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Günter Coenen, Falk Mazelis, Roberto Motto, Annukka Ristiniemi, Frank Smets, Anders Warne, Raf Wouters

Inflation and monetary policy in medium-sized New Keynesian DSGE models

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Abstract

This chapter of the Research Handbook of Inflation (2025) reviews the evolution and current relevance of medium-scale New Keynesian Dynamic Stochastic General Equilibrium (DSGE) models, which serve as part of the core analytical framework in central banks and academic macroeconomics. The chapter assesses their capacity to analyse inflation dynamics, monetary transmission mechanisms, and policy interventions. Despite their exclusion of crisis-specific features, canonical models such as Smets and Wouters (2007) continue to explain inflation and output dynamics in the euro area and the US, owing in part to the differentiated effects of cost-push and demand shocks and the mitigating role of monetary policy. The chapter traces advancements in the European Central Bank's New Area-Wide Model (NAWM), highlighting extensions that incorporate financial frictions, effective lower bounds, and energy price shocks. These enhancements have strengthened the model's forecasting performance and interpretative power, especially during periods of unconventional monetary policy and energy-driven inflation. DSGE models are shown to be particularly effective for policy counterfactuals, enabling real-time assessments of policy decisions relative to model-based optimal policy. A robustness analysis under alternative scenarios demonstrates how policy rules can be evaluated through a welfare lens, informing the design of resilient monetary frameworks. Finally, the chapter identifies key modelling challenges exposed by recent inflation episodes and advocates for richer supply-side structures and nonlinear dynamics to improve the models' capacity to capture complex macroeconomic developments.

JEL codes: E31, E32, E52, E58, C63.

Keywords: Inflation dynamics, forecast evaluation, effective lower bound, optimal policy, policy counterfactuals.

Non-technical summary

The paper takes stock of the evolution of medium-sized New Keynesian Dynamic Stochastic General Equilibrium (DSGE) models, which currently constitute the workhorse macroeconomic models used in central banks and academia. It focuses on how they can help analyse inflation dynamics, monetary transmission, and policy actions.

Inflation dynamics in the canonical DSGE model

The original Smets and Wouters (2007) model, which is the backbone of most DSGE models currently in use, continues to fit data well both in the euro area and the US. This may appear surprising because the model does not directly include features that are commonly regarded as key to account for the global financial crisis, the subsequent period of too low inflation with short-term interest rates at the lower bound, and the more recent inflation surge. The success of the model is partly explained by the propagation of mark-up shocks, which are found to drive inflation dynamics while having a more muted effect on real activity. Somewhat symmetrically, demand-side shocks are central to fluctuations in GDP, while having only a limited impact on inflation. These two factors are largely due to the extremely weak relationship between inflation and economic slack, as captured by the estimated flatness of the Phillips curve, and the strong countercyclical stance of monetary policy, which has acted as a stabilising mechanism. Overall, the observed inflation surge during 2021-2022 is mostly attributed to repeated and persistent cost-push shocks rather than overheating demand.

The evolution of the canonical DSGE model through the lens of the New Area-Wide Model

The quest for a better understanding of the drivers of cyclical fluctuations over the last two decades is reflected in the evolution of the original Smets and Wouters (2007) model, as exemplified by the ECB's New Area-Wide Model (NAWM). Over time, the NAWM has been extended and re-estimated to include financial frictions, the lower bound on short-term interest rates and, more recently, energy as a key good that cannot be easily substituted even when its price rises persistently. The main advantage of these model extensions does not appear to reside on the improved fit but rather on the improved forecasting ability over the relevant policy horizon and its capability to provide strong narratives. For instance, during the post-2008 low-inflation period, the model has provided real-time estimates of the emerging deflation risks – which were quantified at the time to be substantial and persistent – particularly when monetary policy was constrained by the lower bound. Also, the model shows that non-standard monetary policy instruments like asset purchases and forward guidance can prove vital in mitigating the adverse effects of these lower bound constraints. In addition, the latest model version, which incorporates a direct link between oil prices and consumer prices, is found to visibly improve inflation forecasts during the recent energy-driven inflation surge.

Are DSGE models well suited to carry out policy counterfactuals and what do they tell us?

DSGE models are well suited to carry out policy counterfactuals because policy interventions should typically not be seen as random errors or deviations from systematic monetary policy, as alternative modelling approaches such as pure time-series models tend to entail. The strength of DSGE models in carrying out counterfactuals is analysed using the Mazelis, Motto and Ristiniemi model. Comparing the actual monetary policy actions to the prescriptions from optimal monetary policy using real-time information highlights that, while hindsight implies that a more aggressive response might have reduced inflation more quickly, the ECB's real-time policy decisions were generally close to model-based optimal policy given the available information at the time. And deviations from optimal policy can be largely explained by uncertainty and the ECB's role in managing associated risks.

In light of uncertainty over how the economic environment may develop, a robustness exercise is performed to evaluate the economic performance of different policy rules in alternative scenarios according to a welfare criterion. If policymakers have a preference to avoid the worst outcomes, this approach can help to narrow down the choice of options. The prescription may entail an adjustment in the inflation reaction, depending on the alternative environments considered.

Challenges for Future Modelling

The recent inflation episode has exposed limitations in existing models, especially their reliance on linear dynamics, oversimplified production structures and the modest internal propagation of exogenous shocks. Accordingly, the paper advocates more detailed supply-side modelling and nonlinear features that can better capture the effects of large and rapid price movements, supply chain disruptions, and structural shifts like those related to climate change and digitalisation.

1. Introduction

Following the New Keynesian synthesis of Goodfriend and King (1997) and Rotemberg and Woodford (1997) and the extensions and empirical applications of Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2003, 2007), mid-sized New Keynesian DSGE models have become one of the workhorse models in central banking to analyse economic activity and inflation and perform monetary policy analysis.

In this chapter we first briefly review the core features of the canonical New Keynesian DSGE model with a focus on the price and wage Phillips curves. We estimate the model on recent data samples for the United States and the euro area and discuss the determinants of inflation and its interaction with wages through the lens of the model. We find that in line with earlier results in Smets and Wouters (2003, 2007) inflation is mostly driven by price and wage mark-up shocks. Given the simplicity of the canonical model, these mark-up shocks often stand in for other supply and cost-push shocks such as exogenous changes in the prices of energy or other imported intermediate goods or changes in labour supply. While demand shocks are the dominant drivers of economic activity over the business cycle, they contribute relatively little to inflation developments due to the estimated flatness of the price Phillips curve and a strong countercyclical response of monetary policy justifying the assumption of anchored medium-term inflation expectations.

Over the past two decades, the canonical model has been extended in many directions often in response to new economic challenges. Major extensions in the literature involve the inclusion of open economy features such as international trade and capital flows (Justiniano and Preston, 2004; Adolfson et al, 2007a), financial frictions and a financial intermediation sector (Bernanke, Gertler and Gilchrist, 1999; Christiano, Motto and Rostagno, 2014; Gertler and Karadi, 2011), and a more elaborate description of the labour market (Gertler and Trigari, 2009; Christiano, Eichenbaum and Trabandt, 2016). At central banks, extensions have been undertaken to make the models fit for forecasting and monetary policy analysis. Section 3 and 4 present two such models regularly used at the European Central Bank (ECB). Section 3 presents the New Area Wide Model (NAWM). We discuss how the model has evolved in response to challenges facing the euro area such as the global financial crisis and the subsequent period of low inflation and policy rates at the effective lower bound. In two applications we show how the estimated model can be used to analyse the risks of deflation in an environment with an effective lower bound and how non-conventional policy measures such as forward guidance and large-scale asset purchases can be used to overcome such deflation risks. The most recent extension of the NAWM involves the inclusion of a direct oil price propagation channel. We illustrate how the inclusion of this channel affects the conditional inflation forecasts of the NAWM.

New Keynesian DSGE models are also regularly used for assessing alternative monetary policy strategies to deliver price stability. Section 4 uses the Mazelis, Motto and Ristiniemi (MMR) model to address questions such as “What would optimal policy prescribe under the central bank’s baseline projections for inflation?” or “What course of policy action would be robust in the face of risks that inflation may evolve differently from the baseline projections?”. It finds that with the benefit of hindsight the ECB policy should have been more aggressive in 2022-23 in response to the inflation developments. But, conditional on information available in real time as summarised by real-time staff projections, the ECB policy over 2022-23 has been most of times close to the prescriptions from optimal policy. Some small deviations can be understood from a risk management perspective as taking out insurance against bad outcomes.

Finally, the last section discusses some of the challenges for the canonical model that are raised by the recent high-inflation period. The current generation of New Keynesian DSGE models often have a very simple production structure and supply side. The higher frequency of sectoral reallocation shocks due to the pandemic crisis, the energy crisis and ongoing structural changes due to climate change and digitalisation underlines the importance of further developing the supply side and the input/output structure of the current generation of DSGE models. Moreover, the recent shift from low and stable inflation to high and volatile inflation suggests one should also pay more attention to sources of non-linearity in the Phillips curves.

2. Inflation in the canonical New Keynesian DSGE model

This section uses the Smets and Wouters (2007) (SW07) model as a starting point. The core of the model consists of a hybrid price and a hybrid wage Phillips curve.[2] We estimate the model on US and euro area data. We then discuss the determinants of inflation as seen through the lens of the estimated model, distinguishing between demand, supply, and monetary policy sources.

2.1 Hybrid price and wage Phillips curves

The core of the canonical New Keynesian DSGE model consists of a price and a wage Phillips curve.[3] This section briefly reviews the log-linearized versions of these Phillips curves as derived in SW07. A full description of the decision problems of the agents in the economy can be found in Lindé, Smets and Wouters (2016). Inspired by Christiano, Eichenbaum and Evans (2005), the SW07 model contains many frictions and shocks that affect both nominal and real decisions of households and firms. The model economy has a balanced steady-state growth path driven by deterministic labour-augmenting technological progress. Households maximize a non-separable utility function with two arguments (goods and labour effort) over an infinite life horizon. Consumption appears in the utility function relative to a time-varying external habit variable. Labour is differentiated by a union, so there is some monopoly power over wages, which results in an explicit wage equation and allows for the introduction of sticky nominal wages as in Calvo (1983) and Erceg, Henderson and Levin (2000). Households rent capital services to firms and decide how much capital to accumulate given the capital adjustment costs they face. As the rental price of capital changes, the utilization of the capital stock can be adjusted at increasing cost. Firms produce differentiated goods, decide on labour and capital inputs, and set prices, again according to the Calvo model. The Calvo model in both wage and price setting is augmented by the assumption that prices and wages that are not reoptimized are partially indexed to past inflation rates. In both goods and labour markets a Kimball (1995) aggregator instead of the Dixit-Stiglitz (1977) aggregator is used. This introduces strategic complementary in price setting which implies that intermediate firms adjust prices less to a given change in marginal cost.

In the linearised model, profit maximization by price-setting firms gives rise to the following hybrid New-Keynesian Phillips curve:[4]

(1) $$\pi_t = \pi_1 \pi_{t-1} + \pi_2 E_t \pi_{t+1} - \pi_3 \mu_t^p + \varepsilon_t^p .$$

Inflation (π_t) depends positively on past and expected future inflation, negatively on the current desired price mark-up (μ_t^p),

[2] See Erceg, Henderson and Levin (2000) for an analysis of the monetary policy implications of having both price and wage staggering.
[3] See also the textbook treatment in Galí (2015) and Woodford (2003).
[4] For the precise link between the “reduced-form” parameters in equations (1) and (2) and the structural parameters, see SW07.

(2) $\mu_t^p = mpl_t - w_t = -mc_t,$

and positively on a price mark-up disturbance (ε_t^p).

The desired mark-up creates a wedge between the marginal product of labour (mpl_t) and the real wage (w_t) and is equal to the inverse of the marginal cost (mc_t). Due to the Cobb-Douglas production function in capital and labour, the marginal cost is also equivalent to real unit labour costs. SW07 assumes that the price mark-up disturbance follows an ARMA(1,1) process, which helps capturing both high-frequency and more persistent fluctuations in inflation shocks.

When there is no indexation to past inflation, equation (1) reverts to a standard, purely forward-looking New Keynesian Phillips curve. The assumption that all prices are indexed to either lagged inflation or the steady-state inflation rate ensures that the Phillips curve is vertical in the long run.[5] The speed of adjustment to the desired mark-up depends, among others, on the degree of price stickiness, the curvature of the Kimball goods market aggregator and the steady-state mark-up, which in equilibrium is itself related to the share of fixed costs in production through a zero-profit condition. A higher Kimball curvature slows down the speed of adjustment because it increases the strategic complementarity with other price setters. When all prices are flexible and the price-mark-up shock is zero, equation (1) reduces to the familiar condition that the price mark-up is constant or equivalently that there are no fluctuations in the wedge between the marginal product of labour and the real wage.

Similarly, due to nominal wage stickiness and partial indexation of wages to inflation, real wages adjust only gradually to the desired wage mark-up:

(3) $w_t = w_1 w_{t-1} + (1 - w_1)(E_t w_{t+1} + E_t \pi_{t+1}) - w_2 \pi_t + w_3 \pi_{t-1} - w_4 \mu_t^w + \varepsilon_t^w.$

The real wage (w_t) is a function of expected and past real wages, expected, current, and past inflation, the desired wage mark-up (μ_t^w),

(4) $\mu_t^w = w_t - mrs_t,$

and a wage mark-up disturbance (ε_t^w).

In analogy with the price Phillips curve, the desired wage mark-up is the difference between the real wage and the marginal rate of substitution between working and consuming. If wages are perfectly flexible, the real wage is a constant mark-up over the marginal rate of substitution. In general, the speed of adjustment to the desired wage mark-up depends on the degree of nominal wage stickiness, the demand elasticity for labour, which itself is a function of the steady-state labour market mark-up and the curvature of the Kimball labour market aggregator. When wage indexation is zero, real wages do not depend on lagged inflation. As in the case of the price mark-up shock, the wage-markup disturbance is assumed to follow an ARMA(1,1) process. Based on Galí (2011), Galí, Smets and Wouters (2010) slightly modify the SW07 model which allows them to interpret the gap between the real wage and the marginal rate of substitution as proportional to the gap between the actual and the natural unemployment rate.

Together equations (1) to (4) describe the interaction between price and wage dynamics and their link with other endogenous variables such as productivity developments and the unemployment gap. This system has the same flavour as the more empirically motivated formulation of price and wage dynamics by Bernanke and Blanchard (2023), with the indexation parameter capturing a form of real

[5] For an in-depth discussion of the implications of changes in trend inflation for the Phillips curve in a model without indexation, see Ascari and Sbordone (2014).

wage catch-up. Equations (1) to (4) are complemented with equations capturing the main demand components (consumption and investment) and market clearing conditions to describe the dynamic general equilibrium in this economy (see SW07 for details).

2.2 Estimates for the US and euro area economy

This section presents estimates of the SW07 model for the US and euro area economy over recent sample periods. In Table 2.1 of the Appendix, we report estimates for the full sample (US: 1965Q1 – 2019Q4 and EA: 1980Q1 – 2019Q4 respectively) and for a shorter common sample (1995Q1 – 2019Q4).

As in SW07 we use seven quarterly macro-economic US and euro area time series as observable variables: real GDP, consumption and investment, inflation, the real wage, hours worked (employment in the case of the euro area) and a policy-controlled interest rate. In addition, we include a 1-year interest rate and an additional monetary policy forward guidance shock to better capture the impact of forward guidance during the period during which the effective lower bound on the policy-controlled rate was binding.[6] A full description of the data used is given in the Appendix.

Bayesian techniques are adopted to estimate the parameters. Bayesian inference starts out from a prior distribution that describes the available information prior to observing the data used in the estimation. The observed data are subsequently used to update the prior, via Bayes theorem, to the posterior distribution of the model's parameters which can be summarized in the usual measures of location (e.g. mode or mean) and spread (e.g. standard deviation and probability intervals). Some of the parameters in the model that are weakly identified are kept fixed throughout the estimation procedure (i.e., they have infinitely strict priors).[7]

Overall, the estimates of the structural parameters for the full sample presented in Table 2.1.a in the appendix are quite similar across the US and the euro area and over time. Focusing on the parameters that are important for the price and wage Phillips curves, a few observations are worth making. First, the degree of price stickiness as captured by the Calvo parameter is higher for prices than for wages in both areas. A Calvo parameter of 0.82 (US) or 0.85 (EA) suggests an average duration of price contracts of about 6 quarters, which is larger than the average duration of price spells commonly estimated using micro price data in consumer markets. Of course, these estimates also depend on the degree of strategic interaction between price setters which is governed by the calibration of the curvature parameter (assumed to be 10). The relatively high estimates of price stickiness may suggest that the curvature parameter in intermediate goods markets is larger than 10 as argued in Harding et al (2023). For wages, the Calvo parameters of 0.80 (US) and 0.73 (EA) suggests average duration of wage contracts in the order of 4 to 5 quarters, which is closer to the micro evidence of the annual duration of wage contracts. Somewhat surprisingly the average duration of wage contracts is estimated to be slightly longer in the US than in the euro area. For the shorter common sample, Table 2.1.b in the appendix shows that over time the Calvo parameters in the euro area have remained very similar. The overall implication is that both the price and wage Phillips curves are very flat.

