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The effects of the ECB's pandemic-related monetary policy measures

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Abstract

We assess the macroeconomic impact of pandemic-related monetary policy measures of the ECB. Conditioning on counterfactual interest rate paths that would have materialised in the absence of the policies, the macroeconomic effects are measured using structural vector autoregressions. In the framework, multiple monetary policy measures may simultaneously be analysed. According to our results, the asset purchase programmes implemented during the crisis have increased the annual GDP growth by approximate 2 percentage points in 2020–2021 and inflation by 0.5 percentage points. The longer-term refinancing operations have contributed positively but more mildly to the economic activity.

Keywords: Monetary policy, Covid-19, ECB, structural VAR, policy evaluation

JEL codes: C32, C54, E43, E52, E58

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1 Introduction

In March 2020, the deepening of the Covid-19 pandemic triggered an unforeseen global economic crisis. In response to the radically worsened economic outlook and to the financial turmoil in the euro area, the European Central Bank (ECB) launched a series of monetary policies. First, the Governing Council of the ECB expanded its existing Asset Purchase Programme (APP) and started the Pandemic Emergency Purchase Programme (PEPP). Second, the ECB simultaneously recalibrated its targeted longer-term refinancing operations (TLTROs) to keep the bank lending channel operational.

In this paper, we analyse the effectiveness of these two main policies of the ECB during the pandemic. We start from prior knowledge of the effects of the PEPP and TLTROs on the long-term rates, sovereign risk premia and bank lending rate, relying on the existing literature. Based on this judgement, we build counterfactual scenarios in which the monetary policy stance would have been left at the pre-pandemic level, and the interest rates and risk premia would therefore have remained higher. Using a structural vector autoregressive (SVAR) model, we identify the set of structural monetary policy shocks that would have generated the counterfactual interest rate paths in case the pandemic-related policies had not been implemented. With the aid of these counterfactual policy shocks, we can assess the implications of the programmes on the macroeconomy. The modelling framework of this paper is regularly used in policy analyses at the Bank of Finland.

Based on these premises, we estimate that the PEPP coupled with the expanded APP has considerably mitigated the negative impact of the pandemic on the euro area production and prices. The absence of these policy measures would have led to on average 0.5 percentage point slower inflation and 2 percentage point slower annual growth in gross domestic product (GDP). Similarly, the readjusted TLTRO programme has positively contributed through higher lending to the non-financial sector to inflation and economic growth.

This study is related to the recent policy analyses of Aguilar et al. (2020), ECB (2020, Box 3), Moessner and de Haan (2021) and Altavilla et al. (2020). Unlike the papers by Moessner and de Haan (2021) and Altavilla et al. (2020), our analysis is not limited to financial markets or bank lending. Instead, as Aguilar et al. (2020) and ECB (2020, Box 3), we focus on examining the macroeconomic effects of recent policies. Compared to the latter studies, we additionally assess the macroeconomic effects of the TLTROs and the later calibrations of the PEPP. Considering the identification of causal effects, our paper differs from the analyses of Aguilar et al. (2020) and ECB (2020) which are based on the SVAR models of Burriel and Galesi (2018) and Rostagno et al. (2019), respectively. Whereas their identification strategies use conventional sign and zero restrictions, we additionally exploit high-frequency variation during the announcements to recover the causal effects of monetary policy measures. We also explicitly distinguish between two types of policies, the one influencing long-term yields and the other reducing risk premia. According to our model, the GDP response to the PEPP may be larger than suggested by Aguilar et al. (2020). Regarding the TLTROs, we contribute to the literature by providing evidence on their non-negligible macroeconomic effects.

Methodologically, the article belongs to the large empirical literature starting from Christiano et al. (1999) analysing monetary policy (For a recent review, see Ramey 2016). We follow the recent strand of literature that uses the proxy variables to identify monetary policy shocks, starting from Gertler and Karadi (2015) and applied in the euro area by Jarociński and Karadi (2020), amongst others. Based on the work by Inoue and Rossi (2018), monetary policy surprises are measured as shifts in the entire term structure of interest rates. Related to the latter study, Kortela and Nelimarkka (2020) estimate a set of monetary policy shocks that affect the whole yield curve. In their paper, conventional monetary policy, forward guidance and quantitative easing are examined by three monetary policy shocks inducing different changes in the risk-free yield curve. We extend their analysis by two additional policy surprises such that the PEPP and TLTRO programmes may properly be evaluated. First, by a risk premium shock, the dimension of the PEPP related to reducing fragmentation risk and sovereign bond spreads can be captured. Second, by a bank lending shock, the effects of TLTRO programmes may be evaluated.

Our approach uses conditional forecasts to evaluate alternative monetary policy scenarios, also applied to the euro area monetary policy analysis by, inter alia, Altavilla et al. (2016) and Rostagno et al. (2019) (For further references, see Antolín-Díaz et al., 2021). Similar to this study, Rostagno et al. (2019) use conditional forecasts to evaluate the effects of multiple monetary policy tools implemented by the ECB prior to the pandemic. We analyse the monetary policy packages in a more unified framework, where the shocks are simultaneously identified, such that interactions of different policy tools may more carefully be controlled for.

The remainder of the paper proceeds as follows. First, we review the policies conducted by the ECB during the pandemic and discuss their transmission channels. We then discuss the design of the simulation exercise and how the effects are estimated. Subsequently, the results from the empirical analysis are shown. The final section concludes.

2 Monetary policies implemented by the ECB

This section discusses the main monetary policy instruments – asset purchases and longer-term refinancing operations – conducted by the ECB during the Covid-19 pandemic. First, we chronically sketch the monetary policy response in the crisis period 2020–2021. Second, we review the main transmission channels of the monetary policy tools we are analysing.

2.1 The monetary policy response

In March 2020, the global outbreak of the pandemic triggered heightened uncertainty in financial markets, observed as a liquidity squeeze, collapsing stock prices and increasing risk premia. The central banks around the globe reacted swiftly to the financial turmoil by lowering interest rates, easing financing conditions by asset purchases and providing liquidity.

Since the beginning of the pandemic, the ECB has taken various policy measures, listed in Figure 1, to counter the negative consequences of the pandemic. In its regular meeting on March 12, the ECB reacted to the financial turmoil by increasing its existing asset purchase programme (APP) by an additional envelope of 120 bil-

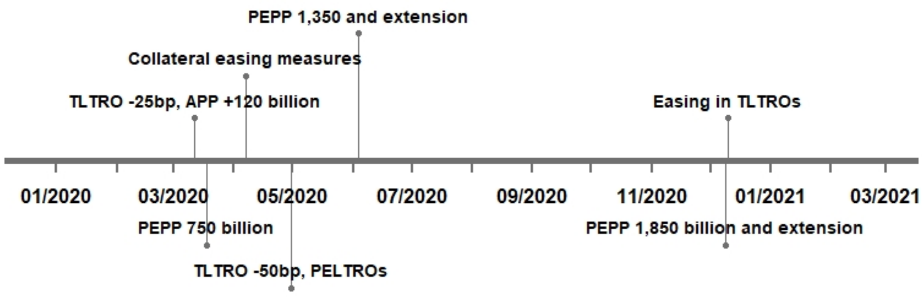

Figure 1: Measures taken by the ECB in 2020–2021
The timeline plots the measures taken by the ECB concerning asset purchases and long-term refinancing operations. In the TLTROs, the rate at which the operations are conducted relative to the rate used in the main refinancing operations is reported in basis points.

lion euro and by lowering the rate liquidity was offered in the targeted longer-term refinancing operations (TLTROs). The ECB also introduced a series of additional longer-term refinancing operations (bridge LTROs) with considerably lower interest rate. Through the longer-term refinancing operations, the financial sector was offered liquidity from the central bank by considerably lower interest rates than from the main refinancing operations (MRO) of the central bank.[1] Despite these measures, the financial uncertainty continued to rise, and the ECB launched in its extraordinary meeting on 18 March the Pandemic Emergency Purchase Programme (PEPP) with the size of 750 billion euro.[2] The programme was aimed to address the risks related to the functioning of the monetary policy transmission, to the fragmentation of the euro area and countering the downward impact of the pandemic on the projected path of inflation.

Because the crisis continued to pose a threat for the functioning of the financial market and led to downward revisions in the economic outlook, the policy measures

[1] In the TLTROs, beginning from the June 2020 operation on, banks were entitled to borrow from the central bank at an interest rate of 25 basis points lower than from the main refinancing operations (MRO) on average. The rate for those financial institutions that would maintain their levels of credit provision in operations ending in June 2021 was even lower, up to 25 basis points below the average deposit facility rate (but in any case not higher than -0.75%). In the bridge LTROs, the rate was even lower, at the average of the deposit facility rate over the life of the respective operation.

[2] At that time, it was announced that purchases will be conducted at least until the end of 2020 and, in any case, until the Governing Council judges that the coronavirus crisis phase is over.

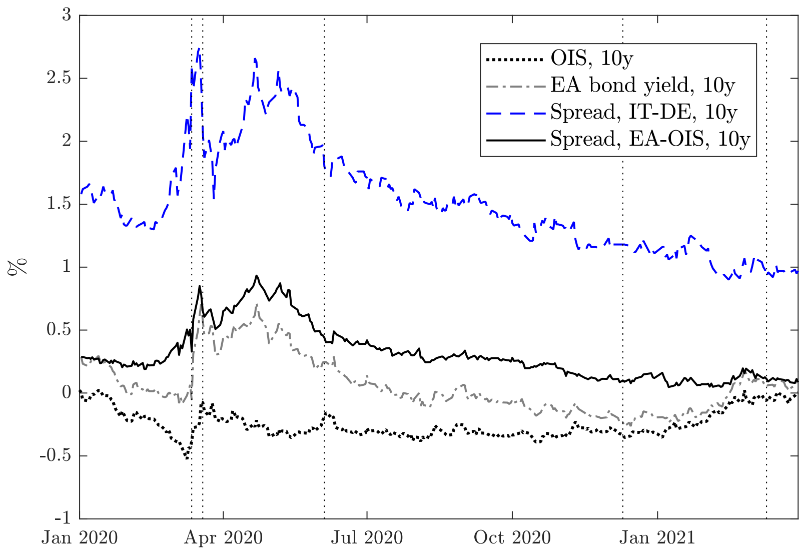

Figure 2: Interest rates and spreads over the pandemic period

The figure plots the 10-year OIS swap rate (OIS, 10y), the euro area 10-year government bond yield (EA bond yield, 10y), the interest rate spread between the 10-year government yields of Italy and Germany (Spread, IT-DE, 10y) and the spread between the euro area 10-year government bond yield and the OIS swap rate (Spread, EA-OIS, 10y). The vertical lines plot dates of monetary policy announcements related to APP and PEPP (12 March 2020, 18 March 2020, 4 June 2020, 10 December 2020, 11 March 2021). Data sources: Bloomberg, ECB and Macrobond.

were further extended. In April 2020, the ECB recalibrated its targeted lending operations to further support the real economy. Additionally, a new series of seven additional longer-term refinancing operations, called pandemic emergency longer-term refinancing operations (PELTROs) were introduced.[3] In June, the envelope of the PEPP was increased to 1,350 billion euro, and its horizon was extended until June 2021.

The financial stress in the euro area was particularly seen as rising sovereign bond premia. Figure 2 shows the evolution of long-term yields and spreads over the crisis period in the euro area. The euro area 10-year bond yield, plotted in a dashed-dotted line, sharply rose at the onset of the crisis.[4] The increase can be decomposed into two factors. First, the long-term risk-free rate of the euro area, shown in a dotted line and measured by the 10-year Overnight index swap (OIS) rate, started to increase in March 2020 from its historically low levels. Second, the uncertainty in the financial market induced a wider spread between the 10-year bond yield and the 10-year OIS rates. The increase in the long-term bond yield was thus predominantly due to the rise in this measure of sovereign bond premium. Moreover, the increase was asymmetric over jurisdictions: the bond spread between the 10-year Italian and

[3]In the second TLTRO recalibrations, the interest rate on all operations was reduced to 50 basis points below the average rate applied in the MROs over the same period and for the banks achieving the lending targets to 50 basis points below the average deposit facility rate (in any case not higher than -1%). In the PELTROs, the interest rates was set to 25 basis points below the average MRO rate.

