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Exchange rate shocks and inflation comovement in the euro area

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Abstract

This paper decomposes the time-varying effect of exogenous exchange rate shocks on euro area countries inflation into country-specific (*idiosyncratic*) and region-wide (*common*) components. To do so, we propose a flexible empirical framework based on dynamic factor models subject to drifting parameters and exogenous information. We show that exogenous shocks to the EUR/USD exchange rate account for over 50% of nominal EUR/USD exchange rate fluctuations in more than a third of the quarters of the past six years, especially in turning point periods. Our main results indicate that headline inflation in euro area countries, and in particular its energy component, has become significantly more affected by these exogenous exchange rate shocks since the early 2010s, in particular for the region's largest economies. While in the case of headline inflation this increasing sensitivity is solely reliant on a sustained surge in the degree of comovement, for energy inflation it is also based on a higher region-wide effect of the shocks. By contrast, purely exogenous exchange rate shocks do not seem to have a significant impact on the core component of headline inflation, which also displays a lower degree of comovement across euro area countries.

Keywords: Exchange Rate, Inflation, Factor Model, Structural VAR model.

JEL Classification: C32, E31, F31, F41.

Non-technical summary

Recent empirical research has shown that the size, duration, and even the sign of the pass-through to prices of exchange rate fluctuations depend on the origin of the shocks behind exchange rate fluctuations (for instance, Forbes et al. (2015, 2018), and following the work of Shambaugh (2008)). Exchange rate fluctuations over a short period of time could be a result of a variety of factors, such as: domestic or foreign demand and supply shocks, monetary policy shocks and risk premium, or exogenous exchange rate shocks. Theoretical models suggest several ways in which the exchange rate-prices nexus is shock-dependent and this is corroborated by the empirical estimates listed above. Yet, if the impact on prices in the euro area varies over time as the result of the changing composition of shocks driving the exchange rate movements, are those time variations related to country-specific or to common euro area-wide forces?

This paper builds on the empirical literature of shock-dependent exchange rate pass-through. It elaborates on the time variation and cross-country differences in responses of different price components to exchange rate changes in the euro area. Our proposed framework fills the gap in literature by jointly estimating the effect of region-wide euro area exchange rate shocks on the inflation rates associated with country-specific economies. There are many sources of exchange rate fluctuations, the paper focuses only on exogenous exchange rate shocks. This is partly because we seek to imitate insofar as possible the concept of exchange rate pass-through in a shock-dependent context: we isolate the transmission to prices of "pure" exchange rate shocks from the joint reaction of prices and exchange rates to other structural shocks such as demand, supply or monetary policy shocks. Our results suggest that such exogenous shocks to the exchange rate are paramount: They are behind more than 50% of nominal EUR/USD exchange rate fluctuations in more than a third of the quarters of the past six years - especially in turning points periods.

Our main results indicate that headline inflation, and in particular its energy component, has become significantly more affected by these exogenous exchange rate shocks since the early 2010s, in particular, for the largest economies of the region. While in the case of headline inflation this increasing sensitivity is solely reliant on a sustained surge in the degree of comovement, for energy inflation it is also based on a higher region-wide effect of shocks. For food inflation, the effect of exogenous exchange rate shocks is similar to that of headline inflation, but to a much lower extent. By contrast, purely exogenous shocks do not seem to have a significant impact on the core component of headline inflation, which also displays a lower degree of comovement across euro area countries.

The framework herein detailed is not meant or able to capture structural differences across countries that are relevant in explaining different impacts of exchange rate movements such as the role of invoicing currency, whether transactions take place between or within firms, the frequency and dispersion of price adjustments, the integration in Global Value Chains (GVC) or the role of competition in final products markets. It does, however, add an important new dimension to the standard approach for analyzing the exchange rate pass-through. Decomposing the effect of pure exogenous exchange rate shocks on euro area countries inflation into country-specific (idiosyncratic) and region-wide (common) components from a time-varying perspective should improve our understanding to assess the impact of currency movements and, as a result, help central banks to set an appropriate monetary policy.

1 Introduction

In the context of flexible exchange rate markets, such as the euro and the USD markets, the exchange rate becomes a relative price which reacts to any news or information that generates changes in the perception of the value of real and financial assets in the corresponding economies. Exchange rate fluctuations over a short period of time may be due to a variety of reasons, which can be broadly grouped into three categories. First, new developments relating to the fundamentals that determine the growth of each economy, on either the demand or supply side. Second, perceived changes in countries' respective monetary policies which, since they determine official interest rates, have a bearing on the relative return or performance of the financial assets associated with each economy. Third, risk premium shocks not directly linked to economic or monetary fundamentals which can prompt strong and swift movements in exchange rate dynamics that are hard to identify and predict; these are usually referred to as exogenous exchange rate shocks.