[6] An alternative approach is to estimate the model imposing the effective lower bound on interest rates. See Lindé, Smets and Wouters (2016) for one approach.

[7] These parameters are calibrated to similar values as in SW07 (see footnote of Table 2.1a/b). In contrast to SW07, we do not estimate the inflation target, but impose it to be 2 percent in line with the recent monetary policy strategy reviews in the US and the euro area.

Second, the estimated degree of indexation is small in both areas. There is a bit more evidence of the indexation of wages to past inflation in the US (0.51) than in the euro area (0.17), but the indexation of prices to past inflation is in both areas close to zero (0.19 in the US and 0.16 in the EA). The latter is in line with the micro evidence which shows the prevalence of zero price changes and is inconsistent with automatic adjustment of all prices. Translating those parameters to the relative weight of past versus forward-looking inflation, it follows that the weight on past inflation is very small. As a result, inflation typically does not have the hump-shaped behaviour in response to various demand shocks.

Third, the two mark-up shocks that directly affect prices and wages are very persistent with a large moving-average component. Over the longer sample period wage mark-up shocks are highly persistent and more so than price mark-up shocks with a persistence parameter of 0.98 for both the US and the euro area. The estimated persistence of both shocks falls significantly in the more recent period, particularly in the United States.

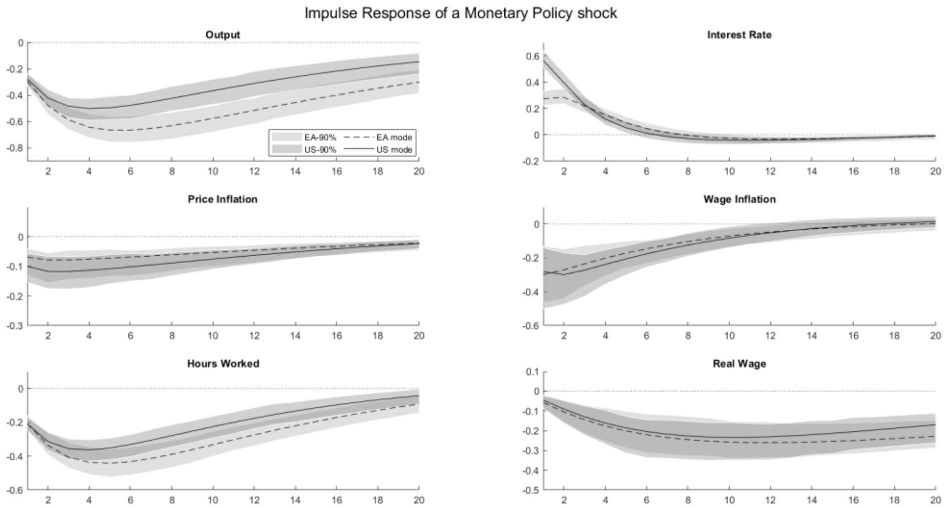
It is also interesting to compare the estimated parameters of the monetary policy reaction function which shows very similar features in both areas. For both the euro area and the US the response of the nominal policy rate to inflation is equal to around 1.75. The persistence of the monetary policy reaction is higher in the euro area (0.91) than in the US (0.83). Finally, in both cases the Taylor rule response coefficient to the growth rate of GDP (at 0.24 and 0.22 respectively) is higher than the response coefficient to the level of the output gap (0.07 and 0.13). In the shorter sample period, those coefficients are smaller (around 0.11) and more similar in both areas.

2.3 What drives inflation in the canonical model?

The propagation of demand and supply shocks to inflation

This section compares the response of output, hours worked, the short-term interest rate, as well as wage and price inflation to the various demand and supply shocks in the two economies. Figure 2.1 shows the impact of a monetary policy tightening. Overall, the monetary transmission process is qualitatively very similar in both regions. Due to the stickiness of prices and wages a monetary policy tightening leads to a slowdown in output and employment which peaks after 4 to 5 quarters. The impact on wage inflation is larger than on price inflation giving rise to a persistent drop in real wages.

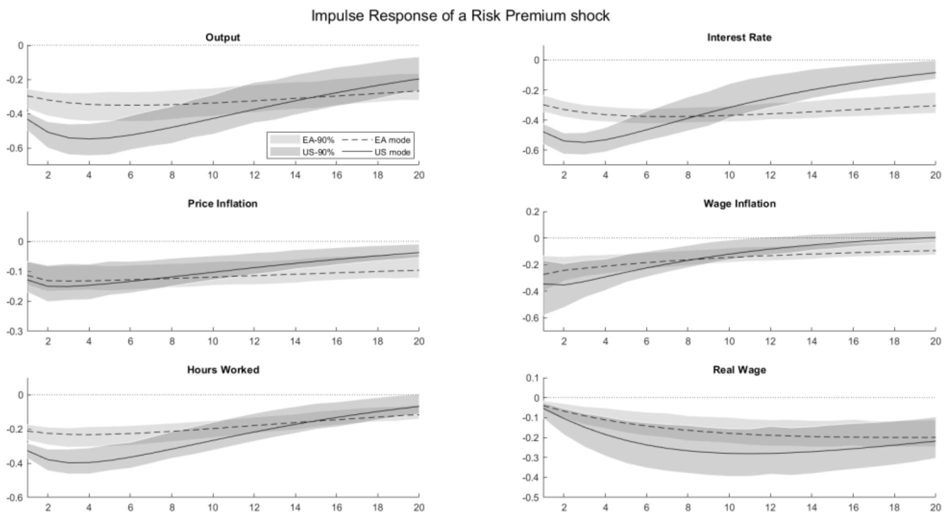
Figure 2.1: A monetary policy tightening in the US and the euro area



Notes: The solid (dashed) line is the impulse response for a one standard deviation shock in the US (EA) model evaluated at the estimated posterior mode. The shaded array around these lines represents the 90 percent highest posterior density intervals.

A similar pattern can be detected following a positive risk premium shock (Figure 2.2). Output, employment, and the real wage, as well as price and wage inflation fall. In contrast to the findings of SW07 for earlier sample periods, this shock is estimated to be much more persistent in the second half of the sample, capturing the prolonged impact of the global financial crisis. In response to this shock, monetary authorities persistently lower nominal and real interest rates, partially capturing the observed secular fall in real rate over the sample.

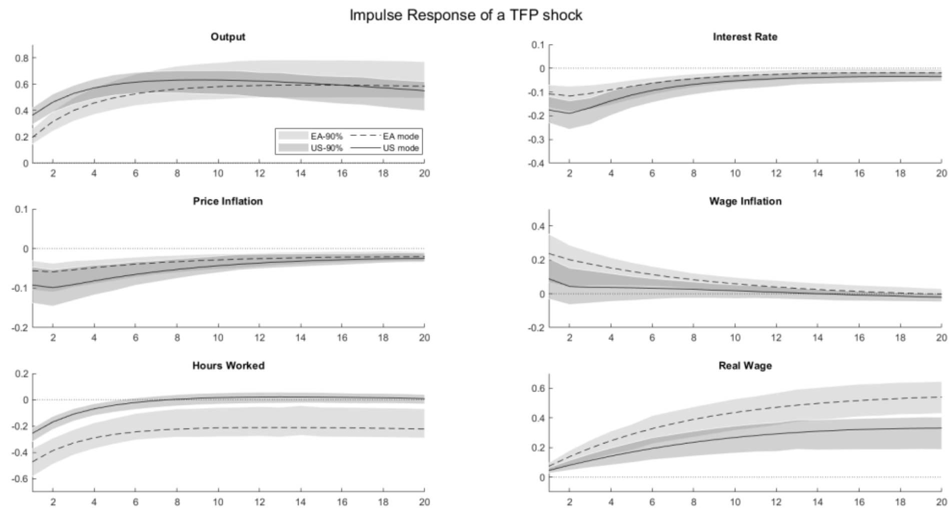
Figure 2.2: A risk premium shock in the US and the euro area



Notes: See Figure 2.1.

Turning to the supply shocks, the total factor productivity shock is the only shock that has opposite effects on price and wage inflation (Figure 2.3). Higher productivity pushes up output and real wages, as well as nominal wage inflation but down price inflation. Lower inflation leads to an easing of monetary policy. In the short run, higher productivity also leads to a fall in hours worked as firms see their short-run profitability go down.

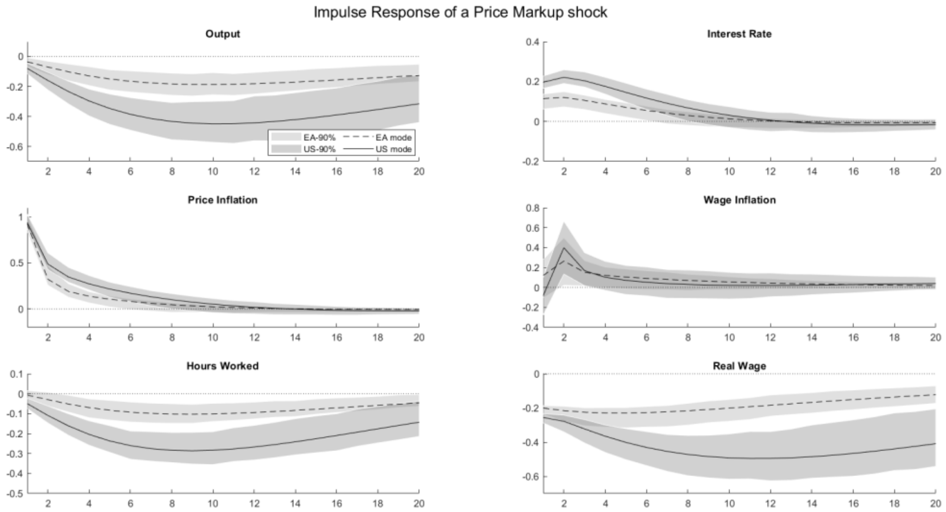
Figure 2.3: A total factor productivity shock in the US and the euro area



Notes: See Figure 2.1

The two most important drivers of inflation in the estimated model are the price and wage mark-up shocks. Figure 2.4 shows the typical impulse response following a price mark-up shock. These shocks will also capture cost-push shocks like energy price shocks. The volatility of the cost-push shocks is quite high. These shocks have a significant negative impact on output. There is some limited pass-through from price inflation to wage inflation. Overall, a price mark-up shock that pushes up inflation by 1% has a delayed peak effect on wage inflation of between 0.2 and 0.4 %. The real wage falls significantly and persistently.

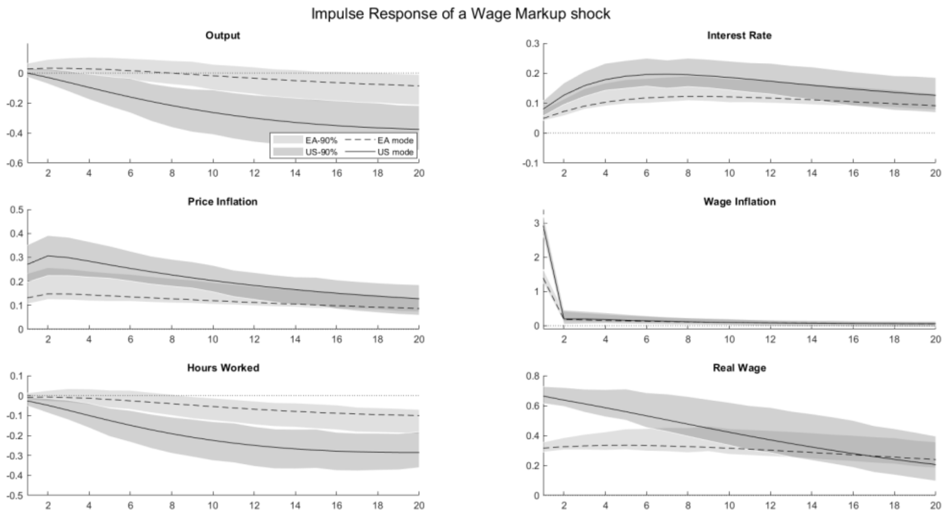
Figure 2.4: A price mark-up shock in the US and the euro area



Notes: See Figure 2.1.

A positive wage mark-up shock on the other hand has a large immediate impact on wage inflation but with a much lower persistence (Figure 2.5). The pass-through on inflation is much more limited reflecting the high estimated degree of price stickiness but is equally persistent. Overall, it leads to a very persistent rise in the real wage and unit labour costs and has a non-negligible cost in terms of employment and hours worked.

Figure 2.5: A wage mark-up shock in the US and the euro area



Notes: See Figure 2.1.

Accounting for inflation developments

Table 2.1 shows the variance decomposition of the main endogenous variables at a horizon of two and half years, which is generally considered as the relevant monetary policy horizon. At this horizon 42% of US output fluctuations and 35% of euro area output fluctuations are driven by the three demand shocks (columns 2 to 4). And about one fourth is explained by changes in productivity growth.

In the euro area monetary policy shocks play a relatively more important role, while in the US price mark-up shocks are more important.

Turning to inflation, in both areas price mark-up shocks are the dominant source of inflation fluctuations at this policy-relevant horizon. The second most important source of fluctuations are the wage mark-up shocks, followed by the risk premium shocks. Price mark-up shocks have only limited influence over fluctuations in wage inflation, which are mostly driven by wage mark-up shocks.

It is also instructive to have a look at the drivers behind the fundamentals of price and wage inflation, i.e. the marginal cost and the marginal rate of substitution. In the US economy, the various supply shocks are dominating the business cycle fluctuations in unit labour costs (wage mark-up shocks with 41%, price mark-up shocks with 28% and TFP shocks with 12%), followed by the demand shocks (risk premium shocks with 9% and monetary policy shocks with 6%). In the euro area TFP and monetary policy shocks are relatively more important in driving unit labour costs.

Following Galí (2011), the wedge between the real wage and the marginal rate of substitution is proportional to the unemployment gap. In the US the most important drivers of the marginal rate of substitution are the demand shocks (risk premium with 35% and monetary policy with 25%), whereas the supply shocks play a relatively less important role. This is similar in the euro area, although there the TFP shocks play a relatively more important role (38%).

Overall, a similar picture emerges in the more recent common sample, but it is worth noting that in the more recent period, wage mark-up shocks have become less important for inflation in the US, but not so in the euro area.

Table 2.1: Forecast error variance decomposition at the 10-quarter horizon

US – 1965Q1:2019Q4

	tfp	risk	exo.dem	inv.spec	mon.pol	price mup	wage mup	yield
y	26.90	20.39	6.28	15.61	15.31	10.19	2.37	2.95
pinf	2.21	7.48	0.54	0.84	4.34	56.89	26.95	0.74
pinfw	0.16	6.50	0.15	1.95	4.22	2.06	84.21	0.75
mc	12.28	8.77	0.27	2.08	6.37	27.74	41.32	1.17
mrs	3.90	35.39	0.54	6.94	24.95	12.83	10.57	4.88

EA – 1980Q1-2019Q4

	tfp	risk	exo.dem	inv.spec	mon.pol	price mup	wage mup	yield
y	25.02	12.41	10.05	12.27	37.61	2.35	0.05	0.24
pinf	1.35	11.00	0.04	0.00	3.25	71.86	12.48	0.01
pinfw	6.28	12.46	0.01	0.79	10.71	4.91	64.80	0.04
mc	29.32	7.77	0.27	0.64	18.62	14.93	28.35	0.10
mrs	37.85	17.90	0.18	2.61	37.97	1.47	1.75	0.27

US – 1995Q1:2019Q4

	tfp	risk	exo.dem	inv.spec	mon.pol	price mup	wage mup	yield
dy	18.81	28.34	18.64	10.06	22.85	0.85	0.07	0.38
y	18.85	28.64	4.72	12.62	33.16	1.88	0.01	0.14
pinf	1.48	4.07	0.09	0.03	6.60	87.44	0.29	0.00
pinfw	0.59	4.67	0.02	0.36	6.14	1.25	86.95	0.02
mc	12.70	24.26	0.43	1.33	31.02	8.07	22.12	0.06
mrs	7.66	42.23	0.20	3.46	44.09	2.04	0.01	0.32

EA – 1995Q1:2019Q4

	tfp	risk	exo.dem	inv.spec	mon.pol	price mup	wage mup	yield
dy	7.15	21.51	19.34	21.92	27.46	1.03	1.28	0.31
y	16.07	18.60	9.82	7.64	44.99	1.99	0.53	0.36
pinf	1.13	1.85	0.03	0.03	6.90	56.13	33.92	0.01
pinfw	5.31	4.58	0.01	0.13	14.47	2.81	72.62	0.06
mc	22.66	6.40	0.22	0.14	18.09	10.55	41.83	0.11
mrs	27.93	27.73	0.12	0.81	39.17	0.99	2.89	0.37

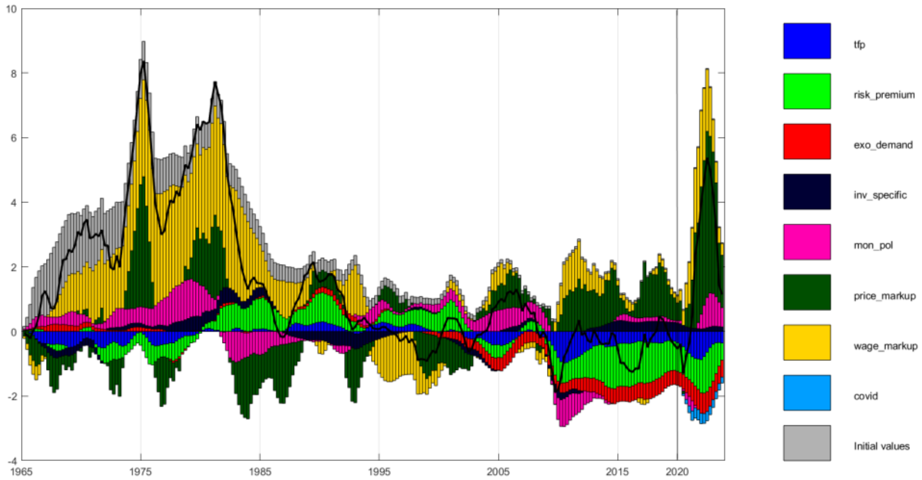
Notes: y=real GDP, pinf=price inflation, pinfw=wage inflation, mc=marginal cost, mrs=marginal rate of substitution.