[4]The euro area bond yield is the GDP-weighted average of the government bond yields of euro area jurisdictions computed by the ECB.

German government bond yields, shown in a blue dashed line, widened by more than 100 basis points.

After major policy interventions by the central banks and governments in the euro area and globally, the financial stress significantly lowered in April and May, observed as declining spreads and long-term yields in Figure 2. Towards the fall of 2020, the financial stress had broadly calmed down and the interest rates were close to their pre-pandemic levels. However, the renewed worsening of the pandemic situation led downside risks to the economic outlook to materialise, resulting in the Governing Council of the ECB to announce in its October meeting its intention to recalibrate the monetary policy instruments. Eventually, in the follow-up meeting in December, the total size of the PEPP envelope was both increased and the horizon of net asset purchases extended to at least the end of March 2022. To enhance lending conditions, the TLTRO programme was simultaneously recalibrated.

Since the December 2020 meeting, the ECB started increasingly emphasise the role of the existing pandemic-related monetary policy measures to maintain favourable financing conditions in the euro area.[5] Consistent with this strategy, the ECB reacted to the rise in the US bond yields, originating from fast immunisation progress, large fiscal stimulus packages and rising inflation expectations, which started to incorporate into the the euro area 10-year risk-free rate as well. Against this development, the ECB announced in March 2021 to conduct asset purchases within the PEPP at higher pace than during the first months of the year.[6]

2.2 Transmission channels of the programmes

Asset purchases

In general, quantitative easing programmes stimulate the economy by reducing longer-term interest rates. However, for this channel to work, the financial markets need to be imperfect.[7] In that case, bonds of different maturities and risk profiles are imperfect substitutes. Quantitative easing is then able to affect the asset valuation: the purchase of long-term bonds will increase their price and decrease their interest rate. The decline in duration risk leads to less risky portfolio and increased asset values, and financial corporations are able to rebalance their portfolio towards lending and investment to more risky projects in the nonfinancial sector.

[5]The definition of favourable financing conditions was explained in more detail in the speech by the Member of the Executive Board Philip Lane in 25 February 2021 and after the monetary policy meeting of March 2021. In the press conference, President Christine Lagarde explained that the ECB monitors financing conditions from the “upstream” to the “downstream”. Upstream variables include risk-free interest rates and sovereign yields. Downstream variables are linked to the bank lending. The ECB communicated that it will monitor upstream and downstream indicators in a holistic and multifaceted way. However, Lagarde stated that “. . . we focus indeed on what is upstream because that’s where we can act and that’s where banks and providers of financing actually take their cue about the credit terms that they’re going to offer”.

[6]The pace had been somewhat lower than before during the first months of 2021.

[7]Otherwise, asset values would be determined by the discounted stream of returns, quantitative easing leading solely to a reallocation of assets (Eggertsson et al., 2003). Quantitative easing would then merely function as a credibility device to enforce forward guidance announced by the central bank, regarded as a signalling channel. However, other propagation mechanisms arise as soon as a marginal investor is no longer indifferent with respect to the risk profile and to type of different assets (See Krishnamurthy and Vissing-Jorgensen, 2011 and Rostagno et al., 2019 for further discussion).

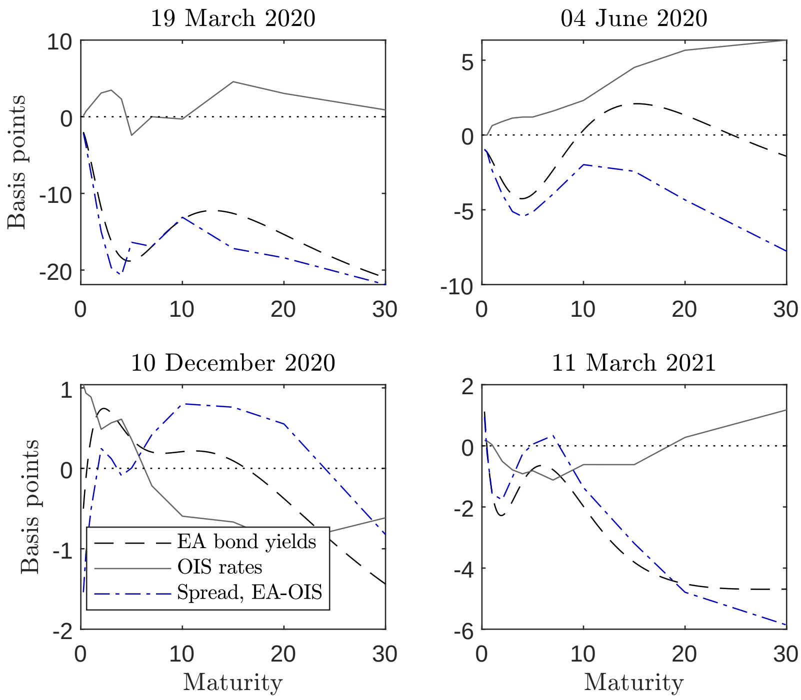

Figure 3: Changes in the interest rates around PEPP announcements
The figure plots a one-day change in the GDP-weighted euro area bond yields (EA bond yields), in the OIS rates and in the spread between the two latter (Spread, EA-OIS) on dates the ECB has communicated about the PEPP. Data sources: Bloomberg and ECB.

Consequently, financing costs and risk premia will be reduced in a broad range of asset classes.

The above transmission mechanism, referred to as portfolio rebalancing, can be regarded as the main transmission channel of the asset purchase programme (APP). Asset purchases are conducted over different jurisdictions according to the ECB capital key and over time by the pace of net asset purchases announced after the monetary meetings of the Governing Council. Central bank purchasing predominantly bonds with longer maturities then compresses the long-term risk-free rates and government bond yields, i.e., they flatten the yield curve. In sum, the portfolio channel operates through the yield curve of the euro area. Eventually, the reduction in financing costs stimulate the economy and increases prices.

The key difference between the APP and the PEPP is the flexibility of the PEPP. As in the APP, the purchase of public sector securities within the PEPP leads to a decrease of long-term bond yields. While the portfolio rebalancing channel significantly characterises the propagation of the PEPP, the programme has additionally an important role in contributing to market stabilisation. That is, amid of market stress and elevated uncertainty, the risk of fragmentation in the euro area heightened, observed as rising sovereign risk premia, seen in Figure 2. The latter trend would have impaired the transmission of risk-free interest rates to sovereign bond yields and to pricing of other assets, hampering efficient monetary policy stimulus. The design of the PEPP particularly serves the market stabilisation role, as the purchases are conducted flexibly over time, jurisdictions and asset classes, depending on the market stress and the need to support favourable financing conditions. In other words, asset purchases within the PEPP and the mere existence of the programme are associated with suppressing the sovereign bond spreads of the euro area jurisdictions.

The character of the PEPP is illustrated in Figure 3 which plots the initial reactions of the risk-free OIS rates, euro area GDP-weighted government bond yields and their difference on dates the ECB has made announcements regarding the programme. On 18 March 2020 late evening, the programme was first announced. On 4 June 2020 and 10 December 2020, the size of the programme was increased and the horizon extended. Finally, on 11 March 2021, the ECB announced to conduct purchases at higher pace than during the first months of the year — during which the pace had been slower than earlier — for the following quarter of the year. As can be seen, the stabilisation role of the PEPP has been prevalent on the announcement dates. On each of the dates the spread between the two interest rates, shown in dot-dashed lines, declined. This euro area sovereign bond spread measure decreased the strongest at the announcement of the programme in March 2020, whereas the change was rather insignificant in December 2020 when the decision was by large expected. On the other hand, the OIS rates, shown in grey solid lines, have moved only moderately on the announcement dates, implying that changes in the spread are mostly due to the compression of average euro area bond yields, depicted in dashed lines. In response to the PEPP announcements, the sovereign bond yields have decreased by remarkably more than the risk-free rates of the euro area.

Longer-term refinancing operations

When considering the transmission channels of TLTROs, a good starting point is to compare these operations with the main refinancing operations (MRO) of the ECB. The first key difference is the maturity. In the MROs, the maturity is one week. In the TLTROs, the maturities of different operations have been multiple years. If no frictions exist, the maturity in refinancing operations plays no role as banks can rollover short-term loans further. However, the maturity becomes important when uncertainty about the future central bank accommodation emerges, the issue referred to as the maturity extension channel (Carpinelli and Crosignani, 2021). That is, the banks could be exposed to rollover risk in the face of possible tightening of the short-term liquidity channel, leading to lower credit supply.

Importantly, the second difference is targeting (T) that makes the TLTROs different from the LTROs. The operations have been targeted on lending to non-financial corporations and households (except loans to households for house purchases): the banks that sufficiently increase their lending to the real economy are entitled to a lower interest rate. The participating banks face thus strong incentives for increasing their lending. This property ensures that banks use the central bank funding for bank lending rather than buying, for example, government debt. Empirical evidence about the effects on bank lending is provided, amongst others, by Benetton and Fantino (2021), Laine (2021) and Andreeva and García-Posada (2021).

Because the participating banks demand less market-based funding, the bank bond yields of participants and non-participants decline. However, the indirect effect on bank lending of non-participating banks is ambiguous (Andreeva and García-

Posada, 2021). On the one hand, the lower funding costs support bank lending. On the other hand, participating banks can gain market shares at the expense of non-participants. Andreeva and García-Posada (2021) find evidence that the former mechanism dominates the latter. In other words, the TLTROs are expected to increase bank lending to non-financial corporations at the aggregate level.

3 The impact of the monetary policy response to the Covid-19 pandemic

This section presents two scenarios to assess what would be the macroeconomic outcome had the ECB kept its monetary policy stance at its pre-pandemic level. First, the design of the simulation and the methodology to measure the effects of monetary policy are discussed. Then, the impact of the asset purchase programmes and longer-term refinancing operations on the macroeconomy is estimated.

3.1 Design of the macroeconomic evaluation of monetary policy measures

We analyse the policy measures by constructing two scenarios. In the baseline scenario, the pandemic-related policy measures have been implemented in their current form. In the counterfactual scenario, no additional measures have been introduced: pandemic-related policy measures would be absent over the period starting from March 2020. That is, monetary policy stance would have been left at the level it was at the onset of the crisis. By comparing the evolution of the variables of interest between the baseline and counterfactual scenarios, the effects of the pandemic-related policy measures can be quantified.

The analysis proceeds in two stages. First, we assess how the interest rates would evolve in the absence of the policy packages. These target interest rates are the variables the programmes are expected to influence directly. As discussed in subsection 2.2, long-term yields and sovereign spreads are directly affected by the asset purchases, whereas the effects of the TLTROs may be seen in the bank lending rate to the non-financial sector. By how much these variables are influenced by the programmes, we rely on evidence from the the existing literature as well as on our personal judgement, discussed in detail in subsections 3.3 and 3.4. Based on this assessment, we build the counterfactual paths that interest rates would follow in the case of less accommodative monetary policy.

Second, conditional on the paths assumed for the interest rates, we use structural vector autoregressions to construct the baseline and counterfactual scenarios for the variables of interest. In particular, we build model forecasts that are policy-conditioned, i.e. they are constructed by variation identified in the SVAR model stemming from monetary policy. Consequently, the difference between the baseline and counterfactual forecasts on variables measure the effects attributable to monetary policy. In the next subsection, we outline the strategy of using structural vector autoregressions in more detail.