From a policymaker's standpoint, assessing the impact that currency movements have on price inflation is crucial for the design of a monetary policy framework. A clearer understanding of the transmission channels may improve the ability to predict the impact, and to better understand the effects of central banks' actions to influence the relative price of their currency and its relation with domestic prices. As a result, a prolific literature has focused on analysing the degree to which a country's import, producer or consumer prices change in response to its exchange rate fluctuations. This is commonly known as exchange rate pass-through (hereafter, ERPT).[1] The literature on ERPT ranges from seminal theoretical studies (Krugman (1987), Dornbusch (1987) and Corsetti et al. (2008)), which showed that ERPT to prices was incomplete due to imperfect competition and pricing-to-market, to cross-country empirical evidence (Campa and Goldberg (2005, 2010)) which focused on slow-moving structural determinants, such as changes in the composition of imports. Recently, there have been more efforts to identify the factors behind the changes in ERPT over time from a micro data perspective on firm pricing (Gopinath et al. (2010), Berger and Vavra (2013), Devereux et al. (2015) and Amiti et al. (2016)). These works

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[1] More specifically, it is usually defined as the percentage change in prices in response to a 1% change in the exchange rate.

highlight drivers such as the role of invoicing currency, whether the transactions take place between or within firms, the frequency and dispersion of price adjustments and the role of competition in final product markets.

A recent line of empirical research has provided evidence that the size, duration and even the sign of the ERPT depend on the origin of the shocks behind exchange rate fluctuations. For instance, Forbes et al. (2015, 2018), following the work of Shambaugh (2008), estimate a structural Vector Autoregression (SVAR) framework for the United Kingdom as a small open economy. The authors highlight that in order to explain how this pass-through has evolved, it is essential to distinguish the driving forces behind the exchange rate fluctuations (i.e. whether they are due to domestic demand, global demand, domestic monetary policy, global supply shocks, domestic productivity, etc.). They find that domestic monetary policy shocks are those with a relatively higher response of prices relative to the exchange rate response. A similar result was found for the euro area by Comunale and Kunovac (2017), using the same methodology. Their estimates point to a large but volatile pass-through to import prices and overall a very small pass-through to consumer inflation in the euro area, lower than in previous decades.[2]

Theoretical models suggest a number of ways in which the exchange rate-prices nexus is shock-dependent and empirical estimates such as the ones above corroborate this. Yet, if the impact on prices varies over time in the euro area due to the changing composition of shocks driving the exchange rate movements, are those time variations related to country-specific and/or euro area-wide forces? The above-mentioned literature is silent on the cross-country heterogeneity inherent in a set of economies that share their currency and monetary policy. Our proposed framework overcomes this drawback by jointly estimating the effect of euro area (region-wide) exchange rate shocks on the inflation rates associated with the different economies (country-specific).

This paper builds on the literature on shock-dependent exchange rate pass-through and

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[2] Using reduced-form approaches (not shock-dependent), a body of empirical literature has put forward ERPT estimates for the euro area, showing evidence that the ERPT to consumer prices is about a tenth of that to import prices. Structural DSGE models, which consider the different transmission of different structural shocks, tend to deliver a higher and more gradual pass-through to consumer prices. For further details, see Ortega and Osbat (2020) and references therein such as Hahn (2003), Ösyurt (2016) and Jasová et al. (2016).

elaborates further on the time variation and cross-country differences in the response of different price components to exchange rate changes in the euro area. Of all the sources of exchange rate fluctuations, this paper focuses only on exogenous exchange rate shocks. This is partly because we seek to imitate insofar as possible the concept of exchange rate pass-through in a shock-dependent context: we isolate the transmission to prices of 'pure' exchange rate shocks from the joint reaction of prices and exchange rates to other structural shocks such as demand, supply or monetary policy shocks. Also, we focus on exogenous exchange rate shocks for an empirical reason. As shown in our empirical results (see Figure 1), structural shocks other than exogenous exchange rate shocks account for an important share of the change in the nominal EUR/USD exchange rate, for around 65% since 1995 to be precise. However, exogenous exchange rate shocks have played a bigger part in unanticipated nominal exchange rate movements, not only in recent years but also during turning point periods. Our findings indicate that they are behind more than 50% of nominal EUR/USD exchange rate fluctuations in more than a third of the quarters of the past six years.