We can use the historical decomposition of inflation to investigate how the various drivers have worked out over time.[8] Focusing first on the US, it is striking that the inflation of the 1960s and 1970s is mostly driven by positive wage mark-up shocks (Figure 2.6). These shocks have become much less important since the 1980s. Price mark-up shocks contribute significantly to most of the peaks and troughs in inflation and they have been the dominant source of the recent high inflation period. These shocks have often been associated with energy price shocks. Monetary policy did significantly

[8] For this historical decomposition we extend the sample till 2023Q3. To take account of the unusual nature of the pandemic crisis in 2022 we include a set of i.i.d. shocks to productivity, consumption and investment in the US and EA model (and hours worked for the EA model only) in 20Q1 and 21Q2. These are captured by the contributions of the covid shocks in Figures 2.6 and 2.7.

contribute to the rise and fall of inflation from the late 1960s to the early 1980s. It also contributed to the disinflation following the global financial crisis, but since then has mostly pushed inflation up and contributed about 1pp to the recent high inflation period according to these estimates. Finally, the demand shocks (and particularly the risk premium shock) have contributed on average about 1pp of disinflation since the global financial crisis, in that process also pushing down the real rate. However, over the past year or so these downward demand pressures have been disappearing.

Figure 2.6: Historical decomposition of inflation in the US

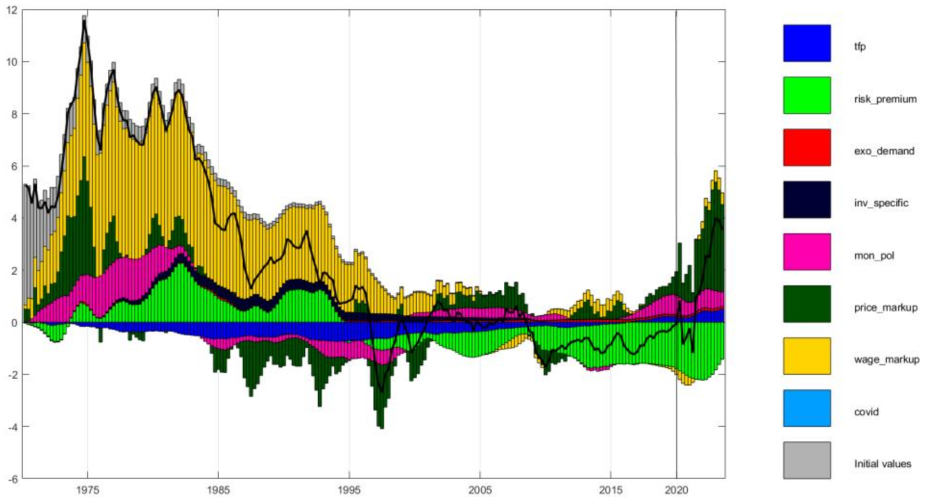


Notes: The solid line is the annual inflation rate of the GDP deflator in deviation from the 2% mean rate.

A broadly similar picture emerges in the euro area (Figure 2.7).

Focussing on the pandemic period since the first quarter of 2020, it is worth highlighting that price mark-up shocks explain most of the rise and fall in inflation. Compared to the high-inflation period of the 1970s, wage mark-up shocks are much less important. Given their temporary nature and the flat Phillips curves, the Covid shocks do not contribute significantly to inflation in this period, but in both areas there is a positive contribution of monetary policy to the rise in inflation, possibly reflecting the impact of the monetary policy strategy reviews concluded in this period. Somewhat surprisingly, the demand shocks appear to have mostly a negative, but dwindling contribution to inflation. Finally, the different productivity developments in the US and the euro area have a differential impact on inflation in this period.

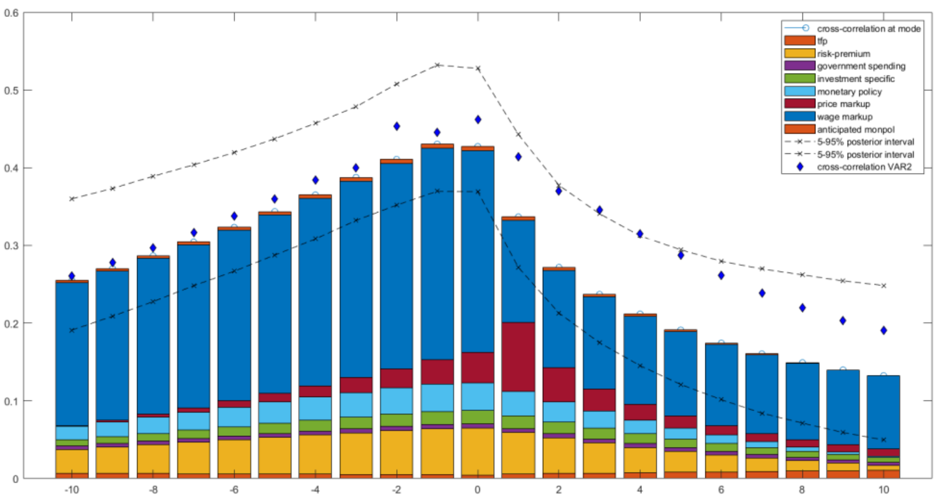
Figure 2.7: Historical decomposition of inflation in the euro area



Notes: see Figure 2.6

To highlight the important role of price and wage mark-up shocks in the dynamics of prices and wages, we can also decompose the cross-correlation between price and wage inflation with respect to the various shocks. As shown in Figure 2.8 for the US, over the full sample wage mark-up shocks are the most important driver of the positive and somewhat leading correlation between wage inflation and price inflation. Price mark-up shocks on the other hand instil a one-period lagging positive correlation between wage and price inflation.

Figure 2.8: Cross-correlation between wage and price inflation (US: 1965-2019)



Notes: The diamonds plot the empirical cross correlation function between wage and price inflation based on a VAR with two lags estimated over the same sample as the DSGE model. This empirical cross correlation is compared with the one calculated from the estimated DSGE model evaluated at the mode and its 5-95% posterior interval.

Overall, we find that in line with earlier results in Smets and Wouters (2003, 2007) inflation is mostly driven by price and wage mark-up shocks. Given the simplicity of the canonical model, these mark-up shocks often stand in for other supply and cost-push shocks such as exogenous changes in the prices of energy or other imported intermediate goods or changes in labour supply. While demand shocks are the dominant drivers of economic activity over the business cycle, they contribute relatively little to inflation developments due to the estimated flatness of the price Phillips curve and a strong countercyclical response of monetary policy justifying the maintained assumption of anchored medium-term inflation expectations.

3. Larger-scale DSGE models for forecasting and policy analysis

For forecasting exercises at central banks, the canonical DSGE model is generally considered as not sufficiently detailed, both in terms of the structure of the economy and the coverage of forecasted variables. Hence, to fit in seamlessly into their forecasting processes, central banks have developed larger and more disaggregate DSGE models that are aligned with the underlying accounting frameworks.

As an example of these model development efforts at central banks, we describe the main features of the New Area-Wide Model (NAWM; Christoffel, Coenen and Warne, 2008), which was originally designed for use in the forecasting process and for policy analysis at the ECB, and how the model has evolved over time in response to the most pertinent challenges facing the euro area economy over the past two decades.[9] These challenges include the need to deal with financial frictions as a key lesson learned from the global financial crisis, the ability to account for the existence of an effective lower bound on nominal interest rates, which hampered the effectiveness of monetary policy during much of the last decade, and the recent inflation surge. We then illustrate several applications of the NAWM with a focus on assessing the severity of deflation risks over the past low-inflation period, the efficacy of monetary policy options in the vicinity of the lower bound and forecasting inflation following the recent large energy price shocks.

3.1 The evolution of the NAWM

We provide an overview of the history of the NAWM focusing on four successive model vintages: (i) the original version of the model (in use from 2008 to 2018, with regular updates albeit limited extensions), (ii) the extension of the model with a financial sector in the aftermath of the global financial crisis, building on the academic advances in modelling financial frictions (NAWM II, in use from 2018 to 2022), (iii) an update of NAWM II in response to the secular changes in the economic landscape, notably the fall in the equilibrium real interest rate, and the ECB's strategy review (in use since 2022), and (iv) a recent extension incorporating a direct oil price propagation channel in response to the inflation surge in 2021-22, which was driven in large part by spikes in energy prices.[10]

The original model

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[9] The group of central banks that adapted larger-scale DSGE models to their forecasting processes at an early stage include Sveriges Riksbank (RAMSES; Adolfson, Laséen, Lindé and Villani, 2007b) and Norges Bank (NEMO; Brubakk, Husebø, Maih, Olsen and Østnor, 2006).

[10] Another major extension of the original NAWM incorporated a rich fiscal sector to study the impact of large-scale fiscal stimulus packages and fiscal consolidation strategies following the global financial and the sovereign debt crises from 2008 to 2011, see Coenen, Straub and Trabandt (2012, 2013) for details. This extension was maintained separately for policy simulations, but it was not used in the regular forecasting process at the ECB.

The original NAWM is an open-economy DSGE model of the euro area building on the Smets-Wouters model, designed for use in the (Broad) Macroeconomic Projection Exercises regularly undertaken by ECB and Eurosystem staff and for analyses of topical policy issues.[11] Its development has been guided by the need to cover a comprehensive set of core projection variables, including a number of foreign variables, which, in the form of exogenous assumptions, play an important role in the preparation of the staff projections.

In a nutshell, the NAWM nests the Smets-Wouters model but extends the production structure to allow for international trade in goods and services and introduces an internationally traded financial asset. In particular, the NAWM distinguishes between domestic producers of tradable intermediate goods and domestic producers of three types of non-tradable final goods: a private consumption good, a private investment good, and a public consumption good. The intermediate-good firms use labour and capital services as inputs to produce differentiated goods, which are sold in monopolistically competitive markets domestically and abroad. In doing so, they set different prices for domestic and foreign markets as a mark-up over their marginal costs. The final-good firms combine domestic and foreign intermediate goods in different proportions, acting as price takers in fully competitive markets and subject to adjustment costs. The foreign intermediate goods are imported from producers abroad, who set their prices locally in euro in monopolistically competitive markets. A foreign retail firm in turn combines the exported domestic intermediate goods, with aggregate export demand depending on total foreign demand. Trade in intermediate goods gives rise to the accumulation of a nominal financial asset the holdings of which are governed by the uncovered interest parity condition. At the level of the intermediate-good firms, nominal frictions arise from Calvo-style staggered price-setting, in combination with (partial) dynamic indexation of price contracts to past inflation, resulting in three distinct hybrid price Phillips curves for domestic, import and export prices, with a gradual exchange-rate pass-through into import prices.

Employing Bayesian methods, the NAWM was originally estimated on 18 key macroeconomic variables, including real GDP, private consumption, total investment, government consumption, exports and imports, a number of deflators, employment and wages, and the short-term nominal interest rate. In addition, data for the nominal effective exchange rate and a set of foreign variables (incl. euro area foreign demand, euro area competitors' export prices and oil prices) are used, which are important variables in the projections capturing the influence of developments in the euro area's external environment. The foreign variables are determined by a structural vector-autoregressive (SVAR) model which is estimated separately and does not feature spill-overs from the euro area, in line with their treatment as exogenous conditioning assumptions in the projections.

The extended model with a financial sector

The financial extension of the NAWM – called NAWM II and described in detail in Coenen, Karadi, Schmidt and Warne (2018) – includes a rich financial sector which is centered around two distinct types of financial intermediaries that are exposed to sector-specific shocks:[12] (i) funding-constrained "wholesale banks" following Gertler and Karadi (2011) which engage in maturity transformation and

[11] For an overview of the ECB/Eurosystem staff macroeconomic projection exercises and a description of the techniques, models and tools used therein, see ECB (2016).

[12] NAWM II also features a number of other extensions of the original model reflecting its practical uses in the policy process at the ECB, including an endogenous mechanism concerning private-sector agents' perceptions of the central bank's inflation objective, which permits to capture possible fluctuations in longer-term private-sector inflation expectations, and uncertainty about shifts in trend productivity growth, which impacts private sector allocations and the central bank's estimate of the equilibrium real interest rate entering its interest rate reaction function.

originate long-term loans, and (ii) "retail banks" following Gerali, Neri, Sessa and Signoretti (2010) which distribute these loans to the non-financial private sector and adjust the interest rate on loans only sluggishly. The long-term loans are required by the non-financial private sector to finance capital investments as in Carlstrom, Fuerst and Paustian (2017). Furthermore, NAWM II includes a set of no-arbitrage and optimality conditions which govern the holdings of domestic and foreign long-term government bonds by the financial and the non-financial private sector, respectively, building on Gertler and Karadi (2013).

The incorporation of these financial extensions into the original model reflects the threefold aim pursued in the development of NAWM II, namely: (i) to account for a genuine role of financial frictions in the propagation of economic shocks and policies and for the presence of shocks originating in the financial sector itself, (ii) to capture the prominent role of bank lending rates and the gradual interest-rate pass-through in the transmission of monetary policy in the euro area, and (iii) to provide a structural framework useable for assessing the macroeconomic impact of the ECB's large-scale asset purchases conducted in the past years. In the model, central bank asset purchases of long-term government bonds ease wholesale banks' funding constraint and create (excess) balance sheet capacity that banks can use to extend new credit to the non-financial private sector. As a consequence, lending conditions improve and stimulate private investment. Concomitantly, the lending rate spread and the expected excess return, or premium, on long-term government bonds relative to yield of short-term government bonds fall and asset valuations rise. This generates windfall gains for the wholesale banks, raising their net worth, and allows them to loosen credit conditions further in a positive feedback loop. The ensuing increase in domestic demand puts upward pressure on firms' marginal cost of production and leads to a rise in domestic prices. The decline in the premium on domestic long-term government bonds comes along with a decrease in the premium on foreign long-term government bonds which is brought about by an instantaneous depreciation of the domestic currency, boosting export demand and increasing import prices.

In estimating NAWM II, six variables were added to the original set of observables, including euro area long-term government bond yields and long-term lending rates, in order to enable identification of the model's financial-sector parameters and shocks.

Coping with the fall in the equilibrium real interest rate

Following the completion of the ECB's review of its monetary policy strategy in 2021, NAWM II was modified in three complementary ways. First, the steady-state inflation rate in the model was raised so as to align its calibration with the adoption of a new symmetric 2% inflation target by the ECB reflecting the need for maintaining a sufficient inflation buffer in order not to compound the distortions resulting from the effective lower bound on nominal interest rates in the low-interest-rate environment brought about by the secular downward trend in the equilibrium real interest rate. Second, to accommodate in part the fall in the equilibrium real rate, the steady-state value of the short-term real interest rate was lowered to 1.25%, broadly consistent with the average value of the short-term real interest rate over the extended sample period used for the re-estimation of the model. And third, following Fahri and Gourio (2018), a new highly persistent discount-rate shock was introduced to better capture the secular downward trend in real interest rates, over and above the effect due to the re-calibration of the model's steady-state real interest rate. This shock generates co-movement among the model's short and long-term interest rates, and its effects can be related economically to the increase in the premium for safe and liquid assets required by investors, as documented, e.g., in Del Negro, Giannone, Giannoni and Tambalotti (2017). While the three modifications improve the empirical fit of the model, notably of the co-movement of interest rates, the overall properties of NAWM II are broadly preserved.