3.2 Identification and estimation of the macroeconomic effects of monetary policy

Before turning to the main assumptions about how the interest rates would have moved without the programmes, let us discuss the recovery of causal effects of monetary policy. To construct counterfactuals by which the macroeconomic effects of the monetary policy tools may be measured, it is necessary to find non-systematic variation in monetary policy (See, e.g. discussion in Ramey, 2016). This variation needs to be exogenous of the current economic state and unexpected to the public. Otherwise, the analysis would be based on endogenous reactions of the central bank to the other shocks of the economy, and the causal effects would not be correctly measured.

We measure the effects with two structural vector autoregressive models that use a combination of identifying restrictions to extract shocks that represent different types of monetary policies. Hence, a large range of monetary policy packages that influence the risk-free rates, risk premia and bank lending rates differently may be investigated. The model framework, presented in detail in the appendix, is regularly applied in the monetary policy analysis at the Bank of Finland.

In the shock identification, first, information about the reactions of financial variables around the monetary policy announcements is used to find variation that is most likely unexpected to the public. Specifically, after a monetary policy announcement, the public responds to monetary policy actions that have not yet been internalised by the financial markets. In this respect, the approach follows the large body of literature using the so-called proxy variables (Stock and Watson, 2012; Mertens and Ravn, 2013; Arias et al., 2021) to find the relevant shocks, used in the monetary policy literature by, inter alia, Gertler and Karadi (2015), Caldara and Herbst (2019) and Jarociński and Karadi (2020).

Second, to refine the identification, additionally restrictions are imposed on the reactions of different interest rates and macroeconomic variables. By this way, it is possible to carefully distinguish different types of policy surprises from each other and extract the exogenous variation that is relevant for the macroeconomy. Hence, our results do not hinge upon whether the proxies are fully uncorrelated with the remaining shocks of the economy or how accurately they are measured.[8]

A total of five shocks are identified in the framework.[9] The first three shocks have an initial impact on different parts of the risk-free yield curve and are identified similar to Kortela and Nelimarkka (2020). We refer to these shocks as short-, medium- and long-term monetary policy shocks. The shocks mainly reflect surprise variation stemming from short-term interest rate policy, forward guidance and quantitative easing.[10] To distinguish the three shocks, we impose restrictions on changes in the yields immediately after the monetary policy announcement and on the yield curve response within a month.

[8]Additionally, our approach includes the proxies into the model, in contrast with the proxy SVAR framework (Mertens and Ravn, 2013). The estimated impulse responses are then less subject to the information insufficiency problem (See Plagborg-Møller and Wolf 2021 for further discussion).

[9]See Appendix A.3

[10]See also Altavilla et al. (2019), for a more detailed characterisation of communication of the ECB around the monetary policy meetings. Similarly, Inoue and Rossi (2018) analyse the U.S. monetary policy through shifts in the term structure.

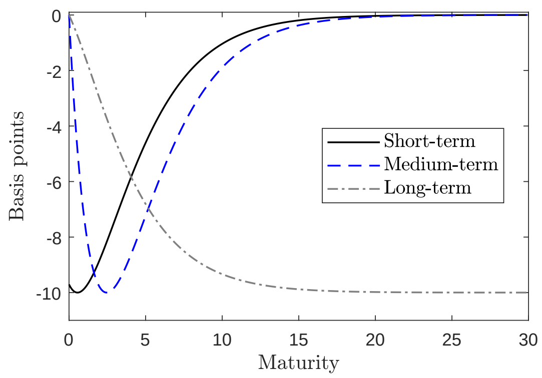

Figure 4: The stylised effects of monetary policy shocks on the forward curve
The figure illustrates the initial effects of the short-term, medium-term and long-term monetary policy on the risk-free forward rates in the face of monetary policy easing.

Figure 4 plots a stylised example of how the short-term, medium-term and long-term monetary policy shocks shift the forward curve immediately after a monetary policy easing measure. First, the central bank may surprise the public by unexpectedly changing the short-term interest rate, i.e. the policy rate. This short-term interest rate shock, shown in the figure with a solid line, is assumed to have the largest impact on the short end of the risk-free yield curve, whereas its effect gradually diminishes on longer maturities. That is, the longer-term rates move according to the expectations hypothesis. In turn, the medium-term monetary policy shock induces a shift in the middle of the forward curve, while the short and long end remain intact, as depicted in Figure 4 in a dashed line. For example, forward guidance informs the economic agents about the future path of the policy rate in the medium term. The changing expectations induce then the strongest shift in the yields maturing from 1.5 to 4 years. The last of the three shocks influences the long-term interest rates the most, while the short end remains intact, depicted in a dashed-dotted line. A prominent example of this policy is quantitative easing that suppresses the term premium of bond yields, as discussed in subsection 2.2.

Let us now introduce the fourth, risk premium shock. Besides the above policies that affect the risk-free interest rates, the central bank may with its communication and actions influence different risk premia and credit spreads directly, without influencing the risk-free yield curve. For instance, by the PEPP, the ECB aimed to prevent the fragmentation of the euro area financial market. To recover surprises in this dimension, we introduce a risk premium policy shock that has no initial effect on the risk-free yield curve. Identified by zero and sign restrictions, the risk premium shock changes the sovereign and corporate bond spreads immediately after the monetary policy announcement and within the same month.

Last, the effects of the TLTRO programme are analysed with a shock on the borrowing costs faced by the non-financial corporations. First, the shock is correlated with changes in the bank bond yields around the dates on which ECB's long-term refinancing programmes have been introduced, discussed or adjusted. Simultaneously, the shock has a zero effect on the risk-free short-term rate. Second, a bank lending shock is assumed to influence the bank lending rate to the non-financial sector in a quarter's time following the shock and changing the aggregate loan volumes with an opposite sign, in line with the main transmission channels of the programme (discussed in subsection 2.2).

To implement the identification, we use the framework of Arias et al. (2018) where a SVAR model with both sign and zero restrictions may be estimated. We use two slightly different model specifications (See Appendix A.2 for details). In the first specification, the PEPP is analysed with the use of the medium-, long- and short-term rate as well as the risk premium shocks. The second specification is used for the evaluation of TLTRO by the three shocks affecting the risk-free yields combined with the bank lending rate shock. The use of two separate but similar models eases computation, as the number of simultaneously identified shocks is shrunk to four and fewer variables are needed in each model. In addition, analysing the PEPP and TLTRO in separate frameworks may allow for complementarities between the programmes to be accounted for (See Ch. 6 of Rostagno et al. 2019 for further discussion).[11]

Finally, the identified shocks are used to construct the counterfactuals, determined by the external information discussed in the next subsections. In particular, we find a series of monetary policy shocks that generate the counterfactual paths for the interest rates in the VAR model. With this shock series, an alternative path for remaining variables of the model is produced, from which the macroeconomic effects may be measured. In other words, we build a forecast conditional on the alternative path of interest rates and compare it with the baseline forecast. The approach is outlined in more detail in Appendix A.5. [12]

With the two SVAR models, we proceed by two simulations that aim to capture the effects of monetary policy measures. In the PEPP simulation, the evolution of variables is computed by the long-term and risk premium shocks conditional on the counterfactual paths of target interest rates with no pandemic-related measures incorporated. Regarding the TLTROs, the counterfactual paths are constructed by the bank lending shock conditional on prior knowledge about the level of bank lending rate in the presence of no additional refinancing operations. In both simulation, the short-term policy rate and its future path is kept at its current level by conventional monetary policy and forward guidance, the path generated by the short-term and medium-term policy shocks.

Naturally, the approach of the paper has certain limitations that induces uncertainty over the estimated effects. First, the SVAR model may not capture the macroeconomic dynamics properly, resulting in distorted estimates. Second, the counterfactual simulations of the study have been made by the perturbation of the system using the monetary policy shocks and their impulse responses. Namely, the results are produced under the assumption that the decision rules of economic agents remain time-invariant despite the arrival of large shocks inducing interest rates to follow the counterfactual paths. If the economic agents would shift their decision rules, our methodology is no more fully valid. Third, the results essentially hinge upon the assessed effects of the policy measures on the interest rates.

[11] As shown in Appendix A.4, the impulse responses estimated from the two models are close to each other for the variables and shocks the models share in common.

[12] Similar strategy in monetary policy analysis has been used, amongst others, by Altavilla et al. (2016) and Rostagno et al. (2019). The approach is more analytically formalised by Waggoner and Zha (1999) and Antolín-Díaz et al. (2021).

3.3 The effects of asset purchases

Let us now consider the impact of pandemic-related asset prices using a scenario, where no additional asset purchase programmes had been implemented.

Assumptions regarding the counterfactuals

We work with an assumption that the risk-free long-term rate and the sovereign bond spread would have remained at higher level if no additional APP envelope and no PEPP had been introduced in March 2020 or later. We first determine the path the interest rates would follow in the absence of expanded asset purchase programmes. Then, the macroeconomic effects are measured from the SVAR model.

As observed in Figure 2, the euro area sovereign bond spread significantly increased in conjunction with both rising long-term rate and euro area government bond yield. The rise in the sovereign bond spread halted shortly after the PEPP was announced. In addition, the 10-year OIS rate started to decline after the announcement of 18 March 2020. While multiple other factors such as the actions of governments and other central banks also explain the stabilisation, the PEPP has arguably played an important role for the dynamics in the euro area financial variables. Its significance can also be seen in Figure 3. On March 19, the euro area government bond spread decreased by almost 20 basis points over the course of the day.

However, determining the exact path for the counterfactual involves a great deal of uncertainty. First, the effects at the announcement dates only capture the unanticipated factor of the programme. However, further actions from the ECB could well have been anticipated at the height of financial stress. Second, the daily change in the yields could have been distorted by counteracting forces related to the ongoing uncertainty present in the financial markets. Third, the situation in the financial market could have escalated in the absence of further measures by the ECB. In that case, the level of risk premia would have been at significantly higher level that could be hard to determine a priori.

We choose to work with an assumption that without the policy packages, monetary policy of the ECB would have tightened, materialising as higher interest rates and spreads. According to our assumption, however, no escalation in the financial markets would have occured but the situation would have been stabilised by factors other than the analysed measures, though, leaving bond yields at a higher level. In recent studies, Aguilar et al. (2020) assess the effects of the March introduction and the June recalibration on the long-term bond yields be approximately 40 basis points. Moessner and de Haan (2021) argue the announcement-related shift of the term premium of government bond yields due to the PEPP was between 10 and 20 basis points, the magnitude also observed in Figure 3. In the preliminary assessment of ECB (2020), the effect of the PEPP on the euro area 10-year government bond yield is assumed to be 45 basis points. In comparison, regarding the pre-pandemic APP programme, Rostagno et al. (2019) work with an estimate that the programme suppressed the 10-year euro area government bond yield by approximately 80 basis points.