The contribution of this paper is twofold. First, we investigate potential changes over time in the effect that exogenous exchange rate shocks have on headline inflation in euro area countries and on its corresponding components. For ease of exposition, we can express this goal in simple terms with the following equation,

$$INF_{i,t} = \phi_i(L)INF_{i,t-1} + \beta_{i,t}\epsilon_t^{ER} + v_{i,t}, \tag{1}$$

where $INF_{i,t}$ is the inflation rate of country i at time t, the term $\phi_i(L)$ helps control for past inflation dynamics, the exchange rate shocks are measured by ϵ_t^{ER}, and $v_{i,t}$ represents an error term.[3] Note that in equation (1), our object of interest is the dynamics of $\beta_{i,t}$, which measures the changing sensitivity of inflation to exchange rate shocks.[4]

Second, we decompose the sensitivity of inflation to exchange rate shocks across euro area economies into two parts: one is exclusively related to the inflation dynamics of

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[3] The lag operator is denoted by L.

[4] The estimation of Equation (1) can be directly calculated for other sources of exchange rate fluctuations, but in those cases it is harder to interpret $\beta_{i,t}$ as ERPT.

country i and the other common to all euro area countries. In other words, the latter can be interpreted as the sensitivity of country i inflation to exchange rate shocks that is formed jointly with other countries of the region. The following equation illustrates this decomposition,

$$\beta_{i,t} = IDI_{i,t} \times COM_t, \tag{2}$$

where $IDI_{i,t}$ denotes the idiosyncratic, country-specific component and COM_t denotes the common, region-wide component. The information contained in equation (2) can be useful for policy makers to understand the extent to which movements in inflation of a given country, brought about by exchange rate shocks, can be attributed to its exclusive and intrinsic economic performance or to the overall performance of all monetary union partners.

To jointly assess both the time-variation in the sensitivity of inflation to exogenous exchange rate shocks and its decomposition into country-specific and region-wide components, we adopt a unified multi-country perspective. In particular, we first identify such exchange rate shocks using a structural VAR model for the aggregate euro area economy. To ensure that shocks have the expected effect on the macroeconomy, according to theoretical models or stylised facts, we base our identification scheme on sign and exclusion restrictions, along the lines of Shambaugh (2008), Comunale and Kunovac (2017) and Forbes (2015, 2018). Next, we use the exchange rate shocks as exogenous information in a dynamic factor model with drifting coefficients for inflation in the euro area economies.[5] This empirical framework allows us to make accurate comparisons of the results across the different economies. In particular, it provides a full spectrum of the effect of exogenous exchange rate shocks on inflation (i) across countries, (ii) by subcomponents and (iii) over time.

The main results show that the sensitivity of headline inflation to exogenous exchange rate shocks has increased since the early 2010s. In other words, an unexpected appreciation of the euro versus the dollar leads to larger declines in inflation than before. Such an increase is systemic and broad based since most euro area countries have experienced it.

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[5] The euro area monetary union comprises 19 EU member states: Belgium (BE), Germany (DE), Estonia (EE), Ireland (IE), Greece (GR), Spain (ES), France (FR), Italy (IT), Cyprus (CY), Latvia (LV), Lithuania (LT), Luxemburg (LU), Malta (MT), the Netherlands (NL), Austria (AT), Portugal (PT), Slovenia (SI), and Finland (FI). Results for Slovakia (SK) are not reported due to data limitations.

This finding may seem contradictory to the literature that estimates lower ERPT now than in previous decades in advanced economies, including the euro area economies (see Ortega and Osbat (2020) and references therein). But, by focusing only on one type of shock, we coincide with the above-mentioned recent shock-dependent ERPT literature that finds sizeable price-exchange rate comovement for each of the structural shocks that moves the exchange rate. These may partially offset each other and yield an ex-post estimated aggregate low ERPT. [6]

When assessing the source of such recent increased sensitivity of headline inflation to exogenous exchange rate shocks, it is found that the euro area-wide component, which can be interpreted as the effect of exchange rate shocks on aggregate euro area inflation, has remained relatively stable over time. By contrast, the country-specific component has displayed a substantial increase since the early 2010s. This implies that the growing sensitivity of headline inflation to exchange rate shocks is heavily reliant on a sustained surge in comovement between the inflation rates of euro area countries seen in recent years.

When applying the proposed empirical framework to the different subcomponents of headline inflation, that is, energy, food and core components, the results indicate some similarities. The sensitivity of the energy component to exogenous exchange rate shocks has also increased significantly in recent years, but by contrast to the case of headline inflation, its increasing sensitivity relies equally on the country-specific and common components. For food inflation, the pattern is similar to that of headline inflation, albeit with less significance. The case of core inflation is somewhat different: core inflation across countries does not seem to be meaningfully affected by exogenous exchange rate shocks, along the lines of the empirical literature findings (Ortega and Osbat (2020)).

