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Matteo Ciccarelli (editor),
Matthieu Darracq Pariès (editor),
Romanos Priftis (editor)

ECB macroeconometric models for forecasting and policy analysis

Development, current practices and prospective challenges

No 344

Contents

Abstract

This paper takes stock of the ECB's macroeconometric modelling strategy by focusing on the models and applications used in the Forecasting and Policy Modelling Division. We focus on the guiding principles underpinning the current portfolio of the main macroeconomic models and illustrate how they can in principle be used for economic forecasting, scenario and risk analyses. We also discuss the modelling agenda which is currently under development, focusing notably on heterogeneity, machine learning, expectation formation and climate change. The paper makes it clear that the large macroeconometric models typically developed in central banks remain stylised descriptions of our modern economies and can fail to predict or assess the nature of economic events (especially when big crises arise). But even in highly uncertain economic conditions, they can still provide a meaningful contribution to policy preparation. We conclude the paper with a roadmap which will allow the ECB and the Eurosystem to exploit technological advances and cooperation across institutions as a useful means of ensuring that the modelling framework is not only resilient to disruptive events but also innovative.

Non-technical summary

This paper takes stock of almost 25 years of macroeconometric modelling strategy at the ECB and complements the ECB's recent occasional paper reviewing macroeconomic modelling in the Eurosystem (Darracq Pariès et al., 2021), prepared as part of the ECB's strategy review. The work – which has been carried out by the ECB's Forecasting and Policy Modelling Division (FPM) – focuses on the guiding principles underpinning the current portfolio of main macroeconomic models and illustrate how they can in principle be used for forecasting, risk and scenario analysis as well as policy simulations.

Monetary policy preparation at the ECB involves a wide range of tools or models which are developed and maintained across various organisation units. The focus of this paper is therefore quite narrow regarding the specific set of analytical frameworks under review and the terminology used thereafter about "main models" is restricted to the large macroeconometric models regularly used by ECB staff both in the context of economic projections and for policy simulations. As a reference, such a narrow focus is consistent with the approach taken in Darracq Pariès et al. (2021).

The paper starts with a well-defined stakeholder map and discusses the factors that have inspired and determined the path taken by the ECB (and many other central banks) in terms of model development and model strategy. These factors are grouped into three broad categories which define (i) the academic or conceptual environment (including technology), (ii) the institutional environment, and (iii) the economic environment.

The paper subsequently describes the most important features and building blocks of the main structural (NAWM II) and semi-structural (ECB-BASE and ECB-MC) models. Alongside these main models, a range of "satellite" models are also developed within the FPM division (and as mentioned before, even more so across the ECB), and notably, satellite empirical tools such as the suite of Bayesian vector autoregressions.

Taken together, these models form a core toolkit which support the Eurosystem economic projections and monetary policy preparation more generally. To this extent, the paper illustrates in a transparent – and sometimes unprecedented – manner how the models can in principle be used for forecasting and policy analysis. In particular, the paper exemplifies how the models can build structural economic narratives (e.g., through shock decompositions), perform economic projections (conditional and unconditional forecasts), provide risk analyses around baseline projections (such as those associated with a change in energy prices and exchange rates), as well as advanced monetary policy simulations.

In the light of prospective challenges and global trends, the paper then explains the pipeline of modelling activities and summarises ongoing work on key themes which have been playing a prominent role (and are expected to continue to do so):

heterogeneity, alternative expectation formation, machine learning and climate change.

Notably, models can fail to predict important events given that they are an imperfect representation of reality. The real test of "knowledge", however, is not truth but utility. The purpose of the material shared in the following pages is, therefore, to show how useful these models have proven to be when used to interpret a complex reality. Our modelling teams strive constantly to increase the accuracy of the ECB's knowledge and to make models more resilient, even in the face of crises and unexpected disruptive events. Policy decisions are inevitably taken under conditions of uncertainty and models, being only approximations of reality, have proven to be indispensable theoretical frameworks and disciplining devices that can inform and even guide decision making. This is especially the case if they are used in combination with other tools, given that there is no one way of interpreting reality that is always accurate.

In parallel with developing new models and incorporating new features into the existing toolkit to cope with an uncertain world, the ECB pays careful attention to choosing an appropriate IT environment and to building up user-friendly infrastructures. This guarantees resilience, shared use of the tools and the preservation of institutional knowledge. The suite-of-models approach and the construction of a modern technical environment have always been the core characteristics of the ECB's modelling strategy.

Finally, Annex I provides a historical perspective on the development of the modelling toolkit since the foundation of the ECB, while Annex II provides a non-exhaustive list of other models used in the division.

"The real test of 'knowledge' is not truth but utility. A theory that enables us to do new things constitutes knowledge."

Yuval Noah Harari

1 Stakeholder map and environment

The purpose of this paper is to take stock of almost 25 years of macroeconometric modelling strategy at the ECB. The paper complements the recent ECB occasional paper reviewing macroeconomic modelling in the Eurosystem, prepared as part of the ECB's strategy review. It is important to note from the outset that the ECB has a vast and expanding galaxy of models which are developed and maintain by various ECB's organisation units. This paper will not describe the entire galaxy but will only zoom in on a constellation of main models regularly used for both forecasting and policy analysis. These models have been developed over time by ECB staff and are now maintained and used within the ECB's Forecasting and Policy Modelling Division. Such a narrow focus implies that several models specifically designed for areas such as fiscal, monetary or macroprudential policy are not within the scope of this review. The paper also explain the guiding principles underpinning the current portfolio of macroeconomic models. A selected list of additional models can be found in the appendix and is unavoidably incomplete.

Before providing an overview of the modelling portfolio, including its details and main properties, this introduction presents the stakeholder map and discusses the factors that have inspired and shaped the path taken by the ECB (and by many other central banks) in terms of model development and modelling strategy.[1] We will divide these factors into three broad categories which define (i) the academic or conceptual environment (including technology), (ii) the institutional environment, and (iii) the economic environment. We assume that the reader is familiar with the concept of an economic model as a simplified and judgement-based approximation of reality designed to implement and test economic theory using analytical tools and data.[2]

Conceptual

Model development in policy institutions is heavily influenced by the **prevailing academic literature**, although with lags that are sometimes rather long.[3] Prior to the publication of the Lucas critique in 1976, the gap between central bank and academic models was relatively small. The dominant paradigm in academic macroeconomics was the IS/LM, and the models employed at central banks and other policy institutions reflected this perspective. The models were large scale, containing a large number of equations[4], and focused on determining the components of real aggregate demand (consumption, investment, etc.). The supply side was relatively neglected while prices were determined by backward-looking

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[1] This chapter has been co-authored with Gabriel Fagan.

[2] See, for example, Ouliaris (2011) for a non-specialist guide to economic models and their use, or Ciccarelli et al. (2023) for a focus on the main ECB models and their use in forecasting.

[3] See Woodford (1999) for an overview of the evolution of macroeconomics. See also Annex I in this paper for a short history of model development at the ECB.

[4] For example, as of late 1986, the Federal Reserve System's main structural model contained 334 equations, of which 128 were stochastic and 206 were identities. It also had 188 exogenous variables.

Philips curve relations. The models' equations were not derived explicitly from economic theory, which was used instead to suggest which variables should be used in the equations. The equations employed were selected on the basis of empirical properties such as goodness of fit, the "correct" signs and statistical significance. The models did not generally contain explicit variables for expectations and, where these were included, this was done in a backward-looking fashion. In particular, the effect of expectations, in line with the prevailing adaptive expectations paradigm, was captured by the inclusion of lagged variables. The effect of expectations was thus mixed with an economy's intrinsic dynamics.

With the outbreak of stagflation in the 1970s and under the weight of criticism received from Lucas (1976), Lucas and Sargent (1979) and Sims (1980), interest in large-scale macro models waned substantially in the academic literature.[5] Instead, attention was focused on smaller (typically three-equation) models with sticky prices and rational expectations (e.g. Taylor, 1979) or real business cycle (RBC) models (e.g. Kydland and Prescott, 1982). In these general equilibrium models the equations were derived from explicit optimisation problems faced by agents, expectations were assumed to be forward looking and fully model-consistent, and – at least initially – parameters were calibrated rather than estimated. A key feature of the RBC class of models was the absence of nominal frictions which meant these models implied no role for monetary policy in influencing output. An alternative approach was a-theoretical, inspired by Sims (1980). This consisted of estimating vector autoregressions in which a vector of macroeconomic variables was modelled as depending on its past without imposing theoretical restrictions (apart from the choice of variables to include in the vector). Vector autoregression (VAR) models can be used in a straightforward manner in forecasting, while the impact of policy actions is assessed using impulse response analysis, under the assumption that policy actions do not lead to a change in VAR coefficients.

In the 1990s, building on important theoretical contributions from, among others, Calvo (1983), Blanchard and Kiyotaki (1987) and Mankiw (1985), attention in the literature shifted to an analysis of monetary policy using small scale models.[6] These models incorporate dynamic optimisation by agents (utility and profit maximisation), rational expectations, imperfect competition and sticky prices.[7] The standard workhorse model in this class comprises three equations: a New Keynesian Philips curve, a dynamic IS curve and a policy rule for the short-term interest rate.[8] The key reference for this in the literature is Woodford (2003).

Prior to the financial crisis, the New Keynesian framework represented a consensus methodology for macroeconomics (Blanchard, 2009). However, a number of variations were explored within this framework, including labour markets and unemployment, as well as alternative expectation formation mechanisms (such as

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[5]   As noted by Brayton et al. (1997), after the early 1970s "a large gulf emerged between applied macroeconomics as practiced by academics and that contained in large-scale models" (such as the Federal Reserve System's MPS model).

[6]   See the survey in Ball et al. (1988).

[7]   Examples include Yun (1996), Goodfriend and King (1997), Rotemberg and Woodford (1997) and McCallum and Nelson (1999).

[8]   The volume edited by Taylor (1999) contains a useful collection of papers applying this approach.

learning and rational inattention). After 2007 the financial crisis led to a shift in focus in academic macroeconomics, with renewed interest being seen in the role played by the financial system and financial shocks in the macroeconomy.[9]

Together with the academic evolution of thought, the **state of technology** has an important influence on the models which can be developed by a central bank. Computer technology (both hardware and software) and algorithms place a significant constraint on what can be done by a central bank. During the lifetime of the ECB there have been substantial advances in the relevant technologies and computer processing power and storage capacities have increased significantly. New algorithms have been developed which speed up the estimation and solution of models. For example, Bayesian estimation of relatively large forward-looking DSGE models (such as the New Area-Wide Model) is now relatively straightforward. This was not possible back in the late 1990s when the ECB was first established. More recently, techniques have been developed which enable the solution represented by heterogeneous agent models. In terms of econometrics, techniques have also been developed (such as high-dimensional VARs and factor models) to enable the use of "Big Data" in economic analysis.

Institutional

Model development at the ECB (and other central banks) reflects the **institutional needs and constraints** of the organisation. In academia, a model is typically developed to answer a specific, well-defined question. By contrast, central banks' models are expected to contribute to a range of tasks. A non-exhaustive list of examples includes macroeconomic forecasting, examining the impact of various shocks on the economy and analysing the impact of alternative policies (such as changes in interest rates or asset purchases) on the economy. More recent uses of models in central banks include stress-testing the financial system and assessing the impact of macroprudential measures.

Within central banks, model developers are typically only a small subset of the staff of the economics/research department. If they are to contribute usefully to the work of the bank, it is therefore essential that they are able to communicate their findings effectively to policymakers and economists in the bank who are not modellers. For example, in the field of macroeconomic forecasting, forecasts in central banks typically follow a regular process which involves bringing staff together from different parts of the bank. The forecasting process is typically centred on a well-established accounting framework which includes a relatively large number of macroeconomic variables. Discussions of forecasts tend to be elaborate, detailed and time consuming. In order to contribute practically to the forecasting process, the accounting frameworks of the models must be aligned with those of the forecast exercises. In short, the models must be able to "fill in the forecast tables".

In the case of the ECB – unlike other central banks – an additional complication arises from the fact that the Eurosystem is a multi-country institution comprising the

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[9]   See the survey in Brunnermeier et al. (2012).

ECB and the national central banks (NCBs) of euro area countries. For this reason forecasts are prepared "bottom up" (i.e. by aggregating a set of 20 individual country forecasts to arrive at an area-wide picture). This is done while ensuring consistency across the individual country forecasts in respect of common external assumptions and trade flows and prices.

Economic environment

Another important factor influencing the choice of central bank models is the constant evolution of the **economic environment** (also linked to geopolitical forces) faced by central banks. During the first decade of the ECB's existence the macroeconomic environment was relatively calm. The "Great Moderation" was in full swing with a low volatility of macroeconomic variables (Stock and Watson, 2002). In addition, the financial system was relatively stable, the usual arbitrage relations (such as covered interest parity and the expectations theory of the term structure) more or less applied and risk premia were contained. Moreover, the economy was a considerable distance from the lower bound on interest rates. In such an environment (approximately) linear models with a limited coverage of the financial sector were adequate for most purposes. With the outbreak of the financial and sovereign debt crises after 2007, however, the situation changed radically. The crisis highlighted the role of the financial system both as a source and as an amplifier of shocks. In both academic and central bank modelling this led, in due course, to a major shift in modelling strategies with an increased emphasis being placed on including financial frictions and the financial sector in models. The aftermath of the financial crisis – and especially the period 2013-20 – introduced an environment in which persistently low inflation and low real interest rates prevailed with monetary and fiscal policies exhibiting strong complementarities (Debrun et al., 2021). The unprecedented economic fallout from the coronavirus (COVID-19) pandemic has also left its mark on specific model development needs related to the treatment of large shocks and uncertainty, or the role of disruptions to market functioning with both demand and supply-side ramifications. Since the end of 2021 an environment of higher inflation, lower growth, higher uncertainty and higher interest rates has changed some macroeconomic relationships once again and has introduced new challenges for policy modelling. At the time of writing, wars in Ukraine and Palestine, quite apart from the lives lost and the dramatic consequences for the citizens and the world's wellbeing, have been disrupting the energy and food sectors. Such wars have the potential to generate far-reaching and structural consequences for the world economy, especially when combined with the consequences of economic activity on climate change.

With this map in mind and given historical trends, the rest of this paper focuses on the current configuration of the modelling portfolio: Section 2 provides details on the current modelling portfolio in relation to forecasting and policy analysis, Section 3 illustrates how these models are used at the ECB in the context of forecasting and policy preparation, and Section 4 proposes some possible challenges and summarises the pipeline of model development projects already in place.

2 The ECB modelling portfolio for forecasting and policy analysis

2.1 Modelling strategy and guiding principles

This section describes the current portfolio of models used in forecasting and policy analysis. Annex I covers the history of macroeconomic model development in the ECB from the late 1990s to the present time. It complements the contextualisation described in the introduction.

The general modelling strategy at the ECB, which has been optimally consolidated over the years, is the suite-of-models approach. This approach in no way aspires to build all-encompassing models – instead, its guiding objective is to build main or core models complemented by satellite tools. The process of building the components of the suite of models is constantly evolving. The consensus surrounding it has been shaped by the intersection of constant tensions between the three forces described in the introduction – the institutional context, the technological paradigm and the economic environment – and a continuous interaction between academic research and policy analysis. As a result, the modelling choices should be seen as optimal responses to various trade-offs between complexity and simplicity, operational risks and business continuity, and empirical fit and theoretical soundness.

Table 1

Academic research and modelling at policy institutions: a continuous interaction

Academic research	Policy modelling
Simple and stylised	Realistic and granular
Deep theoretical foundations	Robust to structural uncertainty
Original and strong policy prescriptions	Continuity and consistency with policy paradigm
Mostly mainstream and frontier	Mainstream but behind the curve

Source: ECB.
Note: Synoptic presentation of the differences between academic research and policy modelling.

This explains why, while modelling at a policy institution is always based on solid academic pillars and on mainstream paradigms, it often finds itself (perhaps consciously) behind the curve or below the research frontier. The reasons for this are easy to grasp: while academic research must be new and original when it comes to prescribing strong policy prescriptions, policy modelling must ensure continuity and consistency with a policy paradigm whose shifts are slow and cautious. In addition, consensus is an important consideration. Moreover, if academic research aims to build deep theoretical foundations with elegance and style, policy modelling aspires to achieve realistic and data-driven relationships, granularity and robustness to

structural uncertainty. Therefore, policy modelling in central banks does not adopt new paradigms or theories before they have become well established or empirical evidence has built enough consensus around them.

As mentioned previously, the results in terms of policy modelling and the gradualism with which the modelling portfolio at the ECB is changed must be contextualised and checked against the predominant paradigm, the existing institutional constraints and the economic and social environment. Moreover, the outcome must guarantee a high degree of continuity in the policy assessment while retaining the flexibility to adapt tools by including new channels and frictions. A notable example of flexibility will be discussed in Section 2.4, which illustrates, for instance, how COVID-19 forced the modification of some existing models through the application of innovative solutions.

At a high-level dimension we can therefore state that the ECB's suite of macroeconomic models is guided by four organising principles: (i) ensuring **robustness** across state-of-the art modelling strategies, (ii) tiering the modelling portfolio into **main and satellite models**, (iii) adopting both a **euro area-wide and a multi-country** perspective for the monetary union, and (iv) supporting an **evolutionary process** to govern the continuous development of the suite of models.

(i) Robustness. To ensure robustness in model-based analysis, it is imperative to exploit the trade-off in macroeconomic modelling between sound theoretical features on the one hand, and high statistical and forecasting performance on the other (see, for example, Pagan, 2005). With this requirement in mind, three classes of modelling technique are considered:

(a) DSGE models: dynamic stochastic general equilibrium (DSGE) models are the workhorse structural models within the central banking community.

(b) Semi-structural models: such frameworks provide a balance between data consistency, modelling flexibility and selected theoretical premises.

(c) Time-series models: such models are supposed to provide empirical benchmarks, in particular with regard to forecasting performance, shock transmission and risk metrics.

(ii) Interactions between main and satellite models. Pride of place in the modelling portfolio goes to main models ("core" or "workhorse" models). The key characteristic of these models is that they are deployed consistently across the various policy processes (such as forecasting exercises). By contrast, the use of satellite models is less systematic. They play an auxiliary role in policy processes and are designed to address specific economic themes or policy issues. Main models are useful for creating a common institutional language (e.g. accounting frameworks). This implies that there should be a limited set of main models and their analytical and policy scope should be adapted appropriately. Such limitations in scope leave room for complementing main models with specialised satellite models.

(iii) Area-wide and multi-country models. The suite of models includes models featuring the euro area as a single region and multi-country models featuring the largest euro area countries. This diversity addresses the business need for country-
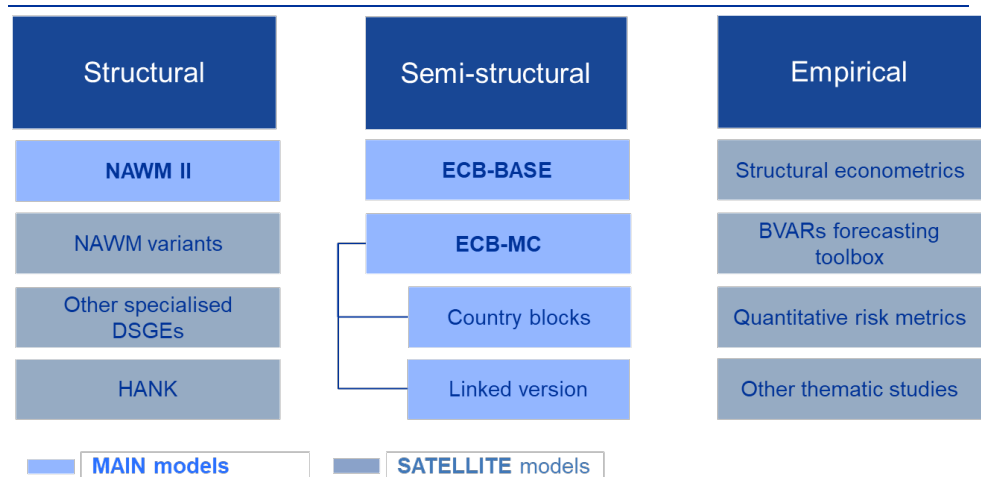
specific analysis with regard to forecasting or assessing monetary policy interactions with jurisdiction-based fiscal or macroprudential policy frameworks. At the same time, euro area-wide models are more manageable, simpler in structure and generally better suited to analysing monetary policy and formulating an economic narrative for the euro area.

(iv) Evolution of models. The modelling portfolio is intended to be in a state of constant evolution. Models are adjusted at different frequencies to reflect the changing nature of the economic environment and new developments in the academic literature. This evolutionary process balances the need to learn from ongoing research against maintaining a high level of consistency or "common language" in the model-based input into the policy process. Ideally, new developments first find their way into satellite models with the relevant connections to main models. New developments of lasting significance might eventually become a feature of main models.

2.2   The ECB's main models for forecasting and policy analysis

In this subsection we provide a bird's-eye view of the main structural and semi-structural models used for ECB projections. **Table 2** summarises the current modelling architecture resulting from the interplay between the various forces and constraints described above.[10]

Table 2
The ECB's suite of models for forecasting and policy analysis

Structural	Semi-structural	Empirical
NAWM II	**ECB-BASE**	Structural econometrics
NAWM variants	**ECB-MC**	BVARs forecasting toolbox
Other specialised DSGEs	Country blocks	Quantitative risk metrics
HANK	Linked version	Other thematic studies

MAIN models   **SATELLITE models**

Source: ECB.
Note: Suite of models used for forecasting and policy analysis.

For area-wide analyses, the extended version of the New Area-Wide Model (NAWM II) and the ECB-BASE model are the main models and are complemented

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[10]   Interested readers should refer to the official guide, which describes the way in which the projections are produced.

by a set of satellite models tailored to address specific economic issues. For multi-country analysis, the ECB-multi-country model (ECB-MC) is the main semi-structural model and is available for the five largest euro area countries. A range of satellite semi-structural tools also exist, among other things, to cover the remaining euro area jurisdictions. Time-series models such as BVAR models are used as satellite empirical frameworks and are estimated either on aggregate euro area statistics or on cross-country data for the largest countries.

Why should two classes of model – DSGE and semi-structural – be included in the set of main models? In particular, why does the ECB continue with semi-structural models? After all, across the modelling portfolio DSGE and time-series models have close ties with large streams of the academic literature, while such a relationship is less clear cut in the case of semi-structural models. Nonetheless, there is a compelling rationale for ECB staff to keep on investing in large semi-structural models. This rationale may be articulated in four points. First, these modelling frameworks constitute an easier way of accounting for the cross-country dimension of the euro area: managing a multi-country/sector dimension is easier, especially in terms of specification and estimation, than using multi-country DSGE models. Second, the conceptual flexibility of semi-structural models means we can introduce alternative specifications (such as hybrid expectation formations or non-linear Phillips curves) and nest satellite blocks such as complementary financial and balance sheet modules. Third, semi-structural models have a large degree of empirical flexibility: they make it possible to exploit a greater range of data sources and sectoral granularity within the same framework.[11] Finally, they provide the institutional flexibility concomitant with the complexity of the policy process. This is important because model-based analysis for policy purposes entails the use of judgement in forecasting activities or a need to compare the general equilibrium model perspective with sectoral and/or country-specific expert assessments.

2.2.1 The ECB structural model: NAWM

NAWM is a DSGE model used for interpreting area-wide projections during regular staff projection exercises, for analysing policy and for conducting research. The original version of the ECB's model of the euro area is on a medium scale with forward-looking expectations and is subject to several real and nominal frictions. The real frictions stem from external habit formation in consumption, through generalised adjustment costs in investments, imports and exports, and through fixed costs in the production of intermediate goods. Nominal frictions arise from Calvo-based staggered price and wage setting along with the partial dynamic indexation of price and wage contracts.

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[11] See, for instance, the recent paper by Bernanke and Blanchard (2023) in which the causes of US (post-)pandemic inflation are explained using a simple semi-structural model of prices and wages. Our team has fitted the model onto euro area data and used it to cross-check internal narratives about the inflation outlook (see Section 2.3).

The original model has two variants, a calibrated version which is richer in detail and more amenable to topical extensions but not suitable for estimation[12] and a simplified estimated version which is smaller in scale.[13] In contrast to the calibrated version, which is a symmetrical two-country model comprising the euro area and the rest of the world, the estimated version employs the simplifying assumptions that the euro area is a small open economy and that Ricardian equivalence holds, allowing for a simple fiscal sector. The assumptions are based on the fact that ECB/Eurosystem staff projections are conditional on assumptions regarding external and fiscal developments. Nevertheless, a fiscal policy extension of the estimated version of the model allows for enriched analysis of fiscal issues.[14] International linkages arise from the trade of intermediate goods and international assets, allowing for limited exchange-rate pass through on the import side and imperfect risk sharing. The central bank sets the short-term nominal interest rate according to a Taylor-type rule to stabilise inflation.[15]

NAWM II is a substantial modification of NAWM and addresses some important limitations. The original NAWM does not contain an explicit financial sector. Instead, the potential influence of shocks on the financial sector is captured by means of domestic risk premium shocks.[16] This approach allows the model to account for movements in the data attributable to financial factors and facilitates the incorporation of these factors into the forecasting process, while also supporting the analysis of some "non-standard" monetary policies such as forward guidance (see, for example, Coenen and Warne, 2014). However, the lack of an explicit financial sector is also restrictive as it makes it difficult to analyse the effects of some important non-conventional policies such as asset purchases programmes.

The main additional feature of NAWM II is the inclusion of an explicit banking sector in the estimated version of the model (Coenen et al., 2018). Banks' assets comprise long-term loans to the private sector for investment purposes, domestic and foreign government bonds and reserves held at the central bank. On the liabilities side they finance themselves via the collection of short-term deposits and retained earnings. Reflecting an agency problem such as that outlined by Gertler and Karadi (2011, 2013) – where banks must hold sufficient capital to reassure their creditors that they will not divert funds – banks are subject to a leverage constraint. The capital position of banks thus influences the response of the economy to shocks via the resulting financial accelerator mechanism. Incorporating adjustment costs into the pricing of loans, the model also includes the sluggish adjustment of lending rates.

Like its predecessor, NAWM II is estimated using Bayesian techniques and the list of observable variables is extended to include key financial variables, in particular bond

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[12] The calibrated version is described in Coenen et al. (2008). It is also available in an ECB working paper prepared by Coenen et al. (2007).

[13] A detailed description of the estimated version of the original NAWM is provided in Christoffel et al. (2008).

[14] The fiscal policy extension, which also includes non-Ricardian consumers, is discussed in Coenen et al. (2012) and Coenen et al. (2013).

[15] The forecasting properties of the model are detailed in Christoffel et al. (2011) and in Warne et al. (2017).

[16] These shocks drive a wedge between central bank interest rates and the rates paid by economic agents. They are modelled as exogenous stochastic processes.

yields and bank lending rates. The set-up of the model means that it is well suited to quantifying the impact of asset purchases made by the central bank (either government bonds or loans to the private sector). Asset purchases drive up the value of banks' assets by increasing reserves and raising the price of domestic bond holdings. This eases the leverage constraint on banks, which in turn leads to an easing of financial conditions (lower loan rates and an expansion of credit), boosting the economy. Further stimulus comes from the resulting depreciation of the exchange rate, which boosts the (domestic currency) value of holdings of foreign bonds and also directly stimulates exports.

NAWM II fully replaced NAWM in the policy preparation process as of 2020.