Our assumptions regarding the contribution of the pandemic-related asset purchase programmes to the long-term interest rate, sovereign bond spread and gov-

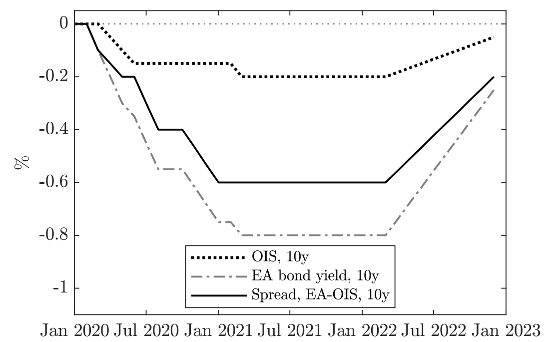

Figure 5: The effects of pandemic-related asset purchases on euro area interest rates (relative to a counterfactual without the measures)
The figure plots the assumed path of 10-year OIS swap rate (OIS, 10y), euro area 10-year government bond yield (EA bond yield, 10y) and the spread between the euro area 10-year government bond yield and the OIS swap rate (Spread, EA-OIS, 10y) relative to the counterfactual scenario without the PEPP and the additional APP envelope.

ernment 10-year bond yield are plotted in Figure 5. The programmes are assumed to have decreased the 10-year OIS rate only moderately, up to 20 basis points, as movements in the variable have been rather small over the course of the pandemic (Figure 2).[13] For the government bond yield, the effects of the March introduction and June recalibration are assumed to be in line with the aforementioned studies, at approximately 40 basis points. However, as the PEPP was further expanded, we assume an additional downward pressure on the euro area government bond spread of approximately 80 basis points by March 2021 due to the programme. In that month, the ECB communicated about accelerating the pace of asset purchases. Combined with Figure 2, our assumptions broadly imply that the euro area interest rates would have remained at the levels they were in March 2020, at the height of the financial turmoil.

Macroeconomic effect of the asset purchases

Given the interest rate paths in Figure 5, we use the SVAR model to estimate the macroeconomic effects. Figure 6 plots the conditional forecasts relative to the counterfactual where the pandemic-related measures would be absent. The policy measures have significantly contributed to the economic growth. On average, the growth of GDP would have been in 2020 and 2021 2 percentage points lower in the absence of additional asset purchases. By the end of 2022, the level of GDP would be approximately 3 percent lower. Similarly, the measures have positively contributed to annual inflation, measured by the year-on-year growth of harmonised index of consumer prices (HICP), that would have otherwise turned persistently negative.[14] Worth mentioning, the policies have additionally had a positive impact on the stock price index (Euro Stoxx 50). In March 2020, the stock price index fell by more than 25 percents. Monetary policy has thus to some extent contributed

[13]It is natural to assume that the additional APP envelope and the PEPP have had an effect on the risk-free long-term rate as well due to the programme following eventually the capital key.

[14]Beyond the horizon shown, the level of GDP converges back to the baseline path in line with the impulse responses plotted in Appendix A.4.

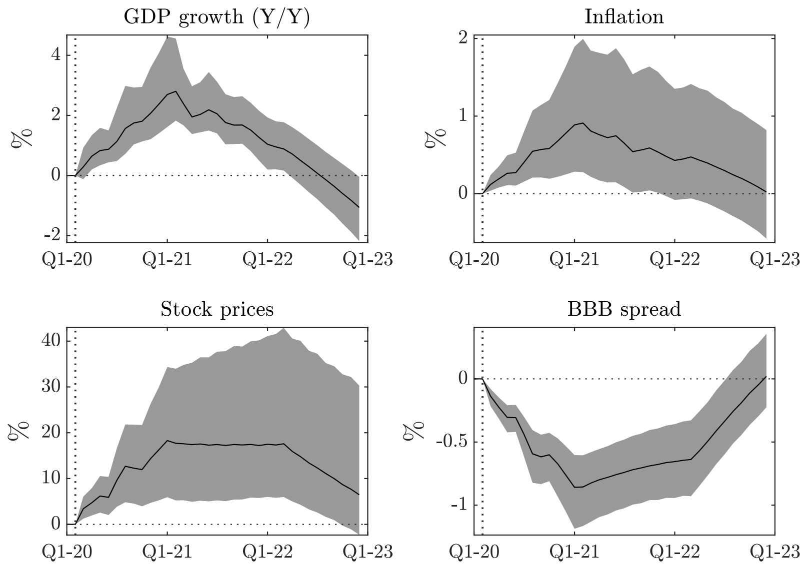

Figure 6: The effects of the pandemic related asset purchases on macroeconomic variables (relative to the scenario with no measures)
The figure shows the path of variables due to the PEPP and additional APP envelope relative to the counterfactual with no policy measures in percentages or percentage points. Posterior medians reported as solid lines. The shaded grey areas are the 68-percent credible sets of the model.

to the recovery of the stock market, although the effects are measured with great uncertainty. Similarly, monetary policy has decreased the spread between the BBB and AAA-rated commercial bond yields.

Our results indicate that the PEPP and the additional APP envelope have had significant macroeconomic effects. Without the measures, the euro area would have experienced even deeper economic recession and longer deflation. Naturally, our results hinge upon the effects presumed on the interest rates, although we judge their magnitude as rather conservative: the counterfactual paths for the long-term rate and sovereign spread are at the levels the interest rates were in 2019. The macroeconomic impact of the extended asset purchases would be considerably larger had the interest rates and spreads hiked up further in the absence of the policy measures, for example, as a consequence of heightened risk of fragmentation.

3.4 The effects of refinancing operations

We turn now to the analysis of pandemic-related TLTRO readjustments. We start by the prior judgement on what are the effects of the policy changes on the bank lending rate to the non-financial sector. Then we present the estimated macroeconomic effects from the SVAR model.

Assumptions regarding the counterfactuals

An increasing number of studies have investigated the effects of longer-term refinancing operations over their existence since 2011. For example, Benetton and Fantino (2021) conclude the first series of the TLTRO to have decreased the lending rate

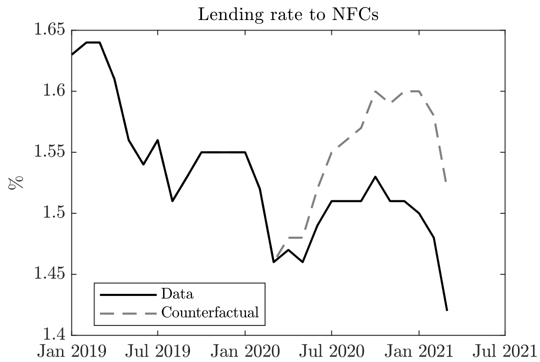

Figure 7: Lending rate to non-financial corporations (NFCs) in 2019–2021 in the actual (data) and in the counterfactual scenario with no recent changes in the refinancing operations
The figure plots the realised path of the lending rate to non-financial corporations (solid line) as well as its assumed counterfactual path (dashed line) where no pandemic-related TLTRO measures are implemented. Data source: Composite cost of borrowing to NFC by the ECB.

by 20 basis points. Laine (2021) estimates the cumulative aggregate effect of the second series of TLTRO on the loan stock to non-financial corporations to be about 10 percent. The results by Altavilla et al. (2020) suggest that the effect of policies during the spring of 2020 averted by about 3 percentage points of the loan volume decline over the period 2020–22. However, as Kwapil and Rieder (2020) note, the estimates seem to be very sensitive to the chosen model specification.

Despite the existence of empirical evidence, determining the counterfactual conditional on a policy with no recalibrations of TLTROs and no PELTROs is challenging. The previous literature focuses on the effects of launching a new series of operations, whereas our aim is to analyse specific changes in the programmes, most notably lowering the interest rate in the existing series of operations. In addition, the effects of the TLTRO parameters specified in these policies may depend on the macroeconomic situation in which they are implemented (see Laine, 2021). Moreover, during the pandemic period, the ECB has made multiple changes to TLTROs. However, in some of these recalibrations, it is not unambiguous whether they have increased or decreased bank lending.[15]

Therefore, the counterfactual exercise regarding the longer-term refinancing operations, which is based on drawing conclusions from the existing literature and on our personal judgement, should be taken with a grain of salt. We assume that without the bank lending related policies during the spring of 2020, the lending rate regarding loans to non-financial corporations would have risen by 10 basis points, as illustrated in Figure 7. We additionally assume the effect of the recalibration of TLTROs and other bank lending related policies materialise with a lag: in the counterfactual the lending rate rises gradually until the end of 2020 and remains at an elevated level until June 2021.[16] The lagged effect is consistent, for example,

[15] For example, at the beginning of the crisis, the ECB lowered the objective for growth in bank lending from 2,5 percent to 0 percent. As a consequence, banks may have even decreased their lending. On the other hand, this recalibration may have increased the lending of other banks that have considered the earlier objective impossible to achieve.

[16] After this period, the path is determined by the model forecast.

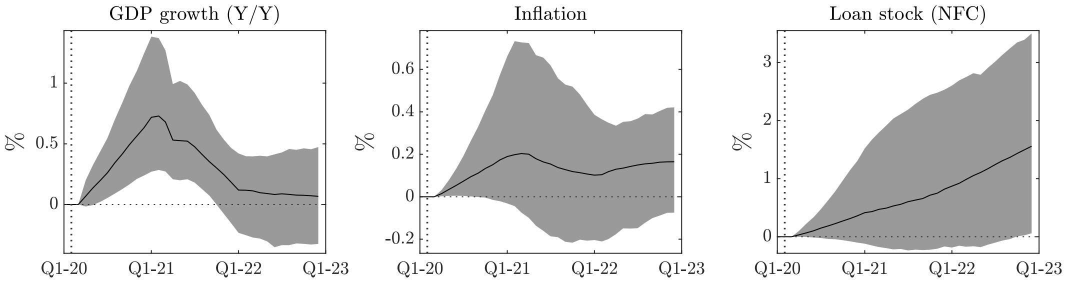

Figure 8: The effects of the TLTRO readjustments on macroeconomic variables (relative to the counterfactual with no measures)
The figure shows the path of variables relative to the counterfactual, where no changes in the bank lending related policies had been introduced. Posterior medians reported as solid lines. Differences shown in percentages or percentage points. The shaded grey areas are the 68-percent credible sets of the model.

with the results of Darracq-Paries and De Santis (2015).

Macroeconomic effects of the TLTRO recalibrations

Figure 8 shows the counterfactuals for the annual GDP growth, annual inflation and loan stock of the financial institutions to non-financial corporations. First, we observe that the assumed path of the lending rate produces a conditional forecast of credit volume relative to the baseline in line with the results of Altavilla et al. (2020). This finding verifies, ex-post, that we are in the right ballpark when it comes to the assumed effect on bank lending rates: both the path of lending rate and the path of lending volume are in line with the existing research.

As seen in Figure 8, the recent bank lending supportive policies have had economically significant macroeconomic effects, given they have put downward pressure on the bank lending rate. Their estimated contributions to the GDP growth and inflation are positive, though, compared to the PEPP, more moderate. Finally, it is important to put emphasis on our working assumption about the path of bank lending rate. In case the latter would have been influenced by the programmes by a smaller (greater) amount, the macroeconomic effects would have been measured less (more) pronounced.

4 Conclusions

In this article, we have evaluated the two main policy measures implemented by the ECB during the Covid-19 pandemic. We find evidence that the extended asset purchases, most notably the pandemic emergency purchase programme (PEPP), and longer-term refinancing operations (TLTROs) have considerably alleviated the negative consequences of the crisis. Among these policies, the PEPP has by its size and significance had the most important contribution to the GDP growth and inflation. By the end of 2021, the level of GDP would be almost 4 percent lower and the level of price index about 1 percent lower, if no additional asset purchases had been made. Had the TLTROs not been recalibrated, the level of GDP would be about 1 percent lower and the level of prices about 0.3 percent lower by the end of 2021.

The analysis has proceeded in two stages. First, we have assessed the financial market reactions of the policy packages and constructed counterfactuals for relevant interest rates. Second, we have employed structural vector autoregressions to measure the effects of the policies on the macroeconomy. Therefore, it must be emphasized, the results hinge upon the assessed effects of the policy measures on the interest rates.

Methodologically, we present a novel identification technique that uses both traditional and proxy-based restrictions to recover the causal effects of monetary policy. Importantly, the framework may be applied to the evaluation of various modern monetary policies and their combinations, once their effects on the yield curve, risk premia and bank lending rate are known.