The structure of the paper is as follows: Section 2 sets out the empirical approach; Section 3 discusses the main findings, with particular focus on the assessment of inflation commonalities across countries; and Section 4 sets out the conclusions.

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[6] See the related similar discussion in Ortega and Osbat (2020)

2 Empirical Framework

In this section, we provide an empirical framework to investigate the effects of exchange rate shocks on inflation in euro area countries across both geographic and time dimensions. Therefore, we are interested in a modelling approach that meets four main criteria. First, to properly identify exchange rate shocks for the euro area economy as a whole, given the unified monetary system. Second, to estimate how the effect of those exchange rate shocks spreads across the different euro area countries. Third, to provide information on the potential changes over time in the sensitivity of each country to those shocks. Fourth, to decompose the changing sensitivity into its country-specific and region-wide components.

We proceed in two steps. First, we use a structural VAR model to identify purely exogenous exchange rate shocks. Second, according to the exogenous exchange rate shocks identified in the first step, we investigate their time-varying effect on inflation across euro area countries using factor models.[7]

2.1 Structural VAR Model

We employ a structural vector autoregression (SVAR) model to investigate the exchange rate sensitivity of euro area inflation, considering how different theory-based shocks may impact the exchange rate and prices. More specifically, we are interested in assessing the effects of five shocks on the euro area economy: domestic supply, domestic demand, global demand, relative monetary policy and exogenous exchange rate shocks. We follow Fry and Pagan (2011), among others, and impose a set of short-run restrictions on the underlying shocks. These rely on open-economy DSGE models and have also been widely used in the related literature.

In such a setting, if euro appreciation is mainly driven by a positive euro area demand shock, domestic markets and domestic prices are expected to grow, partly offset by cheaper importes following the euro appreciation.[8] Theoretically, such an appreciation is expected

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[7] Similar methodological approaches have been used for exogenous changes in oil prices (Kilian (2009)) or for potential output distinguishing between demand and supply shocks (Coibion et al. (2017)).

[8] The higher weight of domestic versus imported goods (home bias) in the demand of most European economies ensures that cheaper imported inflation does not prevail over the inflationary effect of the positive demand shock.

to be associated with a countercyclical monetary policy response and a further exchange rate appreciation due to the corresponding higher asset yields in euro. In an alternative scenario, if the euro appreciation is due to a positive domestic supply shock, it would exert downward domestic price and wage pressure, driving down prices. These would be partially offset by the stronger domestic demand for foreign exports, which would normally increase import prices. Consistently with earlier literature, such as Canova and de Nicolo (2003) and Forbes et al. (2015), if the exchange rate movement is related to a supply shock we would expect a negative correlation between euro area growth and inflation. Alternatively, let us consider a scenario where the shock driving the euro exchange rate is a positive global demand shock. This would be associated with an increase in GDP and in the HICP. Given that demand growth in the rest of the world would be higher, the corresponding monetary policy tightening would probably be stronger than in the domestic economy, thus actually easing monetary policy in relative terms.

If instead the euro appreciation responds to relative monetary policy tightening in the euro area with respect to that of the US Federal Reserve, giving rise to higher relative asset yields in euro, domestic demand is expected to decrease or to be more muted along with prices and wages. In addition, such an appreciation would reduce import prices measured in euro, thus intensifying the fall in prices caused by the monetary tightening. Similarly, if the euro appreciation is due to a purely exogenous change - a risk premium shock not based either real activity fundamentals nor monetary policy - import prices are expected to fall and, therefore, also consumer prices, albeit to a lesser extent. In this case, monetary policy is expected to ease the interest rate in line with An and Wang (2012).[9]

A final important related aspect is the link between oil prices and exchange rate developments. Most of the literature agrees that currency values of commodity exporters contain information about future commodity price movements, as shown by Chen et al. (2010), while commodity prices also have predictive power for commodity currencies, at least at high data frequencies (Ferraro et al. (2012)). In such a setting, supply shocks driving the EUR/USD exchange rate and proxied by HICP inflation could be masking the effects of world oil prices. This paper opts to be agnostic about the source of the possible

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[9] An alternative identification strategy relaxing the latter assumption is shown in the Online Appendix A.2.1, with broadly similar results.

correlation between oil prices and exchange rates. Instead, we acknowledge its influence in a broader sense and use oil price developments as an exogenous variable in the empirical estimation of the structural shocks that drive the exchange rate over time.