Chart 1 NAWM II model**:** a bird's-eye view
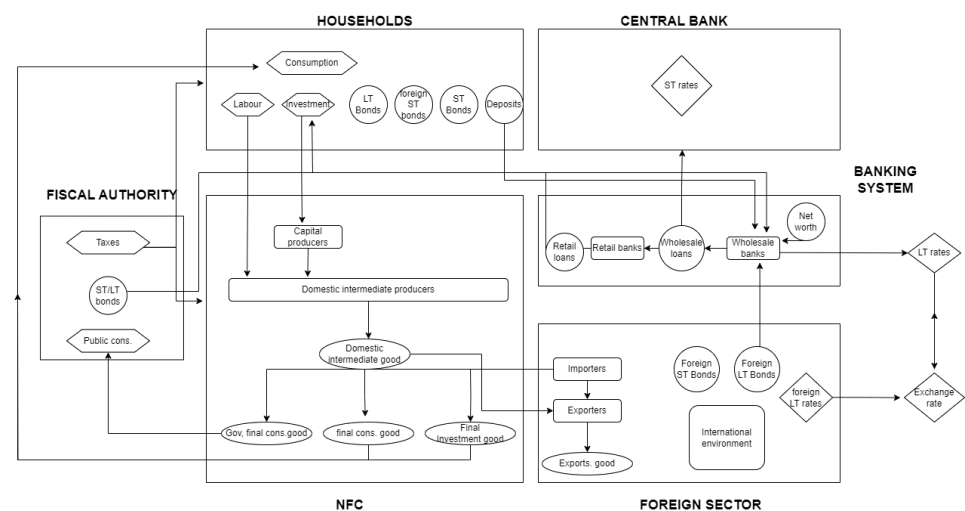
Source: ECB.
Note: A schematic overview of the main building blocks of NAWM II.

2.2.2 The ECB semi-structural model for the euro area countries

Building on earlier work carried out by economists at the Federal Reserve System and the Bank of Canada, ECB staff have developed a set of flexible semi-structural models. Two variants of the model are available, one relating to the euro area (ECB-BASE) and another, the ECB multi-country (ECB-MC) model, which is a single-country version for the big five euro area countries (Germany, Spain, France, Italy and the Netherlands). Both variants are workhorse models used by the ECB to inform the (broad) macroeconomic projection exercises ((B)MPEs). ECB-BASE is the blueprint used to structure the ECB-MC suite of models and its main features are set out in Angelini et al. (2019). The models are designed in accordance with their ultimate purpose, which is to carry out forecasting and policy simulation exercises at the ECB. Their structure therefore accounts for the relationships between key macroeconomic variables, featuring multiple channels of monetary policy transmission and and a realistic assessment of the size and transmission

mechanism of shocks In addition, the design delivers a good performance within an adaptable and user-friendly infrastructure.

The models are large scale with a rich accounting framework matching that of the forecasting process. More specifically, each of the models consists of the following interacting blocks (see **Chart 2**): a domestic demand block encompassing household consumption, business and residential investment, along with fiscal policy; a foreign block, contributing to aggregate demand; a labour market (supply block); wages and prices; and a financial sector. The supply side of the model, and the associated factor demands, are derived from a Cobb-Douglas production structure. Prices and wages are modelled using variants of the New Keynesian Phillips curve. Most of the blocks are estimated equation by equation, except for the individual expectation equations and the wage-price-output gap block (WAPRO), which are estimated as systems. Expectations play an important role and are modelled explicitly based on VARs. These VARs combine a core VAR based on a restricted set of macroeconomic variables (i.e. the policy rate, the GDP deflator and the output gap) with specific variables for which the expectation formation process is modelled.

Chart 2 ECB-BASE: A bird's-eye view – estimation
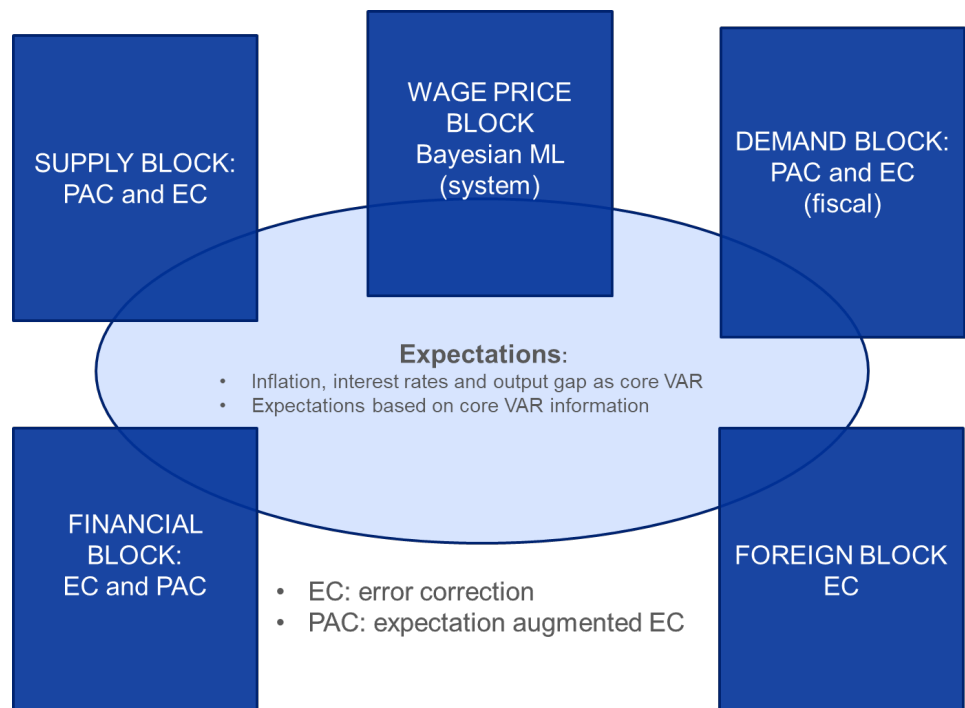
Source: ECB.
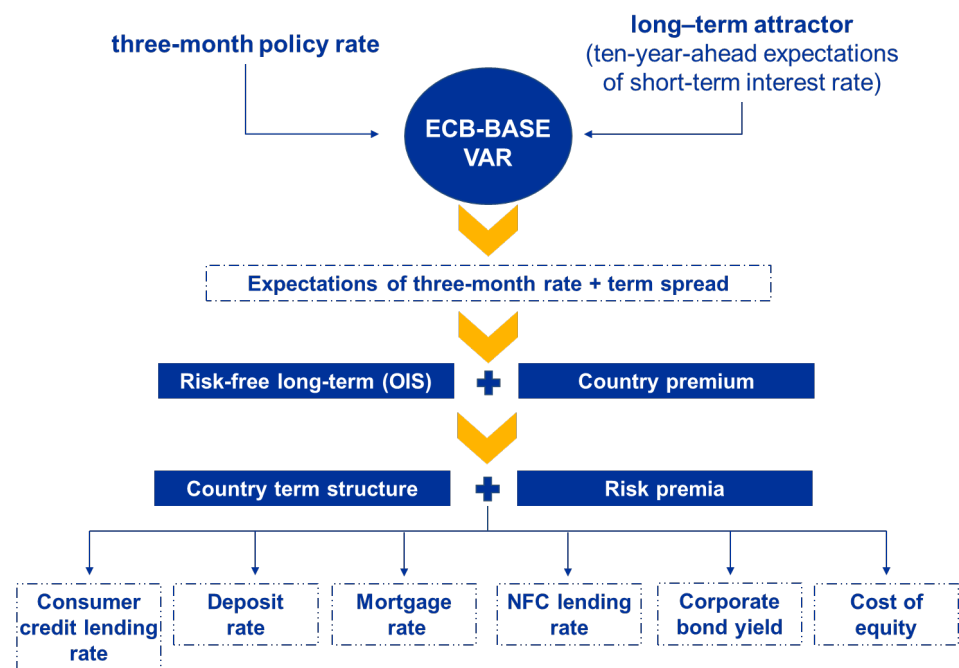Note: A schematic overview of the main building blocks of ECB-BASE.

The model also contains a rich financial block. This includes household wealth and a range of interest rate variables, the latter being determined by the risk-free term structure and a set of endogenous risk premia terms (see **Chart 3**). The euro area risk-free long-term rate is based on the euro area short-term interest rate. The

expected path of the short-term rate is, however, based on the core VAR forecast and the term premium. The country premium is modelled as the difference between the euro area risk-free rate and the corresponding yields on ten-year government bonds. This then provides the basis for the construction of nominal lending rates from the sum of a weighted average of short-term and long-term risk-free rates and a risk spread. The financial propagation also works via household wealth, which is decomposed into financial and housing wealth, and through the impact of financial variables on households' property income.

Chart 3 ECB-BASE: the financial sector

Source: ECB.
Note: A schematic overview of the financial sector in ECB-BASE.

The ECB BASE-MC model is based on the optimising behaviour of economic agents subject to a sluggish adjustment towards optimality conditions. Most equations for the model are derived from agent optimisation subject to polynomial adjustment costs (Kozicki and Tinsley, 2002).[17] This set-up leads to dynamic equations in which the change in the dependent variable depends on its own lags, the difference between the past value of the variable and its theory-based target and expectations about the future changes in the target variable.

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[17] The main idea of the PAC approach is that agents cannot adapt their behaviour instantaneously to align with the optimality condition without there being a cost. Instead, they choose an optimal path for their decision variable subject to minimising an associated general adjustment cost. The order of these adjustment costs in each PAC equation is then determined empirically as part of the estimation process. In the behavioural equations where the PAC approach is used, therefore, there is no external source of serial persistence. For details, see Angelini et al. (2019).

Formally, the target variables are derived as:

$$x_t^* = argmax_x E_t \sum_{t=0}^{T} f(x_t, u_t, t)$$

$$u_{t+1} = g_t(x_t, u_t)$$

$$x_t^* \in \Phi$$

where u_t is the state variable, x_t is the control variable chosen for the optimisation problem, the constraint x_{t+1} specifies the influence that the control exerts on the state and the control variable takes values in a given set Φ. Loosely speaking, this is a generic representation for all optimising problems in the model, such as households' lifetime utility optimisation in consumption or profit maximisation by firms subject to capital accumulation, to determine investment and the optimal level of employment.[18] However, the empirical success of the model crucially depends on the assumption that agents cannot adapt their behaviour instantaneously in line with optimal/theory-based conditions as they face adjustment costs.[19] The assumption of the existence of adjustment costs implies rich short-run dynamic behaviour that resembles an error correction formulation for each modelled variable x_t, Formally,

$$\Delta x_t = a_0(x_{t-1}^* - x_{t+1}) + \sum_{i=1}^{m-1} a_i \Delta x_{t-1} + E_{t-1} \sum_{j=0}^{\infty} d_j \Delta x_{t+1}^*)$$

where a_0 is the coefficient on the deviation of the variable of interest from its target and a_i gives the weights on the backward-looking terms. The term $E_{t-1} \sum_{j=0}^{\infty} d_j \Delta x_{t+1}^*$ represents the expectations of future targets. The dynamic form of the equations is flexible and enables the equation to fit the dynamic patterns in the data.

The parameters of the model are derived from a mix of calibration and estimation. The parameters for the target variables are estimated or calibrated based on theory and micro evidence, while the coefficients of the dynamic adjustment are data driven and are estimated using an iterative OLS technique. The empirical validity of the derived target relations is checked via the use of cointegration techniques. As previously mentioned, most of the equations are estimated on an equation-by-equation basis, reflecting the difficulties involved in estimating such a large model as a system.

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[18]   See Angelini et al. (2019) for a detailed specification of each of these optimisation problems.

[19]   The exact cost function can be expressed as:

$$C_t = E_{t-1} \sum_{i=0}^{\infty} \beta^i [(x_{t+i} - x_{t+i}^*)^2 + \sum_{k=1}^{m} b_k((1-L)^K x_{t+1})^2$$

Where x_{t+1} is the decision variable, x_{t+i}^* is its desired ("optimal") level, m is the order of the polynomial and L is the lag operator.

The model can be simulated using either VAR expectations or model-consistent expectations. In the former approach, future values of the lead variables are replaced by forecasts from a VAR model and the model is then simulated. The VAR expectation case assumes only limited knowledge of the joint dynamics of the variables and corresponds to the same restricted information set used in the estimation of the model. This design may be interpreted as a limited form of rational expectations. Moreover, the model can also be simulated using standard techniques for simulating models with forward-looking terms in a model-consistent manner (rational expectations) or as a combination of the two expectation formation processes. The latter approach is useful in cases where economic agents might differ in their knowledge of the current economy and its outlook.

Box 1 Benchmarking our models against external models for a standard monetary policy shock

Prepared by Srečko Zimic

The quantitative impact of monetary policy varies significantly across model types, with semi-structural models generally showing a more subdued response to policy shocks than their structural DSGE counterparts. This divergence stems from inherent differences in the models' structures and their approach to economic relationships. Structural models are tailored to extract conditional correlations between policy impulses and macroeconomic outcomes, with an often pronounced effect. By contrast, semi-structural models try to strike a balance between an empirical fit and the identification of causal relationships, potentially diluting the isolated impact of policy changes by incorporating a broader array of economic drivers. The nuanced consumption modelling in ECB-BASE, for example, accounts for income risk and varied consumption trends across income types, thereby diminishing the relative influence of expected short-term interest rates on consumption behaviour. Furthermore, the magnitude of the influence of monetary policy in structural models is accentuated by robust expectation channels. Such models (e.g. NAWM) are predominantly forward looking, allowing expectations to adjust swiftly and amplifying the effects of policy shifts. By contrast, semi-structural models typically incorporate expectations with a backward-looking component, leading to a more gradual transmission of shocks.

Real-world economic outcomes are invariably the product of numerous interlinked factors, making it difficult to isolate the effects of monetary policy without relying on model-based analysis. Recognising this, the ECB's approach involves drawing insights from a suite of models to understand and compare different quantitative responses. The assessment faces two principal challenges: disentangling various demand and supply factors from monetary policy's direct impact and addressing uncertainties in policy transmission channels and lags. To address these challenges, a combination of models consisting of a structural DSGE model (NAWM II) and a large-scale semi-structural model (ECB-BASE) is utilised and compared against the predictions of a selected set of external models for the euro area, the United States and Canada. It should be noted that the QUEST3 model is a DSGE model for the euro area, while FRB-US and LENS are semi-structural counterparts to ECB-BASE for the United States and Canada respectively.

Key differences among these modelling paradigms include the following:

Modelling assumptions: In ECB-BASE, consumption modelling accounts for income risk and diverse consumption behaviour, emphasising permanent over current income. By contrast, structural models such as NAWM II rely heavily on the Euler equation, which places a greater emphasis on the intertemporal substitution effect where interest rates play a critical role.

Expectation formation: Structural models generally exhibit robust forward-looking expectation channels, allowing expectations to adjust swiftly and amplifying the effects of policy shifts. On the other hand, semi-structural models often include expectations that have more backward-looking components, leading to a slower transmission of shocks.[20]

Drivers of macroeconomic dynamics: DSGE models assume that macroeconomic dynamics are driven by a relatively small set of structural shocks which propagate through the cross-equation restrictions and generate strong, non-sticky conditional correlations. The remaining dynamics are attributed to autocorrelated measurement errors. By contrast, semi-structural models such as ECB-BASE focus on equation-by-equation fit, assigning macroeconomic stickiness to autocorrelated endogenous variables rather than to external shocks.

Chart A The comparative dynamics of monetary policy impact: ECB-BASE, NAWM II and other economic models

(y-axis: percentage point deviations from baseline; x-axis: quarters)

Notes: The responses of the models are based on publicly available material and may not reflect the most current version of each model. FRB/US: a large-scale general equilibrium model of the US economy with flexible optimisation, developed by the Federal Reserve System; LENS: a large empirical and semi-structural model used by the Bank of Canada for forecasting and policy analysis; NAWM II: the New Area-Wide Model, a structural econometric model used by the ECB within a DSGE framework for the euro area; QUEST III: a macroeconomic model used by the European Commission for policy analysis and research in the EU; ECB-BASE: a semi-structural model used by the ECB for the euro area.

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[20]   In the ECB-BASE model expectations are modelled using VARs.

Chart A provides a comparative analysis of the models' responses to a standard monetary policy shock against a suite of alternative economic models. It is evident from the chart that there is substantial variation in the quantitative impact on both GDP (as measured by the output gap) and annual inflation among the models examined. We observe a clear dichotomy in which semi-structural models such as FRB-US and LENS show a less pronounced response for both variables while DSGE models such as NAWM and QUEST3 show a more pronounced response, particularly on inflation, indicating a higher sensitivity to policy shifts. The ECB-BASE model's response is intermediate, skewing towards its semi-structural counterparts but with a marked responsiveness that is characteristic of structural models sensitive to monetary policy shifts.

Although initial assessments indicate large quantitative differences between various economic models, it has become evident that with certain modifications these models can converge towards more aligned outcomes. In the case of NAWM II, introducing an adaptive learning scheme to make expectations more backward looking markedly reduces the model's inflation response. Similarly, enhancing the ECB-BASE model with more reactive expectations and a stronger impact of asset prices on wealth valuation can bring its responses closer to those of the DSGE models with tempered expectations channels.[21] It is important to note, however, that while individual models may show converging quantitative results through these modifications, the median effect observed across all models remains relatively stable. This suggests that despite the variability and adaptability within each modelling framework, the overarching median effect provides a consistent and perhaps more reliable statistic, reflecting the inherent uncertainty in economic modelling.

2.3   Empirical strategies in support of the main macro models

The existing main models strike a balance between granularity – which is necessary to address the key elements of heterogeneity across the major euro area economies – and simplicity – which is necessary to convey reasonably transparent stories to policymakers. However, a single model will never be sufficient to address all policy questions. Therefore, main models are complemented by satellite tools which address issues not directly embedded in the core forecasting models. The purpose of these satellite models is twofold: on the one hand they are used independently to cross-check core models on issues including the baseline projections, the transmission of shocks and the scenarios and risk analyses. On the other hand, their input is used in the two-step approach followed when deriving macroeconomic scenarios or conditioning information relating to projections from main models. Main models contain the basic mechanisms for transmitting, for instance, an unconventional monetary policy shock, whereas satellite tools are used to derive the effects on key financial variables which can be used as conditioning factors in the macroeconomic evaluation of the measures. Input from satellite tools can also serve as the initial condition or the starting point for main models. In such cases the former make use of information from high-frequency indicators that is not typically included in the latter.

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[21]   See Chart 17 in Section 3.4.1 for an illustration.

The major satellite models are presented in **Table 2** while a more detailed review of the models is presented in Annex II. This set contains a broad range of tools, which can also be classified under the three headings "DSGE", "semi-structural" and "time series".

DSGE

DSGE satellite models focus mainly on specific analyses. For example, macro-financial models concentrate on the two-way linkages between financial variables (such as the yield curve) and the broader macroeconomy. Fiscal DSGE models are another example – they model the fiscal sector of the economy in greater detail (including different types of government expenditure and tax revenues). Another class of satellite DSGE models includes global models which link the euro area with outside countries, allowing feedback in both directions. For example, such models can answer questions about the overall impact of US policies on the euro area economy or, conversely, the impact of euro area developments on other countries. A recent addition to the NAWM family is NAWM-E, an extension with disaggregated energy production and use, which distinguishes between "dirty" and "clean" energy. NAWM-E is used for transition risk analysis related to energy shocks and climate change (Coenen et al., 2023).

Semi-structural

The semi-structural satellite models comprise a broad range of tools. These tools are designed to account for specific economic behaviour and are generally either partial equilibrium frameworks or nest specific features from general equilibrium models.

Two examples are worth mentioning. The first example is the four-equation semi-structural model introduced by Bernanke and Blanchard (2023) and used to reach an understanding of the drivers of post-pandemic inflation dynamics in the United States and various other countries. The model, which is estimated for wages, prices and both short and long-run inflation expectations, has been adapted in order to understand the factors driving wage growth and price inflation in the euro area (see Arce et al., 2024). It incorporates a flexible lag structure, which allows for richer dynamics, and includes measures of key shocks to product and labour markets (such as shortages or energy and food prices) to account more explicitly for the forces affecting inflation. The tool is regularly employed to cross-check the (B)MPE inflation projections, along with a battery of price and wage Phillips curves, with and without inflation expectations, with fixed or time-varying parameters and with different slack, inflation and productivity measures.

The second example is WAPRO, the wage-price-output block of the ECB-BASE model, which was first introduced in Angelini et al. (2019). This is an estimated small open-economy New Keynesian DSGE model of the euro area, with prices and wages modelled with Phillips curves and aggregate demand modelled with a dynamic IS curve. The model can be estimated and simulated under backward-looking or model-consistent expectations. These two types of expectations make it possible to understand the effects of policies (e.g. interest rate forward

guidance) and shocks through the expectation channel, thereby accounting for the sensitivity of the internal propagation mechanism of the model to the way agents form their expectations.

Time-series tools may be used to inform the short-term outlook, to cross-check medium-term projections or provide insights into the transmission of various shocks to the economy. Time-series models are typically flexible in terms of the information set they rely on and easier to estimate than (semi-)structural models.[22] Compared with the latter they also often impose fewer restrictions on the relationships between the variables they include. This makes them useful tools for cross-checking or incorporating a new type of information as it becomes available and/or relevant.

Bridge equations, dynamic factor models and (mixed frequency) VARs are popular tools used to extract information from high-frequency (e.g. weekly or monthly) indicators in order to assess the outlook for key economic variables such as GDP, employment or inflation.[23] Such short-term forecasts can then be used as starting points for main models.

Bayesian VARs are flexible tools that can be used to produce conditional and unconditional point and density forecasts. As such, they can be employed for various purposes: to cross-check projections, evaluate scenarios or assess risks. Forecasts from several models can be combined based on their performance, and off-model information (such as the baseline outlook for the projections) can be incorporated by means of entropic tilting (Cogley et al., 2005, and Montes-Galdón et al., 2023). This can result in asymmetric distributions and can inform the risks to the baseline scenario.

Structural Bayesian VARs can be employed to reach a better understanding of inflation drivers following the COVID-19 pandemic. They do this by analysing the role of drivers not included in main models (such as those related to gas markets specifically or to the inflationary impact of global supply chain bottlenecks). The models can be also employed to understand non-linearities and time variations in the transmission of shocks to inflation (De Santis and Tornese, 2023, and Bańbura et al., 2023b).

2.4 Adapting models in real time: the suite-of-models approach through the COVID-19 pandemic

Employing this model mix presents significant challenges, without even considering the economic environment, which, unfortunately, is not stationary and can prove to be the most challenging force of all. Any adjustments made to the modelling portfolio

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[22] Also, in this class of model it is usually easier to deal with the extreme observations or outliers which affected many key variables during and after the pandemic.

[23] See, for example, Bańbura and Saiz (2020), Bańbura et al. (2023a), Consolo et al. (2023), Bańbura et al. (2024) and Annex II for details.

must deal with sudden shocks, which can lead to (possibly unprecedented) structural changes. The public health emergency caused by the COVID-19 pandemic – which led to huge costs in terms of loss of lives and output – was a perfect storm. Following the outbreak of COVID-19 an unprecedented contraction in activity led to the complete breakdown of established statistical relationships. This, in turn, presented a challenge to the modelling framework used for policy forecasting and scenario analyses – which required a new way of thinking about the impact of a new type of shock. It also presented a challenge to empirical explorations because unprecedented shocks require a much broader landscape of statistical information, which then has to be appropriately modelled.

In this context, the discussions gravitated around two main issues: (i) the kind of additional data that can be used to arrive at more timely and accurate predictions of these economic effects, and (ii) how the available models can be adapted to assess the macroeconomic impact of the COVID-19 shock. The ECB reacted on both fronts, adding new data to the analysis and adjusting the current models and tools. This led to the publishing, for the first time, of variant scenarios instead of baseline forecasts.

In the early stages of the pandemic, the high uncertainty surrounding the economic impact of COVID-19 warranted an analysis based on alternative scenarios (see Battistini and Stoevsky, 2020). This was necessary to account for the progression of the pandemic, the need for and effectiveness of containment measures and the possible emergence of medical treatments and solutions. In particular, the assumed sectoral output losses (based on anecdotal evidence and available survey evidence) helped in the derivation of economy-wide estimates for likely economic losses.

As the COVID-19 shock hit the economy with unseen speed, high-frequency indicators became an important source of information. Non-standard data (e.g. electricity consumption, Google searches and Google mobility indicators) were particularly helpful for gauging the magnitude of the drop in output in real time. That said, as these data are noisy, available for only a short period of time and exhibit complex seasonal patterns (such as exceptional electricity use during a heat wave), they must be handled with care. The ECB standard short-term estimates toolbox was also augmented by including information on credit-card payments (Battistini et al., 2020). This additional information, which sought to capture real-time developments in the service sector, improved the forecasting performance of the standard models.

The big economic slump which followed the pandemic has led to instability in the estimations of the current models and has posed the question of whether to capture information for the pandemic period (and if so, how). Uncertainty related to such a large tail event has also ensued, meaning that besides looking at new types of information, the exceptional nature of the shock has required the appropriate modelling of tail events. The use by Adrian et al. (2019) of available or ad hoc models within the GDP-at-risk framework – with quantile regressions linking each GDP growth quantile (e.g. the 5th percentile) to selected macro and financial variables – has increased enormously since.

When it comes to inference, there are a few issues arising from including extreme COVID-19 observations in the estimations of the models, whether these are

time-series models like standard VAR, structural DSGE models or semi-structural models. Generally, the models are estimated assuming a constant co-variance matrix and coefficients. Including large outliers in the data, which come from high-volatility episodes, might introduce bias into the estimated coefficients and disrupt the estimated historical relationships between the different variables in the model. In particular, the estimators normally use a quadratic loss function which is disproportionally affected by a large outlier, giving a large weight on a single observation. Hence, the adjustment requires the robustification of the estimators via either changing the assumptions regarding the distributions of the stochastic errors or ignoring the observations altogether.

In addition to estimation issues with large shocks, large swings in economic activity also imply that the methods used to produce density forecasts must be revisited. Estimation methods must be adjusted using non-normal distributions, allowing for larger tails that are able to capture extreme events like a pandemic. However, on the normative side it will be important to evaluate and decide how much weight the observations from the pandemic dynamics should have in future forecasts. The ECB has modified some of the available time-series models. Learning from the past about the impact of the pandemic shock on the economy is clearly challenging given that no event in the post-Second World War era can be directly compared with the pandemic.[24] However, sensible adjustments have been made by adapting the approaches proposed, for example, by Primiceri and Lenza (2020), Carriero et al. (2022) and Bobeica and Hartwig (2023), to introduce some form of heteroscedasticity or robust errors in an otherwise standard BVAR model – and Ludvigson et al. (2020) – to forecast the economic impact of COVID-19 by designing the scenarios according to the evolution of exogenous disaster indicators. For the euro area and euro area countries, for instance, the exogenous information employed to discipline the projections and estimate the losses implied by the lockdown measures was the lockdown stringency index (Hale et al., 2021), a synthetic indicator that measures the variation in governments' responses to COVID-19.

Finally, similar techniques have also been developed for the estimation of the structural and semi-structural models. In fact, our core models were flexibly modified to account for the new situation. Following an increasing amount of literature that models the dynamics of the epidemic using an otherwise standard (mainly DSGE) model (Eichenbaum et al., 2022a; Eichenbaum et al., 2022b; Acemoglu et al., 2021; Baqaee and Farhi, 2022; Baqaee et al., 2021; and Favero et al., 2020, among others) ECB-BASIR, a version of ECB-BASE, was developed by augmenting the standard version of the ECB semi-structural model for the euro area with the predictive dynamics of SIR (Angelini et al, 2020), the main epidemiological model. The combined model was designed to shed light on the trade-offs faced by governments obliged to address a public health situation while limiting the economic fallout of the pandemic.

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[24]   See, for example, Barro et al. (2020) or Barro (2020) for references to the Spanish influenza of 1918-19.