Incorporating a direct oil price propagation channel

In response to the inflation surge in 2021-22 due to the direct and indirect effects of exceptionally large spikes in energy prices, alongside COVID-19-related factors and the Russian invasion of Ukraine, NAWM II has most recently been extended with a direct oil price propagation channel.[13] To this end, the aggregate consumption bundle of households has been broken down into an oil-import and a non-oil component, with a low elasticity of substitution between the two components, especially in the short term. Like the aggregate consumption bundle in the original model, the non-oil component of consumption is composed of domestic intermediate goods and imported non-oil intermediate goods, but with a higher elasticity of substitution. In addition, the model extension splits the aggregate import price Phillips curve into two separate Phillips curves for oil and non-oil import prices. This allows capturing the different speeds of pass-through of oil price changes and changes in general external production costs to these two components of aggregate import prices. To aid the identification of the respective Phillips curve parameters, the oil import price deflator is used as an additional observable in the estimation of the extended model.

3.2 Applications of the NAWM

We illustrate several applications of the NAWM vintages over time, drawing on regular uses and topical analyses in the context of the ECB's forecasting and policy preparation process. First, based on stochastic simulations that account for the effective lower bound on nominal interest rates, the earlier vintages have been employed to gauge the evolution of deflation risks over the low-inflation period from 2008 to 2021 in "real time". Second, the financial extension of the NAWM is used to assess the effects of state-dependent large-scale asset purchases and forward guidance on policy rates to mitigate the adverse consequences for overall economic performance arising from the effective lower bound in a low-interest-rate environment. And finally, the extension of the NAWM with a direct oil price propagation channel is used to assess the predictive ability of conditional model-based forecasts to capture the recent energy price-driven surge in inflation.

Gauging deflation risks over the low-inflation period, 2008-21

In view of the sharp disinflation in the immediate aftermath of the global financial crisis and the low-inflation period following the euro area sovereign debt crisis, monetary policymakers, financial market analysists and academics alike were increasingly concerned about the materialisation of deflation risks, which, in the vicinity of the effective lower bound, could eventually lead to the destabilisation of the economy.

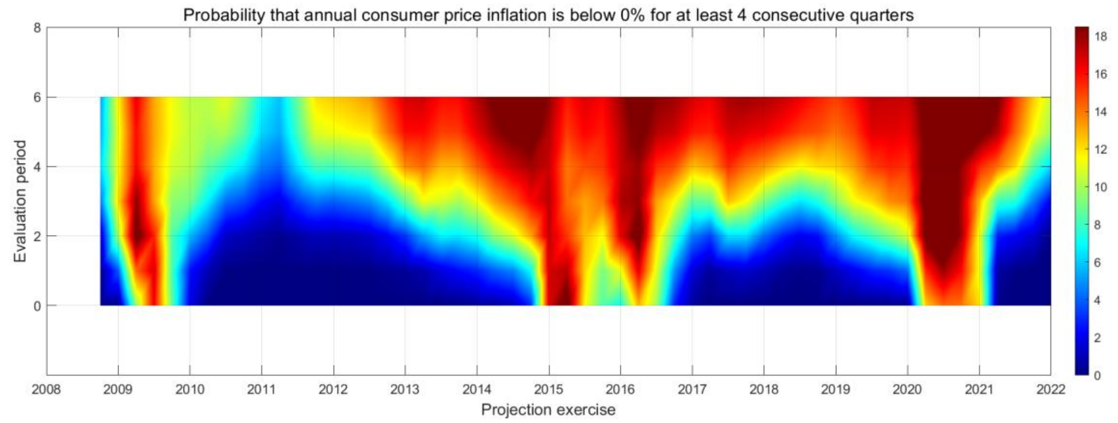
Against this background, the NAWM was used over the period 2008-21 to assess the evolution of possible deflation risks in "real time" around the baseline projections of the regular ECB/Eurosystem (Broad) Macroeconomic Projection Exercises ((B)MPEs). In the model-based assessment of deflation risks, deflation is defined as the event that annual inflation falls below zero for at least four consecutive quarters. The risk of such an event is measured using the model-based predictive distribution of consumer price inflation, which are constructed around the inflation baseline projection using stochastic simulations, allowing the interest rate to react to the simulated current and future shocks according to the model's interest rate reaction function while accounting for the effective lower bound on nominal interest rates.[14] The latter became increasingly important after the summer of 2012 when the interest rate forward curve flattened as the ECB policy rates were expected to operate close to their perceived lower bound. In such an environment, the model-based predictive

[13] The extension draws on Coenen, Lozej and Priftis (2023), who developed a richer calibrated 2-country version of the NAWM with a disaggregated energy sector for studying the impact of carbon transition policies.
[14] See Coenen and Warne (2014) for details on the methodology for constructing the predictive distributions. By contrast, in the construction of the baseline projection around which the simulations are carried out, the interest rate path is conditioned on market expectations of the 3-month Euribor rate (see, ECB, 2016).

distribution for inflation tends to be downwardly skewed since the reaction of monetary policy to new recessionary and deflationary shocks over the projection horizon is persistently constrained by the lower bound.

The length of the horizon of the (B)MPEs varies from exercise to exercise with a minimum of 9 quarters being covered in the December BMPEs. Consequently, there are six overlapping evaluation periods with quarters 1 to 4 as the first evaluation period, quarters 2 to 5 as the second, and so on until quarters 6 to 9 as the sixth period. For a given projection exercise, the probability of deflation can therefore be gauged as the number of times such an event is recorded relative to the number of stochastic simulations for each evaluation period, enabling a granular analysis of deflation risks over the projection horizon.

Figure 3.1: The evolution of deflation risks, December 2008 BMPE to December 2021 BMPE



Notes: Using earlier vintages of the NAWM and NAWM II, this figure shows the evolution of the "real-time" probability (in percent) that annual consumer price inflation falls below zero for at least four consecutive quarters conditional on the ECB/Eurosystem staff projections from December 2008 to December 2021. The probabilities are derived from NAWM-based predictive distributions for inflation, which are centred on the structural shocks that the model has identified for the respective projection baseline. Inflation is measured in terms of the private consumption deflator. A total of six evaluation periods for the risk events are obtained from the initial 9-quarter horizon of each projection exercise, where the first evaluation period covers quarters 1 to 4, the second period quarters 2 to 5, and so on, until the sixth evaluation period covers quarters 6 to 9. The upper limit of the colour-map is computed as 4 times the standard deviation of the time series of the deflation probabilities for the projection exercises from the December 2008 BMPE onwards.

Figure 3.1 displays a colour-map of the real-time evolution of deflation risks through the lens of successive vintages of the NAWM, beginning with the December 2008 BMPE and ending with the December 2021 BMPE. The dates of the projection exercises are indicated on the horizontal axis, whereas the vertical axis shows the evaluation periods. The lower limit of the risk scale is zero, while the upper limit is equal to four times the standard deviation of the time series of the estimated average probability of deflation. The colour bar to the right represents the risk scale based on the dark red upper limit and the dark blue lower limit.

The colour-map shows that the early spell of heightened deflation risk in the immediate aftermath of the global financial crisis is temporary, arguably attributable in large part to a sharp but short-lived drop in oil prices. The second spell is persistent with renewed peaks in deflation risks in 2015 and 2016, reflecting a protracted decline in underlying inflation in response to the double-dip recession owing to the euro area sovereign debt crisis and the sluggish recovery thereafter on the back of a renewed sharp fall in oil prices. With interest rates at or near the effective lower bound, non-standard monetary policies, notably the ECB's asset purchases programmes and rate forward guidance, were adopted to boost the economy by lowering longer-term interest rates. After the introduction of such policies, with their expected effects being incorporated in the baseline projections, inner-quarter, i.e. short-term, deflation risks began to fall towards the end of 2016, while outer-quarter risks remained heightened in the years that follow, especially compared with the steady-state deflation risk of 1.3%. A fourth peak occurred in 2020 during the first year of the COVID-19 pandemic. However, with the steady rise of inflation from early 2021 onwards on the back of sharply rising energy prices, deflation risks have recently largely vanished, also over the outer quarters of the projection horizon.

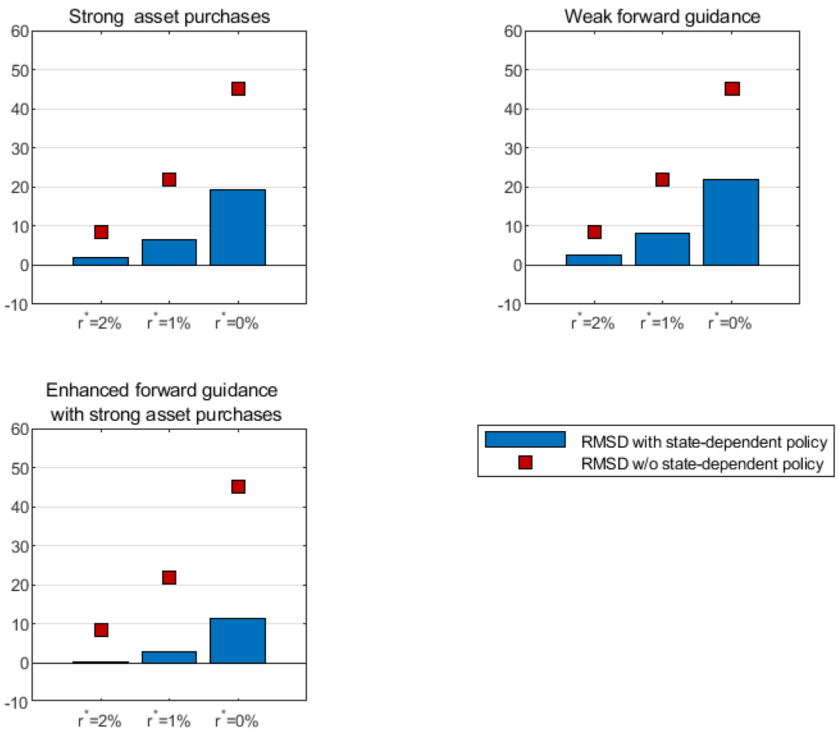
Assessing the efficacy of monetary policy in a low-interest-rate environment

In an environment with a permanently lower equilibrium real interest rate, the heightened frequency of periods with a binding effective lower bound on nominal interest rates can cause substantial macroeconomic distortions. Using stochastic simulations carried out with NAWM II, Coenen, Montes-Galdon and Smets (2023) show that these distortions, as reflected in inflated root mean-squared deviations (RMSDs) of the steady-state distributions for inflation and the output gap, are the larger, the lower the equilibrium real interest rate: As the equilibrium real rate falls from 2% to zero, the frequency of lower-bound episodes rises from 10.3% to 24.0% and the RMSDs for inflation and the output gap increase from 2.9% and 6.0% to 4.2% and 8.6%, respectively. These inflated RMSDs reflect both sizeable shortfalls in the means of the respective steady-state distributions as well as markedly higher standard deviations.

To cushion the detrimental consequences of the effective lower bound for macroeconomic stability, major central banks, including the ECB, deployed non-standard monetary policies such as large-scale asset purchases and forward guidance about the likely path of future policy rates after the policy rates had reached their lower bound. Using again stochastic simulations with NAWM II, and accounting for the state-dependent nature of these policies and their possible interaction, Coenen et al (2023) show that forward guidance, in the form of a "low for longer" policy rate commitment, and asset purchases, if sufficiently strong, can indeed succeed in materially reducing the lower bound-induced distortions. Asset purchases are modelled as a state-dependent rule which relates the size of the central bank's asset purchases to the shortfall of the "shadow" policy rate that would prevail according to its interest rate reaction function if the lower-bound constraint were absent. Forward guidance is modelled as the state-dependent interest rate path implied by a modified reaction function that depends on the lagged shadow policy rate, rather than the lagged realised policy rate.

To address the "forward guidance puzzle" afflicting New Keynesian DSGE models, which concerns the often implausibly large effects of interest rate forward guidance within this class of models (see Del Negro, Giannoni and Patterson, 2023) , Coenen et al (2023) consider two distinct forms of forward guidance: "weak", or imperfectly credible, forward guidance with a low probability of being followed through by the central bank, and "enhanced" forward guidance with a heightened probability of being followed through as the central bank raises the credibility of its commitment through the parallel conduct of asset purchases, akin to a signalling effect.

Figure 3.2: The efficacy of state-dependent monetary policy at the effective lower bound



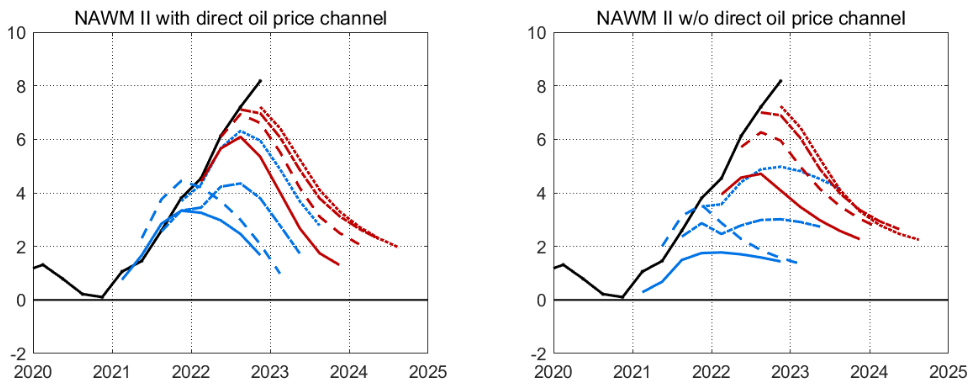
Notes: For alternative values of the steady-state short-term real interest rate r*, the blue bars in this figure show the average root mean-squared deviations (RMSDs) of the NAWM II-based steady-state distributions for inflation and the output gap for state-dependent asset-purchase and/or forward-guidance policies. The red squares represent the RMSDs of the benchmark case with the effective lower bound on the short-term nominal interest rate being taken into account but without state-dependent policies. The RMSDs are plotted as percentage deviations from the RMSDs of the benchmark case without the lower bound.

Summarising the key findings from Coenen et al (2023), Figure 3.2 depicts the average RMSDs of the model-based steady-state distributions for inflation and the output gap for alternative state-dependent monetary policy configurations and for alternative values of the equilibrium short-term real interest rate. In the figure, the RMSDs are reported in relative terms as percentage deviations from the RMSDs for a benchmark case where the lower-bound constraint is absent. The blue bars show the relative RMSDs for three different cases with state-dependent asset-purchase and/or forward-guidance policies, while the red squares indicate the relative RMSDs of a constrained benchmark case where the lower-bound is imposed, but without state-dependent policy support. As can be seen, the state-dependent policies succeed individually in more than halving the distortions due to the lower bound. In contrast, when deployed in combination they can largely eliminate the lower-bound distortions for values of the equilibrium real interest rate as low as 1%, whereas the distortions are reduced to less than one-fourth for an equilibrium real rate of zero.

Forecasting inflation in 2021-22

As a last illustration of the uses of the NAWM, we conduct a small-scale forecasting exercise over the high-inflation period from 2021 to 2022. Specifically, we carry out forecasts with the latest vintage of NAWM II including a direct oil price propagation channel to consumer price inflation using conditioning information for the oil price variable. We compare these forecasts to the forecasts based on the previous model vintage which only accounts for an indirect propagation of oil price fluctuations via aggregate import prices.[15] Recognising that oil prices are themselves driven by the interplay of the variables in the SVAR model capturing the euro area's external environment, the conditional forecasts are performed by employing the Waggoner and Zha (1999) approach. For simplicity, in choosing the conditioning path for the price of oil we use the actual values instead of real-time values, as would be the case in a realistic forecast setting. Notwithstanding this simplification, as both model vintages utilise the same conditioning information the exercise serves as a useful diagnostic check of how well the different vintages make use of this information in forecasting.

Figure 3.3: NAWM II-based conditional forecasts of inflation, 2021-22



Notes: Using the latest and the previous vintage of NAWM II, with and without a direct oil price channel, this figure depicts one-quarter to eight-quarter-ahead conditional point forecasts of annual consumer price inflation. Forecast paths originating in 2021 (2022) are plotted as blue (red) lines, with forecasts starting in Q1 shown as solid lines and forecasts starting in Q2, Q3 and Q4 as dashed, dash-dotted and dotted lines, respectively. The forecasts are performed using the Waggoner and Zha (1999) approach using conditioning information for the oil price variable in the model.

Figure 3.3 displays the one-quarter until eight-quarter-ahead point forecast paths of annual consumer price inflation, also known as spaghetti plots, covering eight forecast "vintages" with the latest data point moving consecutively from 2020Q4 to 2022Q3. The point forecast paths that originate in 2021 (2022) are plotted in blue (red). Forecast paths starting in Q1 of a given calendar year are shown as solid lines, and forecast paths starting in Q2, Q3 and Q4 are shown as dashed, dash-dotted and dotted lines, respectively. The forecasts based on the latest model vintage are depicted in the left-hand panel of the figure, and the forecasts using the previous vintage in the right-hand panel. The actual values are given by the black lines.

