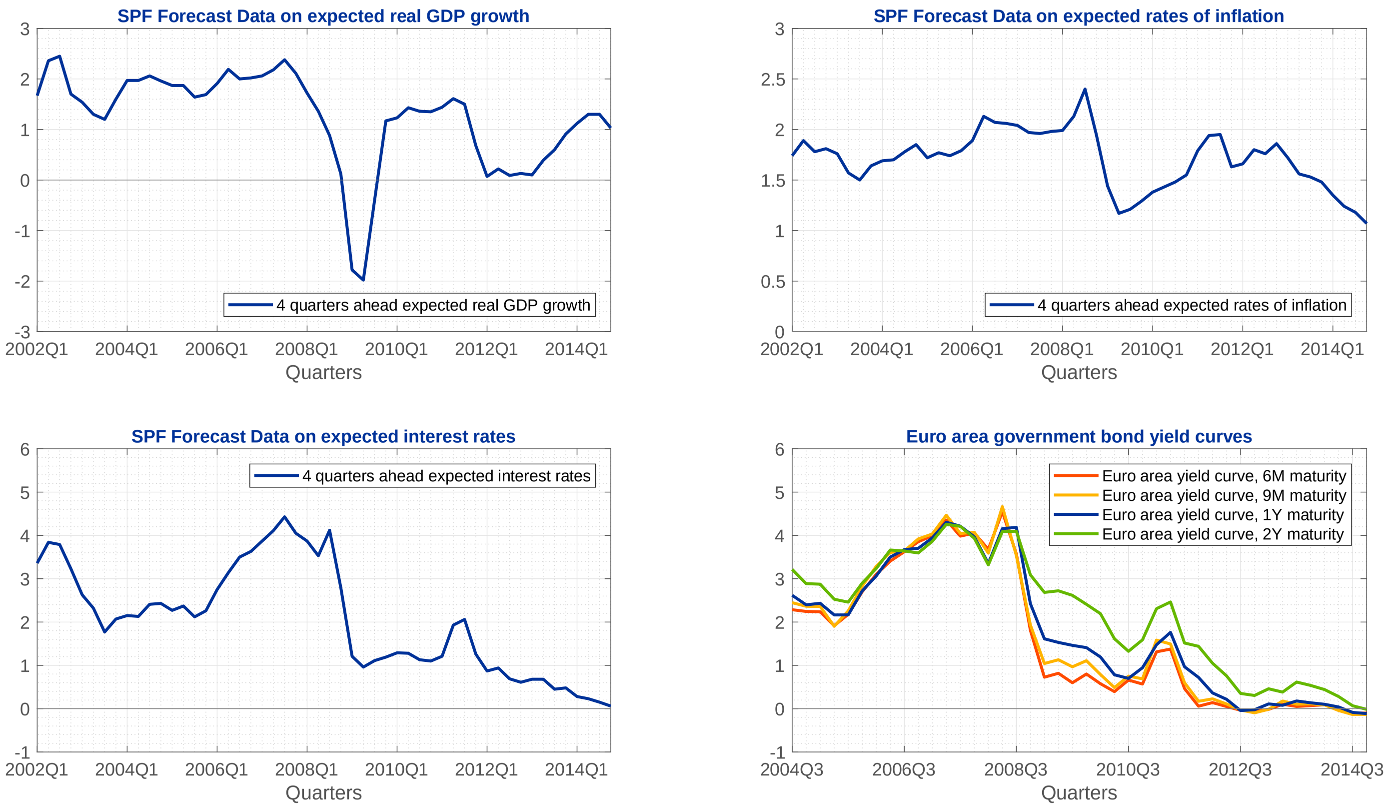

Note: The figure shows the impulse responses of real GDP growth, inflation, the nominal interest rate and real exchange rate in annual terms to a series of forward guidance shocks ranging from 1 to 10 quarters ahead in the baseline NAWM.

**Figure 2:** Observed forecast data vs. model-implied expectations in the NAWM




Note: The figure shows the time series of the observed forecast data on expected one year ahead rates of real GDP growth, inflation and the interest rate in comparison with the model-implied expectations in the baseline NAWM.

**Figure 3:** Observed macroeconomic forecast data




Note: This figure shows the time series for the macroeconomic forecast observables used in the estimation of the NAWM. Details are provided in Section 4.1. SPF forecast data for real GDP growth, inflation and interest rate expectations as well as euro area yield curves are reported in annualised percentage terms.

**Table 1:** Prior and posterior distributions of estimated parameters in the NAMW X

| Parameter | Description | Prior distribution | Posterior distribution | | |
|---|---|---|---|---|---|
| | | | mean | 10% | 90% |
| A. Risk Premium | | | | | |
| $c_4$ | Risk Premium, 1 year maturity | inv. gamma(0.1,0.25) | 0.0459 | 0.0243 | 0.0672 |
| B. Preferences | | | | | |
| $\kappa$ | Habit formation | beta(0.7,0.05) | 0.6670 | 0.6269 | 0.7074 |
| C. Wage and price setting | | | | | |
| $\xi_W$ | Calvo: wages | beta(0.75,0.05) | 0.7501 | 0.6904 | 0.8108 |
| $\chi_W$ | Indexation: wages | beta(0.75,0.1) | 0.6705 | 0.4852 | 0.8565 |
| $\xi_H$ | Calvo: dom. prices | beta(0.75,0.05) | 0.9456 | 0.9326 | 0.9611 |
| $\chi_H$ | Indexation: dom. prices | beta(0.75,0.1) | 0.2420 | 0.1583 | 0.3226 |
| $\xi_X$ | Calvo: exp. prices | beta(0.75,0.05) | 0.8452 | 0.7851 | 0.9046 |
| $\chi_X$ | Indexation: exp. prices | beta(0.75,0.1) | 0.4519 | 0.2795 | 0.6167 |
| $\xi^\star$ | Calvo: imp. prices | beta(0.75,0.05) | 0.4611 | 0.4038 | 0.5139 |
| $\chi^\star$ | Indexation: imp. prices | beta(0.75,0.1) | 0.2995 | 0.1769 | 0.4170 |
| $\omega^\star$ | Oil import share | beta(0.15,0.05) | 0.1473 | 0.1176 | 0.1776 |
| D. Final-good production | | | | | |
| $\mu_C$ | Subst. elasticity: cons. | gamma(1.5,0.25) | 2.3242 | 1.8334 | 2.8033 |
| $\mu_I$ | Subst. elasticity: inv. | gamma(1.5,0.25) | 1.7813 | 1.3734 | 2.1808 |
| $\mu^\star$ | Price elasticity: exp. | gamma(1,0.25) | 0.3133 | 0.2144 | 0.4118 |
| E. Final-good production | | | | | |
| $\gamma_I$ | Adjustment costs Inv. | gamma(4,0.5) | 5.8397 | 4.9099 | 6.7301 |
| $\gamma_{IM^C}$ | Import content:cons. | gamma(2.5,1) | 7.8758 | 5.4204 | 10.3370 |
| $\gamma_{IM^I}$ | Import content:inv. | gamma(2.5,1) | 0.6214 | 0.2567 | 0.9897 |
| $\gamma^\star$ | Export market share | gamma(2.5,1) | 0.3215 | 0.1044 | 0.5424 |
| F. Monetary policy | | | | | |
| $\phi_R$ | Interest-rate smoothing | beta(0.90,0.05) | 0.8985 | 0.8829 | 0.9148 |
| $\phi_\Pi$ | Resp. to inflation | normal(1.7,0.1) | 1.9032 | 1.7643 | 2.0409 |
| $\phi_{\Delta\Pi}$ | Resp. to change in inflation | normal(0.3,0.1) | 0.1575 | 0.1008 | 0.2141 |
| $\phi_{\Delta Y}$ | Resp. to change in output | normal(0.0625,0.05) | 0.0109 | -0.0014 | 0.0238 |
| G. Employment | | | | | |
| $\xi_E$ | Calvo-style parameter | beta(0.5,0.15) | 0.8572 | 0.8168 | 0.8951 |
| H. Autoregressive coefficients | | | | | |
| $\rho_{RP}$ | Risk premium shock: dom. | beta(0.75,0.1) | 0.9706 | 0.9617 | 0.9800 |
| $\rho_{RP^\star}$ | Risk premium shock: ext. | beta(0.75,0.1) | 0.9861 | 0.9766 | 0.9960 |
| $\rho_{g_z}$ | Permanent techn. shock | beta(0.75,0.1) | 0.1613 | 0.1102 | 0.2038 |
| $\rho_\epsilon$ | Transitory techn. shock | beta(0.75,0.1) | 0.9401 | 0.8895 | 0.9962 |
| $\rho_I$ | Inv.-spec. techn. shock | beta(0.75,0.1) | 0.6067 | 0.5072 | 0.7075 |
| $\rho_{\varphi^W}$ | Wage markup shock | beta(0.75,0.1) | 0.2923 | 0.1845 | 0.4039 |
| $\rho_{\varphi^H}$ | Price markup shock: dom. | beta(0.75,0.1) | 0.2546 | 0.1659 | 0.3431 |
| $\rho_{\varphi^X}$ | Price markup shock: exp. | beta(0.75,0.1) | 0.3589 | 0.2159 | 0.4999 |
| $\rho_{\varphi^\star}$ | Price markup shock: imp. | beta(0.75,0.1) | 0.9047 | 0.8705 | 0.9403 |
| $\rho_{IM}$ | Import demand shock | beta(0.75,0.1) | 0.7820 | 0.7061 | 0.8568 |
| $\rho_{\nu^\star}$ | Export preference shock | beta(0.75,0.1) | 0.8898 | 0.8457 | 0.9360 |
| I. Standard deviations | | | | | |
| $\sigma_{RP}$ | Risk premium shock: dom. | inv. gamma(0.217,0.7) | 0.1147 | 0.0926 | 0.1364 |
| $\sigma_{RP^\star}$ | Risk premium shock: ext. | inv. gamma(0.217,0.7) | 0.2187 | 0.1678 | 0.2696 |
| $\sigma_{g_z}$ | Permanent techn. shock | inv. gamma(0.217,0.7) | 1.7496 | 1.5630 | 1.9318 |
| $\sigma_\epsilon$ | Transitory techn. shock | inv. gamma(0.217,0.7) | 1.3464 | 0.8635 | 1.8680 |
| $\sigma_I$ | Inv.-spec. techn. shock | inv. gamma(0.217,0.7) | 0.5218 | 0.4226 | 0.6159 |
| $\sigma_{\varphi^W}$ | Wage markup shock | inv. gamma(0.217,0.7) | 0.7186 | 0.6160 | 0.8238 |
| $\sigma_{\varphi^H}$ | Price markup shock: dom. | inv. gamma(0.217,0.7) | 0.1897 | 0.1624 | 0.2165 |
| $\sigma_{\varphi^X}$ | Price markup shock: exp. | inv. gamma(0.217,0.7) | 1.2085 | 1.0228 | 1.3934 |
| $\sigma_{\varphi^\star}$ | Price markup shock: imp | inv. gamma(0.217,0.7) | 1.5412 | 1.2375 | 1.8357 |
| $\sigma_{IM}$ | Import demand shock | inv. gamma(0.217,0.7) | 6.3976 | 4.8605 | 7.9007 |
| $\sigma_{\nu^\star}$ | Export preference shock | inv. gamma(0.217,0.7) | 2.8712 | 2.1783 | 3.5679 |
| $\sigma_R$ | Interest rate shock | inv. gamma(0.217,0.7) | 0.1007 | 0.0849 | 0.1159 |
| $\sigma_{4,FG}$ | Forward guidance news shock | inv. gamma(0.217,0.7) | 0.1172 | 0.1025 | 0.1322 |
| $\sigma_\pi$ | Measurement error on infl. expect. | inv. gamma(0.07,0.3) | 0.4310 | 0.3375 | 0.5242 |
| $\sigma_{\Delta y}$ | Measurement error on GDP expect. | inv. gamma(0.07,0.3) | 0.5739 | 0.4579 | 0.6888 |