The epidemiological module generates shocks that limit agents' ability to work, consume and invest, and these pandemic wedges propagate in turn through the macroeconomic linkages of the model. With the aim of formulating realistic macroeconomic scenarios for the euro area, various settings for containment policies and several macroeconomic amplification channels are then considered. The advantage of the semi-structural nature of the model is that the extension was implemented relatively quickly and the model estimated, thus following the data closely. The empirical relevance of the model meant it could be used both for forecasting and for counter-factual analyses at the ECB. The combination of various settings for containment policies and macroeconomic amplification channels within ECB-BASE on the one hand, and the risk analysis performed with adjusted BVARs on the other, has been shown to generate realistic macroeconomic scenarios for the pandemic in the euro area (see Angelini et al., 2021 and Section 3.3.2 of this paper for an example of model-based risk analysis during the pandemic).

In summary, the disruption caused by large exogenous shocks (such as that caused by the pandemic) brings to the fore the usefulness of the suite-of-models approach. The flexibility of time-series models was an advantage in the initial stages of the crisis, while later developments in semi-structural and structural models enabled us to better evaluate policy options. After the crisis, it became clear that the estimation of all models must be "robustified", moving away from assumptions as to the linearity or normality of the data. Moreover, models should be flexible enough to take on board non-standard data, primarily by allowing models to be informed by mixed-frequency data and connecting standard macro models with modern machine learning techniques.[25]

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[25] Similar approaches and techniques have also been used for the more recent energy crisis caused by the war in Ukraine.

3 Illustrative policy use of the modelling portfolio

In this section, we present selected illustrations for the typical use cases of the main models. While such model-based analyses are concrete and relevant examples of how modelling capabilities can support monetary policy preparation, they neither encompass the full range of modelling activities dedicated to the ECB policy process nor do they necessarily correspond to specific internal policy preparation material.

Macroeconomic modelling activities involved in monetary policy preparation are essentially confined to three main avenues (see **Table 3**):

- Economic projections: forecasting with judgement and model-based projection narratives for the euro area and the largest individual countries.

- Risk analysis: combining predictive densities from forecasting models; examining risk balance indicators; conducting scenario analysis of relevant macroeconomic contingencies.

- Policy analysis: studying the impact of monetary policy options; considering strategic issues related to the monetary-fiscal-financial policy mix in the euro area.

Table 3

Strategic complementarities within the ECB macro-modelling portfolio

Policy use\Model class	DSGE	Semi-structural	Time-series
Economic projections	Cross-check	Primary use	Cross-check
Risk analysis	Scenario and risk metrics	Scenario and risk metrics	Risk metrics
Policy analysis	Primary use	Cross-check	Cross-check

Source: ECB.

The main trade-off in allocating the various models to specific policy activities has to do with balancing the comparative advantages of each model class against the need to achieve a satisfactory degree of robustness across models in delivering policy inputs.

3.1 Building structural narratives

Model-based decomposition of historical developments or projections into structural economic drivers is a typical use for structural models. This allows us to craft a quantitative model-based economic narrative, for example on the relative role of demand and supply factors or to identify impairments in the monetary policy
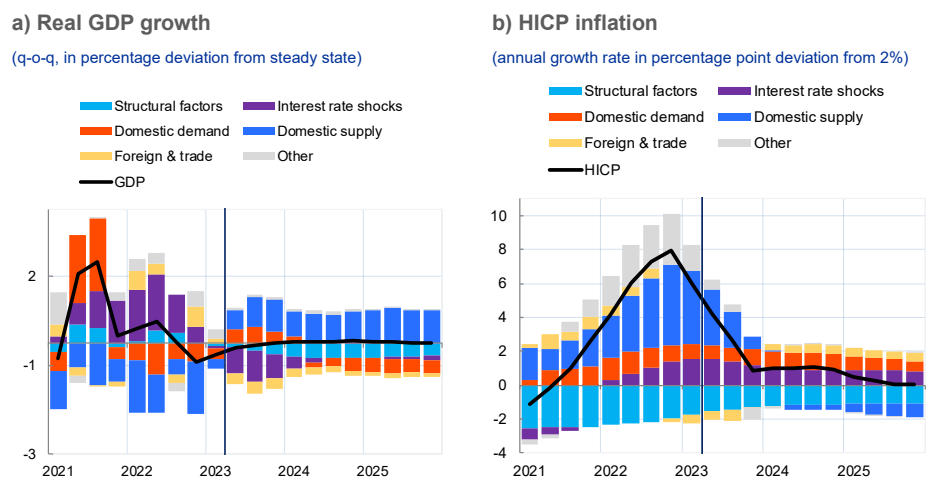
transmission mechanism. Within the projection process, an economic narrative provides a yardstick for assessing new economic developments and frames the quantitative implementation of key judgements when constructing the baseline.

Historical developments and baseline projections: an illustration using NAWM II

NAWM II, for example, is regularly used to provide a structural interpretation of the projection baseline. **Chart 4** shows the NAWM II structural shock decomposition of the June 2023 BMPE baseline over the period 2021-25.[26] The years 2021-22 were marked by several extraordinary shocks to the economy, like the surge in demand that took place with the re-opening after the pandemic and the accompanying supply bottlenecks, exacerbated by the Russian invasion of Ukraine and the additional impact this had on energy costs. With model-based analysis the first set of shocks would be broadly captured by demand shock, the latter by domestic supply contributions. Over the projection period 2023-25 all these shocks tend to unwind, stabilising growth at annual rates of around 1.8% and leading inflation to decline towards 2%.

Chart 4
Structural shock decomposition of the June 2023 BMPE baseline for GDP growth and HICP inflation

a) Real GDP growth

(q-o-q, in percentage deviation from steady state)

b) HICP inflation

(annual growth rate in percentage point deviation from 2%)

Source: ECB calculations using NAWM II and June 2023 BMPE.
Notes: Structural factors include the contributions of the initial state, the discount rate shock and the persistent component of the permanent technology shock. Interest rate shocks comprise the short-term interest rate shock and the shock to the retail bank mark-down. Domestic demand includes domestic risk premium shocks and shocks to government spending. Domestic supply captures supply shocks, namely the transitory component of the permanent technology shock and the transitory and investment-specific technology shocks, as well as wage and price mark-ups. Foreign and trade captures shocks to foreign demand, foreign prices, US three-month and ten-year interest rates, competitors' export prices, oil prices, import demand, export preferences, mark-up shocks to export and import prices and a foreign risk premium shock. "Other" includes the contribution of measurement errors and residuals from bridge equations.

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[26] The version used for this exercise corresponds to the re-estimation documented in an ECB internal note by Coenen et al. (2022). The projection period starts in the second quarter of 2023, but the compilation of this decomposition takes the full sample, including the projection period, as data.

**Measuring the role of systematic monetary policy conduct**

A standard shock decomposition like the one above decomposes observed data into the contribution of each structural shock in a DSGE model. However, when gauging the impact of monetary policy, it is not enough to consider only interest rate shocks in the model. In most New Keynesian DSGE models the short-term nominal interest rate is set according to a policy rule that has two elements: a systematic component (the endogenous response in the short-term nominal interest rate to macroeconomic developments) and a non-systematic one (monetary policy shocks that shift the policy rule for a given set of macroeconomic data). In the decomposition shown, the systematic component is captured within each of the structural shocks, rather than emanating from unexpected changes in interest rates. It is possible to separate the impact of the systematic component in the policy rule to better understand the role of monetary policy in shaping different economic variables. **Chart 5** shows such a decomposition of the June 2023 BMPE projection using NAWM II. The results suggest that most of the impact of monetary policy on growth and the private consumption deflator comes from the systematic response to changes in the macroeconomic environment, while in 2022 there is a mitigating effect from accommodative monetary policy shocks that reflects the fact ECB interest rates did not increase as much as prescribed by the policy rule embedded in the model.

Chart 5

Structural shock decomposition of the June 2023 BMPE baseline for GDP growth and the private consumption deflator: the role of monetary policy
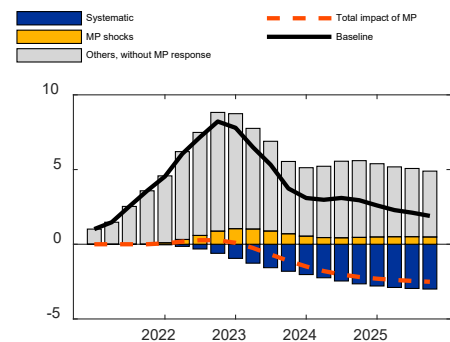
a) Real GDP growth

(q-o-q, in percentage deviation from steady state)
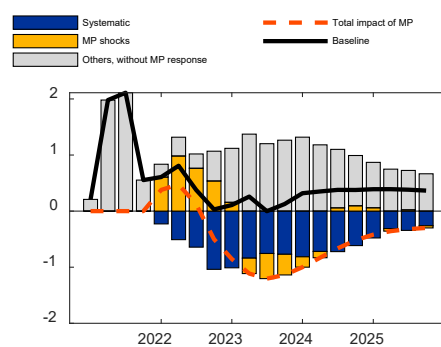
b) Private consumption deflator

(annual, level)

Source: ECB calculations using NAWM II and June 2023 BMPE.
Notes: The chart shows a historical decomposition of the June 2023 BMPE baseline based on NAWM II that identifies the impact of monetary policy (MP) shocks and the impact of the systematic component of monetary policy since December 2021. The latter refers to the historical response in the short-term nominal interest rate to changes in inflation and output according to a policy rule, while the shocks account for deviations from that rule. The grey bars capture the impact of all other shocks in the model, without any monetary policy response.

3.2   Economic projections

3.2.1   Model-based forecasting with judgement

The *main* and *satellite* time-series models are well-suited to producing model-based conditional forecasts for the euro area and its largest jurisdictions. These central tendencies can be made conditional on off-model information related to (i) the international environment, financial conditions, trend supply-side features and fiscal policy, as well as (ii) short-term estimates for the current and following quarters. The interaction of the *main* and *satellite* models allows the forecasts to embody information from a wide range of sources in an efficient manner, while at the same time maintaining the overall coherence of the forecast.

Model-based projections fall into two categories:

Model-based projection updates, which start from the previous baseline, including previous judgement, and update it with (i) the impact of changes in assumptions, (ii) news from incoming data and short-term forecasts, and (iii) changes in other quantitative conditioning factors.

Conditional model-based forecasts, which (without starting from the previous baseline) come closer to a stand-alone model-based forecast conditional on (i) assumptions, (ii) incoming data and short-term forecasts, and (iii) other quantitative conditioning factors.

Model-based projections: an illustration using ECB-BASE

Chart 6 shows selected model-based projections from ECB-BASE against the (B)MPEs. The model-based analysis provides an alternative framework that we use to cross-check the projection baseline and bring more scrutiny to the projection exercise. What stands out from the chart is that the two model-based forecasts are relatively close to the (B)MPE forecasts. This is expected, as both model-based forecasts are conditioned on the same assumptions and, even more importantly, are both conditional on the same short-term forecast.

Projection updates tend to be closer to the final forecast. This is because they not only account for the same assumptions and short-term forecasts, but also inherit judgement from the previous forecast. Therefore the difference between the final forecast and the model-based projection update primarily reflects the arrival of new data and the change in judgement from the previous forecasts. On the other hand, conditional model-based forecasts can exhibit greater deviations. This is because they do not incorporate the judgement from previous forecasts, relying solely on current data and assumptions.

Chart 6

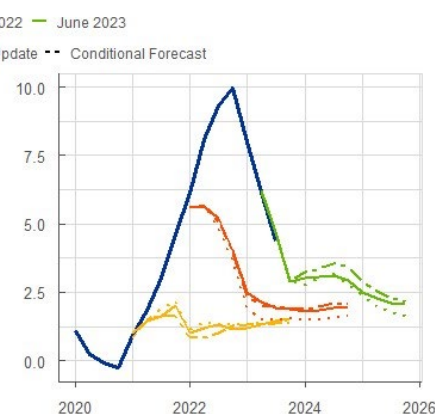Projection updates and conditional forecasts since the March 2021 BMPE

a) Real GDP

(index: 2019Q4 = 100)
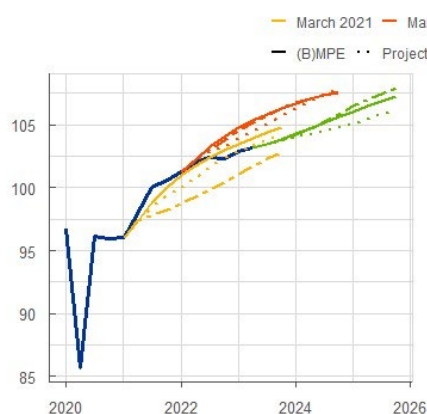
b) HICP inflation

(percentage annual growth rate)

Sources: ECB/NCB projections database and ECB/NCB calculations.
Notes: Projection updates are model-based updates of the previous (B)MPE baseline reflecting changes in assumptions, new data and changes in the short-term outlook up to the first quarter of 2021. Conditional projections are model-based forecasts conditioned on the new assumptions, new data and the short-term outlook up to the first quarter of 2021.

Table 4

Root mean squared errors since the March 2021 BMPE

	Real GDP growth			HICP inflation		
	Three quarters ahead	Four quarters ahead	All forecast horizons	Three quarters ahead	Four quarters ahead	All forecast horizons
(B)MPEs	1.01	0.97	1.09	2.80	4.36	4.28
Projection updates	1.09	1.08	1.08	2.86	4.42	4.31
Conditional forecasts	1.31	1.29	1.23	2.81	4.37	4.23

Sources: ECB/NCB projections database and ECB/NCB calculations.
Notes: Projection updates are model-based updates of the previous (B)MPE baseline reflecting changes in assumptions, new data and changes in the short-term outlook up to the first quarter of 2021. Conditional projections are model-based forecasts conditioned on the new assumptions, new data and short-term outlook up to the first quarter of 2021.

Further insights can be gleaned from **Table 4**, which presents the root mean squared errors of the forecasts in comparison to the actual outcome. It is evident that mechanical updates often perform closely in line with official judgement. However, during rapid shifts in the economic landscape, such as the intense spikes in energy prices or the post-pandemic rebound, these mechanical updates may miss changes in the underlying drivers or transmission channels. A case in point is the yellow lines for March 2021, which depict a much swifter post-pandemic recovery than mechanical updates might have suggested. This is where the (B)MPE baseline, with its incorporation of judgement, proves invaluable. Conversely, model-based forecasts have their moments of utility, especially when they signal a change in trajectory that contrasts with sticky forecasts. A notable instance of this was when

inflation rose in 2022; the model-based forecasts provided a timely indication of the changing tide. Nevertheless, the surge in inflation was a major challenge for both models and expert assessments.

Box 2 Unconditional and conditional forecasting with NAWM II

Prepared by José Emilio Gumiel and Anders Warne

This box presents a forecasting exercise with NAWM II,[27] reporting results on the sensitivity and accuracy of outcomes for different sets of conditioning assumptions.[28] The analysis considers four cases:

Unconditional forecast (UF)

Conditional forecast case 1 (CF1): conditioning on a set of variables that typically form the international environment outlook: euro area foreign demand and prices, short and long-term US interest rates, competitors' export prices and oil prices.[29]

Conditional forecast case 2 (CF2): conditioning on the international environment as in CF1 but excluding foreign demand, to highlight the sensitivity of using this variable as an assumption.

Conditional forecast case 3 (CF3): extending the conditioning on the international environment as in CF1 to include government consumption, the long-term government bond yield, the long-term lending rate and the nominal effective exchange rate, which are typically used as conditioning assumptions in the Eurosystem projections exercises.

The point forecasts up to eight steps ahead for each case and covering the sample from the first quarter of 2001 to the fourth quarter of 2022 for GDP growth and private consumption inflation are shown in **Chart A.** Over the period 2008-22 the euro area experienced several shocks that made forecasting a particularly difficult task. The sample includes the Great Recession around 2008-09, the euro area sovereign debt crises in 2010-12, and the low nominal interest rates close to the effective lower bound that followed before the introduction of non-standard monetary policy measures in 2014. 2020 was greatly affected by the COVID-19 pandemic, and its aftermath saw supply bottlenecks and effects on energy and food prices after the Russian invasion of Ukraine in February 2022.

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[27] See Coenen et al. (2018). The version used in this box is a re-estimation that, among other things, extends the estimation sample to the fourth quarter of 2019 (see Coenen et al., 2022).

[28] Conditioning in the DSGE framework adds a layer of complexity compared to other approaches. It implies setting the path of the conditioning assumptions; in a more traditional modelling framework this would be achieved by making the variable exogenous or manipulating the residuals of the equation explaining that variable. The DSGE framework is based on shocks that have a clear economic interpretation, and the path of a variable can in many cases be achieved by an infinite combination of shocks, each of them telling a particular "economic story". In this exercise the problem is overcome using the Waggoner-Zha methodology, which relies on the whole distribution of shocks, rather than picking specific shocks to carry out the scenario.

[29] NAWM takes the euro area as a small open economy, reflecting the process of how the Eurosystem staff projections are constructed, where conditioning on the international environment comes as a very natural first step.
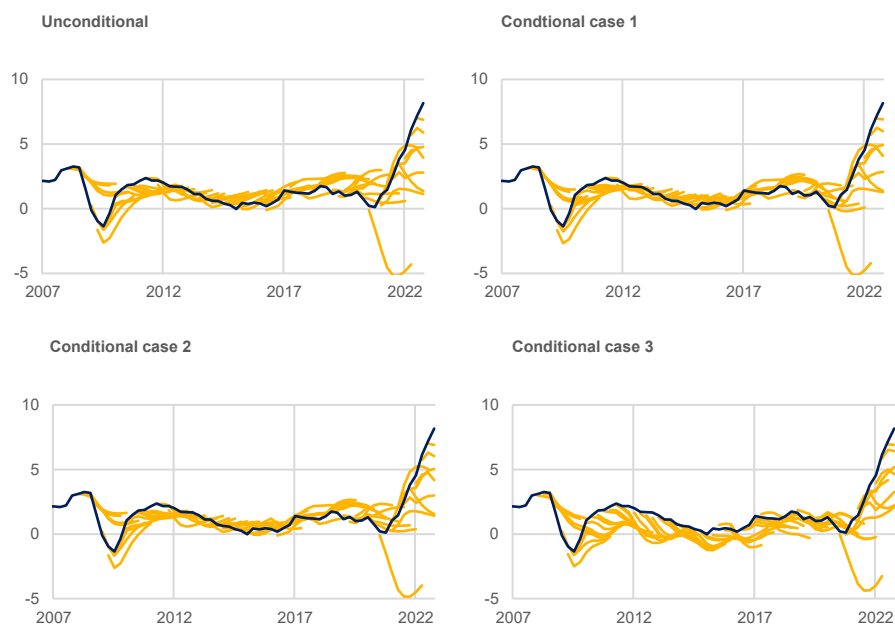
Chart A

Pseudo eight-periods-ahead forecasts

a) Real GDP per head

(percentage y-o-y growth rate)

Unconditional

Conditional case 1

Conditional case 2
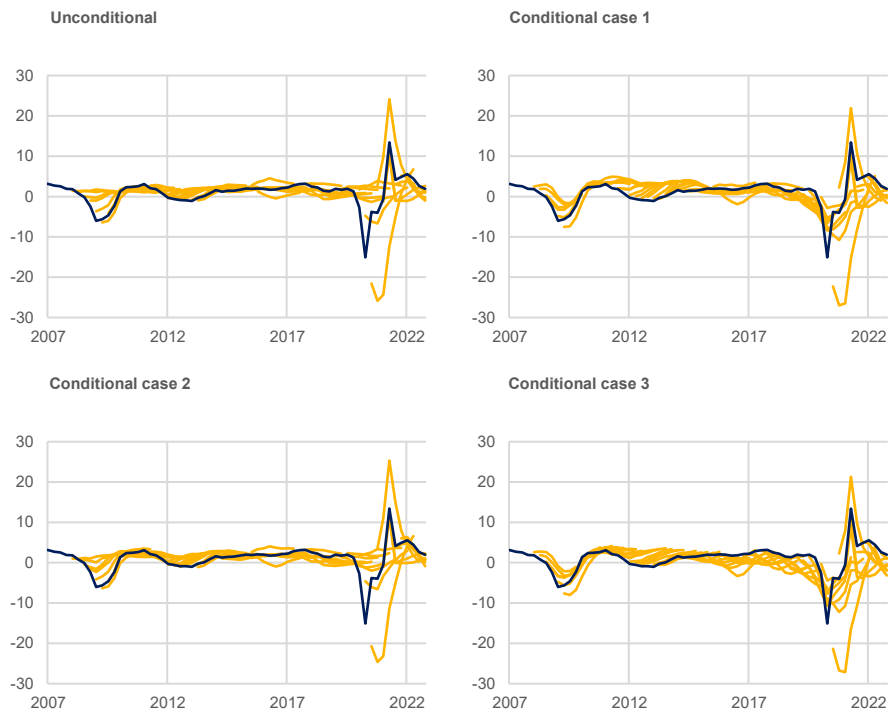
Conditional case 3

b) Private consumption deflator

(y-o-y percentage growth rate)

Unconditional

Condtional case 1

Conditional case 2

Conditional case 3

Source: ECB calculations.
Notes: Conditional case 1 conditions on euro area foreign demand and prices, short and long-term US interest rates, competitors' export prices and oil prices. Conditional case 2 conditions on the same variables as in case 1 but excluding foreign demand. Conditional case 3 extends the conditioning in case 1 to include government consumption, the long-term government bond yield, the long-term lending rate and the nominal effective exchange rate, which are typically used as conditioning assumptions in Eurosystem projections exercises.

The forecasting exercises broadly coincide in terms of the direction of over/underestimation of growth and inflation. In **Chart A** all forecasts of real GDP tend to overestimate growth during the Great Recession and the sovereign debt crisis and underestimate it in the years leading up to 2020. Inflation is overestimated at the beginning of the Great Recession and underestimated during the sovereign debt crisis, but overestimated later during the period of low nominal interest rates. The surge in inflation since 2021 was regularly underestimated in all forecasts.

Looking at mean errors, the UF seems to be quite comparable to the conditional forecasts and in many cases is the best performer, especially at shorter horizons. In the case of real GDP growth, conditioning on the international environment (CF1) worsens the mean error except at longer horizons, while excluding foreign demand helps to reduce the mean error and is comparable to the UF. Regarding private consumption deflator inflation, the performances of UF, CF1 and CF2 are broadly similar. Finally, considering additional conditioning variables seems to worsen performance and CF3 has the highest mean error, except at eight steps ahead for real GDP growth, where, according to this measure, it is the best performer.

Table A
Mean errors

Real GDP growth

Horizon	UF	CF1	CF2	CF3
1	0.05	0.15	0.04	0.21
2	0.04	0.29	0.03	0.86
4	-0.27	0.4	-0.19	1.81
8	-0.59	0.21	-0.61	-0.09

Private consumption deflator inflation

Horizon	UF	CF1	CF2	CF3
1	0.05	0.06	0.06	0.14
2	0.11	0.14	0.13	0.37
4	0.19	0.27	0.24	0.92
8	0.1	0.31	0.27	1.42

Source: ECB calculations.

Focusing on the joint recursive average predictive log-scores of real GDP growth, inflation and the short-term nominal interest rate (**Chart B**), conditioning on the international environment excluding foreign demand broadly outperforms the other cases throughout the sample for one to two steps

ahead, while, according to this measure, conditioning on a wider set of variables (CF3) in general has a worse performance for the one and eight steps ahead forecasts.[30]

The joint log-scores are relatively stable over the forecast sample until the beginning of the pandemic, with strong downward jumps. These drops are all connected to large real GDP forecast errors.

Chart B

Recursive average predictive log-scores

(y-axes: log-scores; x-axes: years)
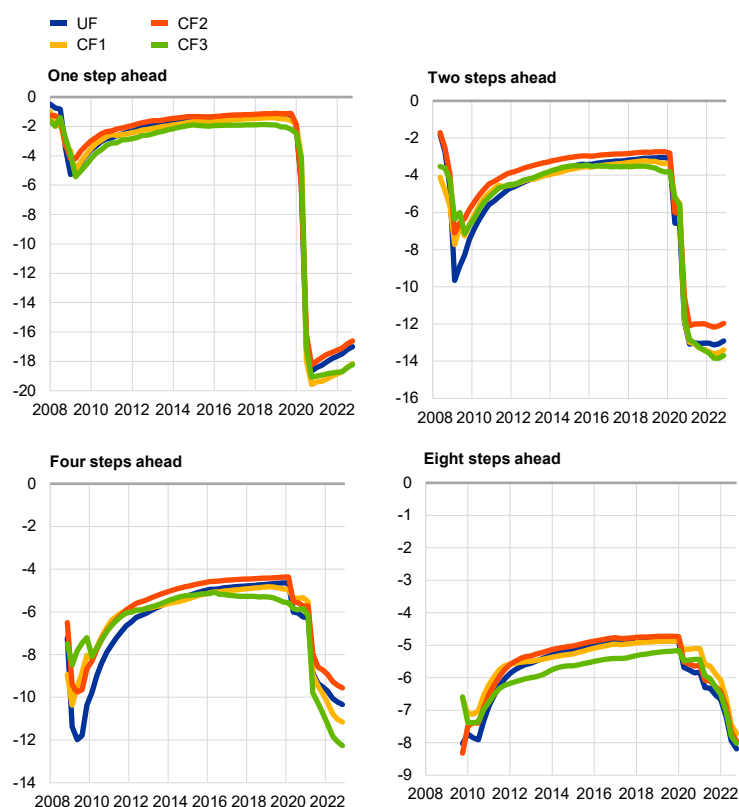
Source: ECB calculations.

As with VAR models, in the DSGE framework it is possible to back out the contribution of each observable variable to the point forecast.[31] In NAWM II there are 24 observed variables, and to sharpen the analysis these are put into seven groups according to a standard typology: domestic activity, domestic prices, domestic interest rates, international environment, output gap and expectations.[32] As an example, consider the unconditional point forecast for the vintage that uses data up to the first quarter of 2009, the trough of the Great Recession (**Chart C**). The forecast for GDP projects a continuation of the fall in GDP in the first quarter of 2009, mainly explained by the

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[30] Recursive average predictive log-scores can be decomposed into a mean squared error (MSE) term (relative to predictive variance) and a predictive variance term. In this exercise, more conditioning may give smaller predictive variances. If forecast errors are similar, then smaller predictive variances entail larger relative MSEs which may lead to lower log scores.

[31] For technical details, see Warne (2023) and Koopman and Harvey (2003).

[32] See notes to Chart C for more details.

data observed on domestic activity and by GDP itself. In the second half of 2009 and in 2010 real GDP growth recovers, with a diminishing negative contribution from domestic activity and a positive contribution from the international environment, domestic prices and the output gap. Regarding inflation, the forecasts in the second quarter of 2009 exhibit a continuation of the deflation observed in the first quarter, with a rebound in the following quarter as in the actual data. Still, the rebound is relatively subdued compared to the observed data, a particular phenomenon of this period and commonly known as the missing disinflation, reflecting how many models struggle with the more significant nominal downward rigidities than anticipated. This profile for inflation is explained mainly by the data on domestic prices and the output gap. In general, observations on domestic activity and prices are the most important contributors to the conditional forecasts over the period covered by this study.