For both model vintages, the forecast paths are overall hump shaped with a peak in late 2021 or in 2022. The peak tends to increase as the vintage end date moves forward, in line with the rise in inflation over these two years. It is striking how close the short-term forecast paths are to the actual values for the latest vintage of NAWM II, while the paths of the previous vintage are generally lower and further below the actual values. While both vintages under-predict inflation for the outer quarters of the forecast horizon, the forecast errors of the latest vintage are overall visibly smaller. Hence, the oil price extension in the latest vintage of NAWM II improves the forecasts relative to the previous

[15] For an illustrative comparison of the performance of conditional versus unconditional forecasts based on the previous model vintage see Ciccarelli, Darracq-Pariès and Priftis (2024), Box 2.

vintage over the two years of sharply rising inflation, at least when having access to the oil price data as conditioning information.[16]

4. Policy counterfactuals

Medium-sized models have proved useful in central banking also for assessing alternative policy strategies to deliver price stability[17] and carrying out real-time counterfactuals that address questions such as "How inflation would evolve if interest rates were kept unchanged?" or "What would optimal policy prescribe under the central bank's baseline projections for inflation?" or else "What course of policy action would be robust in the face of risks that inflation may evolve differently from the baseline projections?".

4.1 Constructing policy counterfactuals

We build on the recent literature on constructing policy counterfactuals using policy shock impulse responses (see De Groot, Mazelis, Motto and Ristiniemi (2021), McKay and Wolf (2023) and Barnichon and Mesters (2023)), but relative to them we focus on a different set of policy counterfactual questions. The approach does not require to filter the shocks or specify a fully-fledged structural model to derive first order conditions for optimality. This facilitates comparison across (classes of) models that exhibit different policy transmission. It only requires two inputs.[18] The first is projections for macroeconomic variables conditional on or consistent with a policy rate path. Macroeconomic projections are typically readily available at policy institutions. They are often judgemental rather than model based. But to construct policy counterfactuals there is no need to know the underlying model or judgement, nor the baseline policy rule (provided it delivers a unique equilibrium). The second input is impulse responses to contemporaneous and expected policy shocks. These impulse responses can derive from a variety of linear(ised) models. The only restriction to the approach is that monetary policy ought not to affect the information set of agents. Most models in use in central banks for policy analysis, typically comprising DSGEs, semi-structural models and identified time-series models, would meet this requirement. In what follows, we restrict the analysis to a medium-sized DSGE model, but the approach can be applied to other (classes of) models. An advantage of using a DSGE model is that evaluating responses to expected policy shocks is straightforward. If the desired counterfactual involves optimal policy, it is necessary to specify the central bank's loss function, which we do below. Intuitively, given that in the models considered here it is the path of the policy instrument that matters rather than its systematic vs. unsystematic components, a counterfactual optimal policy amounts to choosing an alternative policy path that minimises a loss function, whereby the impact of the policy path on the variables entering the loss function is computed via impulse responses to policy shocks.[19] As shocks comprise (current and) expected policy shocks, the approach should be robust to the Lucas critique.

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[16] When judging the absolute predictive ability of the model-based conditional forecasts, it should be recognised that the energy price-driven surge in euro area inflation reflects a broader increase in energy prices, to a significant extent driven by an unprecedented increase in gas prices, over and above the increase in oil prices, with only the latter being included in the model and in the forecasting exercise.
[17] See for instance, Kiley and Roberts (2017).
[18] The appendix presents the details.
[19] Similarly, a given counterfactual policy path can be implemented by using impulse responses to current and expected policy shocks to find the policy path that supports the desired policy path.

4.1.1 MMR model

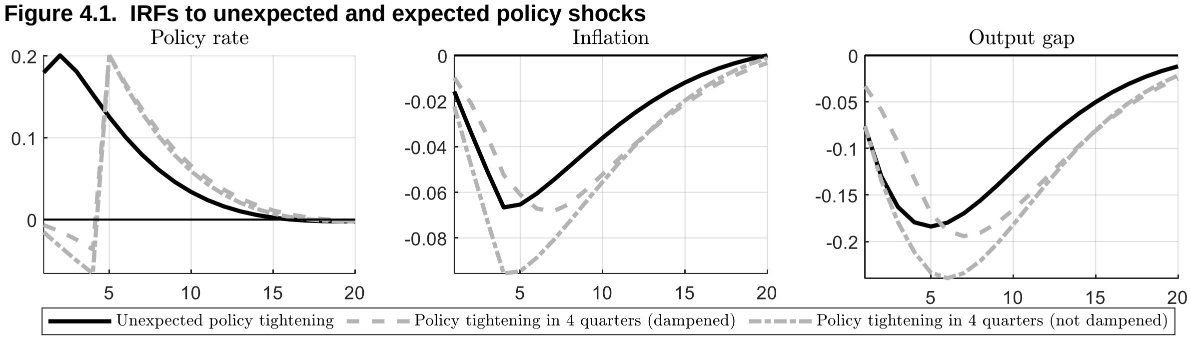
The first input for computing counterfactuals is impulse responses. We use a version of the model described in Mazelis, Motto and Ristiniemi (2023), henceforth MMR. It is a DSGE model within a suite of ECB models for policy analysis. As it shares many similarities with the canonical New-Keynesian DSGE model discussed in the previous sections, we highlight here only the features that have been added to make the model more suitable for policy analysis. Specifically, the level of *r** is allowed to be time varying to capture the secular trend in the data (see below), the model includes non-standard policy measures, the output gap is defined as output in deviation from the labour-augmenting technology shock and its measurement is aligned to policy institutions' estimates rather than relying on the flexible-price concept, and the forward guidance puzzle is dampened by allowing agents to be partly inattentive to the future policy course.[20] To pin down the degree of inattentiveness, the estimated model includes policy news shocks, and the standard set of observable variables is augmented by data on expectations for the short-term interest rate, economic growth and inflation. In addition to including policy news shocks, the Taylor rule is different from the standard one because it features a time-varying intercept, r_t^*, to which the policy rate tends over time. Specifically, r_t^* is modelled as an AR(1) process that depends on the labour-augmenting technology shock in the model, $g_{z,t}$, as well as on an idiosyncratic shock, $\varepsilon_t^{r^*}$, akin to the process in neutral rate models such as Holston, Laubach, and Williams (2016):[21]

$$r_t - r_t^* = \rho(r_{t-1} - r_{t-1}^*) + (1-\rho)[\phi^\pi(\pi_t - \pi^*) + \phi^y(\tilde{y}_t) + \sigma\varepsilon_t\,]$$

$$r_t^* = \rho^{r^*} r_{t-1}^* + \gamma_g g_{z,t} + \sigma^{r^*}\varepsilon_t^{r^*}$$

The estimated policy rule coefficients are ρ*=0.91*, ϕ^π*=1.54*, ϕ^y*=0.09*. We use the model to generate impulse responses to current and policy news shocks at different horizons. The impulse responses are displayed in Figure 4.1. The solid line is the response to an unexpected monetary policy shock. The dashed line is the response to an anticipated policy hike at a horizon of four quarters in the future. Note that the reaction of inflation and output is delayed but of a similar magnitude compared to the

Figure 4.1. IRFs to unexpected and expected policy shocks



Notes: Policy rate, inflation and output gap impulse responses to an unexpected and expected (4 quarters ahead) contractionary monetary policy shock in the MMR Model Reactions displayed in deviation from steady state values. The horizontal axis displays quarters since the shock occurrence in the first period.

unexpected monetary policy shock. This result is largely driven by the dampening of the forward guidance puzzle due to the estimated value of inattentiveness. To document the role played by inattentiveness, the dashed-dotted line shows the response to the same anticipated policy hike when we allow for full attentiveness, which represents the standard case in the canonical model. It shows

[20] For the method behind including policy news shocks and dampening the forward guidance puzzle, see de Groot and Mazelis (2020). For the forward guidance puzzle and ways to address it, see Del Negro, Giannoni and Patterson (2023), McKay, Nakamura and Steinsson (2016) and Gabaix (2020), among others.

[21] See also Corbo and Strid (2020) and Maih, Mazelis, Motto, Ristiniemi (2021).

that with increasing horizons, the impact of news shocks grows out of bounds and to implausible magnitudes, which does not occur instead in our model at the estimated value of inattentiveness.

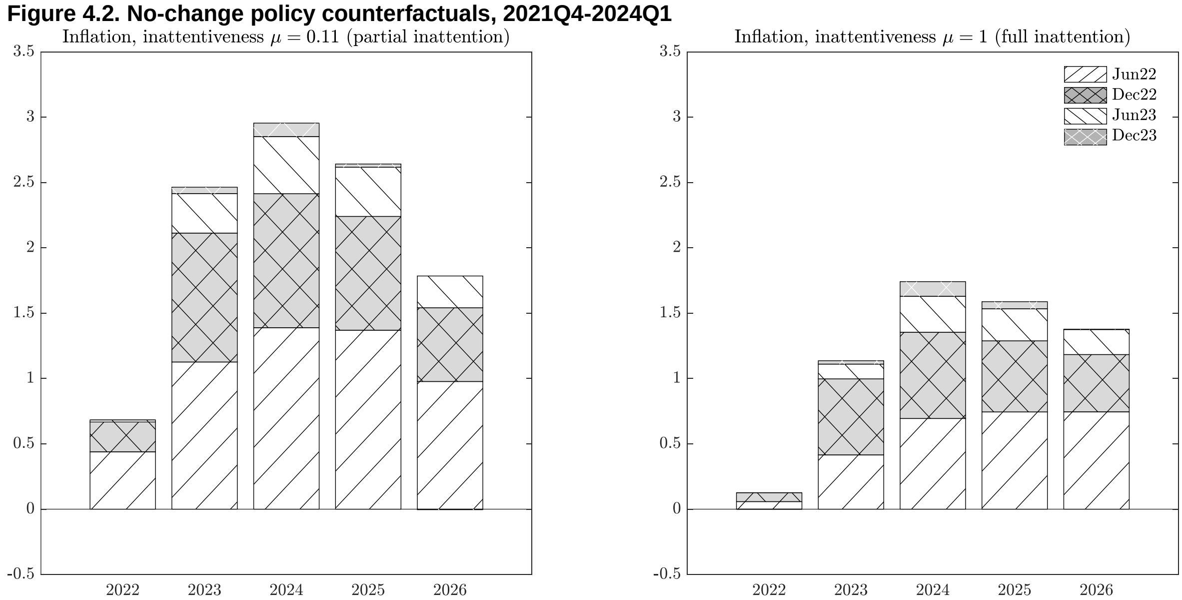
4.1.2 Baseline projections

The second input for computing counterfactuals is projections. We use the ECB/Eurosystem staff projections, which are produced quarterly and published right after the policy meeting in which they are presented to policymakers. They include several macroeconomic variables and are conditional on the market rate path and other assumptions such as oil prices. The projection horizon is typically three calendar years, with the extension of the horizon by an additional year in the December vintage. In the simulations below we extend the projections beyond the published horizon by using expectations from the ECB's Survey of Monetary Analysts. We focus on the projection vintages from 2021Q4 to 2024Q1. The reason for beginning in 2021Q4 is that the ECB announced the first step of the tightening cycle – a slowing down of its asset purchases – at the December 2021 meeting.[22]

4.2 No-change policy counterfactuals

The first counterfactual we carry out addresses the question of what would have happened if the interest rate path had not reacted to the successive revisions in inflation and real economic developments since 2021Q4.[23] This is implemented by assuming that at each projection vintage starting in 2021Q4 the rate path would have been identical to the one embedded in the previous projection vintage. This is a real-time exercise because we are using real-time projection vintages and the impulse responses to policy shocks that we employ to compute counterfactuals are estimated prior to the review period.

Figure 4.2. No-change policy counterfactuals, 2021Q4-2024Q1



Notes: Sequence of counterfactuals whereby at every other projection vintage between 2021Q4 and 2024Q1 the interest rate path over the projection horizon is maintained unchanged compared to the path embedded in the vintage prior to the one considered. The degree of inattentiveness used in the left panel is the estimated one ($\mu = 0.11$), while the one used in the right panel is selected purely for illustration ($\mu = 1$). Counterfactuals are computed using the MMR model. Results are shown in annual percentage points.

[22] The vintages of projections are shown in the appendix.

[23] For this type of counterfactual of no-policy-response, see Bernanke et al. (1997). Given that we carry out the counterfactual with expected policy shocks, our results should be robust to the Lucas critique.

The left panel in Figure 4.2 displays the results for every other projection vintage, while results for the full set of vintages are shown in the appendix. It shows that, absent the interest rate response, inflation would have been higher by 2.5 percentage points in 2023 and 3 percentage points in 2024.[24] It also shows that the restraining effect of policy started well before the actual lift-off in July 2022. This is documented by the bar labelled "Jun22", which represents the impact on inflation under a counterfactual in which the market curve used as conditioning assumption had not increased from December 2021 to June 2022 as instead it did in reality. This impact is explained by the fact that markets anticipated the future policy tightening well in advance to the actual lift-off. In quantitative terms, the size of the bar compared to the total impact represented by the other bars shows that about half of the dampening impact on inflation was generated by policy expectations prior to the actual lift-off of July 2022.

As discussed above, one key parameter in shaping the policy impact is the degree of forward lookingness of agents with respect to future policy, which is controlled in the model by the estimated degree of inattentiveness. The role of this parameter is documented in the right panel of Figure 4.2. It shows that if we set the inattentiveness parameter for mere illustration to 1, meaning full inattention, from the estimated value of 0.11, the impact of policy on inflation becomes much smaller due to agents becoming inattentive to the future course of policy.

4.3 Optimal policy counterfactuals

To compute optimal policy counterfactuals we need to specify a loss function for the central bank. We use a standard quadratic loss function featuring preferences over annual inflation (π_t), in deviation from the 2 percent target (π^*), the output gap ($\widetilde{y_t}$) and the change in the interest rate (Δi_t). The latter is meant to capture concerns for rate volatility that could have detrimental effects for financial stability and preference for gradual adjustments:

$$L_0 = \frac{1}{2}\mathrm{E}_0 \sum_{t=0}^{T} \beta^t \left((\pi_t - \pi^*)^2 + \lambda_y (\widetilde{y_t})^2 + \lambda_i (\Delta i_t)^2 \right)$$

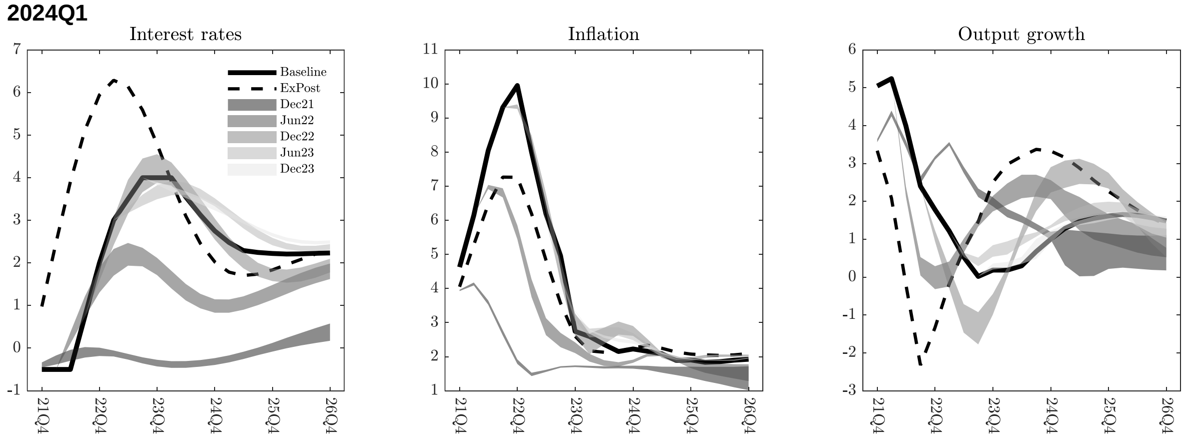
We set the discount factor β to the estimated value of the household discount factor in the MMR. The weights λ_y and λ_i are typically not known and need to be estimated. This can be done by fixing the structural parameters of the economy in the MMR at the estimated values (posterior mode), then discarding the Taylor rule used in the estimation and replacing it with the loss function above, and finally deriving first-order conditions and estimating the weights.[25] This approach helps ensure that optimal policy counterfactuals are not driven by arbitrary values assigned to the weights. The estimated values are $\lambda_y = 0.20$ and $\lambda_i = 1.4$. For comparison, Yellen (2012) presents simulations for the Fed using a weight of 1 on the unemployment gap. Using Okun's law for the mapping into our framework, a weight of 1 on the unemployment gap would correspond to a weight of 0.25 on the output gap (Debortoli et al, 2019). In the counterfactuals below we use our estimated values for the weights and report sensitivity to alternative values.