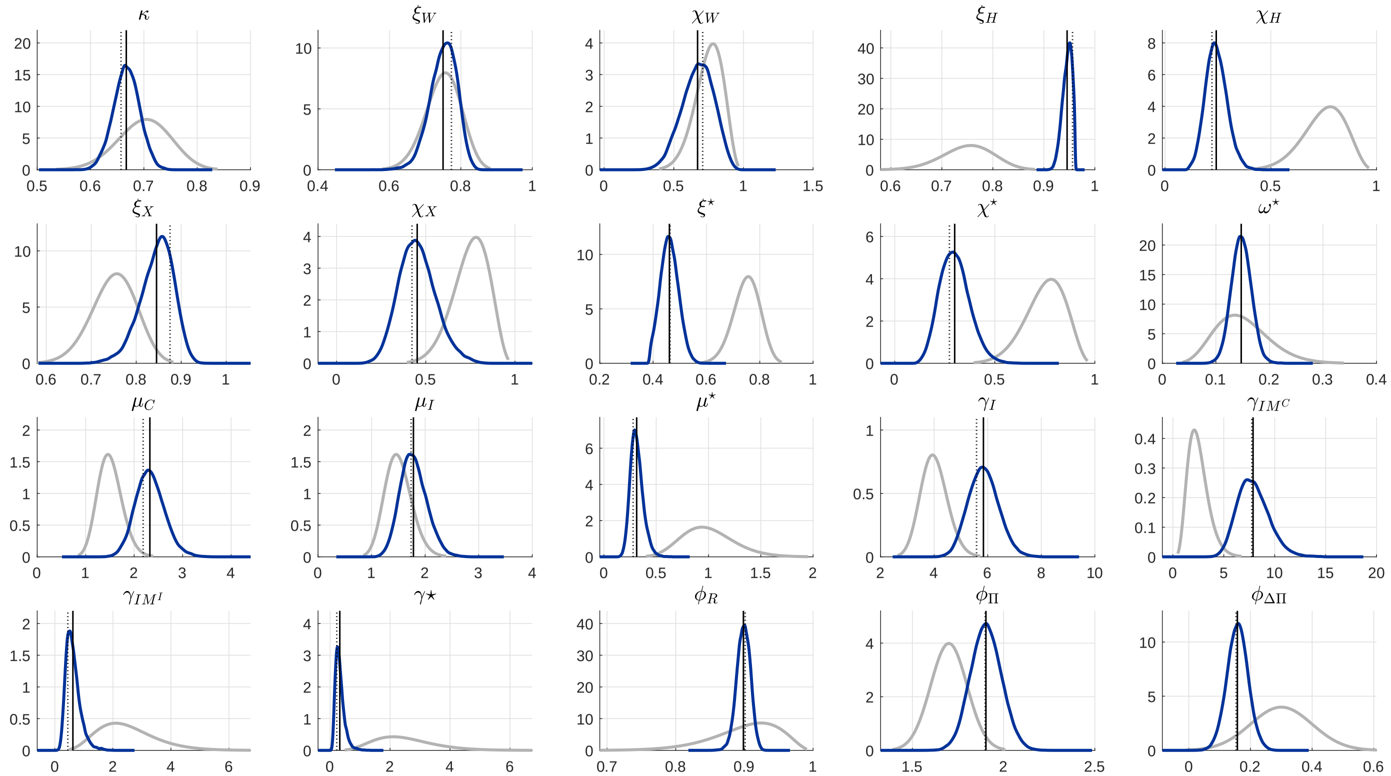
Note: This table reports the prior and posterior distributions of the structural parameters of the NAWM X. The prior distributions are characterised by the parameters determining their respective means and standard deviations. For the posterior distribution, which are based on two Markov chains with 2,000,000 draws with 1,800,000 draws being discarded as burn-in draws, the posterior mean as well as the 10% and 90% percentiles are provided.

**Table 2:** Prior and posterior distributions of estimated parameters - Model comparison

| Parameter | Description | NAWM | NAWM X | Post. distr. SPF | | | Post. distr. 6M9M1Y2Y YC | | |
|---|---|---|---|---|---|---|---|---|---|
| | | mean | mean | mean | 10% | 90% | mean | 10% | 90% |
| A. Risk Premium | | | | | | | | | |
| $c_2$ | 6M yield curve risk premium | – | – | – | – | – | 0.0339 | 0.0214 | 0.0460 |
| $c_3$ | 9M yield curve risk premium | – | – | – | – | – | 0.1141 | 0.0642 | 0.1610 |
| $c_4$ | 1Y yield curve risk premium | – | 0.0459 | – | – | – | 0.1117 | 0.0397 | 0.1735 |
| $c_8$ | 2Y yield curve risk premium | – | – | – | – | – | 0.0808 | 0.0248 | 0.1324 |
| B. Preferences | | | | | | | | | |
| $\kappa$ | Habit formation | 0.566 | 0.6670 | 0.6628 | 0.6224 | 0.7033 | 0.6700 | 0.6336 | 0.7063 |
| C. Wage and price setting | | | | | | | | | |
| $\xi_W$ | Calvo: wages | 0.768 | 0.7501 | 0.7240 | 0.6652 | 0.7823 | 0.7838 | 0.7412 | 0.8276 |
| $\chi_W$ | Indexation: wages | 0.638 | 0.6705 | 0.6597 | 0.4760 | 0.8504 | 0.6727 | 0.4921 | 0.8630 |
| $\xi_H$ | Calvo: dom. prices | 0.921 | 0.9456 | 0.9495 | 0.9404 | 0.9610 | 0.9452 | 0.9335 | 0.9582 |
| $\chi_H$ | Indexation: dom. prices | 0.425 | 0.2420 | 0.2031 | 0.1296 | 0.2734 | 0.2586 | 0.1697 | 0.3477 |
| $\xi_X$ | Calvo: exp. prices | 0.763 | 0.8452 | 0.8144 | 0.7530 | 0.8791 | 0.8569 | 0.8071 | 0.9080 |
| $\chi_X$ | Indexation: exp. prices | 0.509 | 0.4519 | 0.5059 | 0.3178 | 0.6912 | 0.4520 | 0.2881 | 0.6162 |
| $\xi^\star$ | Calvo: imp. prices | 0.531 | 0.4611 | 0.4816 | 0.4266 | 0.5365 | 0.4618 | 0.4051 | 0.5151 |
| $\chi^\star$ | Indexation: imp. prices | 0.498 | 0.2995 | 0.2715 | 0.1598 | 0.3793 | 0.3124 | 0.1894 | 0.4352 |
| $\omega^\star$ | Oil import share | 0.156 | 0.1473 | 0.1528 | 0.1211 | 0.1848 | 0.1375 | 0.1072 | 0.1678 |
| D. Final-good production | | | | | | | | | |
| $\mu_C$ | Subst. elasticity: cons. | 1.996 | 2.3242 | 2.0993 | 1.6592 | 2.5283 | 2.3039 | 1.8442 | 2.7485 |
| $\mu_I$ | Subst. elasticity: inv. | 1.601 | 1.7813 | 1.6254 | 1.2552 | 1.9905 | 1.7571 | 1.3658 | 2.1405 |
| $\mu^\star$ | Price elasticity: exp. | 1.032 | 0.3133 | 0.8209 | 0.6900 | 0.9511 | 0.2172 | 0.1334 | 0.2996 |
| E. Final-good production | | | | | | | | | |
| $\gamma_I$ | Adjustment costs Inv. | 5.167 | 5.8397 | 5.7674 | 4.8534 | 6.6493 | 6.1242 | 5.2193 | 7.0712 |
| $\gamma_{IM^C}$ | Import content:cons. | 5.729 | 7.8758 | 8.1175 | 5.7442 | 10.5688 | 7.0923 | 4.9228 | 9.3767 |
| $\gamma_{IM^I}$ | Import content:inv. | 0.440 | 0.6214 | 0.6408 | 0.2607 | 1.0097 | 0.4674 | 0.1863 | 0.7489 |
| $\gamma^\star$ | Export market share | 2.816 | 0.3215 | 8.1710 | 5.7839 | 10.7060 | 0.2742 | 0.0891 | 0.4606 |
| F. Monetary policy | | | | | | | | | |
| $\phi_R$ | Interest-rate smoothing | 0.867 | 0.8985 | 0.8963 | 0.8829 | 0.9095 | 0.7971 | 0.7676 | 0.8271 |
| $\phi_\Pi$ | Resp. to inflation | 1.90 | 1.9032 | 1.9108 | 1.7794 | 2.0464 | 1.8616 | 1.7228 | 2.0006 |
| $\phi_{\Delta\Pi}$ | Resp. to change in inflation | 0.186 | 0.1575 | 0.2263 | 0.1858 | 0.2654 | 0.1435 | 0.0244 | 0.2644 |
| $\phi_{\Delta Y}$ | Resp. to change in output | 0.153 | 0.0109 | 0.0119 | 0.0003 | 0.0232 | 0.0842 | 0.0540 | 0.1147 |
| G. Employment | | | | | | | | | |
| $\xi_E$ | Calvo-style parameter | 0.850 | 0.8572 | 0.8588 | 0.8326 | 0.8861 | 0.8860 | 0.8636 | 0.9091 |
| H. Autoregressive coefficients | | | | | | | | | |
| $\rho_{RP}$ | Risk premium shock: dom. | 0.920 | 0.9706 | 0.9731 | 0.9656 | 0.9808 | 0.9693 | 0.9596 | 0.9795 |
| $\rho_{RP^\star}$ | Risk premium shock: ext. | 0.822 | 0.9861 | 0.9848 | 0.9758 | 0.9944 | 0.9886 | 0.9808 | 0.9967 |
| $\rho_{g_z}$ | Permanent techn. shock | 0.780 | 0.1613 | 0.1514 | 0.1073 | 0.1888 | 0.1524 | 0.1074 | 0.1890 |
| $\rho_\epsilon$ | Transitory techn. shock | 0.894 | 0.9401 | 0.9582 | 0.9273 | 0.9911 | 0.8778 | 0.8284 | 0.9308 |
| $\rho_I$ | Inv.-spec. techn. shock | 0.710 | 0.6067 | 0.5650 | 0.4709 | 0.6587 | 0.6128 | 0.5129 | 0.7162 |
| $\rho_{\varphi^W}$ | Wage markup shock | 0.661 | 0.2923 | 0.2669 | 0.1647 | 0.3656 | 0.2645 | 0.1639 | 0.3611 |
| $\rho_{\varphi^H}$ | Price markup shock: dom. | 0.397 | 0.2546 | 0.2155 | 0.1360 | 0.2920 | 0.2532 | 0.1613 | 0.3434 |
| $\rho_{\varphi^X}$ | Price markup shock: exp. | 0.386 | 0.3589 | 0.3707 | 0.2231 | 0.5212 | 0.3560 | 0.2137 | 0.4927 |
| $\rho_{\varphi^\star}$ | Price markup shock: imp. | 0.541 | 0.9047 | 0.9173 | 0.8914 | 0.9468 | 0.8936 | 0.8563 | 0.9316 |
| $\rho_{IM}$ | Import demand shock | 0.859 | 0.7820 | 0.7836 | 0.7162 | 0.8531 | 0.8030 | 0.7406 | 0.8709 |
| $\rho_{\nu^\star}$ | Export preference shock | 0.783 | 0.8898 | 0.3287 | 0.1976 | 0.4492 | 0.8670 | 0.8173 | 0.9182 |
| I. Standard deviations | | | | | | | | | |
| $\sigma_{RP}$ | Risk premium shock: dom. | 0.161 | 0.1147 | 0.1026 | 0.0836 | 0.1205 | 0.0834 | 0.0652 | 0.1015 |
| $\sigma_{RP^\star}$ | Risk premium shock: ext. | 0.439 | 0.2187 | 0.2300 | 0.1812 | 0.2767 | 0.2094 | 0.1658 | 0.2515 |
| $\sigma_{g_z}$ | Permanent techn. shock | 0.131 | 1.7496 | 1.7444 | 1.5580 | 1.9250 | 1.7461 | 1.5608 | 1.9293 |
| $\sigma_\epsilon$ | Transitory techn. shock | 1.158 | 1.3464 | 1.2320 | 0.9279 | 1.5357 | 2.0026 | 1.2934 | 2.7288 |
| $\sigma_I$ | Inv.-spec. techn. shock | 0.422 | 0.5218 | 0.5634 | 0.4621 | 0.6639 | 0.5008 | 0.4085 | 0.5904 |
| $\sigma_{\varphi^W}$ | Wage markup shock | 0.118 | 0.7186 | 0.7464 | 0.6459 | 0.8483 | 0.7331 | 0.6283 | 0.8314 |
| $\sigma_{\varphi^H}$ | Price markup shock: dom. | 0.126 | 0.1897 | 0.2064 | 0.1779 | 0.2343 | 0.1853 | 0.1594 | 0.2121 |
| $\sigma_{\varphi^X}$ | Price markup shock: exp. | 1.080 | 1.2085 | 1.2574 | 1.0535 | 1.4636 | 1.1933 | 1.0039 | 1.3745 |
| $\sigma_{\varphi^\star}$ | Price markup shock: imp | 0.994 | 1.5412 | 1.4165 | 1.1416 | 1.6857 | 1.5711 | 1.2777 | 1.8652 |
| $\sigma_{IM}$ | Import demand shock | 4.780 | 6.3976 | 6.6933 | 5.0453 | 8.2293 | 5.7769 | 4.4473 | 7.0065 |
| $\sigma_{\nu^\star}$ | Export preference shock | 8.985 | 2.8712 | 20.7309 | 15.5161 | 26.1676 | 2.6569 | 2.0621 | 3.2248 |
| $\sigma_R$ | Interest rate shock | 0.118 | 0.1007 | 0.1041 | 0.0883 | 0.1189 | 0.2578 | 0.2120 | 0.3011 |
| $\sigma_{1,FG}$ | FG shock: 1 Period | – | – | – | – | – | 0.3203 | 0.2780 | 0.3625 |
| $\sigma_{2,FG}$ | FG shock: 2 Periods | – | – | – | – | – | 0.1877 | 0.1582 | 0.2176 |
| $\sigma_{3,FG}$ | FG shock: 3 Periods | – | – | – | – | – | 0.2190 | 0.1867 | 0.2503 |
| $\sigma_{4,FG}$ | FG shock: 4 Periods | – | 0.1172 | 0.0906 | 0.777 | 0.1035 | 0.1395 | 0.1148 | 0.1627 |
| $\sigma_\pi$ | Measurement error on infl. expect. | – | 0.4310 | 0.3976 | 0.3160 | 0.4759 | 0.5209 | 0.4034 | 0.6375 |
| $\sigma_{\Delta y}$ | Measurement error on GDP expect. | – | 0.5739 | 0.6854 | 0.5422 | 0.8187 | 0.5578 | 0.4594 | 0.6607 |