Chart C

Observation weight decomposition – unconditional annualised forecasts – first quarter 2009

(y-axes: y-o-y growth rate and contributions to the forecast, in percent)
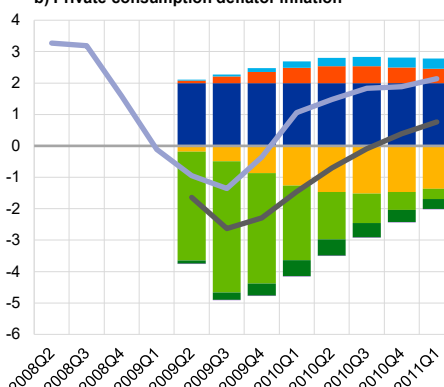

- Steady state
- Output gap
- Domestic activity
- Domestic prices
- Interest rates
- International environment
- Expectations
- Real GDP growth prediction
- Real GDP growth
- Private con. defl. Infl. prediction
- Private con. defl. Infl.

a) Real GDP growth
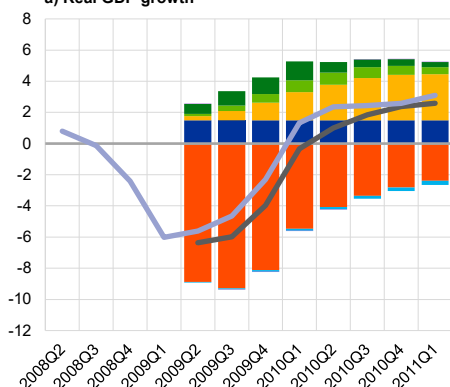
b) Private consumption deflator inflation

Source: ECB calculations.
Notes: The domestic activity group is formed by adding the contributions of the observations on GDP, private and government consumption, investment growth and employment level. The domestic prices block comprises the contributions of GDP, private consumption deflators and wage inflation. Interest rates reflect the contribution of short and long-term interest rates and lending rates. The international environment block groups the contributions of real export and import growth, import deflator inflation, the real exchange rate and foreign demand and prices, US short and long-term rates, competitors' export prices and oil prices.

An additional use for the forecast, beyond providing forecasts for a particular baseline variable, is to assess the impact of new data/errors. Following up with the example above, **Chart D** presents the error made forecasting the first quarter of 2009 when doing the forecast using information up to the fourth quarter of 2008 (the purple bar), and the revisions to the forecast and its contributors comparing the first quarter 2009 forecast vintage versus the fourth quarter of 2008. The negative errors for GDP and inflation are quite sizeable, leading to downward revisions to the forecasts over the whole horizon. In both cases the main explanation for the revision is the error in the variable itself, reflected in the contribution of the domestic activity block in the case of GDP and the domestic prices block in the case of private consumption deflator inflation. A common driver of the

revisions over the medium term would be the more negative output gap in the first quarter of 2009, supporting less negative downward revisions in GDP growth and lower inflation in 2010.

Chart D
Differences in the observation weight decomposition – unconditional annualised forecasts – first quarter 2009 minus fourth quarter 2008

(y-o-y percentage growth rate and contributions to the forecast)

- Steady state
- Output gap
- Domestic activity
- Domestic prices
- Interest rates
- International environment
- Expectations
- Revison in the forecast vs 2008Q4
- Error in 2009Q1

a) Real GDP growth

b) Private consumption deflator inflation
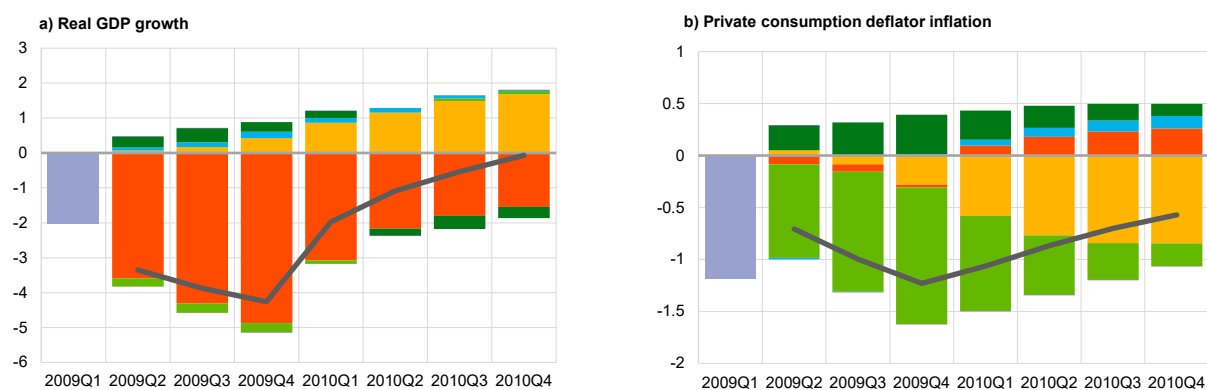
To conclude, during the period considered (from the first quarter of 2008 to the fourth quarter of 2022), forecasts of real GDP growth and inflation show a remarkably similar shape for different conditioning set-ups, implying that the type of conditioning is not decisive compared to other factors, such as recent data. Furthermore, in some circumstances, having additional conditioning assumptions may actually lead to less accurate forecasts.

Formulating model-based judgement

In practice, projection models operate more as an organising and disciplining device for bringing together findings from dedicated satellite tools such as high-frequency short-term forecasting models, sectoral models and long-term supply-side models. Experts intervene on a range of features, bringing external sources of information to the main projection model. Generally, any interventions on model properties or simulation modalities can be interpreted as judgement.

Some practical concepts of model-based projections are explored regularly, by analogy with statistical concepts from the academic forecasting literature. These raise the technical accountability of baseline projections, providing a basis for

extracting model-specific implicit judgement. They can also be incorporated in regular reviews of model properties.

Chart 7 proposes an organising framework to illustrate the analytical process mapping judgemental interventions in model simulations and ultimately delivering baseline numbers. Model-based projections can be seen as a sequence of simulations processing assumptions, incoming data and short-term forecasting information, and long-term anchors. At each step, judgement may be applied based on external ("off-model") information to ensure forecasts take account of all available information. Key judgements in baseline construction can also be expressed through "scenario-type" interventions, possibly quantified in a satellite model (for example, adding judgement to reflect the anticipation effects of announced VAT increases in a backward-looking projection model).

Chart 7
Model-based forecasting with judgement: an analytical roadmap
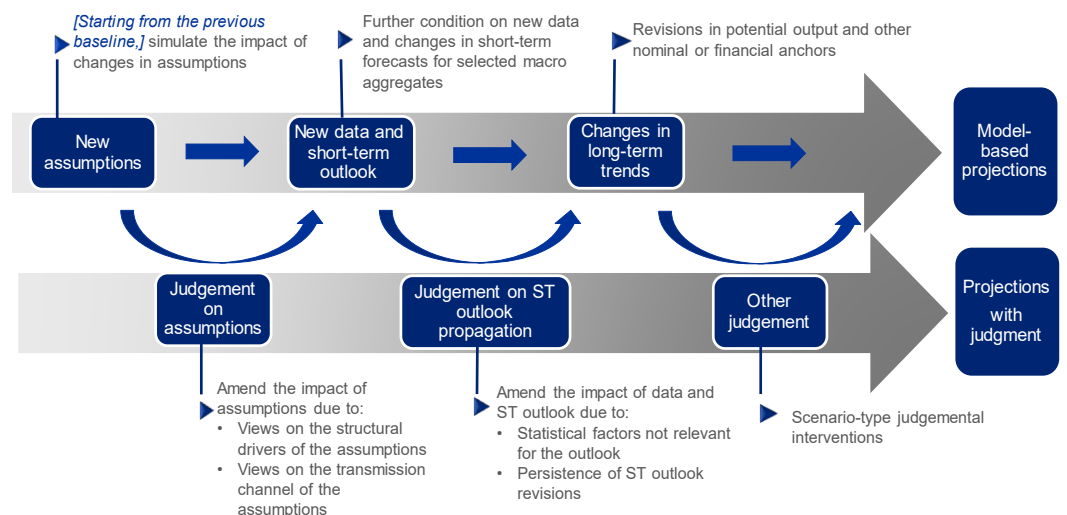
Source: ECB.
Note: An organising framework to illustrate the analytical process mapping judgemental interventions into model simulations and delivering the baseline numbers.

As **Chart 7** points out, judgemental interventions can be made at different stages of the baseline formation process. When processing exogenous assumptions, some judgemental correction to the model simulation can be necessary to account for off-model information clarifying features of the transmission mechanism of the assumptions which for some one-off or temporary reason deviate from what is usually embedded in the models. An example that has gained prominence in the wake of the surge in energy prices since 2021 is the interaction between energy prices themselves and the fiscal support measures taken by euro area governments to alleviate the burden for households and firms. These have a wide array of different designs, but in forecasting models they are usually simulated as having a direct effect on prices, which entails a high pass-through into HICP. This simulation protocol can be problematic when the design of measures is such that a change in the expected fiscal outcome is not necessarily going to have an impact on inflation. This is the case with the energy price caps recently approved in several euro area

countries, as the associated fiscal cost and effect on prices depend on how energy prices move relative to the cap. In this sense, they are better suited to limiting energy inflation over the period they are applied for, but they are only effective if they are binding. Moreover, if the fiscal cost is expected to reduce due to a decline in energy prices, the cap will not be binding, and will not put upward pressures on prices. Hence, when off-model information suggests that such developments are unfolding it is useful to run simulation models like ECB-MC and ECB-BASE excluding energy compensatory measures from the fiscal assumptions, so as to have a quantitative bound on how much judgement would be necessary to amend the impact of assumptions in the direction of having a more reasonable impact on prices.

Judgement can also play a significant role in later stages of baseline construction. For example, information from models that feature a detailed energy sector, where energy is produced with both green and brown technologies, could inform projection models on the medium to long-term effects of the green transition. These models are better suited to capturing the effects of a carbon tax on macro variables, for instance. The recently developed NAWM-E is a good example of a model that could be used for this purpose (Coenen et al., 2023).

3.3 Risk analysis around baseline projections

3.3.1 Model-based risk metrics

As illustrated in the previous section, the *main* projection models produce density forecasts, which can be informative about forecast uncertainty, overall risk balance around technical projections or a given judgemental central tendency, or the probability of given risk events. This can be complemented by parallel assessments based on *satellite* models.

As an example, **Table 5** provides the assessment of risks to inflation projections applied to the June 2023 BMPE baseline. The risks are calculated under the baseline scenario in which the models are used as they are, and under alternative risk scenarios allowing for the possibility of a unanchoring of long-term inflation expectations and/or second-round effects via higher wage demands. These scenarios make it possible to capture potential non-linearities which are not present in the baseline estimations of the models. For example, in periods of high inflation wage demands may increase faster and be more indexed to past inflation. When looking at the model-based results, both ECB-BASE and NAWM suggest that second-round effects can be sizeable. In a context with higher wage indexation and endogenous long-term inflation expectations, for instance, the probability of inflation being above 2.25% in 2024 is on average 12 percentage points higher than in the baseline. This risk analysis proves to be very useful when constructing projections and making monetary policy decisions in periods of heightened uncertainty.

Table 5

Probabilities of high inflation under alternative risk scenarios

	2024		2025	
	HICP between 1.75% and 2.25%	HICP > 2.25%	HICP between 1.75% and 2.25%	HICP > 2.25%
ECB-BASE				
Baseline	**11%**	**85%**	**28%**	**42%**
Uncentred	0%	100%	23%	61%
Higher wage indexation	6%	92%	24%	56%
Unanchoring of long-term inflation	10%	86%	26%	50%
Higher wage indexation and unanchoring	6%	93%	20%	65%
NAWM II				
Baseline	**12%**	**69%**	**14%**	**48%**
With supply risks	9%	80%	11%	57%
Higher wage indexation	9%	73%	13%	55%
Unanchoring of long-term inflation	10%	73%	15%	51%
Higher wage indexation and unanchoring	8%	84%	12%	60%
BVARs				
Small VAR	11%	56%	11%	50%
Large VAR	10%	63%	9%	63%
Small VAR with time-varying coefficients	9%	60%	8%	54%

Sources: ECB calculations and June 2023 BMPE.
Notes: The table shows the probability of different inflation events under different risk scenarios. The probabilities are calculated using stochastic simulations around the baseline. For ECB-BASE, in the case of higher wage indexation the parameter capturing wage indexation in the wage Phillips curve of the model increases from 0.39 to 0.5. The case of unanchoring assumes that long-term inflation expectations are an autocorrelated process that depends on the ECB's inflation target and past inflation outcomes, with the weights for target inflation (72%) and past inflation (28%) calibrated so that long-term inflation expectations in the baseline reach 2.5% at some point during the forecast horizon. For NAWM II, the case of higher wage indexation assumes that the wage indexation parameter in the model increases from 0.37 to 0.5. In the case of unanchoring, long-term inflation expectations are assumed to react to past inflation, such that $\pi_t^* = 0.75\pi_{t-1}^* + 0.25\delta\pi_{t-1}$, with $\delta = 0.32$. "Small VAR" refers to a VAR with GDP growth, headline HICP inflation and the short-term interest rate; "large VAR" includes 14 variables; "small VAR with time-varying coefficients" includes the same variables as "small VAR".

The assessment based on the *main* models can be cross-checked using time-series (*satellite*) models, which often impose fewer restrictions and are more driven by the empirical properties of the data. Among those, Bayesian VARs have become popular tools at central banks (see Domit et al., 2016; Angelini et al., 2019a; and Crump et al., 2021). The lower panel of **Table 5** provides the probabilities using a subset of Bayesian VARs considered in

Bańbura et al. (2021).[33] They signal somewhat smaller risks of high inflation in 2024 but higher risks in 2025.

Bayesian VARs are a valid tool for cross-checking Eurosystem projections (see Angelini et al., 2019a). **Chart 8a** compares the forecast accuracy of three Bayesian VARs used in the exercise above and the projections for year-on-year headline inflation rates on a rolling window.[34] Overall, the accuracy of the models is close to that of the projections. The best model over most of the period appears to be the large Bayesian VAR (with constant coefficients). Interestingly, while the specification with time-varying coefficients seems to underperform in previous periods, it has been the most accurate more recently.

One solution to the problem of time-varying forecast performance or model uncertainty more generally is forecast combination (see Hall and Mitchell, 2007; Geweke and Amisano, 2011; and Bańbura et al., 2021). **Chart 8b** shows the evolution of the optimal weights for the three Bayesian VARs that optimise forecast accuracy for year-on-year headline inflation rates one year ahead. In line with the time-varying relative accuracy described above, we can note the increase in the weight of the time-varying parameter model in the most recent period.

Chart 8
Forecasting inflation with Bayesian VARs: relative model performance over time

a) Rolling RMSFE

b) Weights assigned to models in an optimal pool
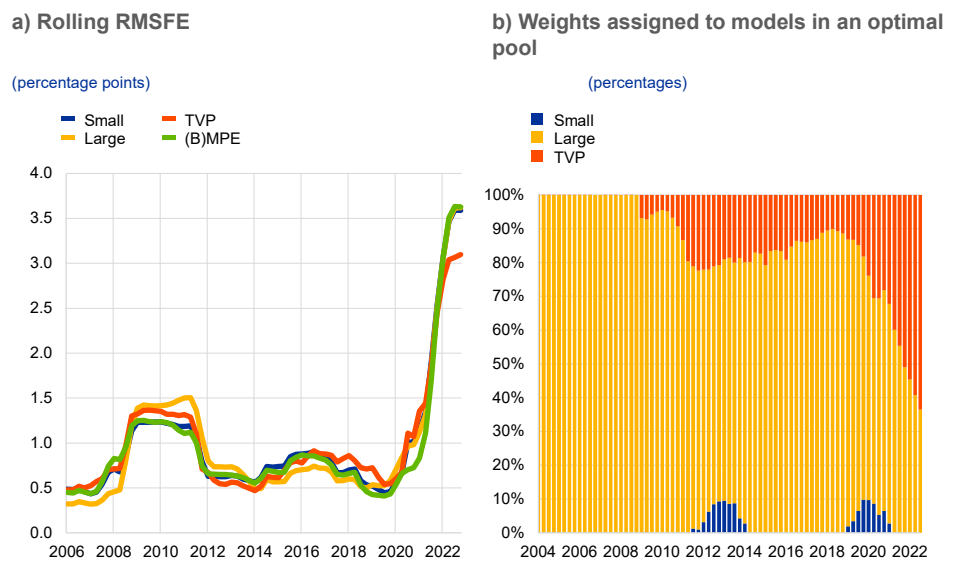
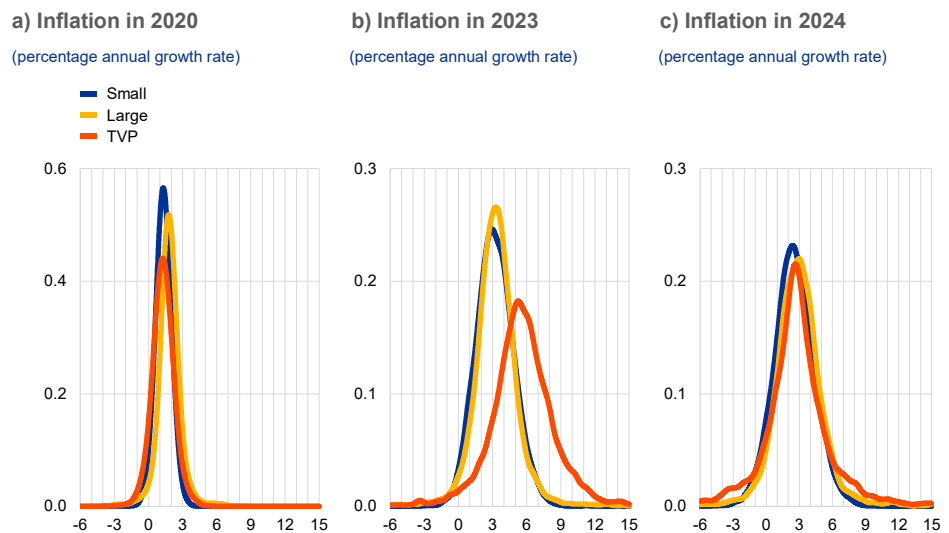Sources: ECB calculations and projections database.

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[33] The models include (i) a small VAR with GDP growth, headline HICP inflation and the short-term interest rate, (ii) a large VAR including 14 variables, and (iii) a three-variable VAR as in (i) but with time-varying parameters. Specifications (i)-(ii) incorporate constant coefficients (with Minnesota-type priors) and time-varying variances (see Bańbura et al., 2021, for details). To account for extreme observations, "outlier correction" in the spirit of Stock and Watson (2016) and Carriero et al. (2022) is incorporated. Specification (iii) follows the estimation approach of Primiceri (2005) and Del Negro and Primiceri (2015).

[34] The forecasts are evaluated based on real-time data vintages as available in the projections. The first available data vintage is that corresponding to the March 2003 MPE. The forecast horizon is four quarters ahead. For the initial quarter, for which partial monthly data are available, we use the projections as the nowcast. The rolling window includes 12 quarters.

To appreciate the within- and across-model uncertainties in forecasting inflation one year ahead, **Chart 9** shows the predictive densities for annual inflation, comparing one-year ahead forecasts for 2020, 2023 and 2024 respectively. We can note a sizeable increase in forecast uncertainty for each model compared to pre-pandemic times. We can also observe notable differences in predictions based on constant and time-varying coefficient specifications for 2023. In particular, the forecasts based on the time-varying coefficient specification were significantly higher compared to those based on constant coefficients. At the same time, it should be stressed that all the models underpredicted inflation in that period.

Chart 9
Evolving uncertainty and disagreement of inflation forecasts

a) Inflation in 2020

(percentage annual growth rate)

- Small
- Large
- TVP

b) Inflation in 2023

(percentage annual growth rate)

c) Inflation in 2024

(percentage annual growth rate)

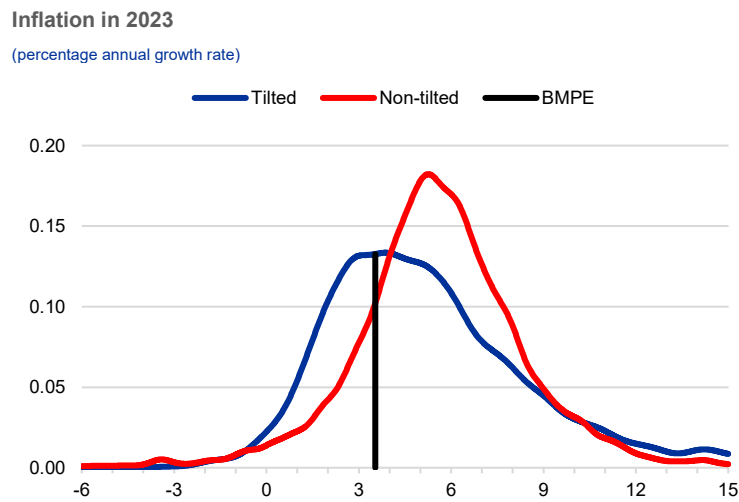Sources: ECB calculations and projections database.
Notes: The chart shows predictive densities from the Bayesian VAR models based on June 2019 BMPE for 2020 (9a), June 2022 BMPE for 2023 (9b) and June 2023 BMPE for 2023 (9c). "Small", "large" and "TVP" refer, respectively, to (i) a VAR with GDP growth, headline HICP inflation and the short-term interest rate (ii) a large VAR including 14 variables and (iii) a three-variable system as in (i) but with time-varying parameters.

The differences in the predictions and relative performance between the constant and time-varying coefficient specifications in 2022 could be related to the large inflationary shocks in that period and associated changes in how they are transmitted to the economy. In particular, Bańbura et al. (2024) find that the elasticities of consumer energy prices to commodity price shocks increase with the level of the latter.

Parametric tilting can be used to link model-based forecasts to the projections and provide a tool to better assess the risks surrounding the baseline produced by the Eurosystem. **Chart 10** illustrates the procedure proposed by Montes-Galdón et al. (2023) whereby a possibly asymmetric predictive density can be constructed combining a model-based density and a non-model forecast. In this example, we impose a condition that the projection should constitute a mode of the new density

and that it should otherwise be as close as possible to the original predictive density from the model (the time-varying parameter VAR). We can see that the resulting density features sizeable right skewness, as the model signals significant upside risks to the projection.

Chart 10
Risks to the June 2022 BMPE

Inflation in 2023
(percentage annual growth rate)

Sources: ECB calculations and June 2022 BMPE.
Note: The chart shows predictive density for annual inflation based on a three-variable Bayesian VAR with time-varying coefficients (the red line) and the model predictive density (parametrically) tilted so that the June 2022 BMPE is the mode of the new distribution (blue line).

3.3.2 Scenario analysis

When there are large shocks, Knightian uncertainty or a multi-modal risk profile, scenario analysis can become the main avenue for risk analysis. The pandemic scenarios introduced since the June 2020 BMPE and a range of cases investigated for assessing the impact of the Russia-Ukraine War are good examples of a risk analysis strategy when the use of statistical risk metrics is technically challenged by unprecedented shocks.

Pandemic scenarios

The unique nature of the COVID-19 shock makes it difficult to use standard econometric analysis to characterise uncertainty; it requires the use of dedicated scenario analysis and warrants preparing alternative scenarios around the baseline. This uncertainty has been addressed in mild and severe scenarios derived via a combination of information from satellite tools and model-based conditional analysis.

Chart 11

Alternative pandemic scenarios for the euro area: an analytical roadmap
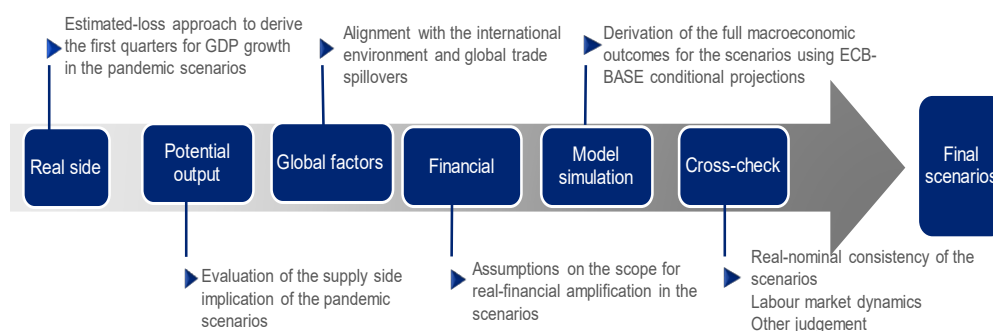
Source: ECB.
Note: An organising framework to illustrate the analytical process used to generate final pandemic scenarios based on information from various sides of the economy and assumptions.

Chart 11 shows how the medium-term scenarios were constructed using ECB-BASE starting from the model-based replication of the baseline with the construction of two alternative scenarios, conditioning (i) on short-term GDP paths,[35] (ii) on potential output projections, (iii) on the associated global trade scenarios, and (iv) on alternative financial spreads and fiscal assumptions. **Chart 12** reports, as an example, the mild and severe scenarios for GDP and inflation prepared for the September 2021 MPE.

Chart 12

Alternative pandemic scenarios in the September 2021 MPE

a) Real GDP growth

(level, 100=fourth quarter 2019)
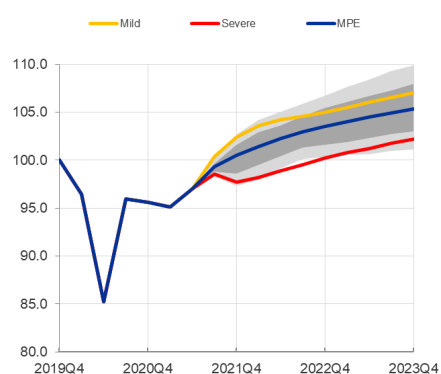
b) HICP inflation

(percentage annual growth rate)
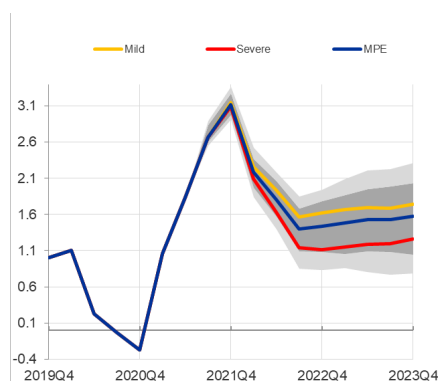
Sources: ECB projections database and ECB calculations based on ECB-BASE for the scenarios.
Notes: The grey areas represent the 90% and 68% confidence intervals from the ECB-BASIR forecast. They are centred around the September 2021 MPE. The density forecast is computed using a bootstrap method that re-samples the in-sample residuals of the model and considers the uncertainty related to pandemic developments, like vaccination efficiency and virus fundamentals.

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[35] The mild and severe scenarios vary according to different assumptions for the short term about: (i) the evolution of the pandemic, including the emergence of new variants of the virus and the timing of the successful implementation of medical solutions, (ii) the stringency and targeting of containment measures, (iii) the behavioural responses by private economic agents, and (iv) the longer-lasting scarring effects on economic activity. The scenarios are also based on alternative projections for euro area foreign demand, bank lending rates and fiscal policy. Conditioning assumptions for the oil price, the exchange rate and government bond yields are unchanged from the baseline.

The scenarios are cross-checked against a wide range of pandemic simulations conducted using ECB BASIR, an extension of ECB-BASE which addresses specific features of the COVID-19 crisis by combining an epidemiological model built on a standard susceptible-infected-recovered (SIR) framework with a semi-structural large-scale macroeconomic model (Angelini et al., 2023; Angelini et al., 2021; and Angelini et al., 2020).