Accordingly, to identify the shocks driving the dynamics of the euro exchange rate against the US dollar we estimate an endogenous multivariate approach that uses quarterly information about the euro area real GDP growth rate (GDP), euro area HICP inflation (INF), relative short-term interest rates (INT) between the euro area and the United States, the EUR/USD nominal exchange rate (FX), the relative euro area activity share with respect to the United States (EA/US), and an additional exogenous component for world oil prices (OIL). Therefore, letting $\mathbf{Y}_t = [GDP_t, INF_t, INT_t, FX_t, EA/US_t]$, and $\mathbf{X}_t = [OIL_t]$, the estimated model is a Structural Vector Autoregression with exogenous information SVAR-X(p, q) [10] given by

$$\mathbf{Y}_t = \Phi_0 + \sum_{p=1}^{P} \Phi_p \mathbf{Y}_{t-p} + \sum_{q=1}^{Q} \Phi_q \mathbf{X}_{t-q} + \mathbf{B}\epsilon_t, \tag{3}$$

where $\epsilon_t \sim N(0, I)$ are the structural innovations and $\mathbf{X}_t$ is assumed to be uncorrelated with ϵ_t for all leads and lags. The reduced form innovations, defined as $\mathbf{u}_t$, are related to the structural innovations through the impact multiplier matrix $\mathbf{B}$, that is, $\mathbf{u}_t = \mathbf{B}\epsilon_t$.

To identify the structural shocks of interest following the macroeconomic relations explained above, we impose sign restrictions on some of the entries of the impact multiplier matrix.[11] In particular, we assume that a positive domestic supply shock, $\epsilon_t^{Dom\_Sup}$, is associated with an increase in domestic output and the relative euro area activity share and a decrease in inflation, interest rates and foreign exchange rates.[12] By contrast, a positive domestic demand shock, $\epsilon_t^{Dom\_Dem}$, would be associated with higher output and relative euro area activity, higher HICP inflation, higher interest rates and euro appreciation. An unexpected tightening of the monetary policy stance, $\epsilon_t^{Mon\_Pol}$, that increases the short-

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[10] In our empirical application, we let the number of lags of the endogenous variables $p = 2$ and that of the exogenous variable $q = 2$.

[11] A similar approach is used in Leiva-Leon (2017) for the case of Spain and Estrada et al. (2019) for EMEs.

[12] A decrease in the FX rate is defined as a reduction in the EUR/USD exchange rate, i.e. euro depreciation.

term interest rate is assumed to be associated with lower inflation, output growth and relative share of euro area activity with respect to the United States. We also assume that an unexpected euro appreciation, $\epsilon_t^{Exo\_ER}$, that increases the EUR/USD exchange rate, would lead to declines in inflation and the interest rate.[13] Lastly, we assume that a positive global demand shock, $\epsilon_t^{Glo\_Dem}$ that reduces the relative size of the euro area economy compared with the world economy (proxied by the United States), exerts upward pressure on euro area output and inflation, but would lead to a relatively looser monetary policy in the euro area than in the United States, where demand expansion would be larger after the positive global demand shock. All these restrictions can be formalised as follows,

$$\begin{bmatrix} u_t^{GDP} \\ u_t^{INF} \\ u_t^{INT} \\ u_t^{FX} \\ u_t^{EA/US} \end{bmatrix} = \begin{bmatrix} + & + & - & * & + \\ - & + & - & - & + \\ - & + & + & - & - \\ - & + & * & + & * \\ + & + & - & * & - \end{bmatrix} \begin{bmatrix} \epsilon_t^{Dom\_Sup} \\ \epsilon_t^{Dom\_Dem} \\ \epsilon_t^{Mon\_Pol} \\ \epsilon_t^{Exo\_ER} \\ \epsilon_t^{Glo\_Dem} \end{bmatrix}, \tag{4}$$

where the "$*$" in the impact multiplier matrix indicates that the entries have been left unrestricted. This combination of sign restrictions is the minimum number of theory-based economic restrictions that allows us to identify the shocks of interest and at the same time to ensure their orthogonality.[14]

We estimate the SVAR-X model, described in equations (3)-(4), using quarterly data for the euro area and the United States for the period from 1995Q1 to 2019Q2 on the following six variables: (i) the euro area real Gross Domestic Product (GDP) growth rate from the European Commission (Eurostat); (ii) inflation based on the Harmonised Index of Consumer Prices (HICP) for the euro area from the European Commission (Eurostat); (iii) relative short-term interest rates between the euro area and the United States, and for the zero lower bound period, shadow rates based on quarterly averages of monthly estimates

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[13] For the sake of robustness, an alternative identification scheme concerning an unexpected appreciation of the nominal euro exchange rate (exogenous exchange rate shock or risk premium shock) is further developed in the Online Appendix A.2.1. It provides broadly similar results.