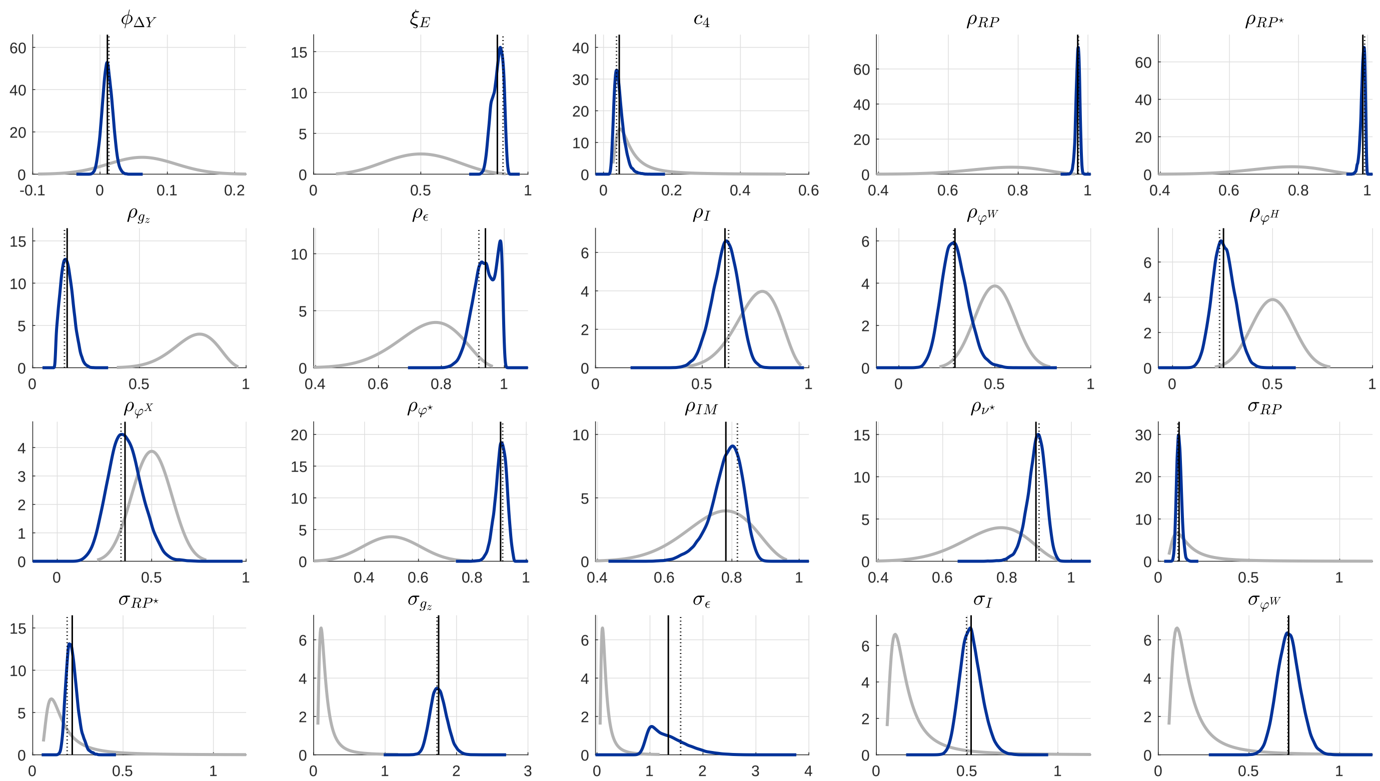
Note: This table provides information on the posterior distributions of the structural parameters as a comparison between the baseline NAWM, the NAWM X, the NAWM estimated with SPF data on expected interest rates and the NAWM estimated with euro area yield curves at maturities of 6 months, 9 months, 1 year and 2 years.

**Figure 4:** Prior and posterior distribution of estimated parameters in the NAWM X



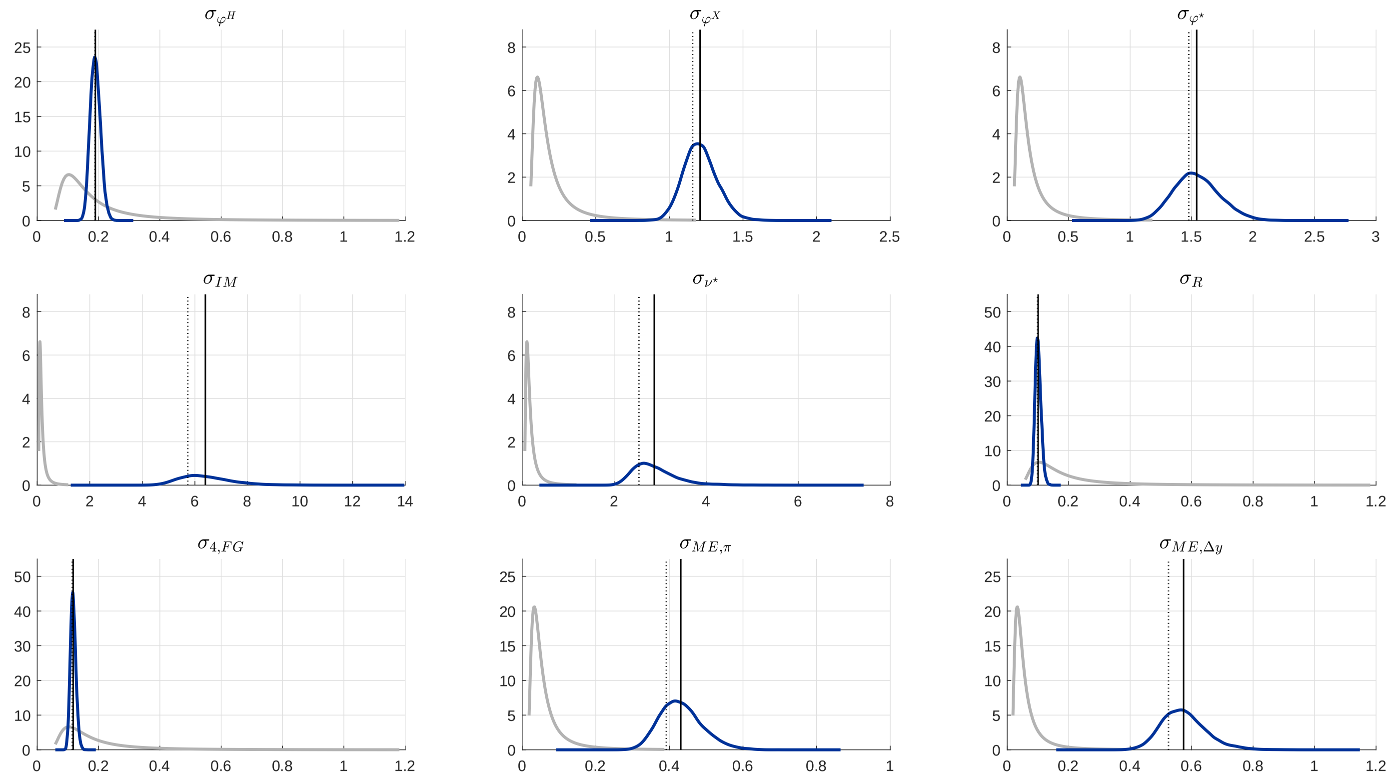

Note: This figure shows the prior distribution (light grey lines) against the posterior distribution (dark blue lines) of the estimated parameters in the NAWM X. The black dotted lines indicate the posterior mode and the black solid lines the posterior mean.

**Figure 5:** Prior and posterior distribution of estimated parameters in the NAWM X




Note: See above.

**Figure 6:** Prior and posterior distribution of estimated parameters in the NAWM X



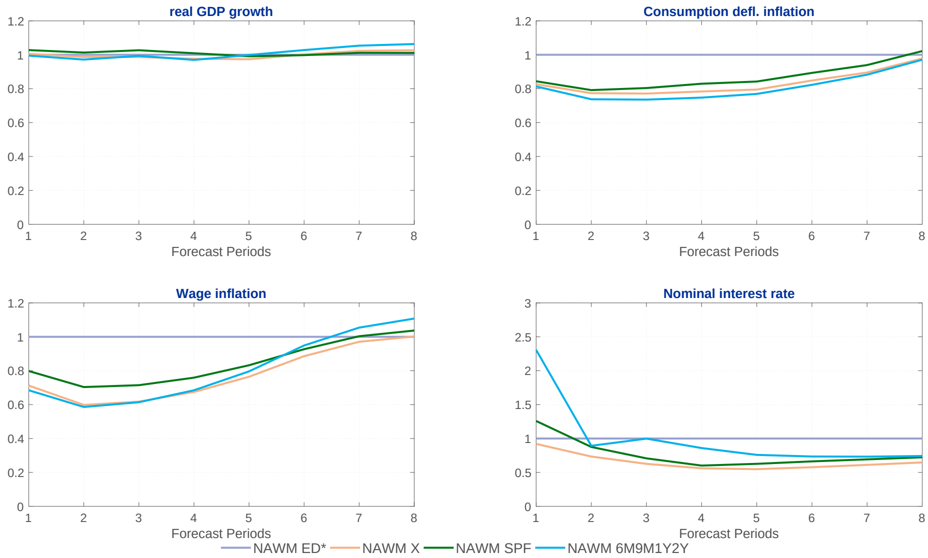

Note: See above.