Chart 13

Pandemic simulations
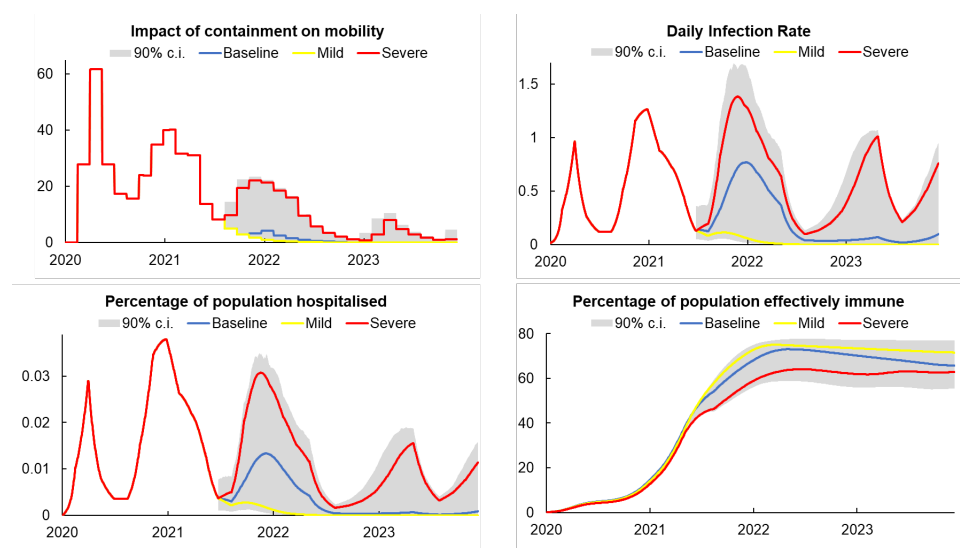
Sources: Google Mobility reports, European Centre for Disease Prevention and Control, and ECB calculations.
Notes: The grey areas represent the 90% confidence interval. The distribution is obtained by random simulations considering uncertainty about: (i) the rate of vaccination U~[0.3% - 0.7%] with the baseline assuming 50%; (ii) the effectiveness of vaccination U~[40%-80%], with the baseline assuming 60%, and reinfection uncertainty U ~[0%-4%] with the baseline assuming a reinfection rate of 2%; (iii) the increase in the infection rate due to the new virus variant N~(60%, 16%); (iv) SIR parameter uncertainty; (v) uncertainty N~(52%, 10%) about learning effects (attenuation of macroeconomic effects from containment measures); and (vi) historical uncertainty captured in residuals. The intensity of containment measures is estimated over history by ECB staff based on Google Mobility data.

As shown in **Chart 13,** the scenarios are broadly supported by the epidemiological model simulations, which entail uncertainty regarding virus variants, efficacy of vaccines and reinfection risks. The severe scenario is characterised by higher infection rates, lower efficiency of vaccines and higher reinfection risk; the mild scenario assumes the opposite, namely lower infection rates, higher vaccine efficiency and lower reinfection risks.[36] According to ECB-BASIR, the more adverse features of the new virus variant assumed in the severe scenario result in a lower proportion of the population being effectively protected. This leads to a strong resurgence of infections and hospitalisations and requires stricter containment measures. In contrast, according to the model results, the more benign

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[36] Specifically, the severe scenario assumes that new infective mutations such as the Delta variant are 10 percentage points more infectious (baseline=60%), that vaccines are 20 percentage points less effective (baseline=60%) and that reinfection risk is 2 percentage points higher (baseline=2%) than in the baseline, while the opposite is assumed for the mild scenario. Vaccinated and recovered people are assumed to have a 90% lower probability of being hospitalised after being infected in the baseline and mild scenarios, while in the severe scenario it is assumed that they have only a 50% lower probability.

epidemiological developments assumed in the mild scenario imply a rapid relaxation of containment by late 2021. Finally, the combination of economic and pandemic-related risk factors translates into high short-term macroeconomic uncertainty, especially in the fourth quarter of 2021 and the first quarter of 2022, as can be seen in the ECB-BASIR implied risk bands in **Chart 12**.

The Russia-Ukraine War scenario

Baseline projections are regularly complemented with scenario analysis of single event-based risk studies. The Russia-Ukraine War triggered unusually high uncertainty over energy prices, supply disruptions and financial market exposure. The ECB-BASE model was used to craft counterfactual projections illustrating a more pessimistic outlook for the economy than embedded in the baseline. Taking the example of the September 2022 MPE, **Table 6** shows economic growth and inflation in the downside scenario as opposed to baseline projections. In a counterfactual exercise like this, the semi-structural projection model for the euro area makes it possible to: a) flexibly evaluate alternative assumptions such as higher than expected prices for oil and gas; b) illustrate downside risks in the transmission of adverse shocks, for example by quantifying second-round effects of additional energy price pressure; and c) assess the scope of policy response in the downside scenario. To produce a counterfactual downside scenario, ECB-BASE was informed by satellite models that assessed the extent of possible production cuts due to the immediate shortfall of energy supplies. This approach made it possible to combine the benefits of using detailed information from the analysis of international production networks with the macroeconomic general equilibrium-disciplining framework that the projection model provides. The uncertainties around the war could disrupt production in the very short term – such special events are usually not captured by the normal business cycle behaviour of the model economy. But conditional on the extra information, the semi-structural model created the ability to think about and quantify the implications for hysteresis effects on productivity, inflation, labour market amplifications and policy reactions.

Table 6

September 2022 MPE baseline projections and downside scenario for the euro area

(annual percentage changes, unless otherwise indicated)

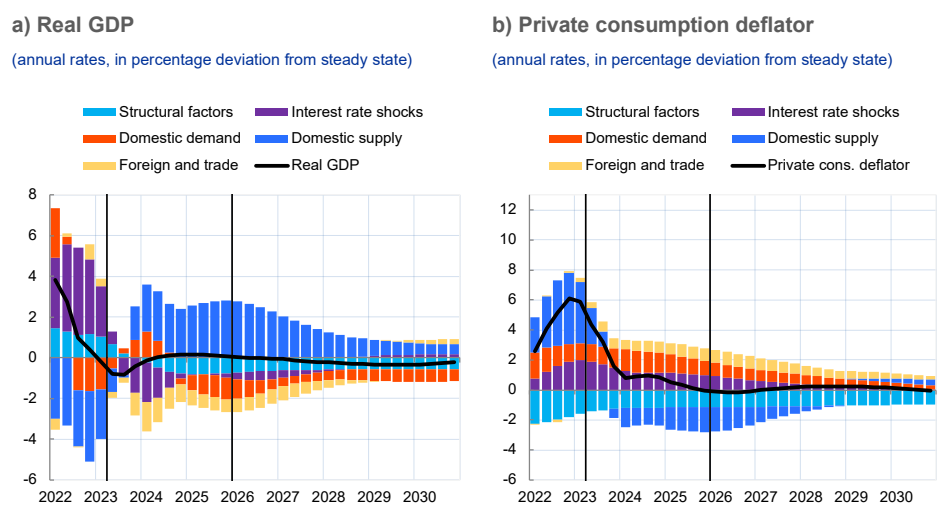|	September 2022 baseline projections			Downside scenario		
	2022	2023	2024	2022	2023	2024
Real GDP	3.1	0.9	1.9	2.8	-0.9	1.9
HICP	8.1	5.5	2.3	8.4	6.9	2.7
HICP excluding food and energy	3.9	3.4	2.3	3.9	3.5	2.4

Source: ECB.

Medium-term reference scenarios

An important contribution of macro-modelling to the ECB's policy discussion is the compilation of medium-term reference scenarios (MTRS). These extend baseline projections beyond the regular projection horizon.

The current methodology uses NAWM II, the most recent version of the ECB's workhorse DSGE model for the euro area.[37] The aim of the exercise is to extend the projection horizon by five additional years, taking the (B)MPE baseline as given and conditioning on assumptions covering the international environment, government consumption, ECB asset purchases and potential output. In technical terms, this conditioning pins down shocks of the model closely related to the assumptions, while the other shocks, representing other economic drivers, are set to follow a decaying path towards their steady state. This decaying path is related to the unwinding of the shocks and narratives identified in the BMPE projection horizon. The procedure allows for expert assessment to decide on the path of the decay, e.g. shock profiles related to temporary factors would tend to decay faster.

Chart 14

The medium-term reference scenario

a) Real GDP

(annual rates, in percentage deviation from steady state)

b) Private consumption deflator

(annual rates, in percentage deviation from steady state)

Source: ECB calculations using NAWM II and June 2023 BMPE.
Notes: The first vertical line represents the start of the BMPE projection horizon while the second vertical line reflects the start of the MTRS projection horizon.
See notes to Chart 1.

Chart 14 presents the shock decomposition results of the MTRS for the June 2023 BMPE for year-on-year real GDP growth and private consumption deflator inflation. In this scenario GDP growth plateaus at the end of the regular projection at around 1.6%, declining in 2027 towards potential output, reflecting the fading-out of catching-up effects of supply after the adverse supply conditions in 2022 and a normalisation of demand conditions. Over the extended horizon from the first quarter of 2026 to the fourth quarter of 2030 the international environment contributes negatively to the GDP growth profile, reflecting, among other factors, the pass-through of foreign inflation to import prices, past commodities shocks and an appreciation of the euro. Finally, the contribution of interest rate shocks is a combination of a negative contribution from short-term rate shocks and a positive contribution from lending rate shocks, the latter reflecting normalisation in the retail

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[37] For a more detailed discussion on the MTRS methodology, see Box 17 in ECB Occasional Paper No 267 by Darracq Pariès et al. (2021). It should be kept in mind, however, that the methodology is not model-dependent and other models, such as ECB-BASE, could be used for the same purpose. Moreover, while the discussion is based on a linear model, it also applies to non-linear models, such as when the effective lower bound on nominal interest rates is imposed.

banking sector. Overall, interest rate shocks contribute negatively over the period 2026-27, remaining broadly neutral for the rest of the extended horizon.

The normalisation of supply conditions after the supply shocks in 2022 (bottlenecks, higher energy and food prices, etc.) is one of the main drivers of the decline in inflation in 2025. From 2027 onwards the tailing-off of these factors leads to an increase in inflation. Interest rate shocks, domestic demand and foreign factors contribute positively to inflation, but those contributions fade over the horizon, more rapidly so for interest rate shocks. As a result, inflation in terms of average annual growth in the private consumption deflator falls below 2% in 2026 before rebounding amid normalising supply conditions and then peaking in 2028 at 2.3% and very gradually declining to 2% by the end of 2030.

3.4 Monetary policy analysis

Main models are designed to address strategic issues of relevance for monetary policy, such as evaluating the impact of standard and non-standard monetary policy measures via enhanced monetary policy simulations. *Satellite* DSGEs complement such analyses and bring a quantitative perspective to the way monetary policy interacts with fiscal, financial and structural policies. In particular, the MMR model from Mazelis et al. (2023) is regularly used alongside ECB-BASE and NAWM II.

3.4.1 Assessing monetary policy's impact on the macroeconomy

A model-based assessment of the macroeconomic impact of the ECB's monetary policy tightening since December 2021[38]

In December 2021 the ECB announced that it would begin normalising its policy stance by slowing the pace of net asset purchases, with net purchases under the pandemic emergency purchase programme (PEPP) and the asset purchase programme (APP) eventually ending in March 2022 and June 2022 respectively. Interest rate guidance was revised in June 2022 and key policy rates were increased by a total of 450 basis points between July 2022 and September 2023, rapidly tightening policy and ultimately taking rates into restrictive territory.

This section uses two empirical macroeconomic modelling frameworks to illustrate the impact on economic activity and inflation in the euro area. Uncertainty about the impact of monetary policy on the economy can be addressed by drawing on a suite of models. This section presents details of a stylised exercise analysing the impact of

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[38] This section is an updated analysis based on previous work prepared by M. Darracq Pariès, R. Motto, C. Montes-Galdón, A. Ristiniemi, A. Saint Guilhem and S. Zimic, also published as part of the ECB Economic Bulletin, Issue 3/2023. For complementary model-based monetary policy analysis using other ECB models see, Mazelis et al. (2023), De Groot et al. (2021), Rostagno et al. (2021) and references therein.

policy tightening so far and illustrates the analytical challenges that surround such an assessment.

There are two main challenges in assessing the impact of policy tightening. First, financial and macroeconomic variables are driven by a host of factors on both the demand and the supply side. These need to be disentangled from the impact of monetary policy itself, calling for a model-based identification approach. Second, there is uncertainty regarding the transmission channels and lags of monetary policy, and it is therefore necessary to consider alternative methodologies with different transmission mechanisms in the interests of robustness. For these reasons, this assessment uses the core structural DSGE model, NAWM II, and the large-scale semi-structural ECB-BASE model. This approach is in line with the conclusions of the ECB's recent monetary policy strategy review, which emphasised the importance of robustness in carrying out model-based analyses within the Eurosystem.

Chart 15

Impact on the €STR forward curve
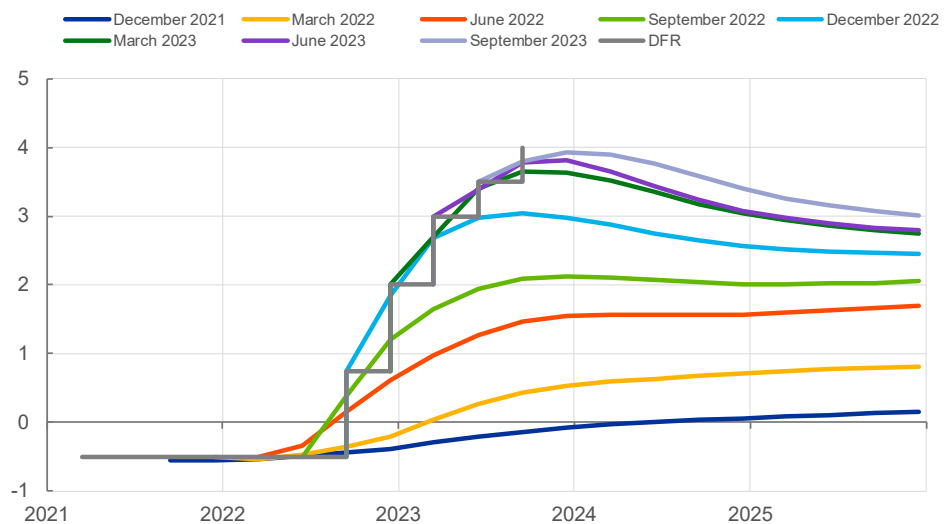
Sources: Bloomberg and ECB calculations.
Notes: This chart shows the €STR forward curve at the cut-off date for each Governing Council monetary policy meeting with updated economic projections. The grey line represents realised values for the deposit facility rate (DFR), with data being adjusted for the DFR space by applying a spread of 8 basis points. The cut-off dates for the data used for the various lines are based on the following final cut-off dates for projections: 23 November 2021 (December 2021), 28 February 2022 (March 2022), 17 May 2022 (June 2022), 22 August 2022 (September 2022), 25 November 2022 (December 2022), 15 February 2023 (March 2023), 23 May 2023 (June 2023) and 22 August 2023 (September 2023).

The assessment is carried out in two steps: first, by estimating the impact monetary policy has on the yield curve, and second, by translating the impact on the yield curve into macroeconomic effects using macro models.[39] The impact on short-term rates is calibrated on the basis of the upward shift observed in the forward curve for the euro short-term rate (€STR) at short to medium maturities since December 2021,

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[39] In practice, market-based financial assumptions also change in an endogenous reaction to other drivers, such as energy prices. In order to compute the impact of monetary policy, this exercise quantifies the macroeconomic impact of policy had it not followed the historical regularities captured by market-based financial assumptions. This counterfactual is computed using policy shocks. Sensitivity to these assumptions is explored in more detail, particularly as regards the role of the expectation formation process.

which reflects both actual increases in policy rates and the anticipation of future increases (**Chart 15**).[40] The impact on long-term rates is derived from the upward pressure on yields exerted by revisions to expected APP and PEPP holdings.[41] In a second step, the policy-related effects on interest rates and the Eurosystem's balance sheet are translated into macroeconomic effects using the macro models, either directly or indirectly via the impact that balance sheet expectations have on long-term rates.[42]

Chart 16
Impact of monetary policy tightening according to a suite of models

a) Real GDP growth

(deviations from annual growth in percentage points)

b) HICP inflation

(deviations from annual growth in percentage points)
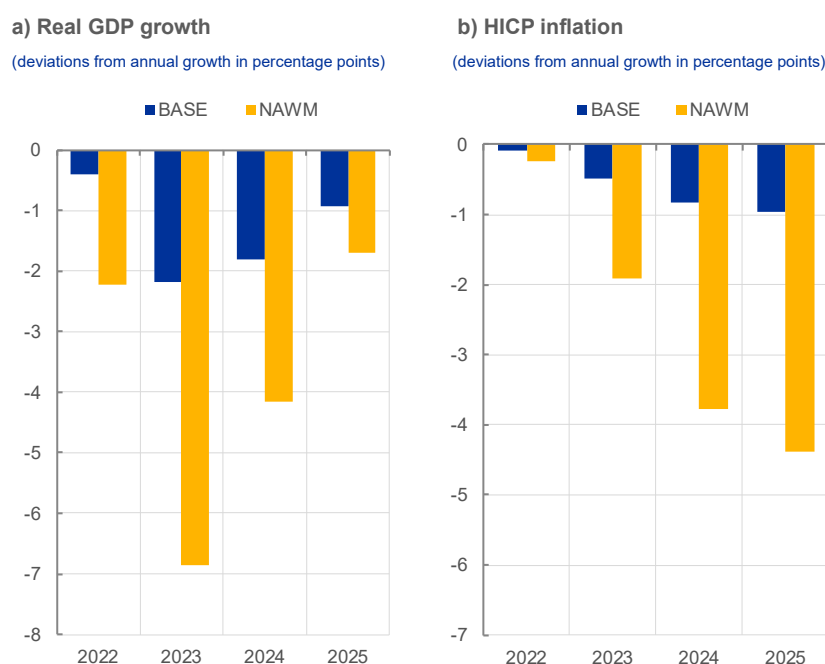
Source: ECB calculations based on NAWM II (see Coenen et al., 2018) and ECB-BASE (see Angelini et al., 2019b).
Notes: This chart reports the results of a simulation involving changes to short-term rate expectations between December 2021 and September 2023 and changes to expectations regarding the ECB's balance sheet between October 2021 and September 2023. The reported values refer to year-on-year growth rates.

The results based on the two models suggest that policy normalisation has exerted significant downward pressure on inflation and real GDP growth across the whole of the projection horizon (**Chart 16**). Most of the impact on inflation is expected to be seen in the period from 2023 onwards and remain significant until at least the end of 2025. The tightening of policy is estimated to have lowered annual inflation by between 0.6 and 2.6 percentage points over the period 2022-25 on average, according to ECB-BASE and NAWM II respectively. The transmission to economic

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[40]   Between December 2021 and September 2023, short-term interest rates increased by around 290 basis points on average over the projection horizon 2022-25. Short-term interest rate expectations began shifting upwards even before the first policy rate increase in July 2022, which shows the importance of accounting for policy expectations. The associated upward shift in the yield curve in turn has an effect on broader financing conditions and exerts a tangible impact on the economy.

[41]   Expectations for long-term interest rates, which account for anticipation, increased by around 266 basis points over the same horizon (a significant percentage of which can be attributed to changes in APP and PEPP expectations).

[42]   In NAWM II, the conditioning on the short-term interest rate is done through unexpected monetary policy shocks. In ECB-BASE, short and long-term interest rates are assumed to be exogenous, and the counterfactual is imposed as an alternative path relative to the baseline (i.e. the interest rate path expected in December 2021).

activity is faster, with the impact on annual GDP growth expected to peak in 2023 according to both models and a downward impact of between 1.3 and 3.7 percentage points over the period 2022-25 on average, according to ECB-BASE and NAWM II respectively.

The impact estimates are surrounded by significant uncertainty, reflecting differences in transmission channels across models, with the structural model displaying a stronger impact. The structural model is specifically designed for the purpose of deriving conditional correlations between identified monetary policy impulses and macroeconomic aggregates, while the semi-structural model seeks to achieve a satisfactory combination of identification and empirical fit.[43] This can result in monetary policy tightening having a more limited impact in the semi-structural model, as the estimated impact based on such models probably conflates the effect of a "pure" monetary policy impulse with that of other non-policy drivers.

Chart 17

Sensitivity to the expectation formation process

a) Real GDP growth

(deviations from annual growth in percentage points)

b) HICP inflation

(deviations from annual growth in percentage points)
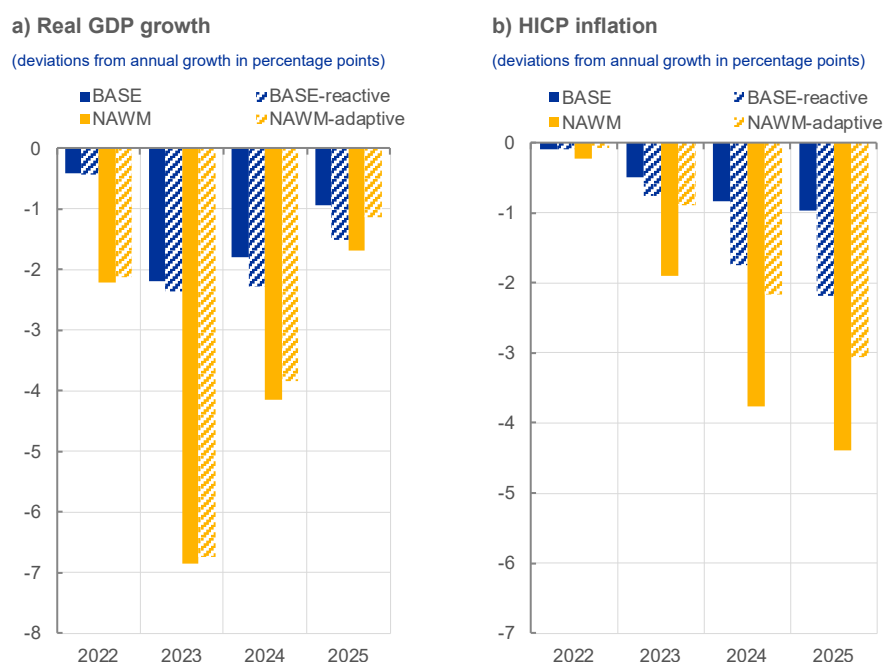
Source: ECB calculations based on NAWM II and ECB-BASE.
Notes: This chart reports the results of a simulation involving changes to short-term rate expectations between December 2021 and September 2023 and changes to expectations regarding the ECB's balance sheet between October 2021 and September 2023. The reported values refer to year-on-year growth rates.

The larger impact of monetary policy in the structural model also reflects stronger expectation channels. In particular, while the structural model is forward looking, the semi-structural model typically involves more backward-looking expectations,

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43 In practice, there is a trade-off between the scale of the model and the number of drivers that can be identified, as abstracting from many of the cross-equation restrictions required for full structural identification allows a richer model structure (e.g. as regards consumption). In NAWM II, consumption is closely linked to expected future short-term rates via the Euler equation. On the other hand, the richer modelling of consumption in ECB-BASE includes individual income risk and differing propensities to consume out of different income sources. This implies that the dynamics of consumption are less dependent on expected short-term interest rates but better capture the observed persistence in consumption.

resulting in slower propagation of shocks. Similarly, in the DSGE model an endogenous fall in inflation expectations in response to a rate rise leads to a further increase in real rates, creating a reinforcing loop – a channel that is not present in the semi-structural model, as it does not directly incorporate expectations of future inflation. This role played by expectations can be illustrated using sensitivity analysis. If it is assumed that in NAWM II, the forward-looking expectations mechanism is modified to incorporate an adaptive learning scheme that makes households' and firms' expectations more backward looking, the impact that monetary policy has on inflation is mitigated (the shaded yellow bars in **Chart 17**). Conversely, using more reactive expectations and strengthening the impact that asset prices have on the valuation of wealth in the ECB-BASE model (the shaded blue bars in **Chart 17**) brings its responses closer to those produced by NAWM II under an adaptive expectations channel.

This model-based assessment can serve as a useful cross-check but is no substitute for a data-dependent approach to setting policy and monitoring transmission over time. First, the current situation is characterised by exceptionally high levels of uncertainty about economic relations. Second, these estimates do not capture the prevention of any adverse non-linear dynamics that might have materialised in the absence of monetary policy tightening, such as a risk of destabilising inflation expectations. Finally, the results point to considerable lags in the transmission of monetary policy to the economy. For all those reasons, while this model-based assessment can serve as a complementary cross-check, it is necessary to monitor indicators such as financial and credit variables, as well as leading indicators of activity and prices, to establish a timely and comprehensive medium-term inflation outlook.

The sacrifice ratio

To put these results and the seemingly large difference between the two models into a better perspective, it can be convenient to compute a relative measure. The sacrifice ratio is an indicator that describes the output decrease necessary to achieve a disinflation effect through monetary policy measures, and thus quantifies macroeconomic stabilisation trade-offs. The sacrifice ratio is commonly defined as the cumulated output loss divided by the magnitude of inflation reduction at a given time horizon.

Theoretical underpinnings

The size of the sacrifice ratio depends on two main building blocks:

1) the price and wage formation mechanism;

2) the central bank reaction function and credibility.

The price and wage formation mechanism depends on the slack in the economy via the slope of the Phillips curve.[44] The flatter the slope, the larger the sacrifice ratio.

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[44] The slope of the Phillips curve may be time-varying and state dependent: in periods of high inflation, firms might pass the higher marginal costs on in their prices faster than in periods of low inflation, hence a steeper Phillips curve and a lower sacrifice ratio.

Since a prominent channel through which monetary policy affects inflation is via its effects on aggregate demand, if inflation is less reactive to slack, the central bank must engineer a larger drop in output to reduce inflation by a given amount. In addition, expectational adjustments directly affect prices and wages, and the more expectations are unanchored, sluggish and backward looking, the larger the sacrifice ratio is. If price and wage expectations are unanchored and backward looking, monetary policy must be more forceful to change inflation. Last, intrinsic adjustment costs such as the degree of price and wage indexation also matter. If there is a large degree of indexation, or it is difficult for firms to adjust their prices after an economic shock, inflation will adjust more sluggishly and monetary policy has to be more forceful, hence a higher sacrifice ratio.

If central bank credibility is too weak and agents do not fully believe in the commitment to its inflation target, the sacrifice ratio is larger because expectations may deviate from the target, sustaining price inflation, and remain above it unless the central bank engineers a significant disinflation.

Model-based estimates

The sacrifice ratio crucially depends on the slope of the Phillips curve and the expectations formation mechanism. Model-based simulations of a 100 basis point disinflationary monetary policy shock using ECB policy models show that the sacrifice ratio is smaller, the steeper price and wage Phillips curves are and the more reactive expectations are (**Chart 18**).

Chart 18

The sacrifice ratio; sensitivity to key model parameters
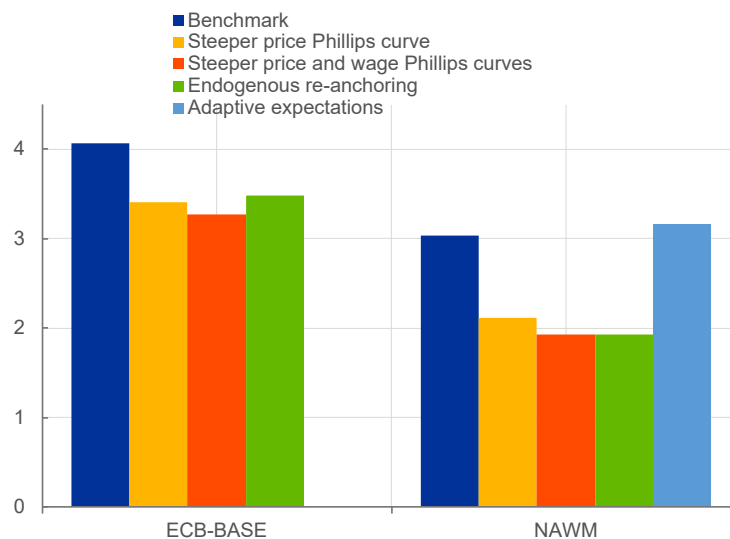
Source: ECB calculations based on ECB-BASE and NAWM II.
Notes: The chart shows the sacrifice ratio after three years associated with a monetary policy shock that increases the interest rate by 100 basis points under different assumptions about the slope of the Phillips curves in the models or about the dynamics of expectations.