[14] A wide range of estimation methodolgy robustness checks is discussed in the Online Appendix. The estimates obtained are qualitatively similar to those obtained with our benchmark specification in equations (3)-(4).

from Krippner (2013);[15] (iv) quarterly average of the monthly nominal EUR/USD reference exchange rate provided by the European Central Bank (ECB);[16] (v) relative euro area activity calculated as the ratio of euro area to US GDP, based on GDP data provided by the European Commission (Eurostat) and the U.S. Bureau of Economic Analysis (BEA); and (vi) world oil prices based on the quarterly average of monthly Europe Brent spot prices FOB published by the U.S. Energy Information Administration (EIA). All variables except the relative interest rate are transformed into quarterly log differences.

Finally, the SVAR-X model is estimated using Bayesian methods. In particular, an independent Normal-Inverse-Wishart prior is assumed to simulate the posterior distribution of the parameters. Structural shocks are identified by following Arias et al. (2018), where sign and exclusion restrictions are imposed on impulse response functions. Further details of the estimation procedure are provided in the Online Appendix A.2.3.

2.2 Factor Model with Exogenous Information

Dynamic factor models have been widely used to characterise the degree of comovement in the dynamics of prices from different levels of disaggregation. Two examples are Del Negro and Otrok (2007), who focus on house prices at the state level for the US economy, and Cicarelli and Mojon (2010), who present a global perspective of synchronised inflation dynamics across industrialised countries. Here, we use this tool to provide a comprehensive assessment of exchange rate effects on inflation in the euro area countries from a unified perspective.

We use the exogenous exchange rate shocks extracted from the structural VAR model described above to assess their effect on inflation in the n euro area countries. As suggested by Mumtaz and Sunder-Plassmann (2013), the effects associated to exchange rate fluctuations in advanced economies are subject to substantial changes over time. Hence, as we are primarily interested in assessing changes in the exchange rate sensitivity of inflation over

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[15] Model results are, in any case, robust to different monetary policy measures, such as relative official interest rates in the euro area and the United States and shadow interest rates constructed using multifactor shadow rate term structure models by Wu and Xia (2016).

[16] Our SVAR-X model results are robust to an alternative estimation using the nominal effective exchange rate of the euro against its main 38 trade partners - NEER-38 countries - although some caveats arise as the variables proxying global demand and relative monetary policy are measured only in relation to the United States, not to the full set of 38 countries used in the NEER definition.

time, we rely on a multivariate framework subject to time-varying coefficients.[17]

Taking the standardised inflation rate of country i defined as $\pi_{i,t} = (INF_{i,t} - \mu_{i,inf})/\sigma_{i,inf}$, where $\mu_{i,inf} = mean(INF_{i,t})$ and $\sigma_{i,inf} = std(INF_{i,t})$, we propose the following time-varying parameter factor model with exogenous information, referred to as TVP-DFX,

$$\pi_{i,t} = \gamma_{i,t} f_t + u_{i,t}, \tag{5}$$

$$f_t = \phi_t f_{t-1} + \lambda_t \epsilon_t^{Exo\_ER} + \omega_t, \tag{6}$$

for $i = 1, 2, ..., n$, and where $u_{i,t} \sim N(0, \sigma_i^2)$ and $\omega_t \sim N(0, 1)$. Note that Equation (5) decomposes country-specific inflation, $\pi_{i,t}$, into a common component, f_t, and an idiosyncratic component, $u_{i,t}$, whereas equation (6) assumes that the common factor follows autoregressive dynamics and that it is also influenced by exogenous information, in particular by the exogenous exchange rate shocks $\epsilon_t^{Exo\_ER}$.

The model parameters are assumed to evolve according to random walks to account for potential instabilities over time,

$$\gamma_{i,t} = \gamma_{i,t-1} + \vartheta_{i,t} \tag{7}$$

$$\phi_t = \phi_{t-1} + \vartheta_{\phi,t} \tag{8}$$

$$\lambda_t = \lambda_{t-1} + \vartheta_{\lambda,t} \tag{9}$$

where $\vartheta_{i,t} \sim N(0, \nu_i^2)$, $\vartheta_{\lambda,t} \sim N(0, \nu_\lambda^2)$, and $\vartheta_{\phi,t} \sim N(0, \nu_\phi^2)$. Most importantly, the time-varying degree of inflation comovement across countries is captured by $\gamma_{i,t}$, while changes in the persistence of the latent factor are collected in ϕ_t, and the dynamic sensitivity of the inflation factor is measured by λ_t.