**Table 3:** Prior and posterior distributions of the discount parameter $\psi$ across models

| Model | Prior distribution | | | Post. distribution | | |
|---|---|---|---|---|---|---|
| | type | mean | std | mean | 10% | 90% |
| NAWM | beta | 0.9 | 0.05 | 0.9948 | 0.9909 | 0.9989 |
| NAWM X | beta | 0.9 | 0.05 | 0.9951 | 0.9913 | 0.9990 |
| NAWM SPF | beta | 0.9 | 0.05 | 0.9966 | 0.9940 | 0.9993 |
| NAWM 6M9M1Y2Y | beta | 0.9 | 0.05 | 0.9930 | 0.9881 | 0.9983 |

Note: This table provides information on the prior and posterior distributions of the discount parameter in the consumption Euler equation in the baseline NAWM, the NAWM X, the NAWM estimated with SPF data on expected interest rates and the NAWM estimated with euro area yield curves at maturities of 6 months, 9 months, 1 year and 2 years.

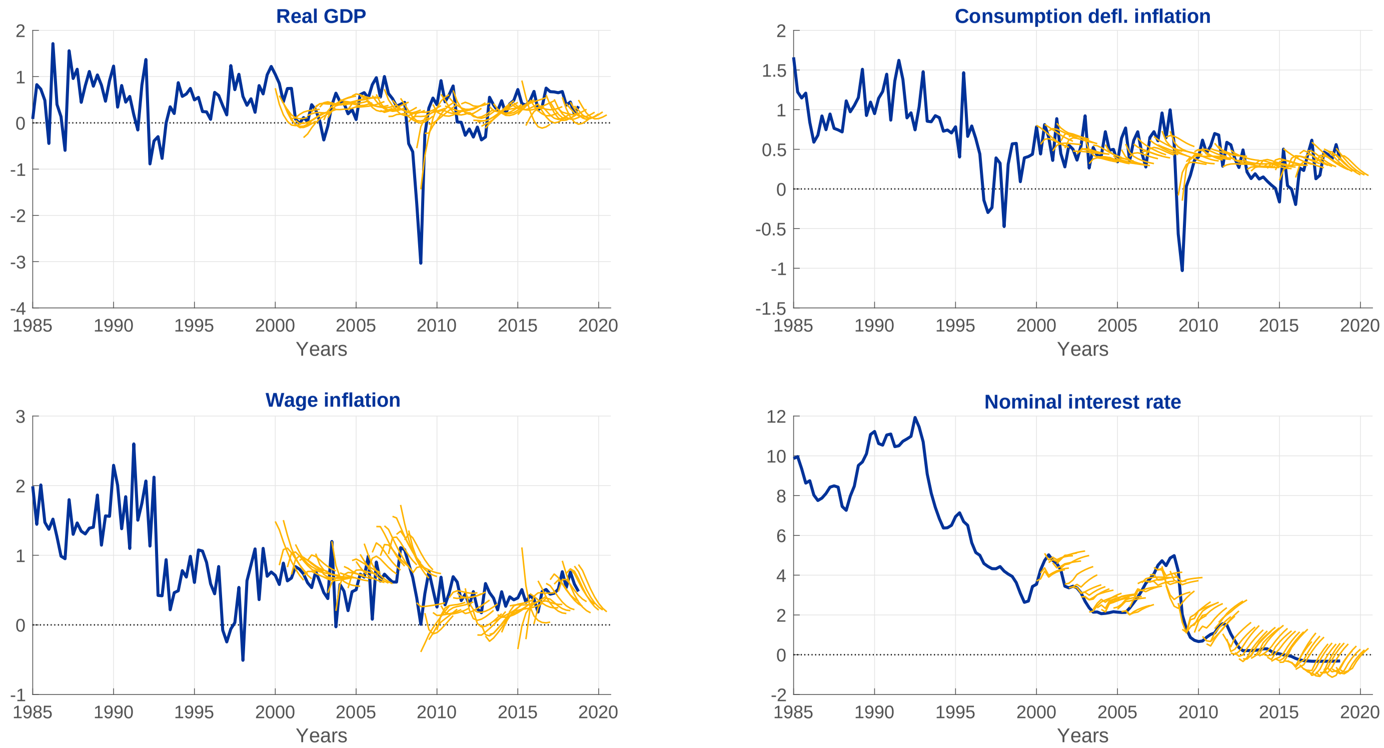
**Figure 7:** RMSE forecast relative to the baseline NAWM




*Baseline NAWM re-estimated with extended sample data to 2014Q4.

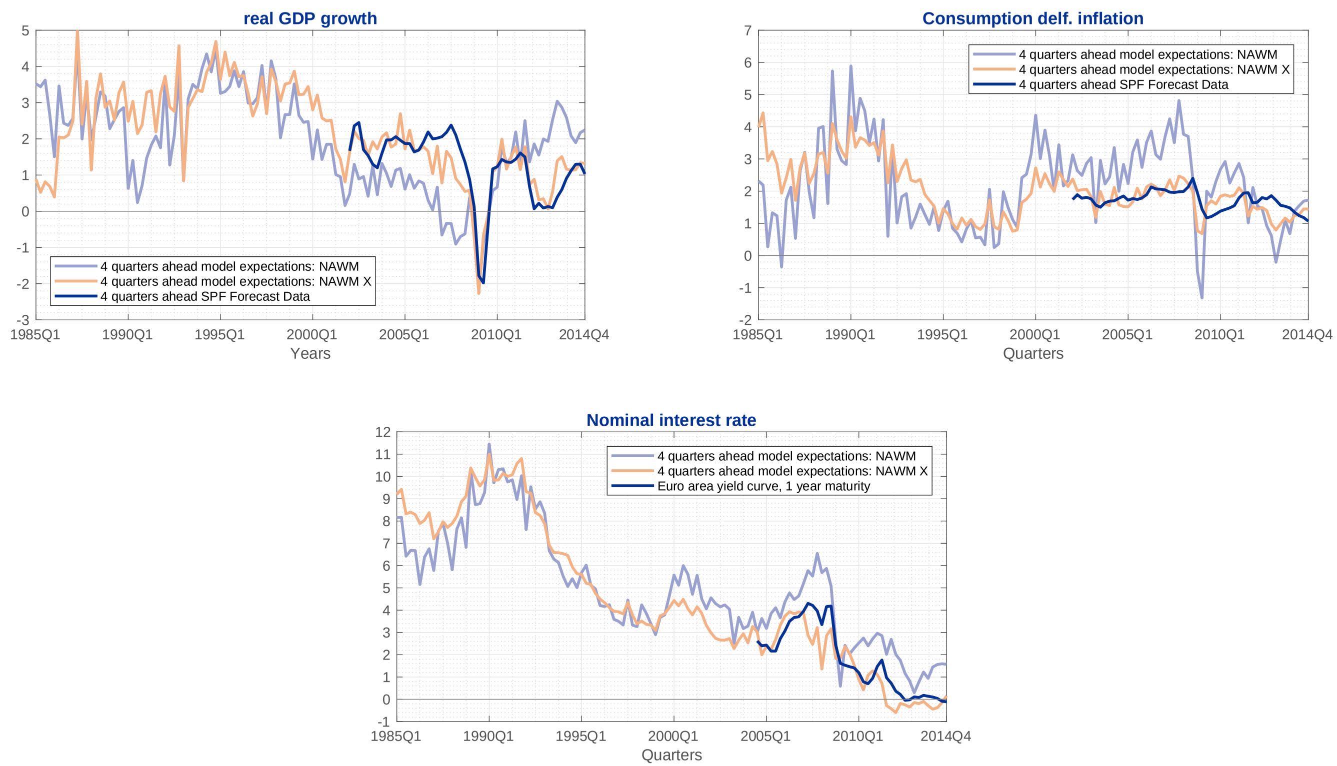
Note: The figure shows the root-mean-square errors forecast as a ratio to the benchmark model (NAWM ED) for one- to eight-quarters ahead forecasts for real GDP growth, consumption deflator inflation, wage inflation and the nominal interest rate. The forecasts are computed out-of-sample over the period 2000Q1 to 2016Q4.

**Figure 8:** Out-of-sample forecasts of the NAWM X



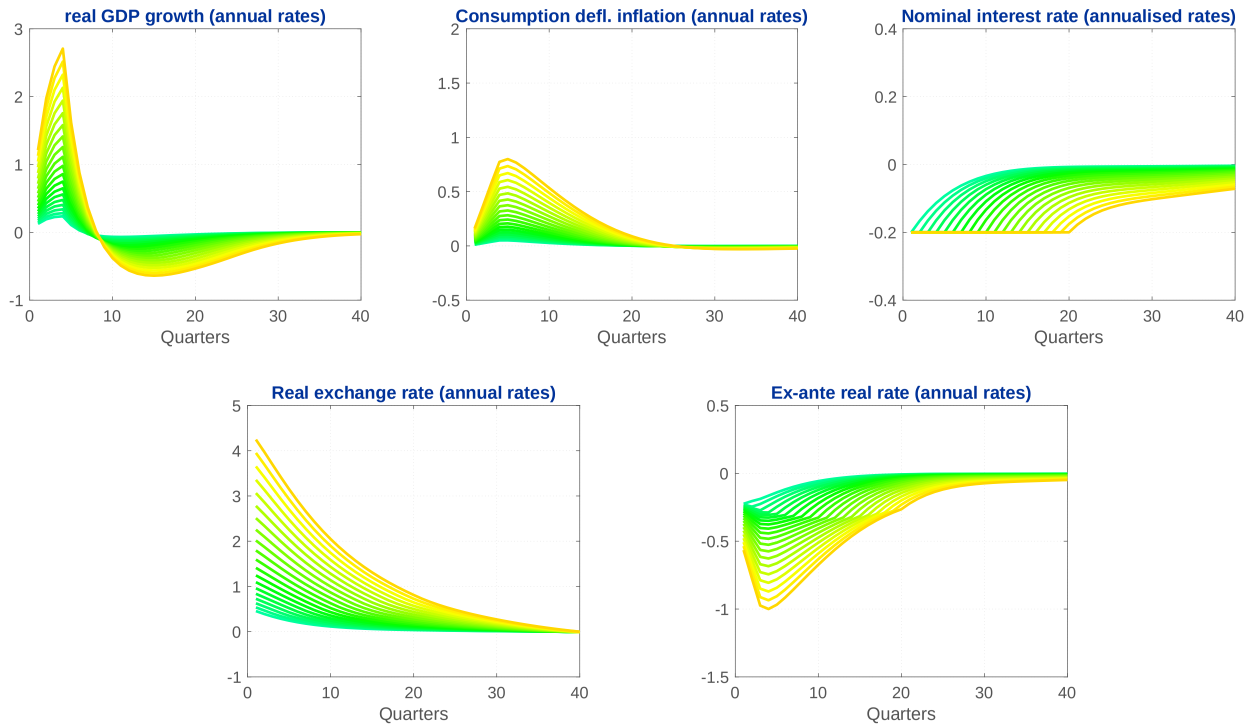

Note: This figure shows the one- to eight-step ahead mean forecast paths of the recursive forecasts between 2000Q1 and 2018Q4 of the NAWM X. While output growth, consumption defl. inflation and wage growth are reported in quarterly terms, the nominal interest rate is shown in annualised terms.