In the benchmark simulations, using the estimated models, the sacrifice ratio ranges from 3.0 (NAWM) to 4.1 (ECB-BASE), implying that the cumulated output losses

amount to between 3.0% and 4.1% of annual output for every percentage point reduction in the inflation rate. The sacrifice ratio is 0.8-1.1 percentage points lower than in the benchmark case if price and wage Phillips curves are steep. If long-term inflation expectations are more sensitive to realised inflation (endogenous re-anchoring), the sacrifice ratio is 0.6-1.1 percentage points lower than in the benchmark case owing to the stronger effects through the expectations channel. NAWM is also used to quantify the impact of relaxing the assumption of forward-looking expectations. This could be a situation in which central bank credibility is weak, and agents base their expectations more on past realisations (adaptive expectations). Inflation expectations are then less reactive to monetary policy announcements, and the sacrifice ratio is 0.1 percentage points higher than in the benchmark case because a larger drop in output is needed to bring inflation down.

Normative concepts for monetary policy conduct

An important aspect related to monetary policy analysis is the evaluation of policy under normative benchmarks. Optimal policy problems characterize how the interest rate can be set endogenously by the central bank to maximize social welfare by responding to the relevant distortions in the economy, and therefore to all welfare relevant variables. Following from the seminal work of Rotemberg and Woodford (1997), Clarida et al. (2001) and Giannoni and Woodford (2003), inflation and the output gap typically consist of the main welfare relevant variables which policy aims to stabilize.

The welfare evaluation of monetary policy from a model-consistent perspective in New-Keynesian models has grown considerably covering an expanded set of dimensions, including different distortions and state-contingencies. Depending on model features, an optimal interest rate policy can be designed to also stabilize a combination of exchange rates (Corsetti et al. 2010), house prices (Adam and Woodford, 2021), macroprudential concerns (Smets, 2014), asset prices (Gali, 2014), or consumption risk (Acharya et al. 2023), among other variables. Occasionally-binding constraints imposed by the effective lower bound also dictate a a "lower-for-longer" optimal monetary policy under commitment (Eggertsson and Woodford, 2003), which can be employed in parallel to optimal quantitative easing policies to stabilize the macroeconomy (Harrison, 2017; Karadi and Nakov, 2021), as well as to determine the optimal allocation of central bank asset purchases across euro area regions in the face of asymmetric financial frictions (Kabaca et al., 2023).

In recent years, larger-scale policy models housed in central banks and policymaking institutions have also embarked on these issues, studying optimal monetary policies under commitment using predetermined loss function specifications approximating social welfare through central bank objective functions (for example, see, Adjemian et al. (2007); Adolfson et al. (2011); Darracq Pariès and Kühl (2016); De Groot et al. (2021); Mazelis et al. (2023), among others).

In this regard, recent work by Darracq Pariès et al. (2024) employs the NAWM II to evaluate how the euro area economy would have performed in the post-pandemic inflation period since mid-2021 under an optimal monetary policy strategy, contrasting it against alternative strategies that differ in their timing, the information

set of the central bank as well as the reflection of monetary policymaker preferences. Under full knowledge of prevailing macroeconomic conditions in 2021:Q3, an optimal monetary policy counterfactual delivers a faster lift-off from the effective lower bound and an overall more hump-shaped path of the short term rate, with inflation peaking at 8% and stabilising sooner under more hawkish preferences. The fact that the timing of the start of the hiking cycle matters for euro area macroeconomic dynamics also becomes apparent if policymakers followed the model-consistent historical reaction function of interest rates: earlier tightening would also prevent inflation from peaking at 10%, but the forceful tightening since 2022:Q3 prevented higher inflation from becoming entrenched. In turn, real-time policy based on quarterly vintages of incoming data imply less steep but more persistent rate increases, which overall attribute inflation dynamics to bad luck, rather than bad policy.

4 Adapting and developing the modelling portfolio

Drawing on recent academic literature debating the need to update the economics profession's benchmark models, in this final section we propose a set of ways in which the ECB's current suite of models could be developed to make them more robust. We also discuss the modelling agenda with reference to the key objectives for the next five to ten years. Progress towards meeting some of these objectives is already at an advanced stage.

Regarding the general modelling strategy, the suite of models has proven overall to be a flexible approach to coping with the uncertainty brought about by changes. The ECB will therefore continue to pursue a suite-of-models approach as a way to cover five complementary objectives: (i) to ensure that model-based policy advice is robust, (ii) to exploit the trade-off between structural features and empirical performance, (iii) to address the business need for euro area and country-specific analysis, (iv) to create a common institutional language through a small number of main models and several specialised satellite models, and (v) to balance the need to learn from ongoing research while maintaining consistent model-based input into the policy process.

The modelling agenda for the 21st century requires an understanding of the various super-trends and their respective drivers, together with the ability to decide accordingly on the investments to be made. Some of these long-term trends are listed in **Table 7**. They will have a major influence on the economy and society in general, and will therefore require major adaptation of our current tools. One of the key questions that central banks are asking model developers, for instance, is how to deal with the dual legacy of the global financial crisis and the COVID-19 pandemic, in a scenario with increasingly high cross-country and cross-sector heterogeneity, with inflation and interest rates going from very low to high, with high private and public debt, and against the backdrop of climate-related events. The answer to this question may lie in the designing of a new generation of enhanced models and advanced empirical and quantitative methodologies with an explicitly integrated policy framework which includes monetary, financial and fiscal policy interactions, and which can deal with the consequences of, for instance, climate-related, technological and demographic changes. The enhanced tools will also have to be adapted for new data which better capture a new, more "digital" reality. This means that, now more than ever, for central banks' modelling units, there is no choice but to consider a holistic approach and team up with scholars of other disciplines to model, for example, human behaviour or inequality.

Table 7

Major trends in the economic environment

Major trends	Economic and social drivers
Globalisation	Economic growth, global supply chains, international competition, volatile markets
Digitisation and technological change	Innovation, machine learning and AI, Big Data and analytics
Future of work and mobility	Mobile work, generational change, sharing economy, work-life balance
Demographic and social changes	Population growth and ageing, social media, inequality
Climate change, resource scarcity, sustainability	Global warming, disasters, circular economy, renewable resources

Source: ECB.

In practical terms, this will also mean that some of these models have to focus not only on the "desirable" transmission mechanism of the balance sheet and unconventional policies, but also on possible unintended consequences and tail risks related to monetary/financial/fiscal policy interaction (Brunnermeier, 2023). In addition, they will need to be conscious of issues, such as climate change, which are not necessarily part of the ECB's primary mandate, but have an impact on inflation, economic activity, financial institutions and markets. Climate change (apart from being a key human and ethical problem) poses several challenges for the conduct of monetary policy, including how best to arrive at the appropriate policy stance and to ensure that when it is implemented, it is successfully transmitted to households and businesses.

Among other things, the above considerations imply that in our modelling efforts over the next five to ten years we will have to (i) take a flexible multi-disciplinary approach to find an appropriate degree of model complexity in dialogue and cooperation with scientists from other disciplines, (ii) include new economic concepts and measurements, and (iii) reflect a new economic mainstream in a safe, stable and user-friendly technological environment.

To incorporate all these elements into the main models would be too ambitious and probably unfeasible and would run the risk of creating models that were too large to be manageable. Therefore, climate-related risks will be better reflected in our macroeconomic models within a suite-of-models strategy. This strategy will remain the best way for the ECB to contend with the climate challenge when designing the new generation of models. The final approach will reflect an awareness of the limitations of a single-story model and will depend on the policy question. However, it will also be crucial to hold discussions and work together with climate scientists and experts in other disciplines to find the right degree of model complexity.

The vision sketched out above is a grandiose and, in some respects, utopian one. Therefore, we conclude this part with a few selected, specific modelling priorities for the coming years. These have emerged in part from the ECB's monetary policy strategy review concluded in July 2021. A more comprehensive overview of analytical gaps and model development needs can be found in Darracq Pariès et al. (2021).

4.1 Climate change and energy modelling

Recent advances in climate models can help explain or project changes in the climate and reproduce temperature anomalies. The current emission levels suggest that we are rapidly approaching the carbon budget consistent with the 1.5°C global warming limit and that we are on track to exceed it.

When designing a course of action, policymakers are interested in understanding the impact of climate-related risks on activity and inflation. They want to understand how physical and transition shocks happen, how they propagate and how they are best mitigated. To better reflect climate-related risks, macroeconomic models will need to consider additional mechanisms:

1.   The risk of physical climate-related shocks (such as storms and floods) growing in frequency, magnitude and persistence has implications for the horizon over which we assess policy: it requires central banks to lengthen their visibility over the evolution of the economy far beyond what they conventionally consider to be the "medium term". Therefore, a modification of the trend or longer horizon configuration of the current models (for instance, to include endogenous growth and model the carbon cycle) will make them better able to address the long-term effects of climate change ("long-term" meaning more than five years in this case).

2.   At the same time, the production structure could include an explicit role for the energy sector and reflect the effects of specific climate change mitigation instruments (such as carbon taxes), which are essentially fiscal instruments and are therefore country-specific.

3.   In turn, this implies that models will need to deal with various sources of asymmetry or heterogeneity in breakdowns by sector/region/country and by type of household, as well as featuring carefully designed expectations formation. This aspect will call for heterogeneous agent models, which are not currently suitable or operational except for a very select set of economic issues.

The ECB is taking several steps to incorporate climate risks into its analytical framework. From a pure modelling perspective, the strategy for the inclusion of climate change considerations in the analytical toolkit is multifaceted and follows a stepwise approach.

First, empirical short-term models are being adapted to incorporate selected climate change transmission channels at business cycle and higher frequency This is to allow the short-term economic impact of climate-related shocks and policies to be

assessed. For the macroeconomic staff projections, the impact of climate change risks and transition policies is better identified and captured in the baseline and risk analyses. These analyses involve extending the scope of the common technical assumption to include EU Emissions Trading Scheme allowance prices, and regularly evaluating the impact of climate-related fiscal policies as well as other transition pathways on the baseline and over the medium term (see, for example, Ferdinandusse et al., 2024) The next steps in this connection will be aimed at developing a framework for analysing the impact of climate change on the long-term (ten-year) projections for potential output. Time-series models for forecasting can also be used to analyse the short-term impact of market and non-market transition policies (Ciccarelli and Marotta, 2021) or of weather-related events on inflation and output by including the effects of extreme weather events on food and energy prices and on aggregate demand (Ciccarelli et al., 2023a and Ciccarelli et al., 2023b).

A second part of the modelling strategy involves developing new climate-specific models to assess the implications of climate change for the transmission of monetary policy and for macro-financial interactions. In addition to adapting existing models, new climate satellite models are being built to conduct policy and scenario analyses. One workstream involves developing a calibrated non-linear "two-country" (euro area; rest of the world) version of NAWM with a disaggregated energy sector. NAWM-E (Coenen et al., 2023) augments NAWM with disaggregated energy production and use, where firms and households demand energy for production and consumption purposes. Energy is produced by an energy provider aggregating "dirty" and "clean" energy varieties, with each variety produced using a combination of value added and a natural resource. The model also features a role for carbon emissions as a by-product of primarily dirty energy production. A second model (Priftis and Schoenle, 2024) focuses instead on the interplay between financial vulnerabilities and climate-related risks. It aims to provide a better understanding of the role played by financial sector features (such as occasionally binding leverage constraints) and energy-related fiscal and central bank policies (namely energy subsidies or green versus brown quantitative easing) in propagating the effects of climate-related risks, such as fossil fuel price increases or devaluations in capital quality.

Other climate models which are being explored belong to the (hybrid) class of CGE-DSGE models and place emphasis on rich sectoral and/or regional breakdowns. The G-Cubed model (McKibbin and Wilcoxen, 2013), features a multi-sector production structure comprising a detailed breakdown of the energy-generating sector (oil, coal, gas, petroleum, etc.) and its associated carbon intensities within a general equilibrium framework for 20 regions of the global economy. As a result, it is particularly suited to investigating the cross-sector and cross-border implications of transition and physical risks. Darracq Pariès et al. (2024) use a variant of the G-Cubed model to assess the implications of sectoral supply shocks for euro area economies and the implications for monetary policy design. Other global models used at the ECB, which trade off the sectoral disaggregation aspect against complexity in other aspects, are the National Institute of Economic and Social Research's Global Econometric Model (NiGEM) and the Oxford Economics Model.

While these differ in terms of scope and features, it is important to maintain a suite-of-models approach in the climate modelling agenda, too, given the inherent model uncertainty regarding predictions of the economic effects of climate-related shocks. We have explored this aspect in recent work, in which we compare the effects of the carbon tax using a range of models (see Brand et al., 2023), and within the context of the Network for Greening the Financial System (Darracq Pariès et al., 2022).

Further potential avenues for new model development could place emphasis on exploring frameworks for formalising the inclusion of physical risks in our toolkits and understanding green funding and investment needs, as well as on the micro-foundations of the relevant externalities, and on nature capital and biodiversity.

Box 3 A carbon tax transition scenario using our climate-augmented models[45]

Prepared by Romanos Priftis

As part of the European Green Deal, the EU has recently taken steps aimed at reducing greenhouse gas (GHG) emissions to net-zero by 2050. These comprehensive measures are outlined in the EU's Fit for 55 package, which, among other targets, requires GHG emissions to be reduced by 55% by 2030 (compared with 1990 levels), using a combination of carbon taxation, regulatory measures and green investments.[46]

This box provides a model-based assessment of the macroeconomic impact of higher carbon taxes on euro area real GDP, headline inflation and carbon emissions. To deal with the uncertainty associated with the multifaceted way in which carbon taxes affect the economy, it employs a suite of models with climate-related features. Some of these models have been developed internally, while others have been sourced externally.

The carbon tax scenario considered is based on the OECD's effective carbon tax rate for 2021, which stands at €85/tCO_2 for the euro area.[47] The terminal value of carbon prices is consistent with the International Energy Agency's net-zero projection and stands at €140/tCO_2 for the euro area, capturing the direct and indirect carbon price effects resulting from the implementation of the Fit for 55 package and other policy initiatives.[48]

The list of models considered is shown in **Table A**. All models feature a set of environmental elements and fall into two classes: (i) three newly developed internal DSGE models and (ii) three large-scale commercial models. While all models allow for the transmission of carbon taxes through the energy sector, they differ in terms of sectoral granularity. The DSGE models distinguish between "dirty" and "clean" energy varieties for consumption and/or production purposes, while the commercial models differentiate between energy inputs such as electricity, gas, oil, coal and renewables. Carbon taxes affect the relative price of carbon-intensive inputs and lead to a reallocation into cleaner energy sources, allowing carbon emissions to decline.

The impact of the carbon tax scenario on real GDP is limited (**Chart A, panel a**). GDP gradually declines over time, falling permanently by 2030 with declines of between 0.5% and 1.2%. Reflecting structural differences in models, the results vary across models, being driven by differing impacts on private consumption and investment. The E-DSGE-RR model, which incorporates financial frictions in the banking sector, shows the most pronounced decline in GDP. The impact on inflation is also moderate and diminishes over time (**Chart A, panel b**), although there are differences across models in the short term. In models with forward-looking price-setting behaviour the impact is more front-loaded, while in backward-looking models the impact is more gradual.

As regards carbon emissions, the median estimate points to a reduction of 11% by 2030, with predictions varying significantly across models (**Chart A, panel c**). Models with low elasticities of substitution between carbon-intensive and renewable energy technologies, high capital adjustment costs and less responsive renewable energy supply typically show lower carbon emission reductions for a given impact on output.

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[45] This box is based on analysis found in Brand et al. (2023), which includes more information on the impact of carbon taxes across our suite of models.

Carbon taxes are just one way of helping to achieve the EU's interim target of a 46% reduction in emissions between 2021 and 2030. Stronger emission reductions could be achieved through higher carbon prices, which would produce stronger inflationary and contractionary effects. However, reaching the EU's climate goals will require a mixture of carbon emission pricing and additional regulatory action and technological innovation, as set out in the Fit for 55 package.

Table A

Main features of the suite of models

	NAWM-E	E-DSGE-RR	FNL	G-Cubed	NiGEM	Oxford
Type	DSGE	DSGE	DSGE	Semi-structural	Semi-structural	Semi-structural
Global	Two-country (euro area and rest of world)	Small open economy	Closed economy	Multi-country global	Multi-country global	Multi-country global
Forward looking?	Yes	Yes	Yes	Mix	Mix	Mix
Energy sector	Disaggregated energy; "clean" and "dirty" inputs; composite for production and consumption	Disaggregated energy; "clean" and "dirty" inputs; composite for production and consumption	"Clean" and "dirty" energy production; incorporates abatement costs	Disaggregated energy production (different fuel types)	Energy input into production function	Energy input into production function
Carbon tax transmission	Direct and indirect	Direct and indirect	"Dirty" firms cut emissions through abatement spending	Indirect	Direct and indirect	Direct and indirect
Sectoral	Limited	Limited	Limited	High	Limited	Limited
Banking sector?	No	Yes	No	No	No	No
Fiscal assumption	Carbon tax is used for lump-sum transfer to households			Carbon tax reduces government debt		
Monetary policy	Model-specific interest rate rule					

Source: ECB.
Notes: NAWM-E: see Coenen et al., 2023; E-DSGE-RR: see Priftis and Schoenle, 2024; FNL: see Ferrari and Nispi Landi, 2024; G-Cubed: see McKibbin and Wilcoxen, 1999; NiGEM: see Hantzsche et al., 2018; Oxford Economics: see "Global Economic Model" on the Oxford Economics website.

[46] For more information on the European Green Deal, see "The European Green Deal – Striving to be the first climate-neutral continent".
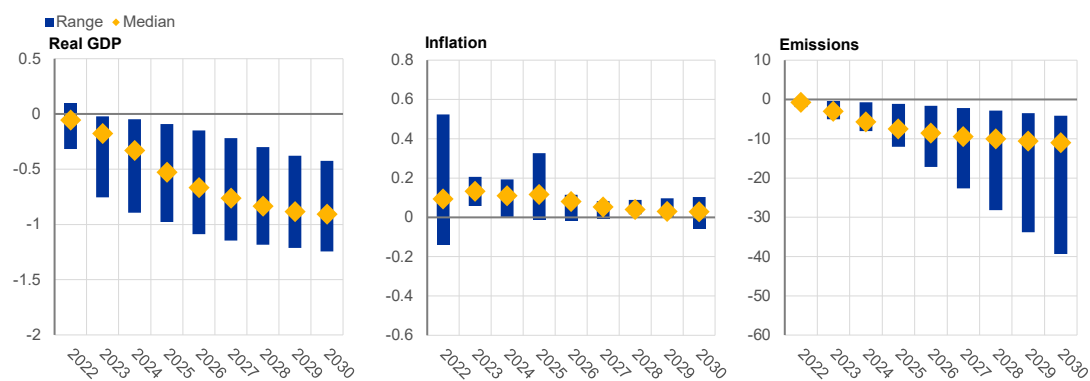
[47] The OECD provides a harmonised composite measure of the price of carbon emissions across a wide range of countries by estimating (net) average ECRs. This measure comprises fuel and energy excise taxes, direct carbon taxes and emission trading schemes at the country level for six economic sectors (road transport, off-road transport, industry, agriculture and fishing, residential and commercial real estate, and electricity).

[48] We assume that the carbon tax increases linearly from its initial value to its terminal value. For regions outside the euro area, the scenario assumes a proportionate increase of 65% from lower levels.

Chart A

Impact of carbon taxes on euro area real GDP, headline inflation and carbon emissions

(percentage/percentage point deviations from steady state)

4.2 Heterogeneity and monetary policy transmission

Economic models for monetary policy that aim to account for the mega-trends outlined in **Table 7** and, at the same time, guarantee a more realistic assessment of the policy stance should, in the first instance, remove the standard homogeneity assumption for households and firms. A new generation of models have emerged which retain nominal rigidities, as in the standard New Keynesian models, but replace the representative agent with heterogeneous households that have uninsurable earnings risk. Kaplan et al. (2018) refer to these as heterogeneous agent New Keynesian (HANK) models, and they are based on the idea that inequality and income risk matter for the business cycle and long-run outcomes. Acknowledging a wider set of agent types in New Keynesian models, with a more realistic treatment of liquidity, can change the conclusions about how monetary policy works and implies that the monetary-fiscal interaction should be taken seriously. One particular implication of HANK models is that Ricardian equivalence does not hold, so the effects of monetary policy become more uncertain because they depend on fiscal policy actions.

The ECB's recent monetary policy strategy review emphasises that "many dimensions of heterogeneity relevant for policy transmission and policy effects are not captured in canonical representative agent models" and "heterogeneity […] can affect the design of optimal monetary policy". Recent ECB occasional papers, summarising the work done on this topic in the context of the strategy review, focus on heterogeneity across households, analysing consumption, employment, income and wealth inequality and the potential implications for the effectiveness of monetary

policy (Darracq Pariès et al., 2021; Brand et al., 2021; and Holm-Hadulla et al., 2021).

A workstream was therefore set up to complement the set of core models for the euro area with the addition of an estimated HANK model featuring household heterogeneity. Given the computational complexities of this kind of model, a possible way forward might be to develop a set of HANK models, each one emphasising some specific features that could serve to answer particular questions. This new generation of models will, for instance, assess the impact that monetary policy has on secondary objectives, inequality and labour market implications, and it will shed light on the implications that household heterogeneity has for the design and calibration of monetary policy action, including non-standard measures.

A first milestone has been the development of a stylised HANK model augmented with search and matching and with ex ante heterogeneity in terms of the labour market, where the job market for less-educated and hence poorer agents is assumed to be more volatile, consistent with empirical evidence. This model makes it possible to assess the change in the monetary policy transmission mechanism that is associated with such heterogeneous labour markets, showing that monetary policy has stronger effects on GDP and consumption (Herman and Lozej, 2022). This result is driven by the fact that the workers whose reaction to a monetary policy stimulus is more pronounced (i.e. less educated/poorer workers) are also those that in the HANK framework have a higher marginal propensity to consume. This direct amplification is further strengthened by a general equilibrium effect, since higher aggregate consumption and output also imply higher labour demand.

A natural next step is to enhance this stylised HANK model with richer household balance sheets that allow the model to reconcile large marginal propensities to consume. These are key elements in determining the transmission of income and labour market shocks to aggregate consumption, with the asset composition of household balance sheets observed in the data. This highlights the importance of using microdata to realistically calibrate the model in terms of income, wealth and consumption inequality.

In conducting quantitative analyses, it is also important to augment the model with a wider set of aggregate shocks, such as monetary, fiscal and productivity shocks, in the same way as in standard medium-scale DSGE models. This will allow the model to be estimated flexibly using euro area time-series data and provide meaningful forecasts, shock decompositions and model-based narratives.

The ECB and the Eurosystem set up various internal task forces and expert groups to work on the modelling of heterogeneous agents. After carrying out a wide-ranging stocktaking exercise across NCBs in the European System of Central Banks (ESCB), the task forces and expert groups concluded that most projects being carried out by NCBs deal mainly with household heterogeneity. The projects cover a considerable span of topics and methods, while the analysis of firm and bank heterogeneity is less developed. It emerges, in particular, that many questions of interest relating to firms and monetary policy have not yet been properly analysed. These questions concern, for example, the decision of whether to use bank loans or

bonds for funding, maturity structure and misallocation. A particularly promising avenue for future analysis relates to the use of production network models with heterogeneity at the sectoral level (instead of heterogeneity at individual firm level). This can help to better reflect the effects of the large sectoral shocks (such as the pandemic shock and the energy shock) that have played such a large role in recent years. Looking at prominent recent papers applying state-of-the-art production network models to such policy questions, Bachmann et al. (2022) use the open-economy multi-sector model devised by Baqaee and Farhi (2021) to quantify the effect on the German economy of a shut-down of energy imports from Russia, while Quintana (2022) carries out similar analysis for the Spanish economy, and Izquierdo et al. (2022) study the aggregate impact of industry-specific shocks and their propagation through global production networks.

4.3   Machine learning

Adding disaggregation and granularity by including more heterogeneity increases the complexity of models. Consequently, in order to calibrate or estimate heterogeneous models, reliable micro-evidence about many of these interactions will need to be obtained, and computational methods for solving and estimating them will need to be developed.

Adding heterogeneity, aggregate uncertainty and non-linearities to a macroeconomic model is computationally challenging because the resulting high-dimensional state space gives rise to the "curse of dimensionality" (Bellman, 1966). This has prompted economists to develop new computational methods tailored to complex models with large state spaces. As with many recent advances in machine learning, these methods are built on deep learning – more specifically, deep neural networks and their ability to approximate high-dimensional functions (Hornik et al., 1989).

Solving an economic model can be approached as an unsupervised learning problem, where we do not know a particular object of interest (for example, a policy function that maps agent states to decisions), but we know the equilibrium conditions that must be satisfied in order to solve the dynamic programming problem. We can use deep neural networks to approximate this unknown function. By adjusting the weights in the network such that the equilibrium conditions are satisfied, we can find a solution to the model. The process of adjusting the weights is called "training" in machine learning terminology.

In a high-dimensional model, only a small fraction of the state space is usually relevant for the model economy. Consequently, many of the recent methods simulate the model to sample from the state space. This stochastic simulation allows the training to focus on the relevant part of the state space. Being able to handle large irregularly shaped domains is another benefit of machine learning-based solution methods.

Rapid progress has been made in the development of deep learning-based methods for solving economic models. Maliar et al. (2021) combine deep neural networks and

stochastic simulation to solve a high-dimensional Krusell and Smith (1998) model. Azinovic et al. (2022) introduce a deep learning-based method and demonstrate it using high-dimensional overlapping generations models. Fernández-Villaverde et al. (2020) develop a method suitable for continuous time dynamic programming problems and apply it to a multi-location and highly non-linear migration model. Azinovic and Zemlicka (2023) use novel deep neural network architecture to automatically enforce market clearing conditions and borrowing constraints. Ebrahimi Kahou et al. (2021) show how the symmetry in heterogenous agent models can be used to make it simpler to find a solution.

Estimating complex non-linear models poses additional computational challenges. First, the model needs to be solved multiple times for different parameter combinations. Second, the likelihood of a non-linear model is harder to compute than that of a linear model. Kase et al. (2022) develop a deep learning-based solution and estimation method for non-linear heterogeneous agent models. By treating parameters of the model as additional dimensions, they are able to find a solution for the model over a range of parameter values and avoid repeatedly solving the model during estimation. To speed up likelihood calculations, they train an additional deep neural network that maps parameter values to model likelihood – a surrogate model for the particle filter.

Creating surrogate models, which are computationally cheaper to evaluate than the original, is another example of how deep learning may be used for making estimations. Chen et al. (2021) develop a structural estimation method based on this idea in the context of option pricing, but a similar technique could be used for other types of model. It is important to note that a surrogate model can be created on the basis of solutions calculated using classical numerical algorithms, making it attractive in the presence of existing models.

Deep learning can also be used to find optimal policies. One approach would be to use a method such as that set out by Kase et al. (2022), but instead of estimating the structural parameters of the model, one could, for example, treat the parameters of a tax function as additional dimensions and find the welfare-maximising combination afterwards. Han, Yang et al. (2021) propose a deep learning-based solution algorithm that can be used to solve both competitive equilibrium and constrained efficiency problems.

In addition to its application to structural models, machine learning can enable the processing of novel datasets consisting of text and images. Textual data gathered from newspaper articles could help to capture the sentiment and confidence of economic agents. Satellite imagery can be used to measure economic activity on a more granular spatial level or in areas where other data sources do not exist or are unreliable. Both sources could help to improve nowcasting performance, as the data could be gathered effectively and processed closer to real time.

4.4 Alternative expectation formation mechanisms

A richer array of agent types might also require different expectation formation mechanisms and the replacement of rationality with bounded rationality, learning mechanisms or inattention. Mackowiak and Wiederholt (2009), for instance, showed that inattention can be incorporated into a DSGE model to (partially) substitute for other sources of stickiness and that, as with the HANK models, welfare analysis of monetary policy could be sensitive to the presence of this complication.