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A Appendix

A.1 VAR model

Let us first introduce the vector autoregressive (VAR) model used for the analysis of macroeconomic effects. The model is similar to the monetary VAR model used by Kortela and Nelimarkka (2020), where the joint dynamics of both macroeconomic variables and the yield curve are used to identify multiple monetary policy shocks. The macroeconomic variables and yield curve collected in a n-dimensional vector y_t evolve according to a VAR model

$$y_t = c_y + \sum_{i=1}^{p} A_{y,i} y_{t-i} + u_{y,t} \tag{A.1}$$

where c_y is a constant parameter vector $(n \times 1)$ and $\{A_i\}_{i=1}^{p}$ are $n \times n$ coefficient matrices of autoregressive parameters. $u_{y,t}$ is a normally distributed n-dimensional error term with zero mean and covariance matrix Σ_{yy}.

Next, consider k proxies, m_t, informative about a set of structural shocks, discussed later in detail. They follow the process

$$m_t = u_{m,t}, u_{m,t} \sim \mathrm{N}(0, \Sigma_{mm}) \tag{A.2}$$

and are related to y_t through covariance matrix $\mathrm{E}[u_{m,t}u'_{y,t}] = \Sigma_{my}$. m_t and y_t can jointly be written as a proxy-augmented VAR model

$$Y_t = c + \sum_{i=1}^{p} A_i Y_{t-i} + u_t \tag{A.3}$$

with

$$\begin{aligned}
Y_t &= \begin{bmatrix} m_t \\ y_t \end{bmatrix} \\
A_i &= \begin{bmatrix} \mathbf{0}_{k\times k} & \mathbf{0}_{k\times n} \\ \mathbf{0}_{n\times k} & A_{y,i} \end{bmatrix}, \\
c &= \begin{bmatrix} \mathbf{0}_{n\times 1} \\ c_y \end{bmatrix}, \\
u_t &= \begin{bmatrix} u_{m,t} \\ u_{y,t} \end{bmatrix}.
\end{aligned}$$

The error term u_t is normally distributed with zero mean and covariance matrix

$$\Sigma = \begin{bmatrix} \Sigma_{mm} & \Sigma_{my} \\ \Sigma_{ym} & \Sigma_{yy} \end{bmatrix} \tag{A.4}$$

of dimension $(N \times N)$, $N = n + k$

A.2 Variables of the model

The VAR model (A.3) for Y_t consists of two sets of variables, m_t and y_t. The first block, m_t includes serially uncorrelated proxy variables informative about monetary policy shocks, used for identification purposes. Those proxies measure changes in financial variables within a short window around monetary policy announcements and are serially uncorrelated over time. The second block, y_t, contains yields and macroeconomic variables whose dynamic effects are of interest.

Let us first discuss the variables of the second block. In particular, we include the monthly average yield curve to the model, condensed into three factors of the Nelson-Siegel model (Diebold and Rudebusch, 2013). Including the yield curve factors allows to control for the variation in the full spectrum of the term structure. In addition, it facilitates the identification of several monetary policy shocks, as the impulse responses may be derived for an interest rate of any maturity. In particular, by three factors $\beta_t = (\beta_{1,t}, \beta_{2,t}, \beta_{3,t})'$, the instantaneous forward rate at time t of maturity τ is given by

$$f_t(\tau; \beta_t) = \beta_{1,t} + \beta_{2,t}e^{-\lambda\tau} + \beta_{3,t}\lambda\tau e^{-\lambda\tau}, \tag{A.5}$$

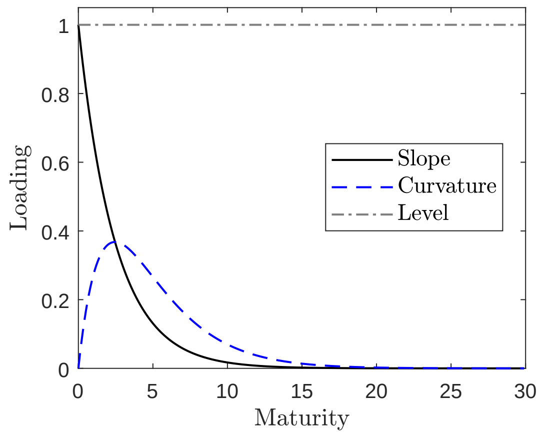


Figure A.1: The loadings of $\beta_{1,t}$, $\beta_{2,t}$ and $\beta_{3,t}$ on the forward curve with $\lambda = 0.4067$.

or, in terms of a yield $y_t(\tau;\beta_t)$ of maturity τ,

$$y_t(\tau;\beta_t) = \beta_{1,t} + \beta_{2,t}\left(1 - e^{-\lambda\tau}\right) + \beta_{3,t}\left(\frac{1 - e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\right) \tag{A.6}$$

From the forward curve (A.5), it is possible to characterise the factors $\beta_{1,t}$, $\beta_{2,t}$ and $\beta_{3,t}$ by their loadings, as illustrated in Figure A.1. $\beta_{1,t}$ with loading 1 is a level factor that has an equal influence on all maturities. It is also the only factor affecting the long-term yields. In turn, $\beta_{2,t}$ has the loading $e^{-\lambda\tau}$ that is decreasing in maturity τ and is called a slope factor. The factor governs the short-term yields and its effects decay to 0 with maturity τ. Finally, $\beta_{3,t}$ is a curvature factor that has the maximum impact on the medium-term maturities, whereas the effect decays to zero when maturity converges to 0 or infinity. The yield curve factors are estimated from daily data on Overnight index swaps (OIS) rates that are generally regarded as proxies for the euro area risk-free yields.[17]

In addition, the following variables are included to vector y_t. First, we consider the euro area Gross Domestic Product (GDP_t), interpolated to monthly frequency by using industrial production and Purchasing Managers' Index (PMI). Prices are measured by the seasonally adjusted Harmonised Index of Consumer Prices ($HICP_t$). The stock price index Euro Stoxx 50 (SP_t) is included to gauge market expectations. The spread between the AAA and BBB-rated commercial bond rates denominated in the euro area ($i_t^{BBB-AAA}$), in turn, controls for changes in credit conditions.[18] The lending conditions to the non-financial sector are measured by loans to the

[17] The OIS rates measure the term structure of EONIA, the overnight unsecured interbank rate in the euro area that closely follows the deposit facility rate of the ECB. The OIS contracts are considered to be free of default risk. We use the OIS data for period starting from 6 January 2006. We extend the time series for the preceding period, from January 1999 to January 2006, by taking the cross-country average of daily yields on government bonds of Germany and France. Using daily data, the yield curve factors are then estimated from the dynamic Nelson-Siegel model with maximum likelihood Diebold and Rudebusch (2013, Ch. 2). Finally, the yield curve factors are aggregated to the monthly frequency.

[18] Data on industrial production, GDP and HICP is collected by Eurostat. The stock price index is formed by STOXX and commercial bond rate series by Macrobond.

non-financial sector (B_t^{NFC}) and by the bank lending rate (i_t^{NFC}).[19] Finally, the sovereign bond spread (i_t^{EA-OIS}) is the difference between the average euro area 10-year government bond yield and the OIS rate, the former computed by the ECB.

In turn, the first block, m_t contains proxies used for the identification of the monetary policy shocks. To introduce notation, consider a change in a financial variable x_t within a short time window on a day the Governing Council of the ECB has held a regular monetary policy meeting, denoted by $\Delta^* x_t$. The time interval starts from the release of the monetary policy statement and ends after the press conference, where the ECB president comments on the decisions made. By the variables of the block, the aim is to capture surprise reactions to monetary policy announcements, i.e. changes in the market expectations about monetary policy. As the variables are measured within a short time interval, it is reasonable to assume them to have no autocorrelation over time, as assumed by the zero restrictions set on the VAR parameters in (A.3).[20]

First, changes in the term structure of risk-free interest rates are captured by the OIS rate movements around the monetary policy meetings of the ECB. These changes are measured by within-day movements in the yield curve factors, $\Delta^*\beta_t = (\Delta^*\beta_{1,t}, \Delta^*\beta_{2,t}, \Delta^*\beta_{3,t})'$.[21] Second, considering the sovereign bond risk around a monetary policy meeting, we use the change in the spread between the 10-year government bond yields between Italy and Germany ($\Delta^* i_t^{10,IT-DE}$). Third, stock prices are taken into consideration by the change in the Euro Stoxx 50 index around the meeting ($\Delta^* SP_t$). The above variables are taken from the Euro Area Monetary Policy Event-Study Database (EA-MPD) compiled by Altavilla et al. (2019) and measured within a time interval starting shortly before the release of the monetary policy statement and ending after the press conference. Additionally, we construct a proxy for surprises in policies affecting the bank lending conditions using changes in the bank bond yields ($\Delta^{**} YTM_t^b$) on dates the ECB has communicated about its longer-term refinancing operations. These dates are the same as used by Altavilla et al. (2020) but extended to cover announcements regarding the third TLTRO programme (TLTRO-III) in 2019.[22]

We specify two VAR models to study on the one hand, the PEPP programme and, on the other hand, the TLTRO programme. In the first, PEPP specification,

$$\begin{aligned} m_t =& (\Delta^*\beta_t', \Delta^* i_t^{10,IT-DE}, \Delta^* SP_t)', \\ y_t =& (\beta_t', GDP_t, HICP_t, i_t^{EA-OIS}, SP_t, i_t^{BBB-AAA})', \end{aligned}$$

while in the second, TLTRO specification,

$$\begin{aligned} m_t =& (\Delta^*\beta_t', \Delta^{**} YTM_t^b, \Delta^* SP_t)', \\ y_t =& (\beta_t', GDP_t, HICP_t, B_t^{NFC}, i_t^{NFC}, SP_t, i_t^{BBB-AAA})'. \end{aligned}$$

[19] B_t^{NFC} is the seasonally adjusted loan stock of monetary and financial institutions to the non-financial corporations taken from the consolidated balance sheet of the ECB. i_t^{NFC} the composite cost of borrowing for non-financial corporations compiled by the ECB.

[20] All proxy variables are aggregated to the monthly frequency by taking the sum. If no announcement takes place in a month, the variable obtains a value of zero.

[21] The high-frequency changes in the factors are derived by ordinary least squares from the static Nelson-Siegel model using the maximum likelihood estimate for λ obtained from the dynamic model.

[22] The additional dates are 7 March 2019 (TLTRO-III announcement), 6 June 2019 (technical details), 29 July 2019 (legal acts published) and 12 September 2019 (interest rate reduced).

By two separate specification, it is possible to shrink the number of variables in a model and to reduce the number of shocks simultaneously to be identified. However, the separation implies that the identified PEPP and TLTRO shocks may be mutually correlated.[23]

As discussed in Appendix A.6 in greater detail, the VAR model is estimated with Bayesian methods using data from 2011M1 onwards. The model is specified in levels.[24] We base the prior distribution on data starting from 1999 until 2010. By the strategy, we focus on the period the ECB has conducted unconventional measures. However, exploiting the presample in the prior allows us to enhance the precision of the estimates.

A.3 Shock identification

To identify the structural shocks, we decompose the reduced-form error term by an impact matrix B $(N \times N)$ as

$$u_t = B\varepsilon_t = B_1\varepsilon_{1,t} + B_2\varepsilon_{2,t}, \tag{A.7}$$

where $\varepsilon_t = (\varepsilon'_{1,t}, \varepsilon'_{2,t})' \sim \mathcal{N}(0, I_N)$, vector $\varepsilon_{1,t}$ contains the n_1 structural shocks of interest and n_2 the remaining, non-identified shocks of the economy, $N = n_1 + n_2$. B_1 and B_2 are matrices of dimensions $(N \times n_1)$ and $(N \times n_2)$, respectively, and $B = \begin{bmatrix} B_1 & B_2 \end{bmatrix}$. Essentially, the identification aims to find the first n_1 columns of impact matrix B, collected in B_1.