**Figure 9:** Observed forecast data vs. model-implied expectations in the NAWM and the NAWM X



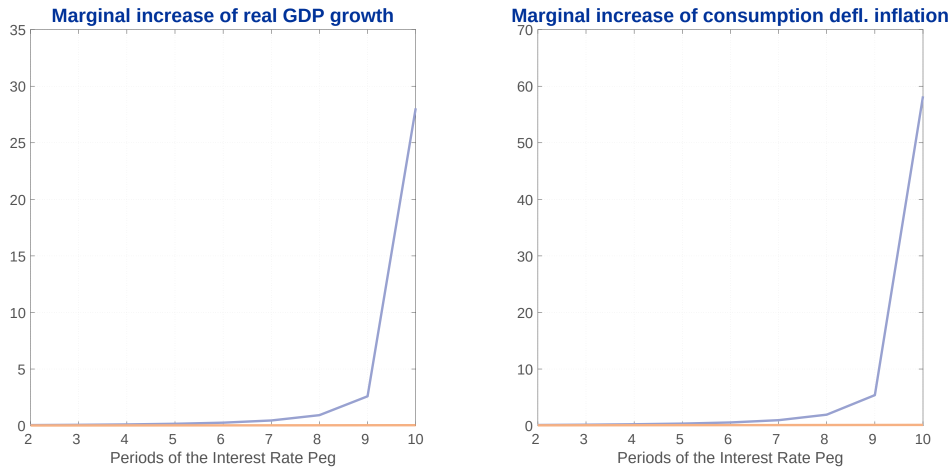

Note: The figure shows the time series of the observed forecast data on expected one year ahead rates of real GDP growth, inflation and the interest rate in comparison with the model-implied expectations in the baseline NAWM and the NAWM X over the whole estimation sample periods 1985Q1 to 2014Q4.

**Figure 10:** Moderating the forward guidance puzzle in the NAMW X




Note: The figure shows the impulse responses of real GDP growth, inflation, the nominal interest rate and real exchange rate in annual terms to a series of forward guidance shocks ranging from 1 to 20 quarters ahead in the NAWM X.

**Figure 11:** Staying *lower for longer*: Marginal impact in the NAWM vs. NAWM X



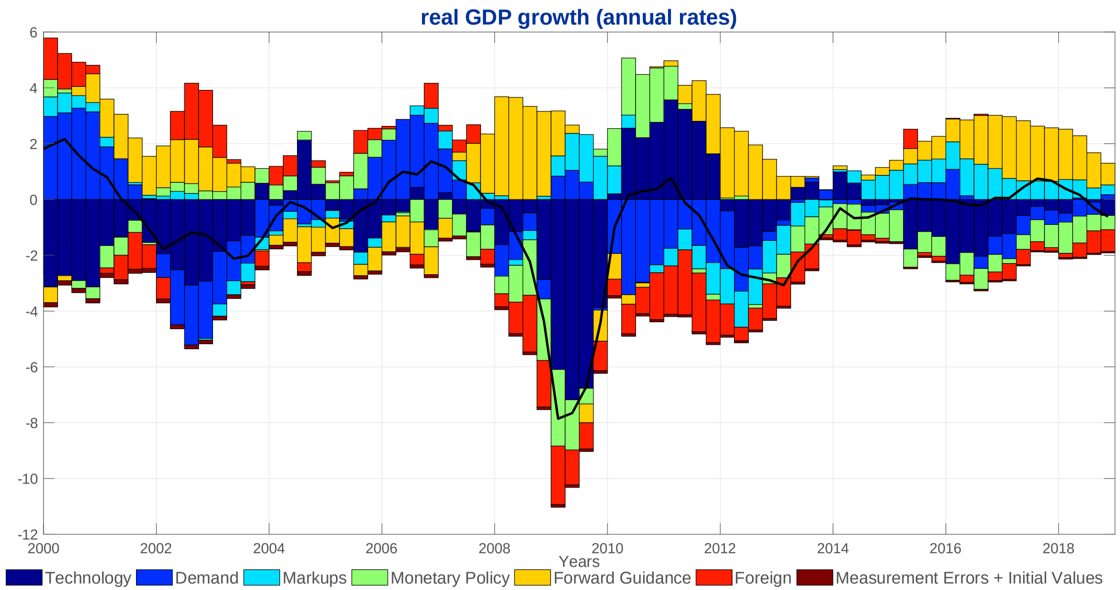

Note: The figures shows the marginal impact of one additional quarter forward guidance for real GDP growth and consumption deflator inflation. The purple line represents the marginal increase in the baseline NAWM and the orange line the marginal increase in the NAWM X. The marginal impact is computed by taking the difference of the year-on-year peak responses.

**Table 4:** Staying *lower for longer*: Marginal impact in the NAWM X

| Observed Variable | Periods of the Interest Rate Peg | | | | | |
|---|---|---|---|---|---|---|
| | 1 Quarter | 4 Quarters | 8 Quarters | 20 Quarters | 40 Quarters | 60 Quarters |
| Real GDP growth | 0.0466 | 0.0729 | 0.1101 | 0.1862 | 0.1840 | 0.2054 |
| Consumption defl. inflation | 0.0101 | 0.0174 | 0.0309 | 0.0633 | 0.0655 | 0.0733 |

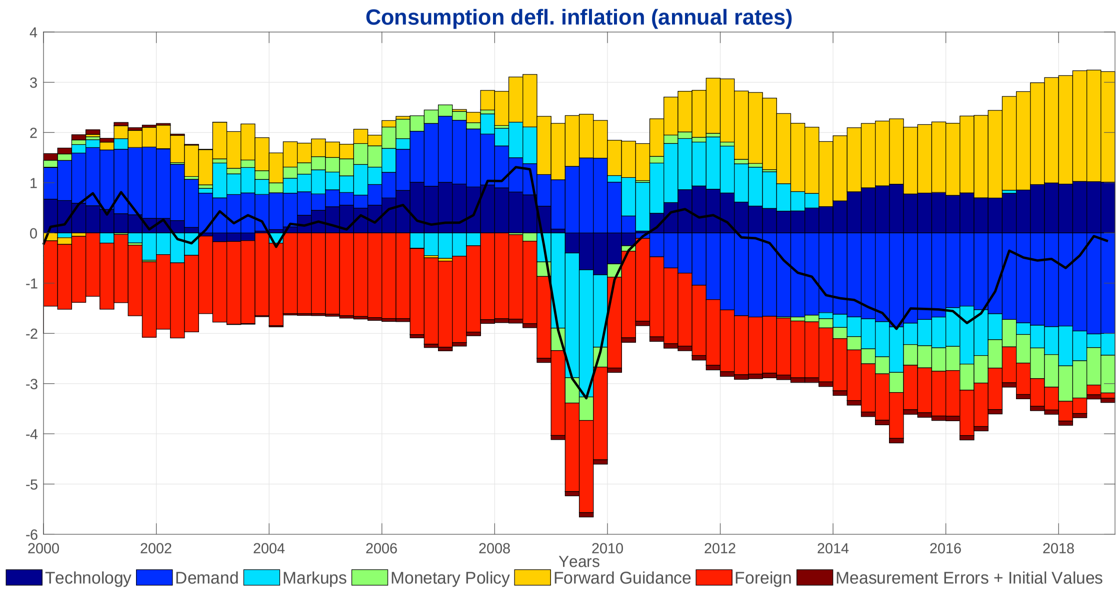
Note: The table reports the marginal impact of one additional quarter forward guidance for real GDP growth and consumption deflator inflation in the NAWM X for selected periods of the announced interest rate peg. The values represent the marginal increase of the peak response of real GDP growth and inflation in annual rates. The marginal impact is computed by taking the difference of the year-on-year peak responses.

**Figure 12:** Historical shock decomposition of real GDP growth in the NAWM X




Note: The figure disentangles the decomposition of annual real GDP growth into the contributions of the structural shocks over the period 2000Q1 to 2018Q4. The shocks are bundled into six groups: technology, demand, markups, monetary policy, forward guidance, foreign, plus the sum of the measurement errors and initial values.

**Figure 13:** Historical shock decomposition of the rates of inflation in the NAWM X




Note: The figure disentangles the decomposition of the annual rates of inflation into the contributions of the structural shocks over the period 2000Q1 to 2018Q4. The shocks are bundled into six groups: technology, demand, markups, monetary policy, forward guidance, foreign, plus the sum of the measurement errors and initial values.

**Table 5:** Forecast-error-variance decomposition for real GDP growth

| Shock Group | 1 Quarter | 4 Quarters | 20 Quarters | 40 Quarters | Unconditional |
|---|---|---|---|---|---|
| Technology | 64.31 | 60.33 | 57.95 | 57.68 | 56.52 |
| Demand | 15.89 | 17.36 | 17.52 | 17.50 | 17.66 |
| Markups | 2.42 | 3.70 | 4.21 | 4.26 | 4.35 |
| Monetary Policy | 3.22 | 3.43 | 3.59 | 3.57 | 3.59 |
| Forward Guidance | 4.15 | 5.47 | 6.08 | 6.07 | 6.09 |
| Foreign | 9.99 | 9.72 | 10.65 | 10.92 | 10.78 |

**Table 6:** Forecast-error-variance decomposition for rates of inflation

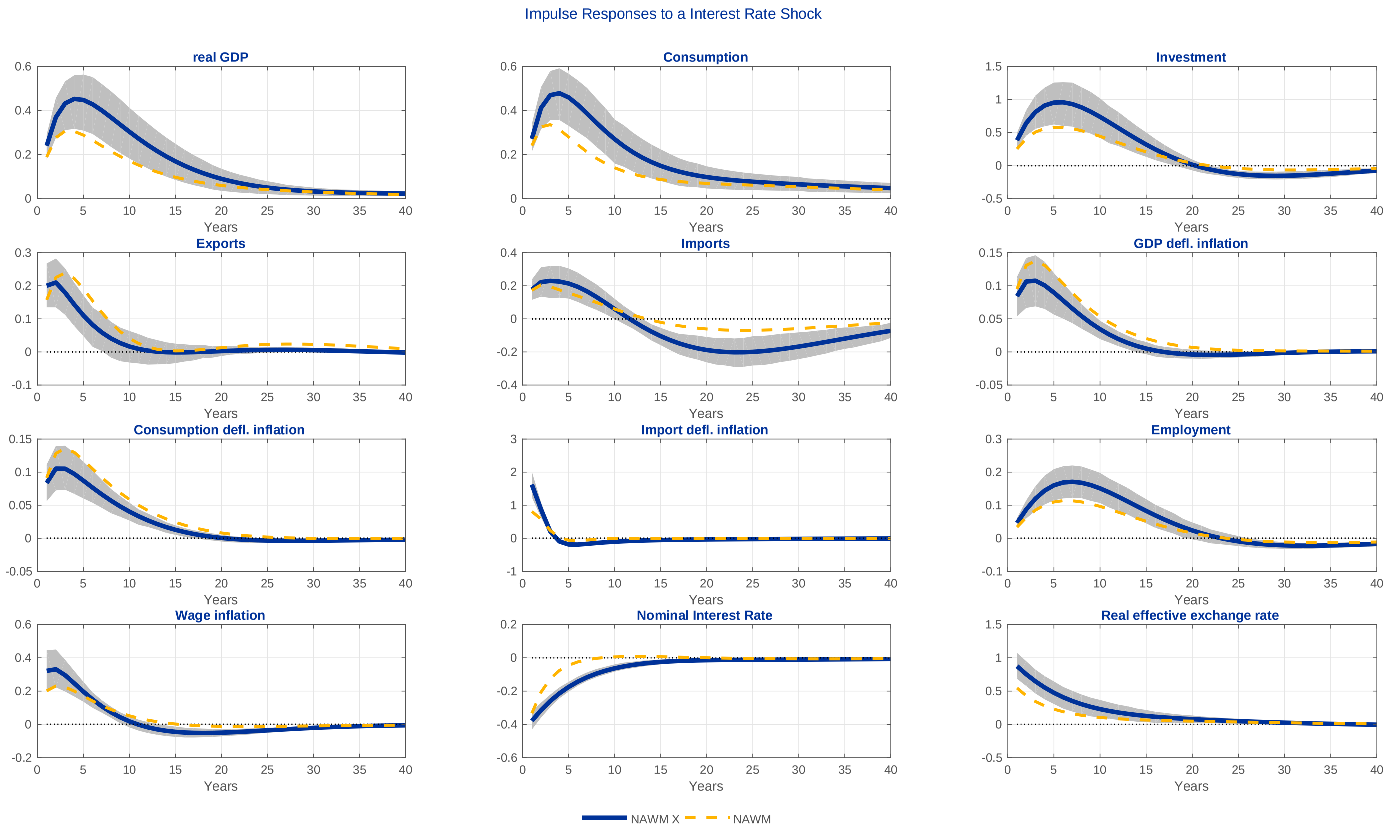
| Shock Group | 1 Quarter | 4 Quarters | 20 Quarters | 40 Quarters | Unconditional |
|---|---|---|---|---|---|
| Technology | 4.77 | 10.93 | 12.10 | 11.07 | 9.45 |
| Demand | 12.06 | 25.91 | 38.07 | 39.54 | 41.25 |
| Markups | 80.56 | 54.37 | 35.14 | 32.35 | 31.84 |
| Monetary Policy | 0.40 | 1.19 | 1.28 | 1.18 | 1.23 |
| Forward Guidance | 0.94 | 3.00 | 3.54 | 3.26 | 3.32 |
| Foreign | 1.25 | 4.64 | 9.98 | 12.61 | 12.93 |