We compute optimal policy counterfactuals for each projection vintage starting in 2021Q4. Optimal policy is computed under commitment. Policy instruments other than the short-term rate, such as QE, are taken as given. The results for mid- and end-of-year projection vintages are displayed in Figure

[24] The simulations presented in this section abstract from the impact of revisions in expectations for the evolution of the central bank's balance sheet. During the review period analysts' expectations for the end of net asset purchases and the subsequent reinvestment phase were revised significantly. Accounting for those revisions would inject additional policy tightening.

[25] See De Groot et al. (2021) for details.

Figure 4.3. Optimal policy counterfactuals for the interest rate and implied inflation and output growth, 2021Q4-2024Q1

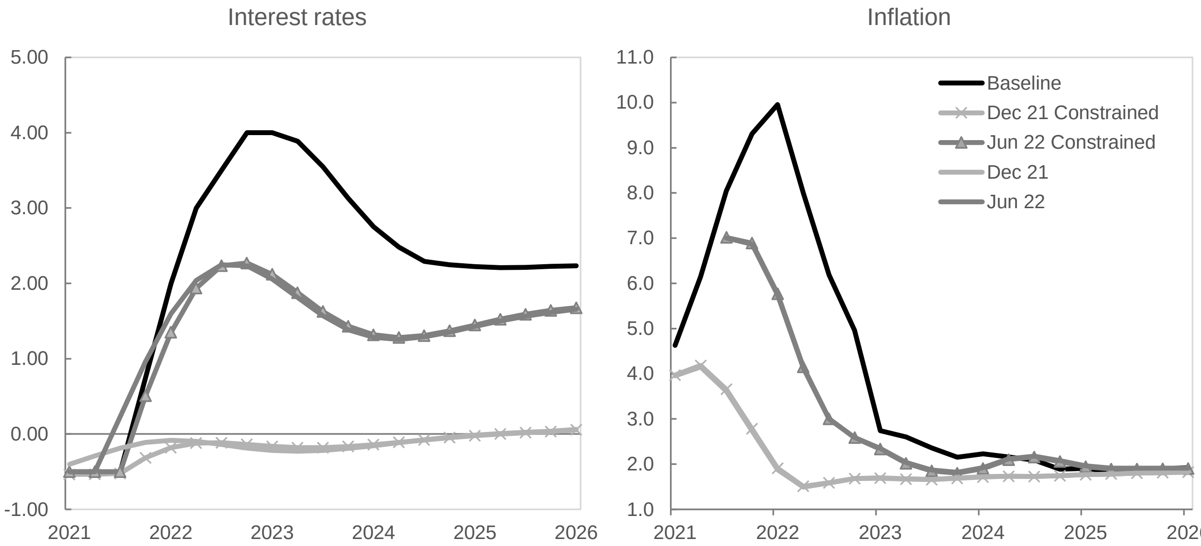


Notes: The "Baseline" denotes historical data and projections available in the context of the March 2024 vintage. The "Ex-post" denotes the optimal policy counterfactual computed in 2021Q4 with the benefit of hindsight by assuming that in 2021Q4 the same information set is available as in the 2024Q1 projection vintage. The other lines are a sequence of optimal policy counterfactuals computed in real time at selected projection vintages over 2021Q4-2024Q1. The shaded areas correspond to the 90 percent confidence interval. The interest rate is in percentages per annum, inflation and output growth are in year-on-year percentage changes. Counterfactuals are computed with the MMR model. The loss-function weights are $\lambda_y = 0.2$ and $\lambda_i = 1.4$.

4.3, while results for the full set of vintages are shown in the appendix. Let us for the time being abstract from the black dashed line that is constructed using actual realised data rather than real-time data and is discussed further below. The shaded areas represent the uncertainty arising from the impulse response estimates and are computed using the draws of the parameters from the posterior density. The main message emerging from Figure 4.3 is that over the review period optimal policy counterfactuals are most of the times similar to actual outcomes. This means that there would have been little scope to improve upon the policy that was actually implemented. The counterfactual evolution of inflation and output growth is shown in the middle and left panel, respectively, of Figure 4.3. Given that policy has been broadly optimal, the optimal-implied inflation is not very different from the baseline projections displayed in appendix.

We zoom-in on two episodes in which there is some divergence between the prescribed and actual interest rate in the order of about 25 basis points. The first episode is in the initial part of 2022, pointing to lift-off already in Q1. The second episode is in September 2023 in which optimal policy would have called for one less rate hike. Counterfactuals can be used to assess the implications of this type of divergences. To provide an illustration based on the first episode, we constrain the optimal

Figure 4.4. Early lift-off counterfactuals, 2021Q4-2022Q2

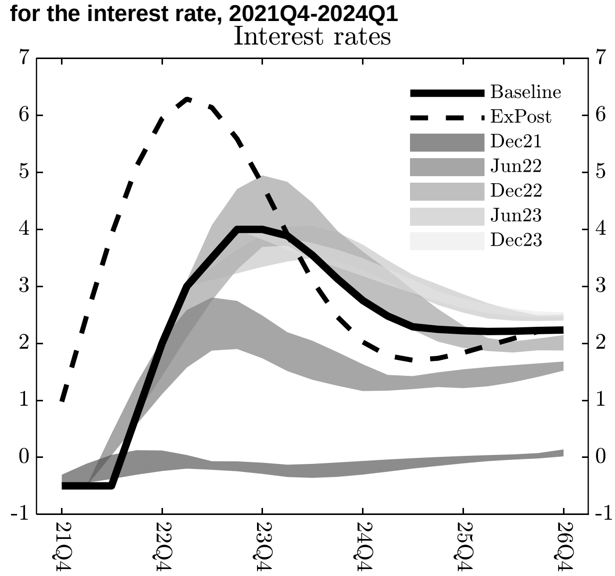


Notes: The "Baseline" denotes historical data and projections available in the March 2024 vintage. The other solid lines are the counterfactuals for March 2022 and June 2022 from Figure 4.3. Each of the grey lines with a marker on the left panel is a counterfactual rate path computed by constraining the lift-off date to match the actual one and letting policy evolve optimally afterwards. The grey lines on the right panel are the impact of the corresponding policy path depicted in the left panel. The interest rate is in percentages per annum and inflation in year-on-year percentage changes. The counterfactuals are computed with the MMR model.

policy path in the first part of 2022 to remain at its realised level until the time in which actual lift-off took place (2022Q3), after which it evolves to minimise the loss function. This is shown in Figure 4.4 with the lines labelled "Dec21 Constrained" and "Jun22 Constrained". To ease comparison, Figure 4.4 reproduces the results for December 2021 and June 2022 shown in Figure 4.3. Figure 4.4 documents that the inflation path under this constrained optimal-policy exercise is very similar to its path derived under the unconstrained optimal policy of Figure 4.3, suggesting that this divergence in the lift-off date is not consequential.

As little information and empirical evidence are available about central banks' preferences and degree of inattentiveness, we carry out sensitivity analysis to alternative values. We vary the weight on slack between [0.1,0.3], the weight on interest rate smoothing between [1,2], and inattentiveness between [0.05,0.2]. The results are displayed in Figure 4.5. Given rapidly rising interest rates and inflation, as well as declining output expectations between March 2022 and June 2023, the uncertainty around the optimal policy projections is larger than after inflation reached the peak and stabilised.

Figure 4.5. Sensitivity of optimal policy counterfactuals for the interest rate, 2021Q4-2024Q1



Notes: The "Baseline" denotes historical data and projections available in the March 2024 vintage. The "Ex-post" denotes the optimal policy counterfactual computed in 2021Q4 with the benefit of hindsight by assuming that in 2021Q4 the same information set of the 2024Q1 projection vintage is available. The other lines are a sequence of optimal policy counterfactuals computed in real time at the December and June projection vintages over 2021Q4-2024Q1. The interest rate is displayed in percentages per annum. Counterfactuals are computed with the MMR model. The loss-function weights are varied as follows: λ_y between [0.1,0.3], λ_i between [1,2], and inattention between [0.05,0.2].

Optimal policy counterfactuals can be computed also with the benefit of hindsight. This can be done by replacing the real-time projections for inflation and economic slack with their observed outcomes. We use the historical data available in the context of the March 2024 projection round. Returning to Figure 4.3, the black dashed line labelled "Ex post" represents the results for the counterfactual interest rate with the benefit of hindsight. While it is obviously not possible for the central bank in real time to act upon information that becomes available only subsequently, this exercise allows to quantify the contribution that forecast errors in the baseline projections played in shaping monetary policy. The black dashed line in the first panel of Figure 4.3 documents that until 2023Q4 optimal policy with the benefit of-hindsight calls for higher rates than those observed. The black dashed line in the middle and left panels of Figure 4.3 shows how inflation and output growth would have developed under optimal policy with-hindsight. Inflation would have peaked at 7.3% rather than 10% and the output gap would have been about 5 percentage points more negative than it was in reality. This implies that the different policy rate prescription with-hindsight compared to the real-time counterfactuals is due to the forecast errors in the real-time projections.[26] Saying it differently, the inflation surge was the result of adverse shocks ("bad luck") rather than bad monetary policy.[27]

4.4 Robustness considerations

We have focused so far on the central tendency of staff projections and on a given model of the policy transmission, abstracting from the fact that a central bank may entertain also alternative forecasts and models. But this represents a limitation especially at times in which a central bank's desire to achieve acceptable performance of monetary policy in the face of uncertainty and take out insurance

[26] In turn, the forecast errors were due to a large extent to errors in the projections of energy prices (see ECB, 2023).

[27] See Christiano, Motto and Rostagno (2008) for a discussion of bad luck (large shocks) vs. bad policy, or change in economic structure.

against bad outcomes becomes the marginal argument in favour of more aggressive or more gradual response than otherwise.[28]

There is an extensive literature on policy under uncertainty.[29] In this section we provide a simple illustration in the spirit of Levin and Williams (2003), who analyse policy robustness in non-nested models. We characterise optimal policy in terms of optimal simple rules as they can be easily applied across the possibly very different models belonging to the central bank's suite of models. A robust policy is taken to be the one that performs best in the worst-case scenario within the specified set of scenarios (min-max criterion).

The first step is to select the alternative scenarios. If the central bank produces scenarios, which may typically be the case although often they are not published, one can jump to the second step. Otherwise, they need to be constructed. For illustrative purposes we simply use here the MMR model to produce three environments. One is based on the model itself at the estimated values; the second is based on a worsening of the trade-off faced by the central bank, as a way to capture the large supply shocks witnessed during the period 2021-23; the third one is based on increasing the role of demand shocks to capture the unusual demand pressure that followed the reopening of the economy after the pandemic.[30]

In the second step we compute environment-specific optimal policy. We optimise the policy rule over the response to inflation and the output gap by using a grid search to minimise a loss function in inflation and the output gap with weights 1 and 0.2, respectively. In our example, the environment with stronger inflation persistence – compared to the estimated case – calls for responding more forcefully to inflation relative to output. The third environment takes developments in economic slack relatively more into account than the reaction function optimised for persistent inflation.

In the third step, we compare the policy performance across environments, restricting the analysis to the set of the environment-specific simple optimal rules. Results are displayed in Table 4.1. Columns display the environments and rows indicate the environment-specific optimal rules. Let us focus first on the top-left two-by-two portion of Table 4.1. The largest loss occurs when the baseline optimal

[28] For instance, two examples in the ECB's 2022-23 tightening cycle appear to be the March 2022 and the September 2023 policy meetings. Specifically, according to the ECB's published accounts of the policy meeting of March 2022, in which the uncertainty created by the Russian invasion of Ukraine a few weeks earlier was extensively debated, the Chief Economist pointed out that "More than ever there was a need to maintain optionality in the conduct of monetary policy. In the current conditions, it was especially important for monetary policy to remain data-dependent and for optionality to be two-sided." According to the accounts of the ECB policy meeting of September 2023, the ECB Chief Economist pointed out that "[…] the choice between holding the deposit facility rate at 3.75% and moving to 4.00% was finely balanced. However, at the margin it was safer to decide on an additional hike, given the highly uncertain environment and the significant disinflation that was still required to return to the inflation target in a timely manner. […] In consequence, a more secure pace of disinflation and greater insurance against upside risks would also reinforce the anchoring of inflation expectations, which remained a precondition for the disinflation process to keep up its pace."

[29] See, Levin, Wieland and Williams (1999), Sargent (1999), Onatski and Stock (2002), Tetlow and von zur Muehlen (2001), Hansen and Sargent (2003, 2008), Levin and Williams (2003), Giannoni (2007), among others.

[30] In reality, alternative scenarios can be computed by modifying a given model along any desired dimension or considering the whole parameter uncertainty or by considering very different models. As we provide here simply an illustration, we make minimal changes to the model to construct the alternative environments, which can be seen as placeholders for more realistic scenarios constructed using a set of very different models. Specifically, our first environment is the model itself at the estimation values; the second environment is generated by making the price mark-up shock more persistent; the third environment makes the risk shock more persistent. In the second and third environments the persistence parameter is raised to the upper bound of the Highest Posterior Density 90% interval. Given that the environments we consider here are illustrative, we abstract from implementing optimal policy in terms of the target criterion (see Giannoni and Woodford (2002, 2003) and Giannoni (2007) for robustness to the statistical properties of the disturbances and parameter uncertainty), as we want to cater for potentially very different models that may be entertained by a central bank.

policy is implemented in the persistent inflation environment. Thus, a min-max approach calls for erring on the side of a relatively stronger response to inflation.

The robust policy prescription depends on the specific environments at hand and in practice there might often be several scenarios, some of which point to upward and others to downside risks. In our illustration in Table 4.1, when we consider also the third environment, it remains the case that a min-max approach would call for a stronger response to inflation. If the selection among the remaining reaction functions is taken on the basis of the same criterion of avoiding the highest (remaining) losses (in rows one and two), a robust policymaker would also avoid the baseline reaction function.

For illustration, Table 4.2 repeats the exercise by altering the third environment. We increase the impact of the interest rate on the real economy by simply adding an amplification parameter of the effect of the interest rate in the Euler equations for consumption and investment to capture in reduced form the possibility that the monetary policy effects may be stronger due to the speed and size of the policy tightening in 2022-23. This leads to a policy reaction function that takes a relatively more cautious approach towards inflation. The ranking of the losses is changed compared to Table 4.1, with the largest loss arising when the optimal policy specific for the inflation persistent environment is implemented in the amplification environment. Thus, a min-max approach calls in this case for the relatively weaker response to inflation prescribed in the baseline rule.

While in this section we have discussed an illustrative example, it highlights that in practice it may be challenging to select the economic scenarios to be entertained.[31]

Table 4.1: Robust policy: the case for a switch to a different reaction function

		Environment		
		Baseline	Persistent inflation	Persistent demand
Reaction function	Baseline	0%	94%	17%
	Persistent inflation	6%	81%	72%
	Persistent risk premia	3%	111%	6%

Table 4.2: Robust policy: the case for maintaining the baseline reaction function

		Environment		
		Baseline	Persistent inflation	Amplification effects
Reaction function	Baseline	0%	94%	86%
	Persistent inflation	6%	81%	135%
	Amplification effects	5%	96%	77%

Notes: The persistent inflation environment is modelled via more persistent price mark-up shocks. The persistent risk premia environment is modelled via more persistent risk premium shocks. The amplification effects environment is modelled via the Euler equations as an amplification effect of policy on consumption, investment and more persistent risk premium shocks. Losses refer to per cent increase in central bank loss relative to the baseline case. The loss function is given by $\sum\left((\pi_t-\pi^*)^2+\lambda_y\tilde{y}^2\right)$ with π_t measuring inflation, π^* the inflation target, $\tilde{y}$ the output gap, and the weight $\lambda_y=0.2$. The rows contain losses for policy rules that are chosen ex-ante. The columns display the environments that materialise ex-post. Each cell therefore displays the loss (in percent deviation from baseline) for a policy rule that was set based on expectations for the contingency presented in a row while instead the contingency presented in the column materialises.

5. Challenges raised by the recent high inflation episode

The high inflation episode of 2021 and 2022 raises new challenges for medium-scale New Keynesian models used at central banks. First, the sudden change in the inflation environment from a period of low and stable levels below 2% to a double-digit peak suggests the presence of important non-linearities such as a steepening of the Phillips curve when capacity and other supply constraints are reached. This is difficult to capture in the mostly linearized DSGE models that are maintained at central

[31] See Bernanke (2024) for a discussion of the use of scenarios in monetary policy making.

banks. Second, the higher frequency of sectoral reallocation shocks due to the pandemic crisis, the energy crisis driven by the Russian invasion in the Ukraine and ongoing structural changes due to climate change and digitalisation suggests that a richer supply side with a non-trivial input/output structure is necessary to capture the cascading effects of such sectoral reallocation shocks. The assumption of a single monopolistically competitive goods sector is not very suited for capturing such network effects. As a result, the estimates of the canonical DSGE model presented in Section 2 tend to capture such reallocation shocks and non-linearities in the form of large and persistent mark-up shocks.