The impact matrix B is recovered from the covariance matrix Σ by

$$\Sigma = BB' = PQQ'P', \tag{A.8}$$

where P is a lower-triangular matrix $(N \times N)$ obtained by Cholesky decomposition $\Sigma = PP'$ and Q is an orthonormal matrix $(N \times N)$ with $QQ' = I_N$. The correct orthonormal matrix Q and the corresponding impact matrix $B = PQ$ is found by identifying zero and sign restrictions on the proxies m_t, on the yield curve factors β_t and on the other macroeconomic variables in y_t.

Table A.1 summarises the identifying restrictions for the five monetary policy shocks, the short-term rate shock ε_t^{SR}, the medium-term rate shock ε_t^{MR}, the long-term rate shock ε_t^{LR}, the risk premium shock ε_t^{RP} and the bank lending shock ε_t^{BL}. Restrictions are set on variables in the specification as well as on their transformations. The identification is implemented by two VAR models specified in the previous subsection. In the PEPP specification, the shocks to be identified are ε_t^{SR}, ε_t^{MR}, ε_t^{LR} and ε_t^{RP}. In the TLTRO specification, the shocks are ε_t^{SR}, ε_t^{MR}, ε_t^{LR} and ε_t^{BL}.

The first ingredient of identification is the set of proxies m_y that are assumed to be correlated with the monetary policy shocks. Second, besides the proxies, additional identifying restrictions on the macroeconomic variables and on the monthly yield curve are set to attain macroeconomic relevance for the shocks. That is, the identification does not solely rely on the presumption that proxies are valid and

[23] A similar strategy has also been used by Rostagno et al. (2019) in the study of pre-pandemic policy tools. They interpret the approach to take complementarities between different programmes into account.

[24] The logarithm is taken from GDP, prices, stock prices and loans to non-financial corporations.

	Monetary policy shock				
	ε_t^{SR}	ε_t^{MR}	ε_t^{LR}	ε_t^{RP}	ε_t^{BL}
$\Delta^*\beta_{1,t} + \Delta^*\beta_{2,t}$	$+$	0	0	0	0
$\Delta^*\beta_{1,t}$	0	0	$+$	0	$\cdot$
$\Delta^*\beta_{3,t}$	$\cdot$	$+$	$\cdot$	0	$\cdot$
$\frac{\partial f_t(\tau;\Delta^*\beta_t)}{\partial\tau}$	$-$	$\cdot$	$+$	0	$\cdot$
$\Delta^{**}YTM_t^b$	0	0	0	$\cdot$	$+$
$\Delta^* i_t^{10,IT-DE}$	$\cdot$	$\cdot$	$\cdot$	$+$	$\cdot$
$\Delta^* SP_t$	$-$	$-$	$-$	$-$	$\cdot$
$\beta_{1,t} + \beta_{2,t}$	$+$	0	0	0	0
$\beta_{1,t}$	0	0	$+$	0	$\cdot$
$\beta_{3,t}$	$\cdot$	$+$	$\cdot$	0	$\cdot$
$\frac{\partial f_t(\tau;\beta_t)}{\partial\tau}$	$-$	$\cdot$	$+$	0	$\cdot$
$i_t^{10,EA-OIS}$	$\cdot$	$\cdot$	$\cdot$	$+$	$\cdot$
$i_t^{BBB-AAA}$	$\cdot$	$\cdot$	$\cdot$	$+$	$\cdot$
$i_{t+j}^{NFC}, j = 0,1,2,3$	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$+$
$B_{t+j}^{NFC}, j = 1,2,3$	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$-$
GDP_{t+1}	$-$	$-$	$-$	$-$	$-$
$HICP_{t+1}$	$-$	$-$	$-$	$-$	$-$
$\lvert y_{i,t}\rvert > 0.01$	$\beta_{2,t}$	$\beta_{3,t}$	$\beta_{1,t}$	$i_t^{10,EA-OIS}$	i_t^{NFC}

Table A.1: Identifying restrictions on the impulse responses of the five monetary policy shocks

"+" stands for a positive and "-" for a negative sign restriction on the impulse response of a variable to shock occuring at time t. The subscript t is the impact effect and $t+j$ the impulse response of lag j. By "$\cdot$", no restriction is set or a variable is not in the VAR specification. The last row reports the variables on which a magnitude restriction of minimum effect of 0.01 % is set.

macroeconomically relevant. Third, by the magnitude restrictions, it is ensured that the shocks explain sufficiently variation in the interest rates.

Let us first discuss the identification of the three monetary policy shocks that affect directly the forward curve, i.e. the short-term rate shock ε_t^{SR}, the medium-term rate shock ε_t^{MR} and the long-term rate shock ε_t^{LR}. As illustrated in Figure 4, the three shocks have different effects on the forward rate curve. These shifts are governed by the identifying restrictions set on the yield curve factors β_t and $\Delta^*\beta_t$ and on the derivative of the monthly and within-day forward curve with respect to maturity τ.[25] The conventional monetary policy shock ε_t^{SR} raises the short-term interest rate on impact, $f_t(0;\beta_t) = \beta_{1,t} + \beta_{2,t} > 0$, while the long end remains intact, $f_t(\infty;\beta_t) = \beta_{1,t} = 0$. The effect on the forward rate curve decays to zero when maturity lengthens, i.e. $\frac{\partial f_t(\beta_t;\tau)}{\partial\tau} < 0$. In turn, the medium-term rate shock ε_t^{MR} induces a bell-shaped effect on the curve with both short-term and forward rate remaining zero, $\beta_{1,t} = \beta_{2,t} = 0$ and the curvature factor positive ($\beta_{3,t} > 0$). Third, the long-term interest rate shock ε_t^{LR} leads to an increase in the long-run rate ($\beta_{1,t} > 0$) with no effect on the short end of the yield curve $\beta_{1,t} + \beta_{2,t} = 0$, while the effect increases in maturity $\frac{\partial f_t(\beta_t;\tau)}{\partial\tau} > 0$.

Regarding the risk premium shock ε_t^{RP}, it is imposed to have a zero impact on

[25] In practice, the sign restrictions on the derivative of the forward curve with respect to τ are checked in a numerical grid.

the risk-free yield curve ($\Delta^*\beta_t = \beta_t = 0$) but a positive effect on sovereign bond spreads. That is, the shock leads to an increase in the sovereign bond spread within the monetary policy meeting day ($\Delta^* i_t^{10,IT-DE}$) as well as in the euro area sovereign bond spread ($i_t^{10,EA-OIS}$) and in the commercial bond spread ($i_t^{10,EA-OIS}$) within the month. The shock is thus related to risk premia independent of changes in the long-term yields.

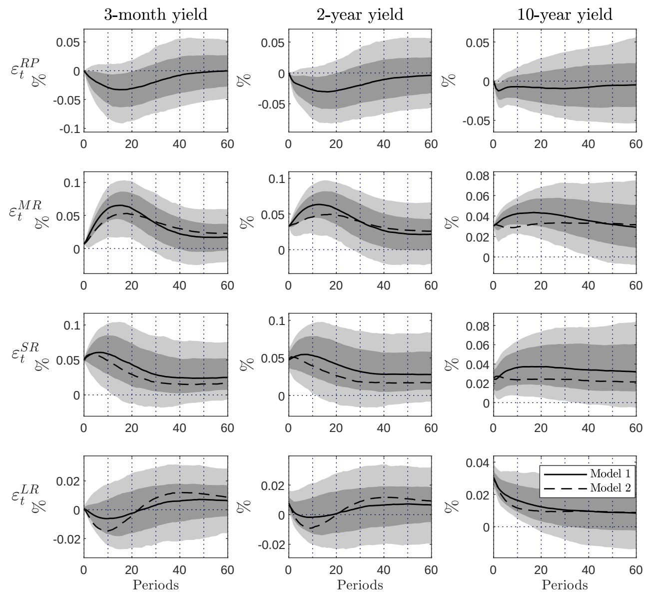
The final shock, ε_t^{BL}, reflects variation in policies related to the bank-lending channel. The contractionary bank lending shock induces a rise in the bond yields of the euro-area-based banks ($\Delta^{**}YTM_t^b$) on days the ECB has communicated about longer-term refinancing operations. We also impose an exclusion restriction according to which the three other monetary policy shocks do not affect the bank bond yields on those days. In addition, the shock is unrelated to conventional policy rate changes: the shock is orthogonal to changes in the short-term interest rate ($\beta_{1,t} + \beta_{2,t} = 0$) but increases the lending rate to non-financial corporations on impact and for the subsequent three months ($i_{t+j}^{NFC} > 0, j = 0, 1, 2, 3$). As monetary transmission of the programme is slow, the shock leads to a decline in the loans to the non-financial sector for the following quarter ($B_{t+j}^{NFC} < 0, j = 1, 2, 3$)

We additionally tackle two additional issue related to the information effect and macroeconomic relevance of the shocks. Shown by Nakamura and Steinsson (2018) for the US and Jarociński and Karadi (2020) for the euro area, the central bank may by its actions inform economic agents about the state of the economy. The existence of this information effect would distort the results as the effects on macroeconomic variables would be of opposite signs. To rule this distortion, we follow Jarociński and Karadi (2020) and impose an additional negative sign restriction on the change of the stock price index around the monetary policy announcement ($\Delta^*STOXX50_t < 0$) for the shocks ε_t^{SR}, ε_t^{MR}, ε_t^{LR} and ε_t^{RP} which are identified by the exogenous variation around the monetary policy announcements. Second, while the proxies provide non-systematic monetary policy variation, all variation does not necessarily incorporate into macroeconomic aggregates in the euro area that is bank-based economy and fragmented into different jurisdictions. We therefore set negative sign restrictions on the first lag of production and prices ($GDP_{t+1} < 0, HICP_{t+1} < 0$).

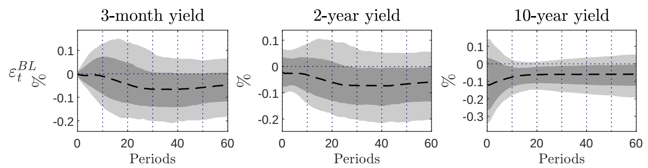
Unlike in the proxy SVAR methodology (Stock and Watson, 2012; Mertens and Ravn, 2013; Arias et al., 2021), we do not impose exclusion restriction on the proxies. The relaxation of the the exclusion restriction provides flexibility to the identification as more zero restrictions on the variables may be set, while still retaining the agnostic nature of the identification. As a further advantage, the number of proxies needs not be equal to the number of identified shocks. We do, however, increase the relevance of the proxies by setting as many zero restrictions in matrix B_2 corresponding to the proxy variables as possible in terms of identifiability.[26] Finally, the relevance of the shocks on the considered interest rate or yield curve factor is ensured by imposing the minimum response to a one-standard-deviation shock be one basis point.

[26]That is, in the methodology of Arias et al. (2018), the number of zero restrictions allowed to be set is $z_j \leq N - j$ for shock j, where z_j is the number of zero restrictions.