**Table 7:** Forecast-error-variance decomposition for nominal interest rates

| Shock Group | 1 Quarter | 4 Quarters | 20 Quarters | 40 Quarters | Unconditional |
|---|---|---|---|---|---|
| Technology | 0.49 | 5.29 | 13.99 | 11.36 | 9.58 |
| Demand | 4.59 | 22.28 | 52.20 | 54.19 | 56.55 |
| Markups | 16.49 | 27.48 | 8.24 | 6.01 | 5.76 |
| Monetary Policy | 77.37 | 38.97 | 7.73 | 5.29 | 4.78 |
| Forward Guidance | 0.54 | 3.15 | 6.61 | 4.26 | 3.94 |
| Foreign | 0.51 | 2.56 | 11.58 | 18.90 | 19.39 |

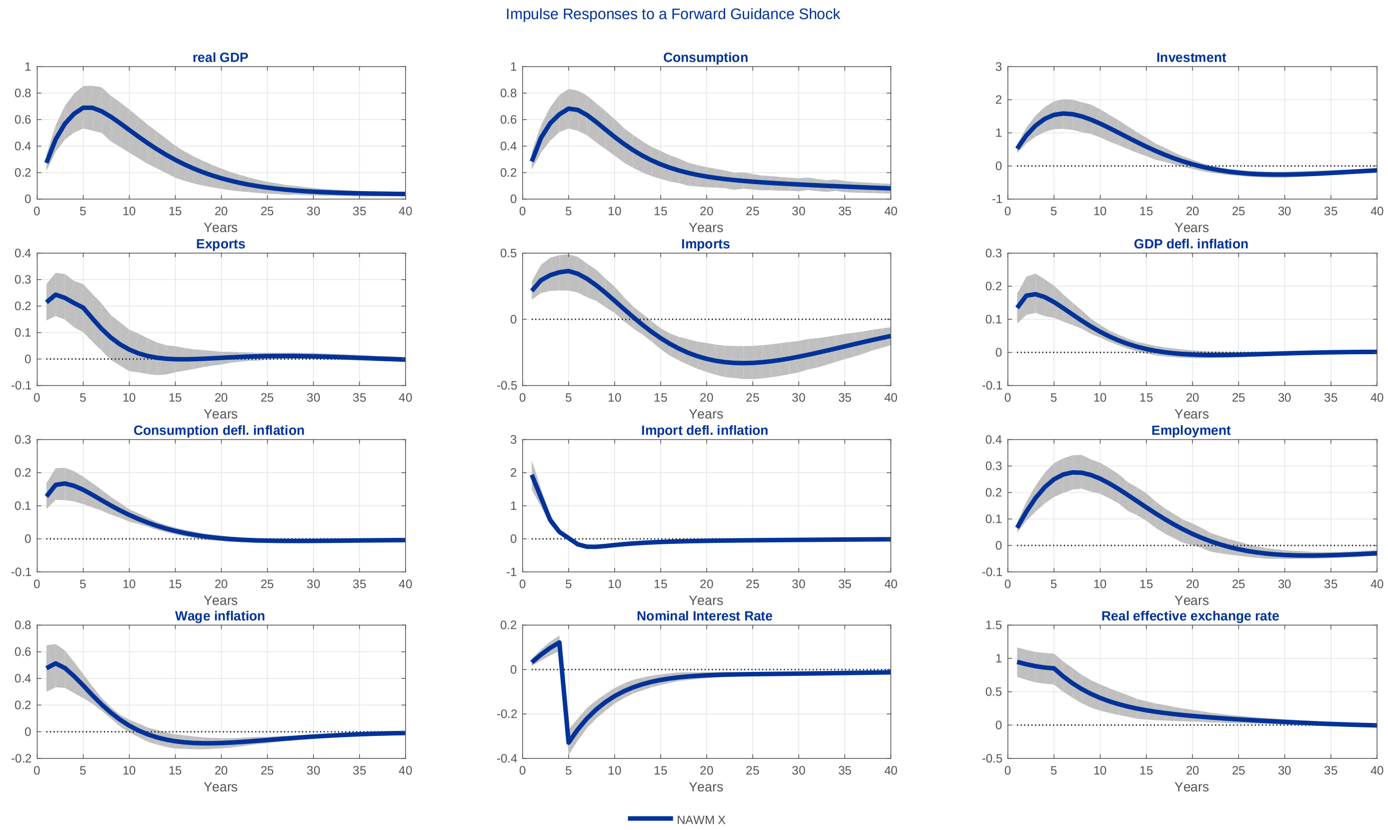
Note: These tables report posterior mean estimates for the contributions of the structural shocks (expressed in percent) of the NAWM X to the forecast error variances of real GDP growth, rates of inflation and the nominal interest rate at the 1 quarter, 4 quarters, 20 quarters and 40 quarters horizon, as well as the unconditional variance decomposition. To enhance readability, the shock contributions are shown only for the share of the forecast errors attributable to the structural shocks. Thus, the shares of the forecast errors due to measurement errors and unobserved state variables are skipped. In addition, the structural shocks are bundled into six groups: technology, demand, markup, monetary policy, forward guidance and foreign.

**Figure 14:** Propagation of an interest rate shock



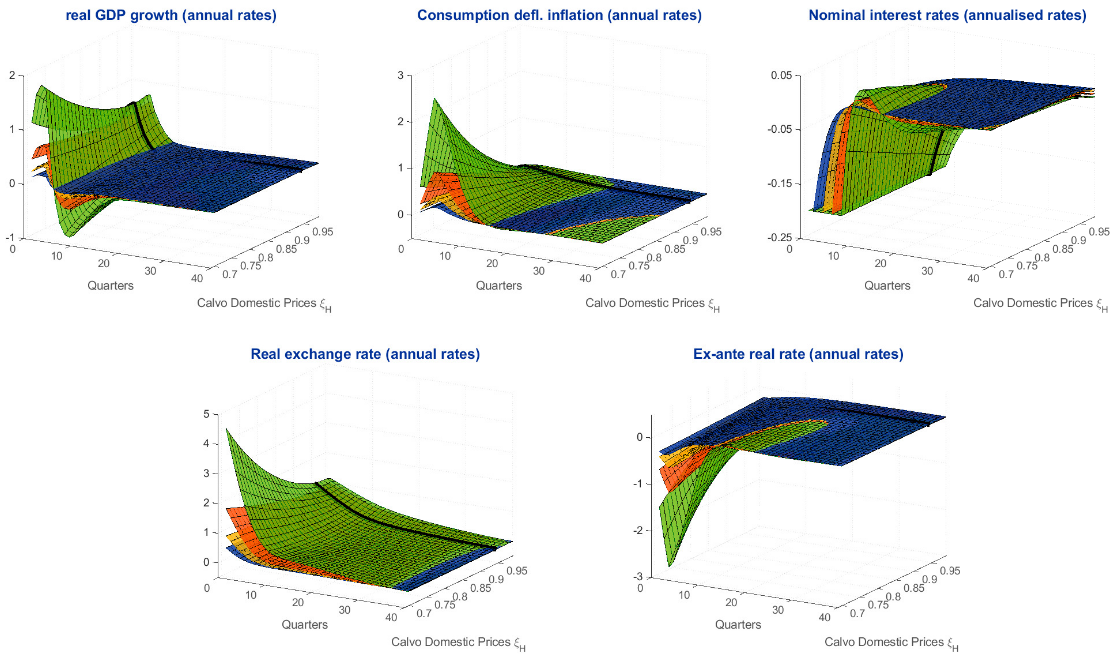

Note: This figure shows the impulse responses of selected observables to a negative monetary policy shock $\epsilon_t^R$ equal to one standard deviation. The dark blue line represents the mean impulse responses of the NAWM X with a 90% level of significance for the confidence interval using the posterior distribution. The orange line shows the posterior mean impulse responses of the baseline NAWM. The impulse responses are given as percentage deviations from the non-stochastic steady-state, apart from the impulse responses of the rates of inflation and the interest rate which are plotted as annualised percentage point deviations.

**Figure 15:** Propagation of a forward guidance shock




Note: This figure shows the impulse responses of selected observables to a negative 4 quarters ahead forward guidance shock $\epsilon_{t-4}^{FG}$ equal to one standard deviation. The dark blue line represents the mean impulse responses of the NAWM X with a 90% level of significance for the confidence interval using the posterior distribution. The impulse responses are given as percentage deviations from the non-stochastic steady-state, apart from the impulse responses of the rates of inflation and the interest rate which are plotted as annualised percentage point deviations.

**Figure 16:** Sensitivity analysis for the Calvo parameter $\xi_H$




Note: The figure shows the impulse responses for annual real GDP growth, inflation, the real exchange rate and the ex-ante real rate of the NAWM X to a series of forward guidance shocks varying the Calvo parameter for domestic prices $\xi_H$. The central bank credibly announces to reduce the interest rate for 2, 4, 6 or 8 quarters by 20 basis points before the Taylor rule afterwards takes over again. We set the lower bound of the parameter range to 0.7 and incrementally increase the value by 0.01 to finally end up at a value of 0.99 for the Calvo parameter $\xi_H$. The solid black lines represent the responses of the NAWM X.