Expectations in DSGE models are typically assumed to be rational, such that the joint probability distribution of the model variables is fully consistent with the model and policy experiments are not, therefore, subject to the well-known Lucas critique; see, for example, Lindé et al. (2016) and Christiano et al. (2018) for recent surveys on DSGE models and their use in policy institutions. The rational expectations (RE) hypothesis places strong cross-equation restrictions on the resulting multivariate stochastic process, which describes the observed and unobserved model variables and helps to identify the structural parameters. Bayesian inference is frequently used for estimation, as priors may also help to steer the parameter estimates into regions considered "plausible", while the calibration of parameters that are hard to identify from macroeconomic data affects relatively few parameters, with microdata being consulted instead.

It may be unrealistic to assume that agents in a model know all its details and collect all necessary information, such that their expectations about the future of the variables are fully model-consistent. Before the RE revolution led by Robert Lucas, Thomas Sargent and other prominent researchers in the 1970s, expectations were typically either backward looking or not even accounted for in macroeconomic models. A few decades after the breakthrough of the RE hypothesis, however, alternative approaches to the modelling of expectations are again being considered in academic literature. These include, for example, the bounded rationality model of Sargent (1993), rational inattention (as seen in Sims, 2003), the sticky information model of Mankiw and Reis (2002), partial information (as seen in Svensson and Woodford, 2003), the learning approach of Evans and Honkapohja (2001) and imperfect knowledge of long-run conditional means (as seen in Eusepi and Preston, 2018). Evans and Honkapohja (2009) and Woodford (2013) provide overviews of such alternatives; see also Evans and McGough (2020) for a recent overview of studies that use adaptive learning (AL) in macroeconomic and financial applications.[49]

The DSGE model of Galí et al. (2012; the GSW model) was first estimated on euro area data by Smets et al. (2014), being used to study the informational content of

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[49] As has been pointed out, one shortcoming of estimated DSGE models under rational expectations is that, from experience, they require highly persistent shock processes to explain observed persistence in the data. For instance, Milani (2007, 2009) and Orphanides and Williams (2005) claim that learning can influence dynamic responses to shocks and thereby increase the persistence of shock responses. Milani (2007) estimates a small DSGE model using US data and finds that learning reduces structural frictions, such as habit persistence, while also improving within-sample fit. By using survey data and adopting a DSGE-VAR approach to assess the extent and sources of misspecification, Cole and Milani (2019) find that the RE assumption is the main reason why their New Keynesian model fails to match the data well.

professional forecasters' data on the model's point forecasts. This model is an extension of the well-known Smets and Wouters (2007) model, adding unemployment and labour supply shocks to the model, and was further examined from a density forecasting perspective in McAdam and Warne (2019) and more recently in Warne (2023). The last of those studies compares the within-sample and out-of-sample fits of the GSW model under RE and in real time for the euro area relative to a variant of the model which has AL expectations. The AL approach used by Warne is the one advocated in Slobodyan and Wouters (2012), which relies on a restricted information set for the formation of expectations.

The AL set-up starts from a standard form of log-linearised DSGE model where current values for the model's variables are related using a system of equations to past values, expected future values and structural shocks. To solve the model under AL, the first step is to specify which model variables are forward looking. Not all variables appearing in expectations need to be or should be included in this group. For example, a shock process is exogenous in a DSGE model and often specified as an autoregressive process, but it may nevertheless appear in expectations in an equation of some kind. Such a variable is not forward looking and should be replaced by its analytical forecast expression under AL. With the exception of such cases, all endogenously determined variables appearing in expectations may be selected as forward looking, although a smaller selection is often possible through substitution.

Second, a "perceived law of motion" (PLM) for the forward-looking variables is specified. The AL variant in Warne (2023) follows the suggestion in Slobodyan and Wouters (2012) and uses a PLM which includes a constant term and two own lags for each forward-looking variable. The coefficients of the PLM are time-varying, and their values are determined by a Kalman filter which provides the learning mechanism for the PLM and includes three additional parameters. The model can now be solved for the assumed PLM, yielding the actual law of motion (ALM), which traces out the actual behaviour of the model variables over time. The ALM typically differs from the PLM, and the expectations mechanism is therefore not model-consistent, whereas the ALM and the PLM are identical under the RE hypothesis.

As regards within-sample fit, Warne (2023) finds that the AL variant of the GSW model has a greater marginal likelihood than the RE model for a euro area sample covering the period from the first quarter of 1985 to the fourth quarter of 2019. This confirms the findings made by Milani (2007) and Slobodyan and Wouters (2012) using US data, with those papers finding, for example, that DSGE models subject to AL fit the estimation data better than RE models. Furthermore, the two types of model are also compared within sample for each first quarter vintage over the real-time forecast sample for the period 2001 to 2019, and again, the AL model obtains larger marginal likelihood values for each first quarter vintage.

Turning to the forecast comparison exercise in Warne (2023), overall the RE model predicts real GDP growth more accurately than the AL model from a point and density forecasting perspective. Inflation is measured by the GDP deflator in the GSW model, and the forecast paths for this variable reflect a sharp difference

between the dynamic behaviour of the two expectation mechanisms, with the RE paths yielding better point and density forecasts within the one-year horizon, while the AL paths form better medium-term forecasts. Overall, the RE model also performs better out of sample for the joint real GDP and inflation forecasts.

An important feature of the AL model is that its dynamics show greater persistence than the RE model's. This may be one reason why the AL model has greater difficulties forecasting real GDP growth, especially after large shocks (e.g. during the Great Recession). At the same time, the AL model's expectation formation and greater persistence may explain why it provides a better within-sample fit than the RE model.

As a next step for using alternative expectation schemes in ECB models, the intention is to study the AL approach of Slobodyan and Wouters (2012) within NAWM II, focusing initially on the resulting impulse response functions when the three free AL parameters are calibrated.

5   Conclusion

This paper has summarised the last 25 years of macroeconometric modelling strategy at the ECB, illustrating in a transparent (and sometimes unprecedented) manner some important policy uses of the main models, and presenting the current and future investments that will be needed to keep abreast of the most important global trends.

We would like to conclude this paper with a humble remark acknowledging the fact that models fail, as well as a forward-looking note on two interconnected elements that will prove to be essential for the future of economic modelling, over and above the inclusion of new economic theories, in order to cope with and leverage these failures: technology and cooperation.

Models are an imperfect representation of reality. As the statistician George Box put it in 1976: *"All models are wrong, some are useful."* The purpose of the material shared on the previous pages is to show how some of our models can be applied to everyday work in a useful manner (despite the answers that they provide not always being correct). None of our models predicted the global financial crisis, for example. In addition, our models encountered difficulties in interpreting the drivers of post-pandemic inflation. However, we were able to quickly adapt them by adding missing elements that made them more resilient and useful. Some of our new models were developed quickly in order to produce reasonable scenarios in an extreme situation such as the COVID-19 pandemic. As the historian Yuval Noah Harari said: *"The real test of 'knowledge' is not truth, but utility. A theory that enables us to do new things constitutes knowledge."* Our modelling teams strive to increase the accuracy of the ECB's knowledge. We should always be looking for evidence of inaccuracies in our models, so that we can adapt them accordingly, making them more resilient. Policy decisions will always be taken under conditions of uncertainty, and, without being perfectly correct, models will always be useful for the decision-making process. This is especially the case if they are used in a suite-of-models framework, given that no single way of interpreting reality is always accurate.

As well as developing new models or incorporating new features into our existing models to cope with an uncertain world, another important requirement is to choose the appropriate computing environment and build user-friendly infrastructure, guaranteeing that the new tools can be used and shared without a hitch and that institutional knowledge is preserved.

New data and technologies are certainly here to stay, while the environment in which the ECB and Eurosystem NCBs operate will continue to evolve – and not necessarily in a linear fashion. Nevertheless, we believe that technologies, data and models will not be enough to ensure that our modelling framework is in tune with the new world. This will also depend on the organisational set-up that we choose and the strategic changes that we make within our institutions. Two ingredients in particular will be vital for creating the conditions and laying the foundations that will allow us to be

more flexible and agile. First, we must acknowledge that central banks are not isolated silos but players within a complex, interconnected and interdependent world. We will therefore need to foster innovation, knowledge sharing and teamwork, both within our own system and with other players in the finance and regulation industry. Second, Eurosystem NCBs should allow their own boundaries to become increasingly fluid by opening up to third parties and building stable networks in order to secure access to know-how, capabilities and expertise on demand.

Both aspects require a structured approach with investment in knowledge management, information sharing and modelling infrastructure. Teamwork and transparent information sharing within the ECB/Eurosystem should be promoted by making use of common technological innovations and focusing on redefining some fundamental processes that are needed to manage interaction and the information flow. The projection process is one of those. The ECB has recently finalised a new projection platform, developed at the interface of business and IT, that could serve as a starting point for closer interaction between the ECB and NCBs. The platform architecture and its aim of providing a data science solution for the internal ECB projections processes has similarities to other IT developments related to data and project management, such as GitLab's source code management. Common platforms can be leveraged not only to ensure a more efficient projection process, but also to share modelling knowledge, to safeguard the traceability and auditability of output, and to guarantee that the model infrastructure is safe and resilient to risks. In addition, a common data and model repository will make greater use of institutional knowledge to create a common ESCB knowledge base and enable the continuous ESCB-wide development of shared models.

The use of common platforms is a key part of the vision for the ECB and NCBs to become borderless organisations, allowing the boundaries of our institutions to gradually become more fluid. Embracing this vision will be beneficial both in economic terms and from an efficiency point of view. Sharing resources is a natural way to alleviate the burden of their scarcity while making it possible to preserve a common technical pipeline and knowledge base across borders. Cross-border cooperation can produce clear efficiency gains in terms of (i) preparing shared procurement contracts to access the same experts, databases, software, etc., (ii) teaming up with a common pool of consultants from universities and technical labs to expand the technical expertise of our working groups in a multidisciplinary manner, (iii) enhancing the current staff exchange programmes and opening them up to other world-leading experts at central banking, financial or regulatory institutions, with multilateral agreements.

These developments will require a change of mindset, which should be the starting point for the modelling considerations in the next ECB strategy review and any future development of models.

6 Annex I: How did we get here? A short history of model development at the ECB

Prepared by Matteo Ciccarelli and Gabriel Fagan

This annex covers the history of macroeconomic model development at the ECB from the late 1990s to the present. We divide the period into four phases: the first phase runs from the late 1990s to the early 2000s; the second covers the mid-2000s; the third covers the financial and sovereign debt crises after 2008; and the final one covers the most recent events.

6.1 The late 1990s and early 2000s: the first models

The ECB was formally established in mid-1998 and began operating as the central bank of the euro area in January 1999. Prior to the establishment of the ECB, the European Monetary Institute (EMI), which had been set up in 1994, was tasked with carrying out the necessary preparations to allow the ECB to carry out its tasks effectively from the start. These preparations covered a wide range of areas of central bank activity, including currency design and production, payment systems, statistics, accounting, monetary policy operations and monetary policy strategy (EMI, 1997). The need to establish modelling infrastructure was recognised early on. For example, in a 1997 report, the EMI's Monetary Policy Subcommittee argued that "in order to carry out monetary policy effectively the ESCB will need to have at its disposal a comprehensive statistical data set and […] will need to have at its disposal analysis capacities, including a broad range of econometric tools" (EMI, 1997). In late 1996, following a recommendation by EMI staff, the Council of the EMI decided to launch a joint EMI/NCB project to develop a multi-country model for the EU Member States, and a special group comprising EMI and NCB staff was established in 1997 to oversee this project.[50]

This preparatory work faced several challenges. First, there was uncertainty about which countries would participate in the monetary union. In fact, the European Council did not reach a decision on the final list of participating countries until May 1997, just seven months before the ECB was due to commence operations. This uncertainty led to issues around the compilation of the necessary databases and model estimation. This put staff under extreme time pressure, as they then had to develop models in time for the start of ECB operations. Priority was therefore given to developing models that could contribute to the ECB's forecasting process and be up and running by the start of the monetary union.

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[50] This group was known as the EMI Modelling Team. Following the establishment of the ECB, this group was transformed into the Working Group on Econometric Modelling (WGEM), a substructure of the ECB's Monetary Policy Subcommittee.

Second, the euro area was a "new economic area" with no recorded economic history. A new set of macroeconomic data relating to the euro area had to be compiled from various national sources, some of which were not fully harmonised.[51] For model development, the data difficulties were compounded by the need for relatively long spans of time-series data for estimation purposes. In addition, apart from in the field of money demand analysis, there were no prior studies analysing euro area data to which model developers could refer.[52]

Third, since the euro area is a multi-country monetary union made up of countries with different institutions, economic structures and national policies, the modelling infrastructure needed to have models relating to individual countries as well as the euro area as a whole. This meant that developing modelling infrastructure for the ECB would be more complicated than is the case for "normal" central banks.

Fourth, in the late 1990s model developers had to deal with the issue of different modelling philosophies. At the time, there was a notable gap between the types of model used in academia and those used by central banks. In the former, there was a preference for small-scale models (such as the New Keynesian model), which were derived from dynamic macroeconomic theory and were usually calibrated. While these models had advantages when used for certain purposes, such as analysing alternative monetary policy rules, they were not sufficient to meet the needs of central banks. In macroeconomic forecasting, central banks had (and still have) a preference for fairly detailed forecasts, with breakdowns for a range of national account aggregates, labour market variables, trade variables and prices. The forecasts need to be communicable to – and understood by – policymakers, so detailed forecast narratives are required.

The models used by EU central banks at the time shared several common features.[53] Typically, long-term developments in the real economy were determined in line with neoclassical theory, while money was neutral in the long term as a result of vertical long-run Phillips curves. Short-run dynamics were linked to the long-run relationships via error correction terms, typically derived using cointegration analysis. However, the dynamics were ad hoc, with parameters being determined by empirical properties. Thus, the models used by euro area central banks diverged sharply from the dominant models in academic literature.

There were, nonetheless, notable differences in views among modellers at Europe's central banks. For instance, there were differences regarding the appropriate size of the model, with national models ranging from 23 to 96 estimated equations. There were also strongly divergent views regarding the role to be assigned to economic theory in the specification of models, with some central banks favouring a tight linkage whereas others believed that the role of theory was merely to suggest a list of variables to be included in the equations. There was also significant divergence when it came to the treatment of expectations, with some models containing explicit

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[51] See Bull (2004) for an overview of preparatory work in the field of statistics.

[52] See Browne et al. (1997) for details of pre-EMU money demand studies.

[53] See Fagan and Morgan (2005) for an overview of the models used at Europe's central banks in the late 1990s and early 2000s.

expectations variables while others dealt with expectations implicitly via the inclusion of lagged variables.

A specific issue in the euro area related to the question of aggregation. Some argued that, because of aggregation problems (such as differences in parameters across countries and/or non-linearities), area-wide modelling (the "top-down" approach) was an invalid strategy for both forecasting and policy analysis (see, for example, Mayes and Viren, 2002, and Monteforte and Siviero, 2002). According to this view, the appropriate approach was to develop models for individual countries and aggregate the results from these individual country models (the "bottom-up" approach). Defenders of the area-wide approach pointed to evidence suggesting that the aggregation bias was fairly limited. They also cited the convenience and efficiency gains which came with the use of area-wide models.[54] In addition to model specification, there was even a debate as to the appropriate method for constructing historical euro area data by aggregating national data.[55] In the end, in both its forecasting exercises and its modelling approach, the ECB adopted a combination of both area-wide and country approaches.

During this period, a range of macroeconomic tools were developed by ECB and NCB staff. However, the main tools were the area-wide model (AWM) (see Fagan et al., 2005) and the multi-country model (MCM).[56] The former was an EMI/ECB staff project. The latter was a joint ECB/NCB effort, overseen by the EMI Modelling Team and later the Monetary Policy Committee's Working Group on Econometric Modelling.

The first stage in the development of these models was to clarify the model specifications. Given the overriding priority of developing tools for the forecasting process, and the pressing time constraints, it was decided to build on the experience of existing NCB models in the EU. Thus, the specification followed NCB practices. The specification of MCM was agreed by the EMI Modelling Team in March 1997.

The need to support the forecasting process meant that accounting frameworks would need to reflect what was envisaged for the ECB's forecasting exercises. This meant modelling a relatively wide set of data, including main components of aggregate demand (volumes and deflators), labour market variables, relevant financial variables (interest rates and exchange rates), trade volumes and prices, and a set of price indicators.

In terms of the underlying macroeconomics of the models, AWM and MCM had similar structures. The long-run properties were derived from neoclassical economic theory (with potential output determined by trend total factor productivity and trend labour force). Prices were determined by accelerationist Phillips curves with wage growth determined, among other things, by the gap between the actual unemployment rate and an estimation of the non-accelerating inflation rate of unemployment. GDP deflator growth reflected, among other things, the output gap

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[54] See Fagan and Henry (1998) for money demand and Fabiani and Morgan (2003) for the Phillips curve.

[55] See Beyer et al. (2001) for a discussion of these issues.

[56] See Karlsson and McAdam (2005) for an overview of MCM.

(actual output minus the model's implied potential output) and a mark-up over unit labour costs. Thus, money was neutral in the long run. Short-run dynamics were not derived explicitly from agents' optimising problems but rather by empirically fitting the equations using a "general to specific" methodology. The long-run relationships entered the equations via error correction terms. This empirical approach reflected the cointegration methodology which was prevalent in macroeconometric modelling at the time.

Since they were designed primarily for forecasting purposes, rather than policy simulation, the models did not include explicit expectations variables. The use of lagged variables meant that the effects of expectations formation and the inherent dynamics of the economy were mixed.

The key difference between AWM and MCM lay in the geographical scope of the variables included in the models. The variables in AWM referred to euro area aggregate variables, whereas MCM dealt with variables for individual euro area countries. In addition, MCM also included a "link block" to ensure consistency of trade volumes and prices across individual euro area countries.

To develop these models, EMI staff compiled an extensive macroeconomic database of quarterly time-series data for the euro area. The data started in the first quarter of 1970. MCM was estimated using quarterly data on individual countries supplied by the respective NCBs.

From the very start of ECB operations in 1999, both models were used extensively in the ECB's forecasting exercises.[57] To understand the role played by the models, it is important to note that they were not used to mechanically produce forecasts. Instead, forecasts were produced by sectoral and country experts, both at the ECB and at NCBs, using a bottom-up approach (meaning that individual country forecasts were aggregated to produce euro area-wide forecasts). In preparing these forecasts, staff used a wide range of tools, including macroeconomic models and time-series tools such as VARs. These forecasts were prepared on the basis of a set of common assumptions for the external environment (world trade and oil prices) and financial variables (exchange rates and interest rates). Forecasts were produced for a wide range of variables compatible with the accounting framework of the models.

The main uses of the models in the forecasting process were as follows. First, the models were simulated to examine the impact that changes to common assumptions had on the forecast variables (e.g. foreign demand). This analysis served as an initial input for the preparation of forecasts. Second, once forecast numbers were available, the models were "run in reverse" to compute implied residuals. This analysis showed how the forecasts diverged from the historical regularities implied by the model's equations and was helpful in identifying forecasting issues which needed to be clarified in subsequent discussions in the relevant forums.[58] The MCM link block was used to assess the cross-country consistency (in terms of trade

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[57] See ECB (2016) for a detailed description of the ECB/Eurosystem forecasting procedures.

[58] These forums comprised (i) the Forecast Task Force and the Forecast Steering Committee within the ECB and (ii) the Working Group on Forecasting and the Monetary Policy Committee at Eurosystem level.

volumes and prices) of the set of country forecasts. The forecasts were revised to reflect the forecasting discussions and the results of the model-based analysis. Third, taking the forecasts as a baseline, the models were used to derive alternative scenarios (looking, for instance, at how a change in the oil price assumption would affect the forecasts), which were regularly presented in the forecast reports.

6.2   The mid-2000s: a shift to DSGE models

While the early ECB models (AWM and MCM) achieved an established position in the forecasting process and were regularly used for forecasting purposes, there were several concerns about the structure of these models. First, the ad hoc nature of the model equations and the absence of explicit expectations variables meant that the models were vulnerable to the Lucas critique. This made it risky to use these models for policy analysis. While this was not an issue for forecasting purposes, which was the dominant concern at the start of the ECB, it became increasingly pressing as time passed. Second, as noted earlier, the predominant paradigm in academic macroeconomics was increasingly the New Keynesian framework, with its focus on agent optimisation, rational expectations and sticky prices. Over time, the gap between the academic frontier and the models used at the ECB became very large. This was an uncomfortable situation for a central bank to be in.

Meanwhile, the existing New Keynesian models were unsuitable for the ECB's forecasting exercises since their accounting frameworks were too rudimentary. Ideally, a central bank would have models which could fit seamlessly into its forecasting process while at the same time being sufficiently robust for policy analysis purposes. This would require a relatively large-scale model (in line with the accounting framework of the forecasting exercise). It would also incorporate the main features set out in academic macroeconomic literature, namely dynamic optimisation by agents and explicit expectations variables, while at the same time incorporating frictions such as sticky prices and wages, as well as adjustment costs, in order to provide a good "fit" to the data.

In the 1990s, the computation technologies available at the time meant that developing such a model appeared unfeasible. However, subsequent developments in computational power and algorithms changed this picture. In particular, the development of efficient algorithms for the solution and Bayesian estimation of large-scale DSGE models removed this feasibility constraint.[59] An early "proof of concept" was provided by Smets and Wouters (2003 and 2007). These authors developed a relatively large (by the standards of the time) DSGE model (for the euro area and the United States) and estimated its parameters using Bayesian techniques. Further work with this model demonstrated that it could, in principle, be used for forecasting purposes in a manner consistent with the ECB's forecasting process (Smets and Wouters, 2004).

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[59]   See Fernández-Villaverde et al. (2016) for an overview of the techniques for estimating DSGE models using Bayesian techniques.

In view of this evidence, it was decided that AWM should be replaced with a New Area-Wide Model (NAWM), which would incorporate the main features of the DSGE approach while at the same time having an accounting framework that was sufficiently rich to enable it to be incorporated into the forecasting process. Work on the development of the new model started in 2005, and NAWM replaced AWM in forecasting processes around 2008.

The main features of NAWM were set out in Christoffel et al. (2008). Briefly stated, these features were as follows. First, the model was relatively large by the standards of the academic literature at the time. This was because the model was designed to be compatible with the accounting framework of the forecasting process. Second, the model's equations were derived from utility- and profit-maximising problems of agents. Third, the model contained various frictions: stickiness in prices and wages, habit formation in consumption, and adjustment costs in investment and trade. These frictions led to richer dynamics, helping to improve the model's "fit" to the data. Fourth, the model was estimated using Bayesian techniques. Finally, it is worth noting that, in line with the macroeconomic consensus at the time, and consistent with the economic environment of the Great Moderation era preceding the global financial crisis, the treatment of the financial sector was sparse, with only a limited number of financial variables being included.[60]

The use of NAWM in the forecasting process was similar in many respects to that of AWM. First, it was used to assess how changes to assumptions (regarding world trade, for example) affected the forecast. Second, by treating the available forecasts as data, it was possible to use the model to "back out" the implied shocks. This procedure helps to identify an underlying narrative for the forecast while identifying relevant forecasting issues. Third, the model was used to extend the forecast horizon and produce a "medium-term reference" scenario. Fourth, a particular strength of the model was in policy analysis and the preparation of alternative scenarios. In particular, because the model contained explicit expectations variables, it could be used to analyse scenarios involving changes in expectations and policy credibility (e.g. the impact on the economy of a unanchoring of inflation expectations).

In parallel with the development of NAWM, the multi-country model was upgraded to incorporate dynamic optimisation by agents and explicit expectations variables. However, given the size of the model, and the need for linking across countries, full Bayesian estimation was not feasible. Instead, a more pragmatic approach was followed with regard to the specification and estimation of the model. The main features of the new multi-country model (NMCM) are set out in Dieppe et al. (2012). The model equations were derived from agents' optimisation problems (utility and profit maximisation) in the context of an overlapping generation framework.

The theoretical core of the model consists of three optimising private sector decision-making agents (i.e. utility-maximising households, profit-maximising firms and trade unions), which minimise the quadratic loss function under the staggered wage adjustment assumption. Monopolistically competing firms set prices and inventories and determine the demand for factors of production under the

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60   See the overview in Blanchard (2009) for details.

assumption of indivisible labour. In the short run, output is demand-determined. Monopoly unions set wages, and overlapping generation households make consumption/saving decisions. Explicit expectations variables are included in the model, which can be solved using various expectational schemes (model-consistent expectation formation and learning with bounded rationality). Under the learning expectations regime, agents form their expectations in accordance with a learning rule, which in NMCM is model-consistent and has stable properties. A notable feature of the model is the rich production structure, with the production function given by the normalised constant elasticity of substitution. This allows for non-unitary elasticity of substitution, non-constant augmentation of technical progress and heterogeneous sectors with differentiated price and income elasticities of demand.

The model is estimated using generalised methods of moments on the basis of quarterly national historical data from 1980 onwards. NMCM covers the five largest euro area countries (Germany, France, Italy, Spain and the Netherlands), with a block covering the smaller euro area countries.[61] In the linked version of the model, cross-country linkages occured through four channels: trade volumes, trade prices, common monetary policy and a common exchange rate. Its country blocks can be used either on a single-country basis (mainly for forecasting purposes) or as a linked euro area multi-country model (especially for policy analysis).

6.3 The 2010s: the financial and sovereign debt crises and the response in terms of model development

The outbreak of the global financial crisis (and later, in the euro area context, the sovereign debt crisis) after 2007 represented a massive change to the economic environment for central banks. It posed formidable challenges in terms of economic analysis and monetary policy, which played a big role in the context of model development. To understand how the ECB internalised the need to modify the modelling toolkit, it is worth mentioning some of these challenges.

First, the crisis highlighted the financial system's role as both a source and a propagator of shocks. As the crisis evolved, the state of household and corporate balance sheets and the prior accumulation of debt were identified as key determinants of the severity of the macroeconomic impact and duration of the crisis. In this regard, in both the United States and some euro area countries, the housing sector was identified as a major culprit. The propagation effect was evident in the macroeconomic impact of the crisis: in line with established empirical literature on financial crises and economic growth, the crisis was accompanied in advanced economies (including the euro area) by the deepest recession since the Second World War, and the subsequent recovery eventually proved to be protracted (see, for example, Reinhart and Rogoff, 2009).

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[61] The previous version of MCM is documented in the following papers: Vetlov and Warmedinger (2006), Boissay and Villetelle (2005), Estrada and Willman (2002), and Angelini et al. (2006a and 2006b).

Second, the connection between macroeconomics and finance also highlighted the multi-dimensionality of the problem in at least three respects:

1. Confidence in having a price stability objective (with flexible exchange rates) that was independent of financial regulation and supervision was "shattered by the scale and synchronization of asset price booms and busts" (see Canuto and Cavallari, 2013). As a result, changes were made to the regulatory landscape which shifted the focus to interdependence between macroeconomic and financial stability and the need for coordination between monetary policy and macroprudential regulation. At the same time, the sovereign debt crisis in the euro area highlighted the importance of fiscal issues with regard to the stance and sustainability of fiscal policy. These aspects had been somewhat neglected in earlier analysis.

2. For the implementation of monetary policy, this also meant introducing multiple policy instruments. The official interest rates of many central banks hit the "lower bound" (the level below which central banks were unable or unwilling to cut rates), a development which previous studies, based on Great Moderation data, had found to be highly unlikely (Chung et al., 2012). Crucially, the crisis led the ECB (and other central banks) to adopt a wide range of "unconventional measures", such as enhanced forward guidance, negative interest rates, targeted liquidity provision (such as targeted longer-term refinancing operations) and outright purchases of government and corporate bonds.[62] The introduction of so many unconventional instruments comes with obvious drawbacks. They make monetary policy implementation more difficult to understand, and there is no clear framework or historical precedent for what combination is best (Morris and Shin, 2016, and Rostagno et al., 2019).