A.4 Impulse responses of the variables



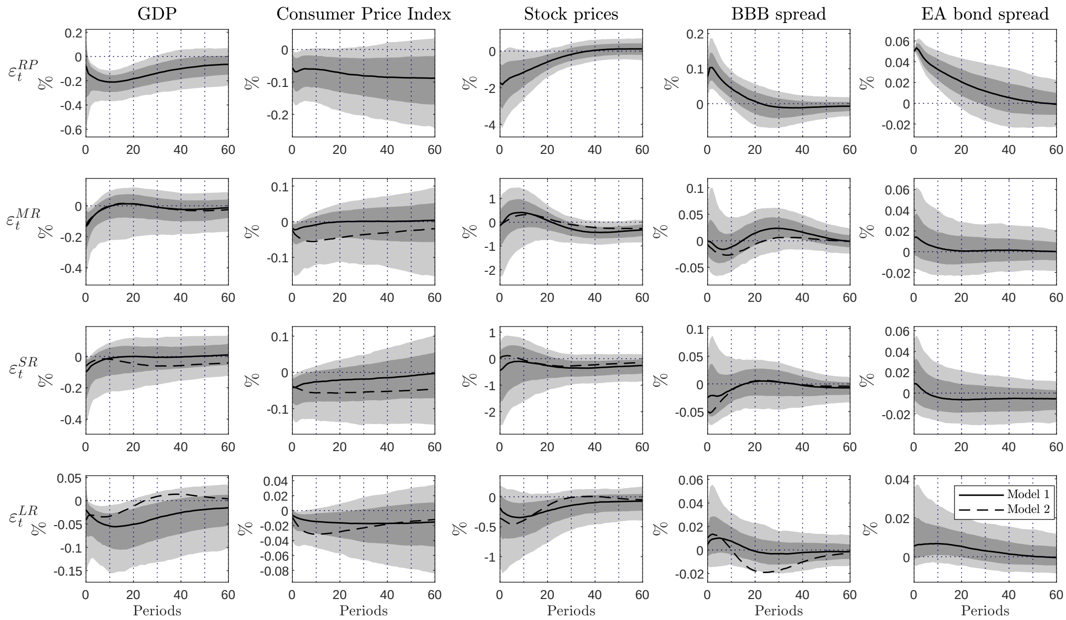
(a) Impulse responses to the shocks ε_t^{RP}, ε_t^{MR}, ε_t^{SR} and ε_t^{LR}



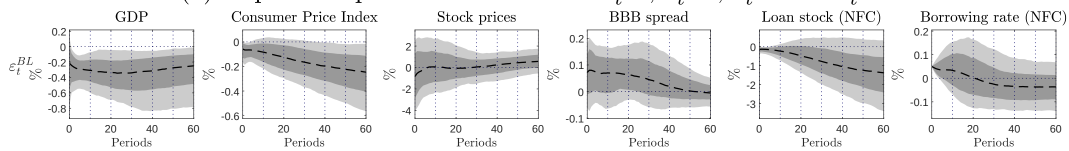
(b) Impulse responses to the shock ε_t^{BL}

Figure A.2: Impulse responses of the interest rates to the identified monetary policy shocks

Impulse responses of the interest rates from the two specifications. The interest rates are derived from the impulse responses of the yield curve factors. Posterior medians reported. Model 1 (solid lines) refers to the specification for the PEPP analysis, Model 2 (dashed lines) to the specification analysing the TLTRO programme. In panel a) 68 % and 90 % credible sets from the Model 1 shown in dark and light grey lines, respectively. In panel b), the credible sets shown from the Model 2.



(a) Impulse responses to the shocks ε_t^{RP}, ε_t^{MR}, ε_t^{SR} and ε_t^{LR}



(b) Impulse responses to the shock ε_t^{BL}

Figure A.3: Impulse responses of to the identified monetary policy shocks
Impulse responses of the interest rates from the two specifications. Posterior medians reported. Model 1 (solid lines) refers to the specification for the PEPP analysis, Model 2 (dashed lines) to the specification analysing the TLTRO programme. In panel a) 68 % and 90 % credible sets from the Model 1 shown in dark and light grey lines, respectively. In panel b), the credible sets shown from the Model 2.

A.5 Simulation design

This subsection sketches the design of the simulations used in Subsections 3.3 and 3.4. More formally, let y_t be a vector of macroeconomic variables. y_t is further decomposed into n_1 target interest rates $(y_{1,t})$ and n_2 other variables $(y_{2,t})$, $n = n_1 + n_2$, $y_t = (y'_{1,t}, y'_{2,t})'$. In the PEPP simulation, the target interest rates are the short-term interest rate $(\beta_{1,t} + \beta_{2,t})$, the 10-year OIS rate $(y_t(10; \beta_t))$ and the euro area sovereign bond spread (i_t^{EA-OIS}). In the TLTRO scenario, the target interest rates are the bank lending rate (i_t^{NFC}) and the short-term interest rate. Our interest is to find a path of macroeconomic variables in the counterfactual, $y_t^* = (y_{1,t}^{*}{}', y_{2,t}^{*}{}')'$, relative to the baseline, $y_t^{bl} = (y_{1,t}^{bl}{}', y_{2,t}^{bl}{}')'$, i.e.

$$y_t^* - y_t^{bl} = \mathrm{E}[y_t | y_{1,t}^*, y_{t-1}^*, \ldots, y_{t_0}^*, y_{t_0-1}, \ldots] - \mathrm{E}[y_t | y_{t-1}^{bl}, y_{t-2}^{bl}, \ldots], \tag{A.9}$$

for the period $t = t_0, t_0+1, \ldots, t_1$ before which the counterfactual and baseline paths are equal. The second term, $E[y_t|y_{t-1}, \ldots]$, is a conditional expectation obtained from the SVAR model. In turn, the first term is a conditional expectation computed from the SVAR model given the a-priori target interest rate path $\{y^*_{1,t}\}_{t=t_0}^{t_1}$ that is induced by the monetary policy considered (Rostagno et al., 2019). The path for target interest rates relative to the baseline,

$$y^*_{1,t} - y^{bl}_{1,t} = \mathrm{E}[y_{1,t}|y^*_{1,t}, y^*_{t-1}, \ldots, y^*_{t_0}, y_{t_0-1}, \ldots] - \mathrm{E}[y_{1,t}|y^{bl}_{t-1}, y^{bl}_{t-2}, \ldots], \tag{A.10}$$

is determined a priori as discussed in the beginning of subsections 3.3 and 3.4. In other words, the left-hand side of the latter equation is known.[27]

Equation (A.9) can be derived after obtaining an expression for its first term. By assumption, the path $\{y^*_{1,t}\}_{t=t_0}^{t_1}$ is generated by monetary policies considered in the analysis. Hence, to compute the policy-induced paths, we use the monetary policy shocks to generate interest rate paths in the SVAR model that align with the counterfactuals. In particular, for the PEPP simulation, the monetary policy shocks used are the forward-guidance-adjusted long-term and risk premium shocks as well as the short-term interest rate shock. By the latter, the short-term interest rate is kept at the level of the baseline scenario. For the TLTRO simulation, the corresponding shocks are the forward-guidance-adjusted bank lending and the short-term interest rate shock. How the forward guidance adjustment is made to the original shock is explained at the end of this subsection.

Let us collect the shocks used in the simulation in vector $\varepsilon_{t,m}$. Note that the first term of (A.9) is equal to

$$\begin{aligned} &\mathrm{E}[y_t|y^*_{1,t}, y^*_{t-1}, \ldots, y^*_{t_0}, y_{t_0-1}, \ldots] \\ =&\mathrm{E}[y_t|y^*_{t-1}, y^*_{t-2}, \ldots, y^*_{t_0}, y_{t_0-1}, \ldots, \varepsilon^*_{m,t}, \varepsilon^*_{m,t-1}, \ldots, \varepsilon^*_{m,t_0}]. \end{aligned} \tag{A.11}$$

where $\{\varepsilon^*_{m,t}\}_{t=t_0}^{t_1}$ are the shocks that generate the target interest rate path relative to the baseline. The latter can be computed from the SVAR model in a straightforward manner when $\{\varepsilon^*_{m,t}\}_{t=t_0}^{t_1}$ are known. These shocks can be recursively derived from

$$y^*_{1,t} - y^{bl}_{1,t} = \mathrm{E}[y_{1,t}|y^*_{t-1}, y^*_{t-2}, \ldots, \varepsilon^*_{m,t}, \varepsilon^*_{m,t-1}, \ldots, \varepsilon^*_{m,t_0}] - \mathrm{E}[y_{1,t}|y^{bl}_{t-1}, y^{bl}_{t-2}, \ldots]. \tag{A.12}$$

by computing SVAR model forecasts with all except the shock $\varepsilon^*_{m,t}$ known.[28] The forecasting period is starting from $t_0 = 2020M3$. After t_1, the computation is continued by unconditional VAR forecasts.

Last, we discuss the forward guidance adjustment made for the monetary policy shocks. As seen in the interest rate responses of Figure A.2, the shocks induce a lagged adjustment of the short-term interest rate. With the policy rate adjustment, instead, the ECB keeps the short-term interest rate at its present level. We exploit the short-term and medium-term shocks to offset the short-term interest rate reactions in the scenarios. First, we derive monetary policy shock that are forward guidance adjusted by considering a linear combination of the policy shock of interest and the medium-term shock, i.e.

$$\tilde{\varepsilon}^i_t = \varepsilon^i_t + a_i \varepsilon^{MR}_t, i = LR, RP, BL. \tag{A.13}$$

[27] Waggoner and Zha (1999) and Antolín-Díaz et al. (2021) derive conditional forecasts for the case, where uncertainty about $y^*_{1,t} - y^{bl}_{1,t}$ is involved. Instead, we choose to work with scenarios where the uncertainty reflected in the results stem from the SVAR model. The results are easily scalable for different magnitudes in the interest rate paths.

[28] This is equivalent to scaling a series of impulse responses of the target interest rates to the considered monetary policy shocks to align with $y^*_{1,t} - y^{bl}_{1,t}$.

Constant a_i is found from the optimisation problem

$$a_i = \arg\min \left(\sum_{j=1}^{24} \frac{\partial(\beta_{1,t+j} + \beta_{2,t+j})}{\partial \varepsilon_t^i} + a_i \frac{\partial(\beta_{1,t+j} + \beta_{2,t+j})}{\partial \varepsilon_t^{FG}} \right)^2 . \tag{A.14}$$

In other words, forward guidance adjustment implies that the impulse response of the policy rate is set for the following 2 years to be on average 0. Second, as the forward guidance adjustment does not imply an exact equality between the counterfactual and baseline short-term interest rate paths, the remaining discrepancy is removed by the short-term interest rate shock according to (A.10). The used strategy takes more properly into consideration the anticipation effects compared to offsetting the adjustment by the surprise short-term interest rate shock only.

A.6 Bayesian estimation of the model

The model is estimated with Bayesian methods with normal-inverse-Wishart prior distribution. However, unlike in the standard approach, the zero restrictions set on the autoregressive matrices $\{A_i\}_{i=1}^p$ imply that the posterior distribution is non-standard. In the usual setting, a standard Gibbs sampler could be used to draw the posterior draws. However, the combination of sign and zero restrictions implies that the model is only set-identified. To construct credible sets and posterior medians, we follow Arias et al. (2018) and infer the sign restrictions being a part of the prior distribution such that posterior distribution reflects uncertainty in both reduced-form parameters and structural identification. This requires, in turn, that the parameters should efficiently and independently be drawn from posterior distribution, as the latter is conditional on the imposed sign and zero restrictions.