Plugging Equation (6) into Equation (5) gives us the following expression for country i inflation dynamics,

$$INF_{i,t} = \tilde{\beta}_{i,0} + \tilde{\beta}_{i,1,t} f_{t-1} + \tilde{\beta}_{i,2,t} \epsilon_t^{Exo\_ER} + \tilde{v}_{i,t} \tag{10}$$

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[17] A similar factor model with time-varying coefficients is also used in Ductor and Leiva-Leon (2016) to unveil an increasing synchronization in global real activity.

where $\tilde{\beta}_{i,0} = \mu^{i}_{i,inf}$, $\tilde{\beta}_{i,1,t} = \sigma_{i,inf}\gamma_{i,t}\phi_t$, $\tilde{\beta}_{i,2,t} = \sigma_{i,inf}\gamma_{i,t}\lambda_t$, and $\tilde{v}_{i,t} = \sigma_{i,inf}(\gamma_{i,t}\omega_t + u_{i,t})$. Note that there is a direct correspondence between Equation (10) and Equation (1), in particular, between the coefficients measuring the sensitivity of inflation to exchange rate shocks in both equations, i.e. $\tilde{\beta}_{2,i,t}$ and $\beta_{i,t}$, respectively.

The main advantage of the proposed TVP-DFX model is that it allows the effect of exchange rate shocks on inflation, $\tilde{\beta}^{i}_{2,t}$, to be decomposed into two components: the country-specific, $\gamma_{i,t}$, and the euro area-wide component, λ_t, which would correspond to the terms $IDI_{i,t}$ and COM_t, respectively, in Equation (2). The term λ_t provides information about the changing effect that exchange rate shocks have on euro area inflation dynamics, proxied by the factor f_t. By contrast, the term $\gamma_{i,t}$ provides information on the changing propagation of those shocks across the different countries of the euro area. Equation (10) is first estimated on headline HICP inflation across the euro area economies. Section 3.2 discusses the findings, as well as the estimation of Equation (10) on the three components of HICP inflation (food, energy and the core component, i.e. total HICP excluding food and energy prices). Note that an additional advantage of the proposed framework is that it can be used to incorporate structural shocks obtained from any other kind of model for validation purposes, i.e. semi-structural or DSGE models. However, in the current application we only focus on the shocks from the structural VAR model described in Section 2.1.

3 Sensitivity of Prices to Exchange Rate Shocks

3.1 An Aggregate Assessment

This section aims to help understand the link between movements in the EUR/USD exchange rate and euro area consumer prices. We analyse what types of shocks have driven euro exchange rate fluctuations in the period 1995Q1-2019Q2 by examining historical shock decompositions from the SVAR-X described in Section 2. [18] To begin with, Figure 1 presents the corresponding historical decomposition of quarter-on-quarter EUR/USD exchange rate dynamics, to permit a better understanding of whether the relative weight of different shocks varies significantly over time. An increase (reduction) is defined as an

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[18] Estimates for 2019Q2 are based on data available at the cut-off date (September 2019).

increase (reduction) in the EUR/USD exchange rate, i.e. euro appreciation (depreciation) against the dollar. We focus on the most recent period and report the contributions of the potential driving factors identified in the SVAR: (i) innovations to real activity (either from domestic demand and supply or from rest of the world demand); (ii) relative monetary policy shocks; and (iii) exogenous exchange rate shocks not directly linked to fundamentals or monetary policy. As discussed earlier, these exogenous factors most notably reflect changes in confidence, sentiment or perception (optimism or pessimism) among traders operating on foreign exchange markets and proxy risk premium shocks. They are usually sudden, strong and difficult to predict.

A quick glance at Figure 1 suggests that there are important differences in the sources of EUR/USD movements at different points in time. This decomposition clearly suggests that structural shocks other than exogenous exchange rate shocks account for a large share of the changes in the exchange rate; for around 65% over the sample period to be precise. Therefore, treating all exchange rate fluctuations as exogenous exchange rate shocks is unlikely to adequately capture the underlying dynamics, especially if the mix of shocks driving the exchange rate varies over time as discussed in Section 1. However, exogenous exchange rate shocks have played a bigger part in unanticipated nominal exchange rate movements, not only in recent years but also in turning point periods. Our findings indicate that they are behind more than 50% of exchange rate fluctuations in more than a third of the quarters of the past six years, as shown in Figure 1.