# A Appendix

**Table A.1:** RMSE forecast for real GDP growth

| Model | 1 Quarter | 2 Quarters | 3 Quarters | 4 Quarters | 5 Quarters | 6 Quarters | 7 Quarters | 8 Quarters |
|---|---|---|---|---|---|---|---|---|
| NAWM ED | 0.5227 | 0.6078 | 0.6005 | 0.5940 | 0.5857 | 0.5795 | 0.5690 | 0.5696 |
| **NAWM 1Y YC** | 0.5254 | 0.6000 | 0.5923 | 0.5799 | 0.5703 | 0.5808 | 0.5822 | 0.5847 |
| NAWM 1Y YC Disc | 0.5259 | 0.5995 | 0.5928 | 0.5809 | 0.5704 | 0.5811 | 0.5828 | 0.5852 |
| NAWM SPF | 0.5372 | 0.6157 | 0.6165 | 0.5993 | 0.5805 | 0.5783 | 0.5756 | 0.5759 |
| NAWM SPF Disc | 0.5379 | 0.6158 | 0.6172 | 0.6005 | 0.5814 | 0.5789 | 0.5763 | 0.5766 |
| NAWM 6M9M1Y2Y YC | 0.5200 | 0.5906 | 0.5967 | 0.5759 | 0.5850 | 0.5957 | 0.5996 | 0.6056 |
| NAWM 6M9M1Y2Y YC Disc | 0.5215 | 0.5896 | 0.5968 | 0.5763 | 0.5841 | 0.5952 | 0.5989 | 0.6041 |

**Table A.2:** RMSE forecast for consumption defl. inflation

| Model | 1 Quarter | 2 Quarters | 3 Quarters | 4 Quarters | 5 Quarters | 6 Quarters | 7 Quarters | 8 Quarters |
|---|---|---|---|---|---|---|---|---|
| NAWM ED* | 0.3462 | 0.4205 | 0.4345 | 0.4304 | 0.4121 | 0.3820 | 0.3658 | 0.3336 |
| **NAWM 1Y YC** | 0.2861 | 0.3252 | 0.3351 | 0.3372 | 0.3275 | 0.3240 | 0.3275 | 0.3262 |
| NAWM 1Y YC Disc | 0.2857 | 0.3243 | 0.3342 | 0.3367 | 0.3277 | 0.3241 | 0.3275 | 0.3268 |
| NAWM SPF | 0.2921 | 0.3329 | 0.3492 | 0.3569 | 0.3470 | 0.3411 | 0.3436 | 0.3409 |
| NAWM SPF Disc | 0.2917 | 0.3317 | 0.3479 | 0.3556 | 0.3459 | 0.3401 | 0.3427 | 0.3402 |
| NAWM 6M9M1Y2Y YC | 0.2815 | 0.3102 | 0.3195 | 0.3217 | 0.3169 | 0.3142 | 0.3228 | 0.3238 |
| NAWM 6M9M1Y2Y YC Disc | 0.2818 | 0.3111 | 0.3208 | 0.3233 | 0.3186 | 0.3156 | 0.3233 | 0.3250 |

**Table A.3:** RMSE forecast for wage inflation

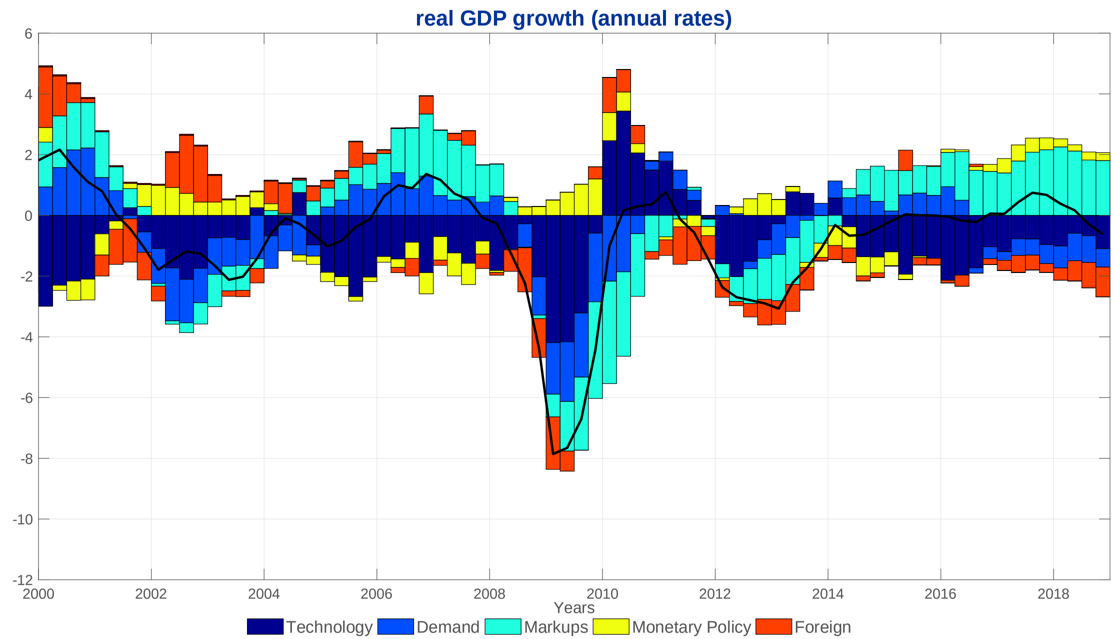
| Model | 1 Quarter | 2 Quarters | 3 Quarters | 4 Quarters | 5 Quarters | 6 Quarters | 7 Quarters | 8 Quarters |
|---|---|---|---|---|---|---|---|---|
| NAWM ED | 0.6686 | 0.7108 | 0.6437 | 0.5225 | 0.4457 | 0.3610 | 0.3211 | 0.2911 |
| **NAWM 1Y YC** | 0.4763 | 0.4252 | 0.3976 | 0.3525 | 0.3407 | 0.3198 | 0.3117 | 0.2916 |
| NAWM 1Y YC Disc | 0.4792 | 0.4179 | 0.3903 | 0.3463 | 0.3353 | 0.3153 | 0.3087 | 0.2889 |
| NAWM SPF | 0.5336 | 0.5000 | 0.4600 | 0.3966 | 0.3709 | 0.3347 | 0.3223 | 0.3019 |
| NAWM SPF Disc | 0.5293 | 0.4909 | 0.4524 | 0.3907 | 0.3663 | 0.3313 | 0.3203 | 0.3009 |
| NAWM 6M9M1Y2Y YC | 0.4577 | 0.4166 | 0.3953 | 0.3577 | 0.3548 | 0.3426 | 0.3386 | 0.3225 |
| NAWM 6M9M1Y2Y YC Disc | 0.4705 | 0.4153 | 0.3939 | 0.3566 | 0.3531 | 0.3408 | 0.3373 | 0.3206 |

**Table A.4:** RMSE forecast for the nominal interest rate

| Model | 1 Quarter | 2 Quarters | 3 Quarters | 4 Quarters | 5 Quarters | 6 Quarters | 7 Quarters | 8 Quarters |
|---|---|---|---|---|---|---|---|---|
| NAWM ED | 0.4178 | 0.8233 | 1.2059 | 1.5577 | 1.8691 | 2.1138 | 2.3212 | 2.4710 |
| **NAWM 1Y YC** | 0.3846 | 0.6044 | 0.7553 | 0.8735 | 1.0240 | 1.2192 | 1.4189 | 1.5997 |
| NAWM 1Y YC Disc | 0.3863 | 0.6062 | 0.7567 | 0.8754 | 1.0277 | 1.2233 | 1.4229 | 1.6031 |
| NAWM SPF | 0.5259 | 0.7209 | 0.8532 | 0.9362 | 1.1715 | 1.4012 | 1.6077 | 1.7864 |
| NAWM SPF Disc | 0.5266 | 0.7217 | 0.8541 | 0.9369 | 1.1714 | 1.3997 | 1.6049 | 1.7820 |
| NAWM 6M9M1Y2Y YC | 0.9640 | 0.7349 | 1.2042 | 1.3388 | 1.4181 | 1.5534 | 1.7000 | 1.8340 |
| NAWM 6M9M1Y2Y YC Disc | 0.9592 | 0.7263 | 1.1992 | 1.3313 | 1.4159 | 1.5553 | 1.7055 | 1.8426 |

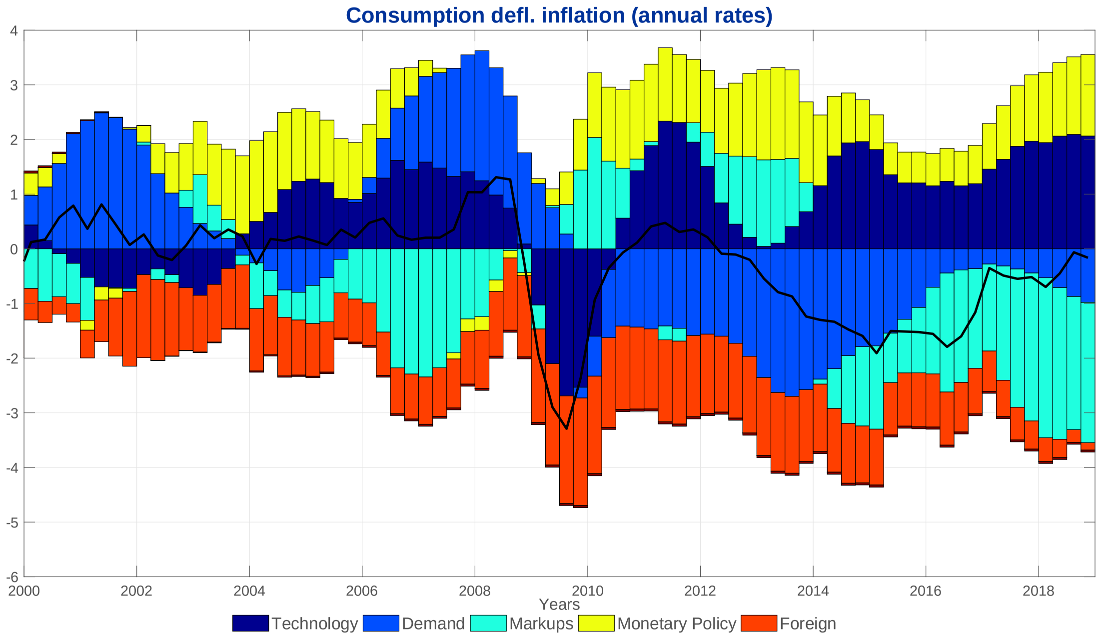
Note: These tables report the root-mean-square errors (RMSE) forecast for real GDP growth, inflation, wage inflation and the nominal interest rate for one- to eight-quarters ahead forecasts computed for the periods 2000Q1 to 2016Q4.