3. The impact of the crisis differed across euro area countries, with some countries being severely affected while others escaped relatively unscathed. What is more, monetary policy implementation also had to cope with differences in sensitivity to long and short rates across countries and possibly asymmetric responses to standard and non-standard policy shocks. This brought into sharp focus the heterogeneous nature of our monetary union (see, for example, Ciccarelli et al., 2013, and Burriel and Galesi, 2018).

Third, the crisis bought a number of key financial markets to a standstill and caused a breakdown in the key arbitrage relationships that had characterised the pre-crisis period. These relationships included, for example, covered interest parity, the term structure of interest rates, and the size and stability of a range of intra-country and cross-country interest rate spreads (such as the spread between official interest rates and unsecured money market rates and various lending rates in the economy). These developments hampered monetary policy transmission mechanisms, with the result that the ECB had to implement policy measures to ensure the effective transmission of its stances.

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[62] See, for example, Hartmann and Smets (2018) and Rostagno et al. (2019) for an overview of the ECB's response to the crisis and a history of monetary policy over the last 20 years.

Fourth, the global financial crisis exacerbated the protracted downward trend in real interest rates and pushed them to historically low levels in most advanced economies. This development contributed to a decline in the natural or neutral rate of interest (r*) – a core (but unobserved) concept in modern macroeconomics. The protracted downward trend in r* indicates elevated risks of monetary policy becoming constrained by the lower bound on nominal interest rates in the future. Thus, factors necessitating changes to monetary policy strategies and instruments can sometimes be driven by developments that cannot be addressed by – or are not completely within the control of – central banks (see Brand et al., 2018 and references therein).

Fifth, these structural changes (in demographics and technology, for example) were also consistent with the observed declines in trend inflation, which, for a given economic cycle, not only put under scrutiny one of the core mechanisms in our models, the Phillips curve, but also undermined the credibility of the target inflation anchor – another key concept at the heart of our models and policy prescriptions. Although the Phillips curve remained a useful tool for understanding inflation dynamics in the most recent period, the main potential consequence of low inflation was that it might become self-sustaining through the expectations channel and lead to an unanchoring of inflation expectations. Ciccarelli and Osbat (2017) show that potential risks of an unanchoring of inflation expectations emerged in 2014, following a prolonged period of low inflation due to a sequence of adverse shocks at the effective lower bound (ELB) of interest rates. While agents' confidence in the central bank's commitment to its stated objective remained largely intact, the risk of unanchoring grew because of the increased persistence of inflation – which, at the ELB, reflects both the sequence of negative shocks and the longer than usual time lag in monetary policy transmission. In other words, it may take agents some time to learn about the effectiveness of policy instruments in such a challenging environment.

Against the backdrop of the above challenges brought about by the changes in the economic environment, there were increased doubts in academic circles about the prescriptions resulting from the mainstream models, while policy institutions (including the ECB) were forced to adapt their narratives and prescriptions within an unchanged institutional setting.

On the one hand, experience of the crisis led to a sharp rise in criticism of DSGE models,[63] some of which had even been endorsed by ECB policymakers (see, for example, Constâncio, 2017). The criticism focused on five points. First, objections were raised to the "representative agent" assumption underlying most of these models. Second, it was argued that the assumption of rational expectations, routinely employed when these models were being solved, was not appropriate since it assumed information-processing capabilities on the part of agents which were not credible. Third, reflecting their origins in literature on the real business cycle, the financial sectors in these models were rudimentary and thus unable to satisfactorily account for – much less predict – the financial crisis. On a related note, these models could not adequately capture the effects of unconventional monetary policies. Fourth, the underlying micro-foundations – agent optimisation subject to

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[63] See Blanchard (2018) for a balanced review of the main issues.

resource or budget constraints – was also questioned, with some critics expressing a preference for more rule-of-thumb behavioural approaches, which, they argued, are more consistent with the evidence from microdata. Fifth, while it was acknowledged that DSGE models could fit the macrodata reasonably well, there was scepticism that this would be achieved by adding persistent "shocks" which were difficult to relate to observable experience. The implication was that the models had limited internal propagation mechanisms and, what is more, the postulated shocks were not credible.

On the other hand, from an empirical perspective, even if multi-dimensionality and changes in the environment might not have affected past relationships (in a statistical sense), the ECB needed to account for them to build a credible narrative based on quantitative prescriptions for real-time policy advice and to preserve consistency between macro- and microdata over time. In the light of the various points discussed above, it became apparent that the available set of models (described in the previous section) was ill-suited to coping with these developments and contributing in a realistic and consistent manner to the forecasting process and the assessment of the balance of risk. Major changes would also be needed in terms of infrastructure and frameworks to help ensure informed debates. Model development is a resource-intensive – and, more importantly, time-consuming – process. In a crisis environment, the central bank could not afford to embark on longer-term model development projects and await the results. Instead, the immediate approach was to complement the main models with other tools more attuned to dealing with the issues at hand. This involved the use of satellite models, using partial equilibrium analysis and various empirical tools. The results from these analyses could then be fed into the main macroeconomic models to give a coherent overall macroeconomic analysis.

This is best illustrated by two concrete examples. First, in late 2008 it was clear that the growth forecasts emanating from the standard tools were too optimistic, in view of the existing evidence on the effects that financial crises have on growth. In response, downward adjustments were made to the model forecasts, which were calibrated on the basis of historical evidence on the macroeconomic impact of financial crises. Second, event studies were carried out to assess the impact of non-standard measures on financial markets. The results of these studies were mapped to the risk premium variables in the models, which were then used in a simulation to arrive at an overall assessment of these policies' macroeconomic effects.

How did the ECB respond to the challenges in terms of the development of its main models? Bearing in mind the experience of the crisis and the criticism aimed at the previous set of DSGE models, the main response in terms of model development was twofold. The first component was the development of an extended New Area-Wide Model (NAWM II), which essentially modified the existing NAWM by incorporating a richer financial sector with an explicit banking sector and a set-up better equipped to quantify the impact of asset purchases by the ECB. The second was the development of a new multi-country model (ECB-MC), which represented a more radical shift away from the DSGE paradigm and towards a "semi-structural"

approach than the shift represented by NMCM. The new semi-structural model is characterised by its looser link with theory, its greater emphasis on flexibility and on fitting the data, and its more granular and (potentially) partial equilibrium approach. The two models are used side by side in the policy process.

6.4   The early 2020s: COVID-19 and the return of inflation

As seen above, the financial and sovereign debt crises posed big challenges for the economics profession in general and macro modelling in particular. Models were criticised for not having the right mechanisms in place – either to predict what was coming or to describe it after the shock had hit. All central banks were affected by financial markets' almost complete absence from aggregate models of the economy and the neglecting of macro-financial linkages. All central banks diligently adapted their models – the ECB being no exception – in an effort to re-establish a consensus around modified versions of the mainstream models.

However, the development process is in constant evolution and the environment is changing all the time. What happened after the criticisms were initially taken on board following the financial crisis? Some academic scholars called for additional – and somewhat radical – adjustments to the framework for (mainly DGSE) mainstream models. A consistent and comprehensive illustration of the discussion can be found, for instance, in Vines and Wills (2018). In their final summary, the authors compare the need to change macroeconomic theory and rebuild the New Keynesian paradigm after the financial crisis to "the situation in the 1930s, at the time of the Great Depression, and in the 1970s, when inflationary pressures were unsustainable".

Therefore, in addition to the need to add financial frictions, the academic profession has also seemed to converge on other important aspects, which are consequences not only of the academic debate but also of the various actors' responses to the economic situation that emerged after the Great Recession and the financial crisis. In particular, while the ECB has recently focused on designing a coherent framework for monetary policy which includes conventional and unconventional policies in a changing world, for all European institutions there is a larger and more interconnected set of monetary, financial and fiscal policies to evaluate within the monetary union. At the same time, the profession is debating the need to relax some of the fundamental assumptions of the current macroeconomic paradigm, such as the rational expectation and representative agent frameworks, and rely on more appropriate micro-foundations.

The COVID-19 pandemic and its economic consequences have challenged the modelling framework used for policy forecasting and scenario analyses. They have also called into question the basis for all empirical explorations, because unprecedented shocks require a much broader set of statistical information, which will have to be modelled appropriately. The pandemic also erupted in an environment of persistently low inflation and low real interest rates following the financial crisis, in which there were significant complementarities between economic policies –

especially monetary and fiscal policies (Debrun et al., 2021). And while academic research shows that when interest rates are low, the effects of expansionary fiscal policy are stronger (Christiano et al., 2011; and Eggertsson, 2010) and the trade-off between economic stabilisation and debt sustainability is relaxed (Blanchard, 2019; Bonam, 2020; and Mehrotra and Sergeyev, 2021), the pandemic confirmed the view that monetary and fiscal policies can indeed reinforce each other while operating independently. In response to the pandemic, all euro area authorities reacted forcefully to support economic activity, which was also helped by the proximity of the ELB. The ECB's actions not only ensured the proper transmission of the monetary policy stance to all parts of the euro area, but also indirectly benefited governments by keeping funding costs low and preventing non-fundamental surges in sovereign risk premia. In addition, the Next Generation EU initiative was established to increase public investment with the aim of boosting long-term growth, facilitating the green and digital transitions, and improving the resilience of the EU. These measures proved crucial in minimising uncertainty and helping to ensure a quick macroeconomic recovery. It was in this environment that the review of the ECB's strategy took place. For macroeconomic modelling in the Eurosystem, the main conclusions are summarised in Darracq Pariès et al. (2021), an occasional paper that delivers four main contributions: (i) it provides an overview of the macroeconomic modelling portfolios currently in use or under development within the Eurosystem; (ii) it explores analytical gaps in the Eurosystem models and investigates the scope for further enhancing the main projection and policy models, and creating new models; (iii) it reviews current practices in model-based analysis for monetary policy preparation and forecasting, and provides recommendations and suggestions for improvements; and (iv) it reviews existing cooperation modalities on model development and proposes alternative sourcing and organisational strategies to close any knowledge or analytical gaps identified.

Since the end of 2021, the macroeconomic environment has again changed dramatically. The euro area, like many other economies, has seen inflation surge, reaching very high levels from a historical perspective. This has brought new challenges, for instance with regard to the interactions between monetary and fiscal policies. The surge in inflation has been due in part to a pandemic-related mismatch between supply and demand, dramatically exacerbated by the war in Ukraine, which has caused a supply shock of unprecedented scale. In particular, international prices for fossil fuels and other commodities have risen sharply owing to increased uncertainty surrounding international supplies. In pursuit of its price stability objective, the ECB has increased interest rates at an unparalleled pace with the firm intention of bringing inflation back down to its target of 2% over the medium term. In so doing, it is seeking to prevent high levels of inflation from becoming a more persistent phenomenon and prevent inflation expectations from becoming unanchored. The need for a restrictive monetary policy stance may contrast with the fiscal policy stabilisation role, particularly when an increase in inflation is largely driven by supply factors (Auclert et al., 2023; and Fornaro and Wolf, 2022). Obtaining the correct outlook for inflation in this uncertain environment is very challenging. The ECB framework for forecasting inflation is currently being revamped to include new data and technologies for its short, medium and long-run projections. At the same time, significant work is being done to reinforce the risk analysis around

the ECB projections and to benchmark our understanding of monetary policy effectiveness in an uncertain world.[64]

[64] See ECB Economic Bulletin, Issue 3/2023.

7 Annex II: Other models

7.1 Satellite DSGE models

Satellite DSGE models complement the main DSGE models for scenario analysis, elaborating on macro-financial interactions, structural or labour market features, policy mix issues or global economy issues. Such models are particularly well suited to exploring interactions between monetary, financial and fiscal policy.

Since the financial crisis, an extensive body of literature has emerged on the effect that financial instability has on the aggregate economy, highlighting the transmission channels from the financial system to the macroeconomy. There are various satellite DSGE models focusing on those issues, with some financial frictions included in their policy analysis and simulation exercises. These models are typically extensions of Bernanke et al. (1999) or Kiyotaki and Moore (1997), designed to include more complex bank structures that capture disruptions in intermediation and account for some form of non-linearity. Cozzi et al. (2020) perform a model comparison exercise looking at the DSGE models used to evaluate macroprudential policies and their interactions with monetary policy.

Current model development plans are targeting the explicit modelling of macro-financial linkages, such as endogenous interest rate spreads, endogenous housing investment and prices, or endogenous credit, or the modelling of different parts of financial institutions' balance sheets.

Turning to fiscal policy, satellite DSGE models are also used to analyse fiscal multipliers under constrained monetary policy, and with forward guidance and quantitative easing. Coenen et al. (2012) and Kilponen et al. (2019) conduct model comparison exercises based on such models. These models often include a relatively rich array of fiscal policy instruments (taxes, transfers to different types of household and various forms of government expenditure). These models are well suited to exploring policies that involve several fiscal policy instruments, such as fiscal devaluation or optimal financing of government investment.

Finally, satellite DSGE models are used to address global issues or cross-country heterogeneity and spillovers across the monetary union. With regard to multi-country DSGE modelling, the EAGLE model in Gomes et al. (2010) provides a coherent framework for evaluating the euro area-wide and country-specific transmission of global shocks, such as the international transmission of increases in tariffs or other protectionist measures. The EAGLE-FLI extension of the model includes financial frictions and non-standard measures. As regards monetary policy analysis, Darracq Pariès and Papadopoulou (2020) explore the country-specific macroeconomic transmission of selected non-standard ECB measures using a global DSGE model with a rich financial sector that includes credit and exchange rate channels for central bank asset purchases.

7.2 Satellite semi-structural models

These models are designed to account for specific forms of economic behaviour and are generally partial equilibrium frameworks.

In particular, some sectoral modules have been developed on the basis of ECB-MC blocks and are designed to support the analysis of sectoral developments within the ECB's Directorate-General Economics (such as trade, demand components, price and wage setting, the supply side and financial transmission).

As regards the euro area's international relationships, large-scale semi-structural models have been developed to conduct global simulations and spillover analysis. The ECB-Global model in Dieppe et al. (2018) is a "workhorse" satellite model in this respect.

The BB-ECB model

The semi-structural model estimated by Bernanke and Blanchard has been adapted to provide an understanding of the factors driving wage growth and price inflation in the euro area (see Arce et al., 2024, and Bernanke and Blanchard, 2023). This model of aggregate wage-price determination contains four equations that jointly determine nominal wages, prices, and short and long-run inflation expectations. The estimation strategy follows a hybrid approach that approximates a structural vector autoregression (SVAR) with added exogenous variables. In order to account more explicitly for the forces affecting inflation, the empirical model incorporates a flexible lag structure to allow for richer dynamics and include measures of key shocks to product and labour markets, such as global supply chain pressures, energy and food prices, and the ratio of job vacancies to unemployed people.

The model is particularly well suited to explaining post-pandemic inflation dynamics and is therefore a useful benchmark for cross-checking inflation forecasts at present. Looking ahead, the model's specification could be improved to cope with future monetary policy challenges, for instance by including (i) an explicit role for demand-side policies (and consequently for monetary and fiscal policies), (ii) more forward-looking expectations, or (iii) the modelling of labour market tightness and global supply chain pressures. These changes would help to capture the general equilibrium effects of policy changes and equip the model with a better expectations channel for policy announcements. Several central banks in advanced economies, including the Bank of Canada, the Bank of England, the Bank of Japan and the European Central Bank, have adapted the model to their own country or area. The model also provides a unified framework for analysing and comparing inflation dynamics globally.

WAPRO

WAPRO is a small open-economy New Keynesian DSGE model estimated for the euro area, with prices and wages modelled using Phillips curves and aggregate

demand modelled using a dynamic IS curve. The model is closed, with an inertial Taylor rule. WAPRO is a standalone model consistent with the wage-price-output block of the ECB-BASE model, and was first introduced in Angelini et al. (2019b). It has a well-defined steady state with a nominal anchor of 2% and a time-varying real natural rate. The model's state space representation and system properties make it possible to estimate unobserved concepts such as the output gap or the natural unemployment rate. These variables are estimated as state variables in a model-consistent way, so output, prices, wages and various measures of slack are jointly determined. Reduced-form coefficients are obtained through the Kalman filter-based general equilibrium estimation of the parameters in a Bayesian setting using sample data covering the period from the first quarter of 1995 to the fourth quarter of 2019.

The model can be estimated and simulated using backward-looking or model-consistent expectations. Agents' expectations are backward-looking if they are formed using a small-scale auxiliary VAR model forecasting the economy. They are model-consistent when the expected paths of the state variables are consistent with the model-based forecast for these variables. These two extremes make it possible to understand the effects of policies (e.g. interest rate forward guidance) and shocks through the expectations channel, thereby accounting for the sensitivity of the model's internal propagation mechanism to the way agents form their expectations.

7.3 Satellite time-series models

Several time-series models are used as satellite models, complementing the main models in four ways. First, time-series models, such as BVARs or Phillips curves, are used to provide benchmark predictive densities and conditional projections against which the main models can be evaluated. Second, time-series models featuring relevant structural identification strategies are used as an empirical yardstick for (i) cross-checking certain aspects of the main models' properties (such as oil prices, or the transmission of financial or monetary policy shocks) or (ii) giving information on transmission channels not explicitly included in the main models (for instance, global supply chain bottlenecks). Third, time-series frameworks focusing on short-term forecasting include higher-frequency information and are used to condition the projection updates or the predictive densities of the main models over the first quarters of the forecast horizon. Fourth, time-series techniques are used to derive risk metrics around the projection baseline by either optimally combining predictive densities or modelling non-Gaussian predictive distributions.

Time-series models for medium-term forecasts

One notable example of a satellite time-series model is the multi-country BVAR (see Angelini et al., 2019a), which captures the four largest countries in the euro area. This empirical model is used for cross-checking the consistency of projections against technical assumptions. The model can also be used to identify the main judgemental elements in the projections. It does this by characterising them as major

gaps relative to the paths implied by historical regularities in the data. In order to appropriately capture historical regularities, a very general linear model is used, namely the VAR model. It is designed as a multi-country model so as to mirror the features of the Eurosystem's projection exercises and includes variables for the four biggest euro area economies (namely, France, Germany, Italy and Spain), which account for about three-quarters of euro area GDP. For all countries, target variables (meaning the variables to be forecast) are real GDP, real total investment, the HICP, the GDP deflator, wages, loans to firms and lending rates. A set of variables that are regarded as technical assumptions in projection exercises – particularly those capturing the policy context and the global environment in which the euro area operates – are also included. These variables are the euro area short-term interest rate (proxied by a measure of the three-month money market rate), the US dollar/euro exchange rate, the oil price, foreign demand, US GDP and the US short-term interest rate. Bayesian techniques are used to estimate this large and complex model. The model parameters are shrunk toward those of a random walk model by imposing a Minnesota prior and two priors on the sum-of-coefficients (see Doan et al., 1984, Litterman, 1979, and Sims, 1996). The informativeness of the prior distributions (prior tightness) is governed in a hierarchical manner – i.e. captured by random variables, as suggested in Giannone et al. (2015), which are then drawn from their posterior distribution to account for the uncertainty related to the set-up of the prior tightness.

Other types of BVAR are also used. The suite of BVARs contains several model variants, making it possible to hedge against model uncertainty and deal with the sensitivity of forecasts and scenarios to model specifications. The variants differ in the following respects: (i) dataset size and composition (including versions for the aggregate euro area and for the largest countries), (ii) degree of time variation, and (iii) prior specifications. Several variants are described in Bańbura et al. (2021). Versions with skewed errors (Montes-Galdón and Ortega, 2022) or outlier correction for the covariance matrices (to deal with COVID-19 pandemic observations) are also available.

A battery of price Phillips curves, with and without inflation expectations, and with fixed or time-varying parameters, are regularly used to cross-check the (B)MPE inflation projections (see Bobeica and Bańbura, 2023, Eser et al., 2020, or Ciccarelli and Osbat, 2017). Similar exercises are conducted using a battery of wage Phillips curves with different slack, inflation and productivity measures (see Nickel et al., 2019).

The outlook for inflation can also be cross-checked by looking at measures of underlying inflation. Many different measures are available and monitored (see, for example, Bańbura et al., 2023b). One of those is the persistent and common component of inflation (PCCI), which uses a generalised dynamic factor model estimated on around 1,000 HICP items from 12 euro area countries (see Bańbura and Bobeica, 2020). The PCCI is a weighted average of low-frequency common components of inflation rates for those items (where "low frequency" means capturing cycles longer than three years). As such, it aims to capture widespread

and persistent developments in inflation. It tends to show turning points in the annual HICP inflation rate with something of a lead.

Structurally identified (B)VARs (S(B)VARs)

One example of a structurally identified BVAR is is a medium-sized structural BVAR for the euro area economy, which is used to explain structural drivers of inflation, particularly since the COVID-19 pandemic (see Bańbura et al., 2023c). In addition to more "traditional" shocks, this model also incorporates drivers that have become prominent more recently – most notably, drivers related to gas prices and global supply chain bottlenecks. The latter are often missing from structural and semi-structural models. In order to deal with higher dimensionality than is typical for structural BVARs, the residuals are assumed to admit a factor structure, and the shocks are identified via zero and sign restrictions on factor loadings (as in Korobilis, 2022). The framework is also appropriate for real-time data (also called "ragged edge" data because of the differences in publication delays) and for extreme observations (typical of the pandemic and post-pandemic periods). The baseline specification incorporates eight shocks covering demand and supply-side drivers of inflation. The supply-side shocks relate to oil supply, oil-specific demand, gas commodity prices, global supply chain bottlenecks, domestic supply and the labour market. On the demand side, it includes both an aggregated domestic demand shock and a foreign demand shock. Model extensions also include monetary policy and food price shocks. It turns out that supply-side shocks explain the bulk of the post-pandemic surge in both headline and core inflation, with the "new" types of shock featuring prominently.

Other SVARs dedicated to disentangling the underlying drivers of inflation (demand versus supply, or domestic versus global shocks) are proposed in Bobeica and Jarocinski (2019), for example. An SVAR for assessing the pass-through from labour costs to inflation and its relationship with the level of inflation can be found in Bobeica et al. (2019). Meanwhile, the SVAR proposed by Hahn (2019) is applied to analysis of the wage-price pass-through in the euro area, with a focus on demand shocks and wage mark-up shocks.

Further examples relate to the identification of credit supply shocks and their contribution to cyclical conditions. Altavilla et al. (2019) and Gambetti and Musso (2017) provide two structural strategies for identifying credit supply shocks in time-series models for the euro area. These are regularly used in the context of monetary analysis for policy preparation.

Short-term forecasting tools

ECB staff have developed specific tools for short-term forecasts of developments in real GDP and its main expenditure components – both for the euro area as a whole and for individual euro area countries, as well as for some non-euro area countries. Information from timely high-frequency (e.g. monthly or daily) economic indicators is

used to derive expected short-term developments in real GDP (and its components) over the following two quarters. The short-term forecasts are currently based mainly on models of the bridge equation type (see Bańbura and Saiz, 2020), as mixed-frequency factor models (which were used previously) turned out to be somewhat less robust to structural changes. In particular, bridge equations link the target low-frequency variable (quarterly real GDP growth, for example) to higher-frequency predictors (such as monthly industrial production or monthly survey information) aggregated to the lower frequency. These predictors are, in turn, forecasted using multivariate models such as (Bayesian) VAR or dynamic factor models (at a higher frequency, such as monthly).

Similar models (including mixed-frequency factor models and mixed-frequency Bayesian VARs) are used for short-term employment growth forecasts (Bańbura et al., 2023a; and Consolo et al., 2023).

As regards the HICP, a suite of BVARs is used to forecast energy components of the index and look at how shocks to energy commodity prices are transmitted to consumer energy prices (Bańbura et al., 2024). The suite incorporates a wide range of drivers of consumer energy prices, including crude and refined oil prices, natural gas prices, energy producer prices and taxes, using information with weekly and monthly frequencies. The model specification allows for state-dependent elasticities to commodity price shocks, with the results indicating stronger transmission at higher commodity price levels.

Model combinations and the inclusion of off-model information

In order to summarise information and improve the forecasting accuracy of individual models, the forecasts from different models can be combined. (For a comprehensive review, see, for example, Hall and Mitchell, 2007; Jore et al., 2010; Geweke and Amisano, 2011; or Bassetti et al., 2020.) One approach for density forecasts (such as those produced by Bayesian VARs or the Phillips curves) is the linear opinion pool, whereby the (optimal) weights associated with individual densities are selected so as to maximise the predictive accuracy of the combined density forecast (as measured by log predictive scores; see Geweke and Amisano, 2011, or Bańbura et al., 2021, for details).

Parametric tilting in line with Montes-Galdón et al. (2023) can be used to incorporate external off-model information in a broad set of empirical models (for instance, incorporating an external forecast as a mode of a model distribution resulting in asymmetric risks).

7.4   Satellite finance models

Satellite finance models include affine yield curve models. These are used, both with and without survey information, to assess market expectations about future interest

rates and to interpret movements in long-term risk-free rates. The models rely on the approach taken by Adrian et al. (2013) and by Kim and Wright (2005) for the US yield curve. Lemke and Werner (2020) develop a similar model for the Bund yield curve, whereas other internal models focus on the overnight index swap (OIS) curve. An extension of this analytical framework to provide a benchmark for euro area term premia is in the process of being prepared.

As monetary authorities have ventured into unconventional instruments, several extensions to yield curve models have been considered or undertaken. In particular, yield curve models have been augmented with supply factors in order to quantify the impact that central bank asset purchases have on the euro area yield curve. Eser et al. (2019) present a "workhorse" model in this respect. In addition, a shadow rate yield curve model with a time-varying lower bound makes it possible to assess the combined effect of interest rate cuts and changes to the effective lower bound on key policy interest rates. Lemke and Vladu (2016) provide an example of such a model.

Beyond yield curve modelling, other tools are used to interpret developments in other financial instruments (namely, credit spreads or equity). In particular, dividend discount models are used to evaluate the cost of equity in the euro area or provide a structural narrative on the stock market (see Geis et al., 2018, or Ampudia et al., 2020, for example).

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Editors

Matteo Ciccarelli
European Central Bank
email: matteo.ciccarelli@ecb.europa.eu

Matthieu Darracq Pariès
European Central Bank
email: matthieu.darracq_paries@ecb.europa.eu

Romanos Priftis
European Central Bank
email: romanos.priftis@ecb.europa.eu

Contributors

Elena Angelini
European Central Bank

Marta Bańbura
European Central Bank

Nikola Bokan
European Central Bank

Rodolfo Dinis Rigato
European Central Bank

Gabriel Fagan
Trinity College Dublin

José Emilio Gumiel
European Central Bank

Hanno Kase
European Central Bank

Antoine Kornprobst
European Central Bank

Iason Koutsoulis
European Central Bank

Magdalena Lalik
European Central Bank

Carlos Montes-Galdón
European Central Bank

Georg Müller
European Central Bank

Joan Paredes
European Central Bank

Romanos Priftis
European Central Bank

Sergio Santoro
Banca d'Italia

Anders Warne
European Central Bank

Srečko Zimic
European Central Bank

Contributors to Boxes

Box 1: Benchmarking our models against external models for a standard monetary policy shock (**Srečko Zimic**)

Box 2: Unconditional and conditional forecasting with NAWM II (**José Emilio Gumiel** and **Anders Warne**)

Box 3: A carbon tax transition scenario using our climate-augmented models (**Romanos Priftis**)

Annex I: How did we get there? A short history of model development at the ECB (**Matteo Ciccarelli** and **Gabriel Fagan**)

Research assistance

Stella Brunotte
European Central Bank

Sara Cocchi
European Central Bank

Alessandro Giammaria
European Central Bank

Marco Invernizzi
European Central Bank

Eliott Von-Pine
European Central Bank