To derive the posterior, let us first consider the standard likelihood function of the system

$$p(Y|A, \Sigma) \propto |\Sigma|^{-T/2} \exp\left(-\frac{1}{2} \mathrm{tr} \left(Y - ZA)'(Y - ZA)\Sigma^{-1} \right) \right), \tag{A.15}$$

where $Y = \begin{bmatrix} Y_1 & \cdots & Y_T \end{bmatrix}'$, $Z = \begin{bmatrix} Z_1' & \cdots & Z_T' \end{bmatrix}'$, $Z_t = \begin{bmatrix} Y_{t-1}' & \cdots & Y_{t-p}' & 1 \end{bmatrix}$, $A = \begin{bmatrix} A_1 & \cdots & A_p & c \end{bmatrix}'$. Matrices Y, Z, and A are of dimensions $(T \times N)$, $(T \times K)$ and $(K \times N)$, respectively, and $K = Np + 1$. Assuming a general, independent normal-inverse-Wishart prior distribution

$$p(\alpha_y) = \mathcal{N}\left(\underline{\alpha}_y, \underline{V}_\alpha \right), \tag{A.16}$$

$$p(\Sigma) = \mathcal{W}^{-1}\left(\underline{S}, \underline{\nu} \right), \tag{A.17}$$

with $\alpha_y = \mathrm{vec}(A_y)$, $A_y = \begin{bmatrix} A_1 & \cdots & A_p & c_y \end{bmatrix}'$, $\alpha = R_\alpha \alpha_y$, degrees of freedom $\underline{\nu}$ and positive definite $(N \times N)$ scale matrix $\underline{S}$, it is straightforward to show that the posterior distribution reads as

$$\begin{aligned} p(A_y, \Sigma|Y) \propto & \exp\left(-\frac{1}{2} (\alpha_y - \underline{\alpha}_y)' \bar{V}_\alpha^{-1} (\alpha_y - \underline{\alpha}_y) \right) \\ & |\underline{V}_\alpha|^{-1/2} |\Sigma|^{-\frac{\bar{\nu}+n+1}{2}} \\ & \exp\left(-\frac{1}{2} \left(\underline{\alpha}_y' \underline{V}_\alpha^{-1} \underline{\alpha}_y - \bar{\alpha}_y' \bar{V}_\alpha^{-1} \bar{\alpha}_y \right) - \mathrm{tr}\left(\underline{S} + Y'Y \right) \Sigma^{-1} \right), \end{aligned} \tag{A.18}$$

where $\bar{\nu} = \underline{\nu}+T$, $\bar{V}_\alpha^{-1} = R'_\alpha(\Sigma\otimes Z'Z)R_\alpha+\underline{V}_\alpha^{-1}$ and $\underline{\alpha}_y = \bar{V}_\alpha\left(R_\alpha(\Sigma^{-1}\otimes Z)y+\underline{V}_\alpha^{-1}\underline{\alpha}_y\right)$, $y = \text{vec}(Y)$. Here, R_α is a $(KN \times KN - r^*_\alpha)$ selection matrix that maps the unrestricted elements of A, collected in a $n(np+1)$-dimensional vector $\alpha_y = \text{vec}(A_y) = \text{vec}\left(\begin{bmatrix}A_{y,1} & \cdots & A_{y,p} & c_y\end{bmatrix}'\right)$ to parameter vector α such that matrices $\{A_i\}_{i=1}^p$ are defined according to (A.3). Hence, the number of restrictions is equal to zeros in matrix A, i.e. $r^*_\alpha = k + kNp + nkp$.

In (A.18), the first row corresponds to the posterior distribution of α_y conditional on Σ. On the hand, the second and third row represent the unconditional posterior of Σ. However, given the general prior distribution (A.16), the latter posterior is of unknown form and difficult to draw from. What follows, we assume the prior distribution be conditional normal-inverse-Wishart, $p(A_y,\Sigma) = p(A_y|\Sigma)p(\Sigma)$:

$$\alpha_y|\Sigma \sim\mathcal{N}\left(\underline{\alpha}_y, \bar{\Sigma}\otimes\underline{Q}\right), \tag{A.19}$$

$$\Sigma) \sim\mathcal{W}^{-1}\left(\underline{S},\underline{\nu}\right), \tag{A.20}$$

where $\bar{\Sigma} = \Sigma_{yy} - \Sigma_{ym}\Sigma_{mm}^{-1}\Sigma_{my}$. In particular, the choice of $\bar{\Sigma}$ given the selection matrix R_α allows us to write the posterior variance of α_y as

$$\bar{V}_\alpha = \left(\left(\bar{\Sigma}^{-1}\otimes Z'_yZ_y\right)+\left(\bar{\Sigma}^{-1}\otimes\underline{Q}\right)\right)^{-1} = \bar{\Sigma}\otimes\left(Z'_yZ_y+\underline{Q}\right)^{-1}, \tag{A.21}$$

where $Z_y = \begin{bmatrix}Z'_{y,1} & \cdots & Z'_{y,T}\end{bmatrix}'$ and $Z_{y,t} = \begin{bmatrix}y'_{t-1} & \cdots & y_{t-p}\end{bmatrix}$. The prior is thus a standard normal-Wishart Minnesota-Littermann prior but with one modification for the autoregressive parameters of y_t: the variance of A_y is scaled by matrix $\bar{\Sigma}$ instead of Σ_{yy}. Conveniently, if no proxies are included, the prior reduces to the conventional normal-inverse-Wishart prior, and the posterior is standard with covariance of α given by $\bar{V}_\alpha = (\Sigma_{yy}\otimes Z'_yZ_y)$. When proxies are included, the scaling of variance of autoregressive parameters through $\bar{\Sigma}$ takes the joint dynamics of Y_t into account.

Using this prior, it is possible to derive the posterior for reduced-form parameters as

$$\begin{aligned}
p(A_y,\Sigma|Y) \propto\ & \underbrace{|\bar{V}_\alpha|^{-1/2}\exp\left(-\frac{1}{2}(\alpha_y-\underline{\alpha}_y)'\bar{V}_\alpha^{-1}(\alpha_y-\underline{\alpha}_y)\right)}_{\alpha_y\sim\mathcal{N}(\underline{\alpha}_y,\bar{V}_\alpha)}\cdot\\
& \underbrace{|\Sigma_{mm}|^{-\frac{\bar{\nu}-n+k+1}{2}}\exp\left(-\frac{1}{2}\text{tr}\left((\Phi_{mm}+\Omega_{y,mm})\Sigma_{mm}^{-1}\right)\right)}_{\Sigma_{mm}\sim\mathcal{W}^{-1}(\Phi_{11}+\Omega_{y,11},\bar{\nu}-n)}\cdot\\
& \underbrace{|\bar{\Sigma}|^{-\frac{\bar{\nu}+n+1}{2}}\exp\left(-\frac{1}{2}\text{tr}\left(\bar{\Phi}\bar{\Sigma}^{-1}\right)\right)}_{\bar{\Sigma}\sim\mathcal{W}^{-1}(\bar{\Phi},\bar{\nu})}\cdot\\
& |\bar{\Sigma}|^{-\frac{k}{2}}|\Phi_{mm}^{-1}|^{-\frac{n}{2}}|\Sigma_{mm}|^{-n}\exp\Bigg(-\frac{1}{2}\text{tr}\Big(\left(\Sigma_{mm}^{-1}\Sigma_{my}-\Phi_{mm}^{-1}\Phi_{my}\right)'\cdot\\
& \underbrace{\Phi_{mm}(\Sigma_{mm}^{-1}\Sigma_{my}-\Phi_{mm}^{-1}\Phi_{my}\Big)\bar{\Sigma}^{-1}\Bigg)}_{\Sigma_{mm}^{-1}\Sigma_{my}|\Sigma_{mm},\bar{\Sigma}\sim\mathcal{MN}_{k,n}(\Phi_{mm}^{-1}\Phi_{my},\Phi_{mm}^{-1},\bar{\Sigma})}\quad,
\end{aligned} \tag{A.22}$$

where Φ_{mm}, $\Omega_{y,mm}$, $\bar{\Phi}$ and Φ_{my} are functions of hyperparameters and data. In other words, $\bar{\Sigma}$ and Σ_{mm} can be unconditionally drawn from the inverse-Wishart distributions. Conditional on $\bar{\Sigma}$ and Σ_{mm}, $\Sigma_{mm}^{-1}\Sigma_{my}$ can be drawn from the matrix variate normal distribution and be solved for Σ_{my}. Using these draws, it is possible to solve for Σ_{yy} and construct the covariance matrix Σ. Finally, conditional on Σ, the autoregressive parameters in A_y can be drawn from the normal distribution and be mapped into A by the selection matrix R_α.

Turning to structural analysis and to constructing the corresponding credible sets, we follow the strategy of Arias et al. (2018) that provide inference based on zero and sign restrictions. By the orthonormal matrix Q, the reduced-form parameters may be mapped into the structural parameters. Furthermore, treating matrix Q random with prior density $p(Q)$ allows us to draw structural parameters from the posterior density

$$p(A_y, \Sigma, Q|Y) \propto p(A_y, \Sigma|Y)p(Q)S(A_y, \Sigma, Q) \tag{A.23}$$

where $p(Q)$ is the uniform distribution with respect to the Haar measure $(\mathcal{O})(\mathcal{N})$ conditional on the zero restrictions set on matrix B.[29] In addition, $S(A_y, \Sigma, Q)$ is an indicator function obtaining a value of 1 if the sign restrictions are satisfied and 0 otherwise.

Using these results, drawing from posterior conditional on the sign and zero restriction may be proceeded by the following steps. First, draw A_y and Σ from $p(A_y, \Sigma|Y)$ and construct A and decompose $\Sigma = PP'$. Second, for each shock $j = 1, \ldots, n$, draw the jth column of matrix Q from $p(Q)$ conditional on z_j zero restrictions, $0 \leq z_j \leq N - j$, collected in a $(z_j \times r)$ matrix Z_j such that the impulse responses of r variables to shock j, $F_j(A, P, Q)$ of dimension $(r \times 1)$ satisfy $Z_j F_j(A, P, Q) = 0$. This second step is proceeded by the algorithm described in Arias et al. (2018). Third, given the draws A_y, Σ and Q, compute the relevant impulse responses and use function $S(\cdot)$ to check whether the sign restrictions hold. If they hold, keep the posterior draws and disregard otherwise. Finally, the algorithm is repeated until the required number of accepted draws is obtained. After drawing a sufficient number of posterior draws, the construction of posterior medians and credible sets is straightforward.[30]

We estimate the model for sample covering the months from 2011M1 until 2020M3, into a period when the ECB has introduced various unconventional policy measures. In addition, we use data from 1999M1 until 2010M12 as our presample, on which the prior distributions are based. Specifically, we apply the Minnesota prior to estimate the parameters of the model in the presample for variables in y_t, and the obtained posterior is used as a prior for the estimation of the model in the main sample starting from 2011.[31]

[29] For a more thorough exploration of the issue, see Arias et al. (2018).

[30] In contrast to Arias et al. (2018), we do not take the volume element into account in the computation of the posterior draws. For a large number of variables and shocks as well as restrictions set on the reduced-form parameters, the computation of the term suffers from numerical instability. It is also arguable that the risk of reordering of the shocks can be treated small given a large number of sign restrictions and shocks in the model.

[31] That is, we estimate the model $y_t = c_y + \sum_{i=1}^{p} A_{y,i} y_{t-i} + u_{y,t}$ on the presample with priors $\alpha_y|\Sigma_{yy} \sim \mathcal{N}(\underline{\alpha}_y, \Sigma \otimes \underline{Q})$ and $\Sigma_{yy} \sim \mathcal{W}^{-1}(\underline{S}_{yy}, \underline{\nu})$ to obtain the conjugate posterior for α_y and Σ_{yy} that follow $\mathcal{N}(\bar{\alpha}_y, \Sigma \otimes \bar{Q})$ and $\mathcal{W}^{-1}(\bar{S}, \bar{\nu})$, respectively (see. e.g. Dieppe et al. 2016 for a detailed

derivation). We impose the unit-root prior for the mean $\underline{\alpha}_y$. The prior variance of autoregressive parameter of equation i corresponding to variable j on lag l is set to $\frac{\sigma_i^2}{\sigma_j^2}\left(\frac{\lambda_1}{l^\delta}\right)^2$ with overall tightness $\lambda = 0.2$ and decay $\delta = 2$. The prior variance considering the constant is diffuse. $\bar{\alpha}_y$, $\bar{Q}$ and $\bar{S}_{yy}$ are used as prior in deriving the final posterior.