**Figure A.1:** Historical shock decomposition of real GDP growth in the NAWM



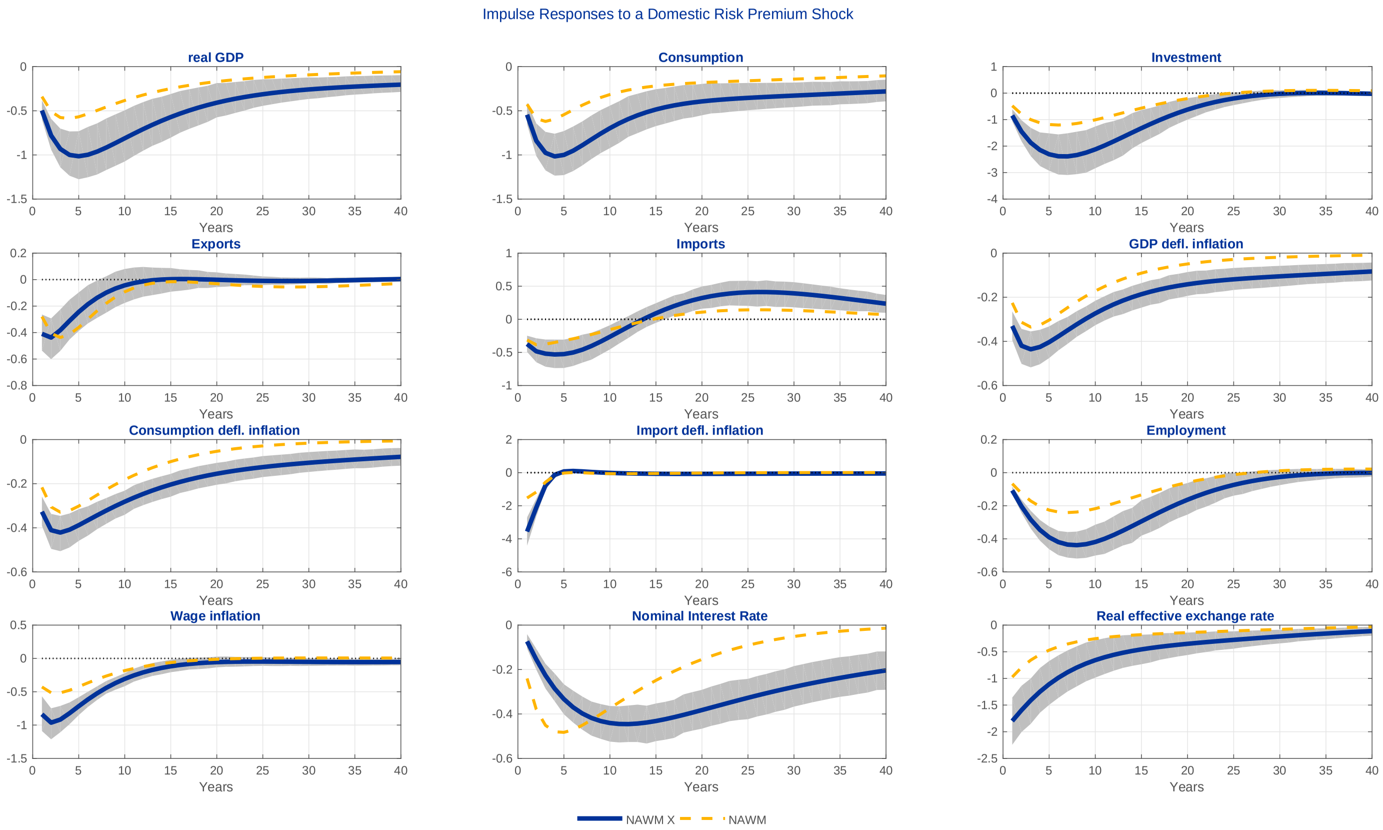

Note: The figure disentangles the decomposition of consumption defl. inflation into the contributions of the structural shocks over the period 2000Q1 to 2018Q4. The shocks are bundled into five groups: technology, demand, markups, monetary policy, foreign, plus the sum of the measurement errors and initial values.

**Figure A.2:** Historical shock decomposition of the rates of inflation in the NAWM



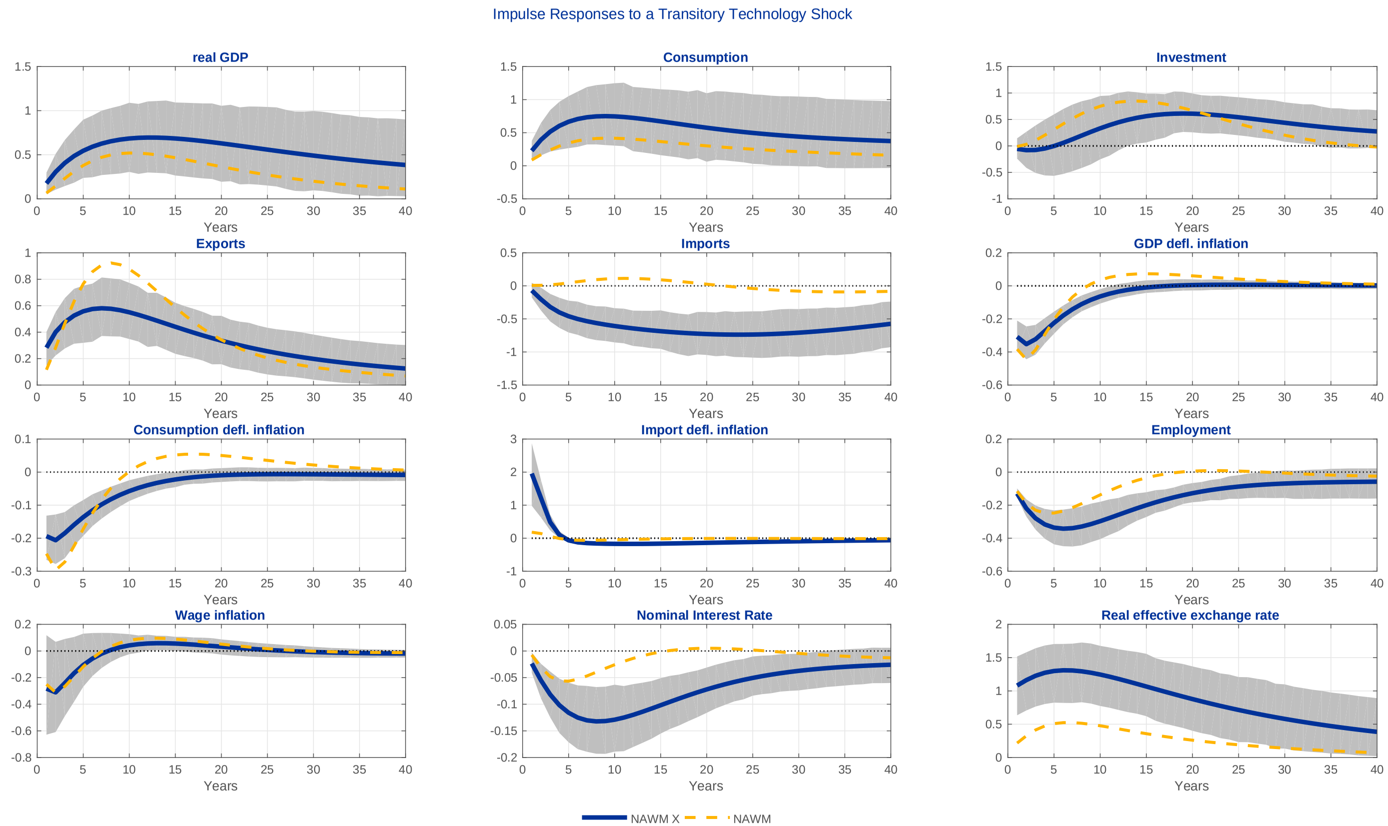

Note: The figure disentangles the decomposition of real GDP growth into the contributions of the structural shocks over the period 2000Q1 to 2018Q4. The shocks are bundled into five groups: technology, demand, markups, monetary policy, foreign, plus the sum of the measurement errors and initial values.

**Figure A.3:** Propagation of a risk premium shock



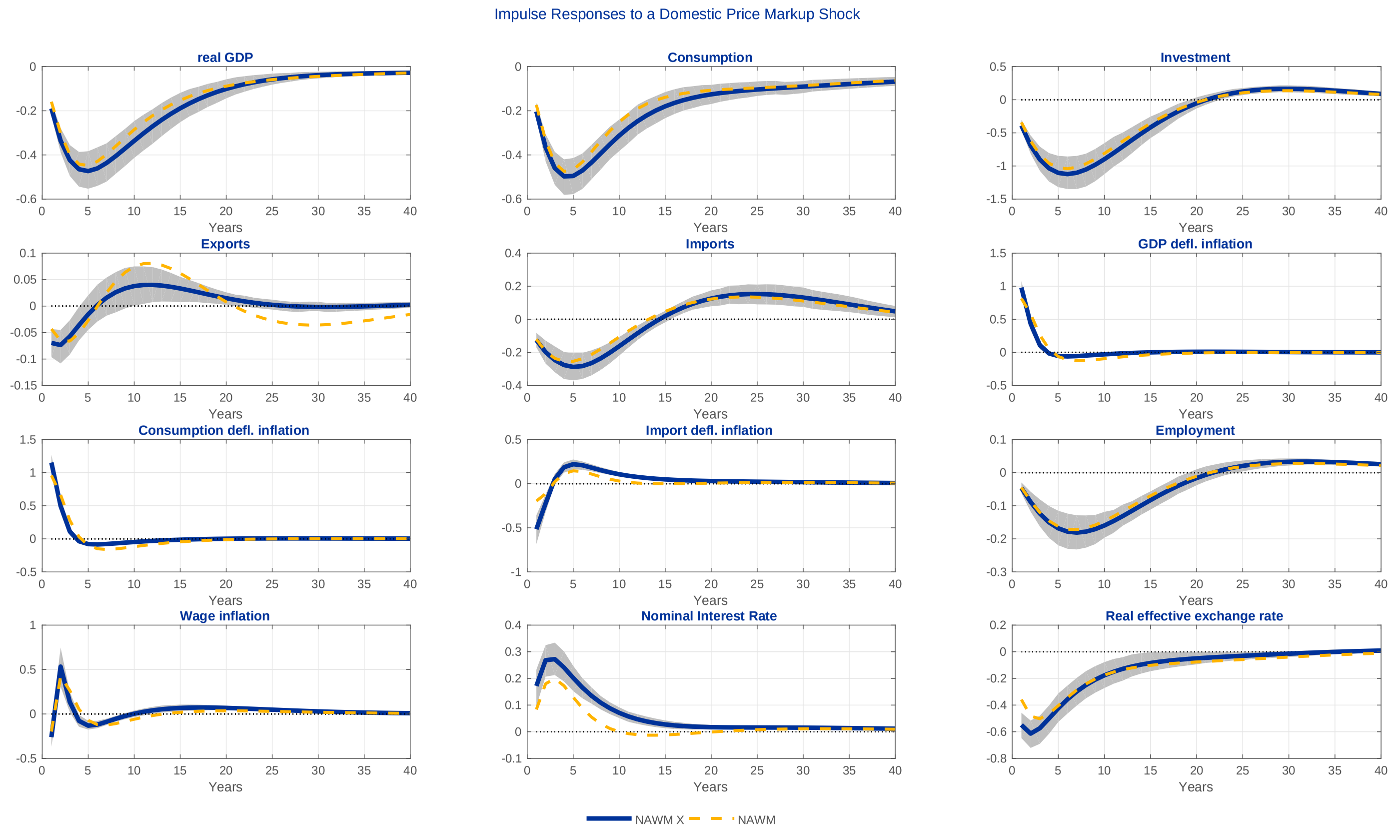

Note: This figure shows the impulse responses of selected observables to a positive domestic risk premium shock $\epsilon_t^{RP}$ equal to one standard deviation. The dark blue line represents the mean impulse responses of the NAWM X with a 90% level of significance for the confidence interval using the posterior distribution. The orange line shows the posterior mean impulse responses of the baseline NAWM. The impulse responses are given as percentage deviations from the non-stochastic steady-state, apart from the impulse responses of the rates of inflation and the interest rate which are plotted as annualised percentage point deviations.

**Figure A.4:** Propagation of a transitory technology shock




Note: This figure shows the impulse responses of selected observables to a positive transitory technology shock $\epsilon_t$ equal to one standard deviation. The dark blue line represents the mean impulse responses of the NAWM X with a 90% level of significance for the confidence interval using the posterior distribution. The orange line shows the posterior mean impulse responses of the baseline NAWM. The impulse responses are given as percentage deviations from the non-stochastic steady-state, apart from the impulse responses of the rates of inflation and the interest rate which are plotted as annualised percentage point deviations.

**Figure A.5:** Propagation of a domestic price markup shock




Note: This figure shows the impulse responses of selected observables to a positive domestic price markup shock $\varphi_t^H$ equal to one standard deviation. The dark blue line represents the mean impulse responses of the NAWM X with a 90% level of significance for the confidence interval using the posterior distribution. The orange line shows the posterior mean impulse responses of the baseline NAWM. The impulse responses are given as percentage deviations from the non-stochastic steady-state, apart from the impulse responses of the rates of inflation and the interest rate which are plotted as annualised percentage point deviations.

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**Tobias Müller**
Boston College, Chestnut Hill, United States; email: tobias.mueller@bc.edu

**Kai Christoffel**
European Central Bank, Frankfurt am Main, Germany; email: kai.christoffel@ecb.europa.eu

**Falk Mazelis**
European Central Bank, Frankfurt am Main, Germany; email: falk.mazelis@ecb.europa.eu

**Carlos Montes-Galdón**
European Central Bank, Frankfurt am Main, Germany; email: carlos.montes-galdon@ecb.europa.eu



Postal address 60640 Frankfurt am Main, Germany
Telephone +49 69 1344 0
Website www.ecb.europa.eu



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