One avenue for reconciling the recent experience with estimates of a historically flat Phillips curve is to explicitly allow for non-linearities and state dependence in price and wage setting. Harding et al. (2023) propose a macroeconomic model with a nonlinear Phillips curve that has a flat slope when inflationary pressures are subdued and steepens when inflationary pressures are elevated. Following Harding et al. (2022), they use the nonlinear formulation of SW07 allowing for a more prominent role for Kimball (1995) quasi-kinked demand in goods markets. The Kimball aggregator implies that the demand elasticity for intermediate goods is state-dependent, i.e. firms' demand elasticity is an increasing function of their relative price and the demand curve is quasi-kinked. Due to the rising demand elasticity, firms' marginal revenues are a concave function of their prices. Consequently, the optimal price setting becomes asymmetric since firms equate marginal revenue to marginal cost. If the latter rise or fall, the resulting optimal price setting becomes asymmetric as firms find it optimal to increase prices more than to decrease them. When the economy is exposed to large shocks, the state-dependence of the quasi-kinked demand curve becomes quantitatively important and the linear approximation ceases to provide accurate results. The more prominent role for quasi-kinked demand in the non-linear specification increases the marginal data density provided that the average mark-up aligns with micro- and macroeconomic empirical evidence. The model can jointly account for the modest decline in inflation during the Great Recession and the surge in inflation during the Post-Covid period. Harding et al. (2023) show that cost-push shocks can propagate more than four times stronger in the non-linear model relative to the linearized model when inflation is high. The nonlinearity implied by the Kimball aggregator is the key model feature that accounts for the differences between the linearized and nonlinear model solutions.

Harding et al. (2023) focus on non-linearities in the price Phillips curve. Other papers have emphasized non-linearities in wage-setting due to downward nominal rigidities or labour supply constraints. Benigno and Eggertsson (2023) propose a non-linear New Keynesian Phillips curve to explain the surge of inflation in the 2020s. Economic slack is measured as firms' job vacancies over the number of unemployed workers. After showing empirical evidence of statistically significant non-linearities, they propose a New Keynesian model with search and matching frictions, complemented by a form of wage rigidity, in the spirit of Phillips (1958), that generates strong nonlinearities in the wage Phillips curve.[32]

The production structure in the canonical model is very simple. There is a single domestic composite good which consists of an aggregate of intermediate goods produced in a monopolistically competitive goods market. The pandemic crisis with its supply chain disruptions and the energy crisis following the Russian invasion of the Ukraine have highlighted the importance of having a more disaggregated production structure to take into account how sectoral shocks propagate through the input/output network of the economy including through international supply chain linkages.

[32] See also Gagnon and Sarsenbayev (2022), Ball, Mankiw and Romer (1988) and Boehm and Pandalai-Nayar (2022).

The simplest way of modifying the baseline model is to allow for an additional intermediate goods sector which can either be domestically produced (through a round-about structure) or imported. One recent contribution in this direction is Chan et al. (2023) who allow for imported energy goods to be a complementary input in production along labour. They emphasise the importance of complementarity in production and the presence of credit-constrained households in generating negative demand effects from positive energy price shocks. The role of energy in both consumption and as an input in production has also been emphasized in Gagliardone and Gertler (2023). They also emphasise the role of a low elasticity of substitution between oil and labour to match the quantitative impact of an oil shock in a structural VAR.[33] In a similar vein, Coenen, Lozej and Priftis (2023) have built an extended version of the NAWM, which features a disaggregated energy sector with energy being used both for consumption and in production. More general input/output structures in a New Keynesian framework have been proposed by Rubbo (2022) and La'o and Tahbaz-Salehi (2022) and a growing literature that investigates the importance of those network effects for the propagation of sectoral shocks.[34]

A recent paper that combines a multi-sector economy with input/output linkages and the presence of capacity constraints is Comin, Johnsson and Jones (2022).[35] Using the model, they evaluate how potentially binding capacity constraints, and shocks to them, shape inflation and show that binding constraints for domestic and foreign producers shift domestic and import price Phillips curves up, similar to reduced-form markup shocks. Applying the model to interpret recent US data, they find that binding constraints explain half of the increase in inflation during 2021-2022. Tight capacity served to amplify the impact of loose monetary policy in 2021, fuelling the inflation take-off.

The increased frequency of sectoral reallocation shocks due to structural developments such as climate change, digitalisation and AI, and the deglobalisation due to geopolitical tensions underlines the importance of further developing a more detailed account of an economy's supply side in New Keynesian DSGE models.

[33] See also Guerrieri et al. (2022) and Guerrieri et al. (2023).
[34] See also Baqaee and Fahri (2022).
[35] See also Ferrante et al (2023)

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Appendix

Description of the dataset used for updating the SW model for US and EA

The US-model is estimated using eight quarterly macro-economic time series. The dataset is similar to SW2007: real GDP, consumption, investment, hours worked, real wages, prices and a short-term interest rate. This dataset is augmented with a long-term yield.

GDP, consumption and investment are taken from the U.S. Bureau of Economic Analysis. Real Gross Domestic Product (GDPC1) is expressed in Billions of Chained 2017 Dollars. Nominal Personal Consumption Expenditures (PCEC) and Fixed Private Domestic Investment (FPI) are deflated with the GDP-deflator.

Inflation is the first difference of the log of the Implicit Price Deflator of GDP (GDPDEF).

Hours and wages come from the BLS (hours and hourly compensation for the NFB sector for all persons). Hourly compensation (COMPNFB/PRS85006103) is divided by the GDP price deflator in order to get the real wage variable. Hours are adjusted to take into account the limited coverage of the NFB sector compared to GDP (the index of average weekly hours for the NFB sector (PRS85006023) is multiplied with the Civilian Employment (16 years and over - CE16OV).

The interest rate is the Federal Funds Rate. The long term yield is a zero-coupon yield (SVENYXX) available on the FederalReserve webpage "Nominal Yield Curve" and based on: "The U.S. Treasury Yield Curve: 1961 to the Present" by Refet S. Gurkaynak, Brian Sack, and Jonathan H. Wright 2006-28.

The aggregate real variables are expressed per capita by dividing with the population over 16 trend (CNP16OV). All series are seasonally adjusted. Consumption, investment, GDP, wages, hours, government consumption and investment and government transfers are expressed in 100 times log. The interest rate and inflation rate are expressed on a quarterly basis corresponding with their appearance in the model.

consumption = LN((PCEC / GDPDEF) / LNSindex) * 100

investment = LN((FPI / GDPDEF) / LNSindex) * 100

output = LN(GDPC96 / LNSindex) * 100

hours = LN((PRS85006023 * CE16OV / 100) / LNSindex) * 100

inflation = LN(GDPDEF / GDPDEF(-1)) * 100

real wage = LN(PRS85006103 / GDPDEF) * 100

interest rate = Federal Funds Rate / 4

1Y yield = SVENYXX / 4

The Euro Area model is estimated using eight quarterly EA macro-economic time series taken from the AWM database (awm19up18) extended after 1995 with the corresponding concepts from the ECB data portal. The dataset is similar to SW2003: real GDP, consumption, investment, employment, real wage per employee, prices and the short-term interest rate. This dataset is augmented with the 1 year euribor.

Real Quarterly Gross domestic product at market prices, Euro area 20 (fixed composition)

(Series key: MNA.Q.Y.I9.W2.S1.S1.B.B1GQ._Z._Z._Z.EUR.LR.N from 1995Q1 onwards, extended backwards with AWM data: YER from AWM19upd18).

Quarterly Deflator Gross domestic product at market prices, Euro area 20 (fixed composition)

(Series key: MNA.Q.Y.I9.W2.S1.S1.B.B1GQ._Z._Z._Z.IX.D.N from 1995Q1 onwards, extended backwards with AWM data: YED from AWM19upd18).

Real Quarterly Private final consumption, Euro area 20 (fixed composition)

(Series key: MNA.Q.Y.I9.W0.S1M.S1.D.P31._Z._Z._T.EUR.LR.N from 1995Q1 onwards, extended backwards with AWM data: PCR from AWM19upd18).

Real Quarterly Gross fixed capital formation, Euro area 20 (fixed composition – adjusted for country outliers) (Series key: MNA.Q.Y.I9.W0.S1.S1.D.P51G.N11G._T._Z.EUR.LR.N from 1995Q1 onwards, extended backwards with AWM data: ITR from AWM19upd18).

Euro area Short rate, Euribor 3-month, Historical close, average of observations through period, Quarterly (Series key: FM.Q.U2.EUR.RT.MM.EURIBOR3MD_.HSTA from 1995Q1 onwards, extended backwards with AWM data: STN from AWM19upd18).

Euro area 12 month interest rate, Euribor 1-year, Historical close, average of observations through period, Quarterly (Series key: FM.Q.U2.EUR.RT.MM.EURIBOR1YD_.HSTA from 1995Q1 onwards, extended backwards with AWM data: STN_1y is weighted series of STN and LTN from AWM19upd18).

Employment (in thousands of persons), Euro area 20 (fixed composition), Quarterly

(Series key: ENA.Q.Y.I9.W2.S1.S1._Z.EMP._Z._T._Z.PS._Z.N from 1995Q1 onwards, extended backwards with AWM data: LNN from AWM19upd18).

Compensation per employee, Euro area 20 (fixed composition), Quarterly

(Series key: MNA.Q.Y.I9.W2.S1.S1._Z.COM_PS._Z.J._Z.IX.V.N from 1995Q1 onwards, extended backwards with AWM data: WIN from AWM19upd18).

Population in the Euro Area from 15 to 64 years (POP1564 linear interpolated annual series Source: OECD).

output = LN(YER / POP1564) * 100

consumption = LN(PCR / POP15644) * 100

investment = LN((ITR / POP15644) * 100

employment = LN(LNN / POP15644) * 100

inflation = LN(YED / YED(-1)) * 100

real wage = LN((WIN / LNN) / YED) * 100 interest rate = STN / 4

1Y yield = STN_1y / 4

Table 2.1a

	prior distribution	US model 1965Q1:2019Q4 posterior distribution mode	US HPD interval	EA model 1980Q1:2019Q4 posterior distribution mode	EA HPD interval
σ_c	N (1.500 , 0.3750)	1.28	[1.06 , 1.45]	1.51	[1.09 , 1.42]
h	B (0.700 , 0.1000)	0.58	[0.52 , 0.68]	0.55	[0.77 , 0.58]
σ_l	N (2.000 , 0.7500)	1.62	[0.64 , 2.46]	0.03	[0.03 , 0.28]
ξ_w	B (0.500 , 0.1000)	0.80	[0.68 , 0.87]	0.73	[0.73 , 0.76]
ξ_p	B (0.500 , 0.1000)	0.82	[0.76 , 0.89]	0.85	[0.83 , 0.84]
ι_w	B (0.500 , 0.1500)	0.51	[0.28 , 0.71]	0.17	[0.18 , 0.19]
ι_p	B (0.500 , 0.1500)	0.19	[0.07 , 0.30]	0.16	[0.17 , 0.16]
φ	N (4.000 , 1.0000)	3.54	[2.66 , 4.95]	4.14	[4.99 , 4.61]
ψ	B (0.500 , 0.1500)	0.81	[0.68 , 0.91]	0.73	[0.64 , 0.71]
Φ	N (1.250 , 0.2500)	1.55	[1.40 , 1.73]	1.73	[1.70 , 1.70]
α	N (0.300 , 0.0500)	0.18	[0.16 , 0.22]	0.28	[0.29 , 0.28]
r_π	N (1.500 , 0.2500)	1.77	[1.54 , 2.02]	1.72	[1.80 , 1.77]
r_ρ	B (0.750 , 0.1000)	0.83	[0.80 , 0.87]	0.91	[0.94 , 0.92]
r_y	B (0.125 , 0.0625)	0.07	[0.04 , 0.10]	0.13	[0.14 , 0.15]
$r_{\Delta y}$	B (0.125 , 0.0625)	0.24	[0.20 , 0.29]	0.22	[0.15 , 0.22]
γ-cte	N (0.430 , 0.0250)	0.38	[0.34 , 0.41]	0.36	[0.32 , 0.37]
β^{-1}-1	G (0.250 , 0.1000)	0.11	[0.06 , 0.21]	0.18	[0.12 , 0.20]
y1-cte	U (1.000 , 0.5774)	-0.04	[-0.13 , 0.01]	0.05	[0.02 , 0.05]
ω_{y1}	B (0.500 , 0.2000)	0.85	[0.59 , 0.97]	0.75	[0.66 , 0.69]
L-cte	N (0.000 , 2.0000)	1.76	[-0.62 , 3.22]	-	[- , -]
L-adj	N (0.000 , 2.0000)	-	[- , -]	0.71	[0.66 , 0.70]
σ_a	IG (0.100 , 2.0000)	0.45	[0.41 , 0.50]	0.48	[0.40 , 0.49]
σ_b	IG (1.000 , 2.0000)	0.87	[0.62 , 1.20]	0.72	[0.94 , 0.79]
σ_g	IG (0.100 , 2.0000)	0.47	[0.44 , 0.52]	0.29	[0.27 , 0.29]
σ_l	IG (0.100 , 2.0000)	0.50	[0.40 , 0.65]	0.58	[0.48 , 0.57]
σ_r	IG (0.100 , 2.0000)	0.22	[0.20 , 0.25]	0.14	[0.10 , 0.14]
σ_{y1}	IG (0.100 , 2.0000)	0.14	[0.13 , 0.16]	0.04	[0.04 , 0.04]
σ_p	IG (0.100 , 2.0000)	0.13	[0.11 , 0.15]	0.16	[0.14 , 0.16]
σ_w	IG (0.100 , 2.0000)	0.36	[0.33 , 0.40]	0.16	[0.09 , 0.16]
ρ_a	B (0.500 , 0.1750)	0.98	[0.96 , 0.99]	0.99	[0.99 , 0.99]
ρ_b	B (0.500 , 0.1750)	0.87	[0.78 , 0.91]	0.98	[0.93 , 0.98]
ρ_g	B (0.500 , 0.1750)	0.97	[0.96 , 0.98]	1.00	[0.99 , 0.99]
ρ_l	B (0.500 , 0.1750)	0.90	[0.84 , 0.99]	0.96	[0.74 , 0.95]
ρ_r	B (0.500 , 0.1750)	0.13	[0.07 , 0.21]	0.42	[0.47 , 0.41]
ρ_{y1}	B (0.500 , 0.1750)	0.81	[0.74 , 0.89]	0.85	[0.88 , 0.87]
ρ_p	B (0.500 , 0.1750)	0.89	[0.77 , 0.96]	0.82	[0.63 , 0.76]
ρ_w	B (0.500 , 0.1750)	0.98	[0.95 , 0.99]	0.98	[0.97 , 0.97]
μ_b	B (0.500 , 0.1750)	0.66	[0.46 , 0.76]	0.88	[0.82 , 0.88]
μl	B (0.500 , 0.1750)	0.52	[0.35 , 0.65]	0.84	[0.64 , 0.83]
μ_p	B (0.500 , 0.1750)	0.79	[0.55 , 0.88]	0.77	[0.52 , 0.66]
μ_w	B (0.500 , 0.1750)	0.96	[0.92 , 0.97]	0.94	[0.85 , 0.93]
δ_{ga}	N (0.500 , 0.2500)	0.49	[0.37 , 0.61]	0.13	[0.14 , 0.13]

Fixed: π-cte=0.5, depreciation = 0.025, G/Y=0.18, wage-markup=1.5, price-markup=Φ, Curvature Demand Elastisities=10

Table 2.1b

	prior distribution			US model 1995Q1:2019Q4 posterior distribution mode	HPD interval		EA model 1995Q1:2019Q4 posterior distribution mode	HPD interval	
σ_c	N	1.500	0.3750	1.26	1.07	1.47	1.09	1.09	1.09
h	B	0.700	0.1000	0.61	0.53	0.70	0.77	0.77	0.77
σ_l	N	2.000	0.7500	0.37	0.03	0.81	0.03	0.03	0.25
ξ_w	B	0.500	0.1000	0.67	0.55	0.78	0.73	0.73	0.73
ξ_p	B	0.500	0.1000	0.89	0.85	0.94	0.83	0.83	0.81
ι_w	B	0.500	0.1500	0.38	0.19	0.64	0.18	0.18	0.19
ι_p	B	0.500	0.1500	0.23	0.10	0.41	0.17	0.17	0.20
φ	N	4.000	1.0000	5.30	4.16	6.69	4.99	4.99	5.38
ψ	B	0.500	0.1500	0.88	0.76	0.95	0.64	0.64	0.64
Φ	N	1.250	0.2500	1.46	1.28	1.74	1.70	1.70	1.72
α	N	0.300	0.0500	0.19	0.15	0.22	0.29	0.29	0.29
r_π	N	1.500	0.2500	1.48	1.08	1.84	1.80	1.80	1.79
r_ρ	B	0.750	0.1000	0.91	0.88	0.94	0.94	0.94	0.94
r_y	B	0.125	0.0625	0.11	0.06	0.17	0.14	0.14	0.14
$r_{\Delta y}$	B	0.125	0.0625	0.13	0.09	0.18	0.15	0.15	0.13
γ-cte	N	0.430	0.0250	0.39	0.35	0.42	0.32	0.32	0.31
β^{-1}-1	G	0.250	0.1000	0.12	0.05	0.23	0.12	0.12	0.15
y1-cte	U	1.000	0.5774	-0.01	-0.04	0.02	0.02	0.02	-0.22
ω_{y1}	B	0.500	0.2000	0.79	0.44	0.95	0.66	0.66	0.70
L-cte	N	0.000	2.0000	-0.04	-1.44	1.34	-	-	-
L-adj	N	0.000	2.0000	-	-	-	0.66	0.66	0,00
σ_a	IG	0.100	2.0000	0.43	0.38	0.50	0.40	0.40	0.40
σ_b	IG	1.000	2.0000	0.50	0.31	0.80	0.94	0.94	0.95
σ_g	IG	0.100	2.0000	0.34	0.30	0.39	0.27	0.27	0.28
σ_l	IG	0.100	2.0000	0.36	0.28	0.46	0.48	0.48	0.49
σ_r	IG	0.100	2.0000	0.09	0.08	0.11	0.10	0.10	0.09
σ_{y1}	IG	0.100	2.0000	0.09	0.07	0.11	0.04	0.04	0.04
σ_p	IG	0.100	2.0000	0.12	0.09	0.14	0.14	0.14	0.15
σ_w	IG	0.100	2.0000	0.55	0.47	0.63	0.09	0.09	0.09
				0.00			0.00		
ρ_a	B	0.500	0.1750	0.97	0.95	0.99	0.99	0.99	0.99
ρ_b	B	0.500	0.1750	0.90	0.85	0.94	0.93	0.93	0.90
ρ_g	B	0.500	0.1750	0.93	0.88	0.96	0.99	0.99	0.99
ρ_l	B	0.500	0.1750	0.83	0.75	0.93	0.74	0.74	0.66
ρ_r	B	0.500	0.1750	0.53	0.45	0.63	0.47	0.47	0.44
ρ_{y1}	B	0.500	0.1750	0.65	0.52	0.79	0.88	0.88	0.95
ρ_p	B	0.500	0.1750	0.73	0.47	0.86	0.63	0.63	0.60
ρ_w	B	0.500	0.1750	0.31	0.11	0.54	0.97	0.97	0.96
μ_b	B	0.500	0.1750	0.54	0.33	0.70	0.82	0.82	0.75
μl	B	0.500	0.1750	0.46	0.23	0.64	0.64	0.64	0.53
μ_p	B	0.500	0.1750	0.62	0.29	0.77	0.52	0.52	0.49
μ_w	B	0.500	0.1750	0.46	0.29	0.61	0.85	0.85	0.83
δ_{ga}	N	0.500	0.2500	0.53	0.39	0.68	0.14	0.14	0.16

Fixed: π-cte=0.5, depreciation = 0.025, G/Y=0.18, wage-markup=1.5, price-markup=Φ, Curvature Demand Elastisities=10

Appendix to section 4

A.4.1 Constructing counterfactuals

We begin with a finite T-period Baseline projection, , with dimension n_Y ×(T+1), where $Y_t = (L'_t, X'_t)'$ with L_t representing policy target variables (e.g. inflation and output gap) of size n_L and X_t representing policy instruments of size n_X, thus n_Y=n_L+n_X. We use the following notation: $Y^B \equiv vec\{Y_t^B\}_{t=0}^T$. There is no need to specify the origin of the baseline projections, they could be judgmental.

Next, we construct an alternative policy projection. We require unanticipated and anticipated impulse responses to policy instrument shocks. They could come from a fully structural or identified time series model. Let V_0 be a $(H+1) \times n_X$ innovation matrix of policy shocks where the row denotes the horizon at which an innovation announced at time t is realised. Hence, $H \leq T$ is the maximum horizon for expected policy shocks. Given that in section 4 we use only one policy instrument, in what follows we assume that $n_X = 1$ to simplify the notation. Shocks are *iid(0,*Ω_V). Non-policy shocks are not relevant here, so we abstract from them.

Define the vector $A^{y,h} \equiv \left(A_0^{y,h}, A_1^{y,h}, \dots, A_T^{y,h}\right)'$ which contains the impulse response coefficients for variable $y \in \{L^1, L^2, \dots, L^{n_L}, X\}$, to a policy shock announced in t and to occur in *t+h*, with $h \in \{0,1, \dots H\}$. This implies that the impact of shocks announced in t on variable y at time $j \in \{0,1, \dots T\}$ is $y_{t+j} = \left(A_j^{y,0}, A_j^{y,1}, \dots, A_j^{y,H}\right)V_0 = A_j^y V_0$.

The response of variable *y* for the entire length is constructed using y_{t+j} with $j \in \{0,1, \dots T\}$, that is $y^{IR} \equiv (y_t, y_{t+1}, \dots, y_{t+T})' = \left(A_0^y; A_1^y; \dots; A_T^y\right)V_0 = A^y V_0$.

Let's select the policy rate, $y \equiv X$. An Alternative interest rate path is simply given by the linear sum of the baseline projection and the impulse responses: $X^A = X^B + X^{IR} = X^B + A^X V_0$. To implement a given counterfactual interest rate path, $X^* = X^B + A^X V_0^*$, we compute the shocks that will deliver this rate path: $V_0^* = (A^X)^{-1}(X^* - X^B)$. The counterfactual path for any variable of interest, L^*, conditional to X^* can be computed using V_0^*, as follows: $L^* = L^B + A^L V_0^*$.

To compute optimal policy, we collect impulse responses for all variables: $Y_t^{IR} = (y_{Y_1,t}^{IR}, y_{Y_2,t}^{IR}, \dots, y_{Y_{n_Y},t}^{IR})'$ and $Y^{IR} \equiv vec\{Y_t^{IR}\}_{t=0}^T = AV_0$ with A constructed using the elements of A^y where $y \in \{Y^1, Y^2, \dots, Y^{n_Y}\}$. An alternative projection is computed as: $Y^A = Y^B + Y^{IR} = Y^B + AV_0$. We consider a loss function $\frac{1}{2}\sum_{t=0}^T \beta L'_t Q L_t$ where $\beta \in (0,1)$ is the discount factor and Q is a symmetric positive semidefinite matrix conformable with L_t containing the central bank's preference parameters. The policy problem can be defined as:

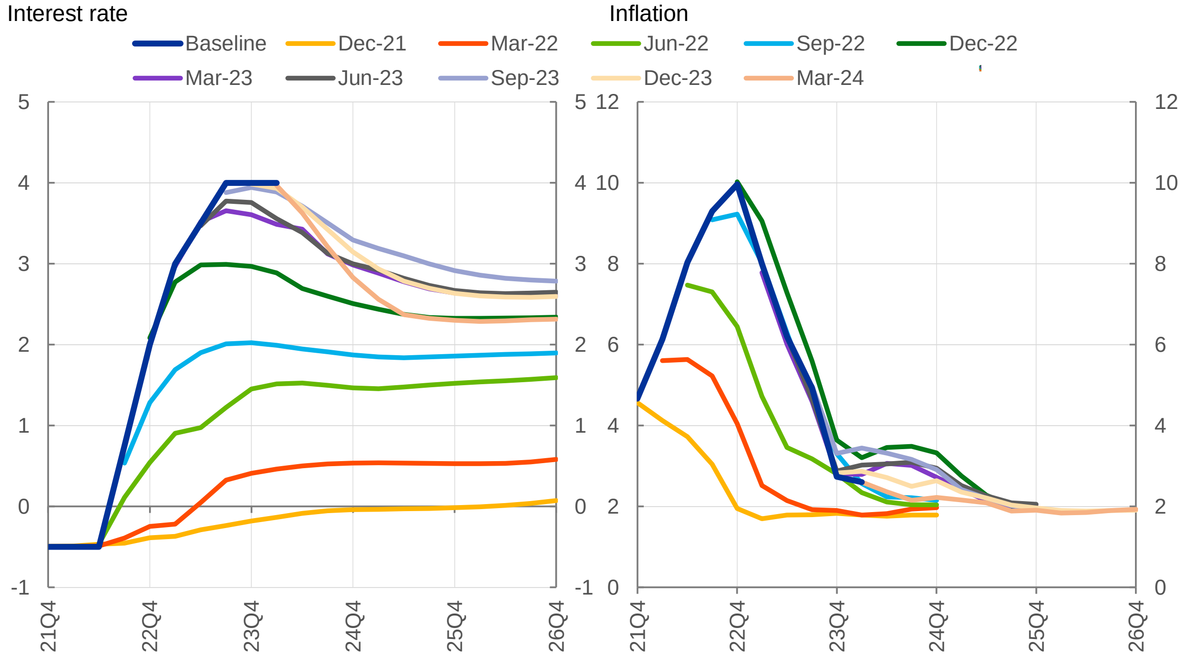
$$\min_{V_0} \frac{1}{2} V'_0 (A^L)' \Omega A^L V_0 + (L^B)' \Omega A^L V_0$$

where $\Omega \equiv diag(1, \beta, \dots, \beta^T) \otimes Q$. Therefore, the optimal set of shocks is: $V_0^* = -((A^L)'\Omega A^L)^{-1}(A^L)'\Omega L^B$. Optimal policy counterfactuals for variables Y can be computed as: $Y^* = Y^B + AV_0^*$.

A.4.2 Baseline projections

Figure A.4.1 displays the realised short-term interest rate over our review period, as well as the sequence of rate paths on which each of the ECB/Eurosystem staff projection vintages was conditioned. The realised interest rate remained at -0.5% until lift-off in July 2022, while the expected

Figure A.4.1. Baseline projections for the interest rate and inflation, 2021Q4-2024Q1



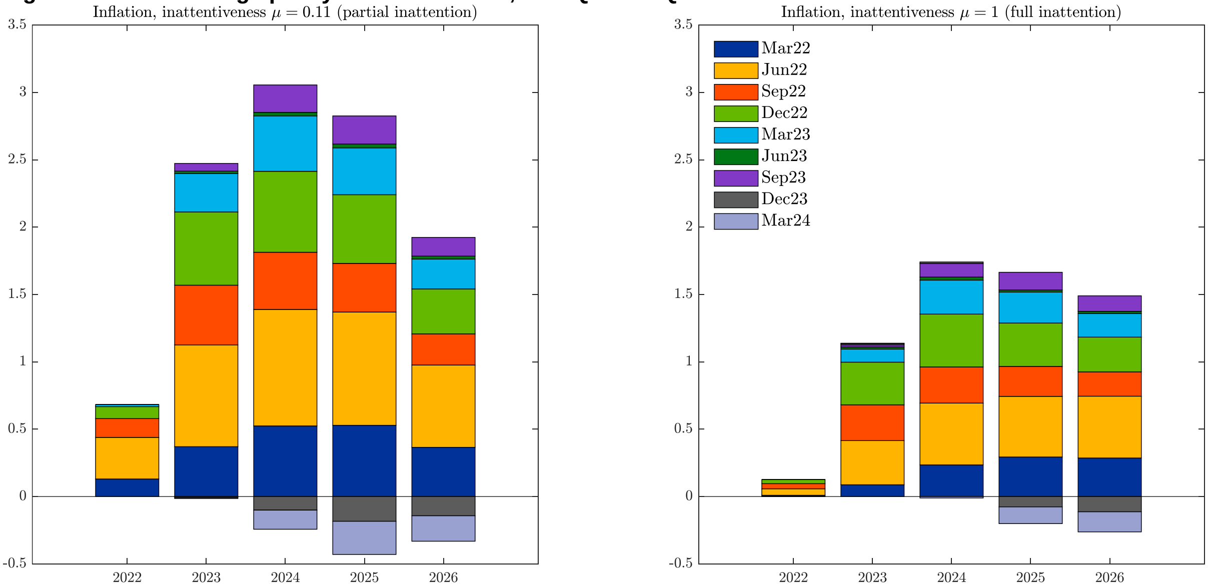
Notes: Sequence of real-time projections for the short-term interest rate and HICP inflation over 2021Q4-2024Q1. The interest rate paths are based on monetary policy-dated forward contracts.

rate path appeared to mildly trend up in the 2021Q4 projection round (it was flat in the 2021Q3 round) and became quite steep already in 2022Q1. Figure A.4.1 displays also the realised inflation rate and the sequence of ECB/Eurosystem staff inflation projections. Note the large upward revisions in the inflation path across the early vintages which suggests the presence of large forecast errors.

A.4.3 No-change policy counterfactual

Figure A.4.2 shows the no-change policy counterfactuals for all vintages of ECB/Eurosystem staff projections between 2021Q4 and 2024Q1.

Figure A.4.2. No-change policy counterfactuals, 2021Q4-2024Q1

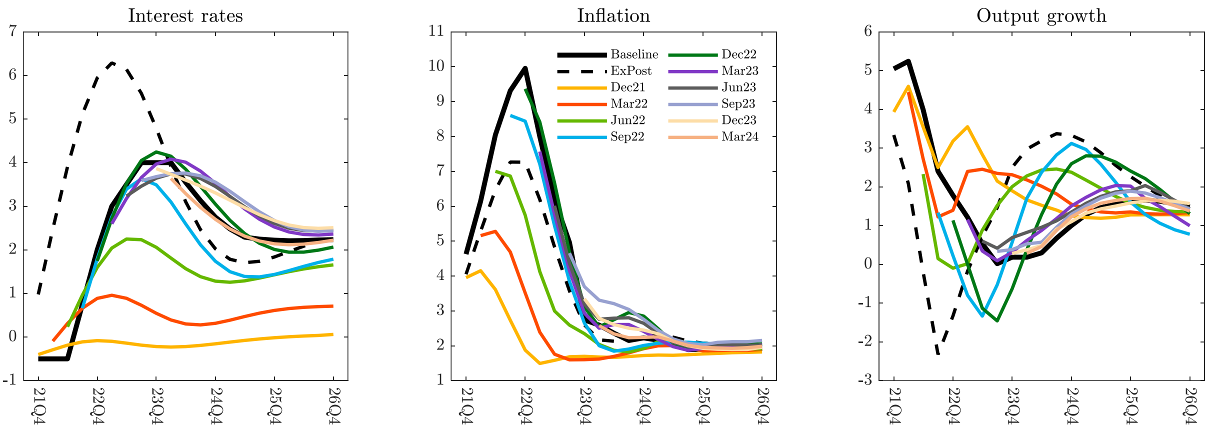


Notes: Sequence of counterfactuals whereby at each projection vintage between 2021Q4 and 2024Q1 the interest rate path over the projection horizon is maintained unchanged compared to the path embedded in the vintage prior to the one considered. The degree of inattentiveness used in the left panel is the estimated one ($\mu = 0.11$), while the one used in the right panel is selected purely for illustration ($\mu = 1$). Counterfactuals are computed using the MMR model. Results are shown in annual percentage points.

A.4.4 Optimal policy counterfactual

Figure A.4.3 shows the optimal policy counterfactuals for all vintages of ECB/Eurosystem staff projections between 2021Q4 and 2024Q1.

Figure A.4.3. Optimal policy counterfactuals for the interest rate and implied inflation and output growth, 2021Q4-2024Q1



Notes: The "Baseline" denotes historical data and projections available in the context of the March 2024 vintage. The "Ex-post" denotes the optimal policy counterfactual computed in 2021Q4 with the benefit of hindsight by assuming that in 2021Q4 the same information set is available as in the 2024Q1 projection vintage. The other lines are a sequence of optimal policy counterfactuals computed in real time at all projection vintages between 2021Q4 and 2024Q1. The interest rate is in percentages per annum, inflation and output growth are in year-on-year percentage changes. Counterfactuals are computed with the MMR model. The loss-function weights are $\lambda_y = 0.2$ and $\lambda_i = 1.4$.

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Günter Coenen
European Central Bank, Frankfurt am Main, Germany; email: gunter.coenen@ecb.europa.eu

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

Roberto Motto
European Central Bank, Frankfurt am Main, Germany; email: roberto.motto@ecb.europa.eu

Annukka Ristiniemi
European Central Bank, Frankfurt am Main, Germany; email: annukka.ristiniemi@ecb.europa.eu

Frank Smets
Bank for International Settlements, Basel, Switzerland; email: frank.smets@bis.org

Anders Warne
European Central Bank, Frankfurt am Main, Germany; email: anders.warne@ecb.europa.eu

Raf Wouters
Nationale Bank van België/Banque Nationale de Belgique, Brussels, Belgium; email: rafael.wouters@nbb.be

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

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