For example, according to our analysis, the euro appreciation between 2017Q2 and 2018Q1 could have been driven by at least three factors, ranked in order of importance. First, due to higher relative euro area growth. Second, exogenous factors are found to be a key driver as well, given higher relative confidence in the euro over the second half of 2017. Third, the perception that the ECB's monetary policy was somewhat less relaxed at the end of 2017, relative to the Fed's, than in previous quarters (in 2016Q4-2017Q1 it was the other way round) also contributed to the euro appreciation. The shocks leading to greater GDP growth in the euro area would have exerted an inflationary pressure. But this positive impact on inflation would have been partly offset by the deflationary effect of the change in the perceived monetary policy stance and the exogenous factors of appreciation (through a reduction in import prices), in line with the arguments suggested by Coeuré (2017), with data up to 2017Q2. [19] Coeuré (2017) is an example of how shock-dependent estimates of the exchange rate-prices nexus are affecting the monetary policy debate. However, as argued in Ortega and Osbat (2020), when estimating the quantitative contribution of different shocks to the exchange rate developments at a specific point in time, it has to be considered that these estimates may be very sensitive to the particular model specification (sample period, identification scheme, choice and measurement of variables). With this caveat in mind, preliminary estimates for the recent depreciation of the euro since February 2018 identify exogenous, risk premium shocks as a key driver. Clearly, various global factors - such as uncertainty over the US trade tariff policy, the Brexit process, the recent fall in oil prices or the Chinese economic slowdown - have likely been behind the unexpected, exogenous exchange rate shocks. In addition, these findings suggest that, to a lesser extent, the lower relative growth rate of activity in the euro area would also have played a role in depreciation periods.

A full set of different model variants have also been estimated to test whether our findings are sensitive to: alternative identification strategies, different lag orders and sign restriction periods and a time-varying parameter approach to the SVAR (TVP-SVAR). The robustness results are summarised in the Online Appendix and show no remarkable differences neither in the historical decomposition of exchange rate shocks or in specific, extracted shocks.

3.2 The Role of Inflation Commonalities

After estimating the proposed dynamic factor model with drifting coefficients and exogenous information, described in equations (5)-(9), we proceed to assess the effect of exchange rate shocks on inflation (i) over time, (ii) across countries and (iii) by price component.

We begin by focusing on the case of headline inflation. The common factor extracted from headline inflation across the euro area countries is plotted in Figure 2. This is f_t

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[19] In particular, Coeuré pointed out that there were three forces, of roughly equal strength, that helped explain the euro's marked appreciation at that time: (i) improved euro area growth prospects; (ii) an exogenous component; and (iii) a tightening in the relative monetary policy stance vis-à-vis the United States.

in Equation (5) estimated using total HICP data for the euro area countries. It shows a strikingly similar pattern to actual headline inflation for the euro area. Therefore, the estimated common factor f_t can be interpreted as a proxy for euro area headline inflation dynamics.

Figure 3 plots the *total* estimated time-varying sensitivity of the euro area countries' headline inflation to exchange rate shocks, that is, $\tilde{\beta}_{i,2,t}$ in Equation (10). The estimates suggest a persistent increase in the effect of shocks on inflation occurred around 2010. This is a general pattern for most countries, but is especially acute for the largest economies. In particular, France, Germany and Italy, exhibited a sensitivity of around 0.1 before 2010, but which has since continued to increase, up to 0.2. For Spain the increase is even larger, up from 0.2 before 2010 to around 0.4 subsequently. Some smaller economies, such as Portugal, Finland or Malta, have also experienced increasing sensitivity, but less persistently.

As the estimated common factor is a good proxy for euro area headline inflation, the time-varying parameter λ_t in Equation (6) can be interpreted as the changing effect of exchange rate shocks on the aggregate euro area inflation rate. Figure 4(a) plots the dynamics of the *region-wide* component of the *total* sensitivity, λ_t, showing that, in general, it has remained steady, the only exception being the Great Recession period when exogenous exchange rate shocks did not seem to have a significant effect on euro area headline inflation. In particular, a 1% exogenous appreciation of the euro would be associated with a decline in euro area HICP inflation of around 0.15% on impact.[20] By contrast, Figure 4(b) plots the time-varying persistence of the common inflation factor, showing a slightly declining pattern since 2008. This implies that inflation has potentially become more difficult to predict, at least with autoregressive models, since the Great Recession.

Increasing sensitivity across countries along with relatively stable sensitivity for the aggregate euro area can be explained by an increasing degree of commonality in headline inflation across euro area countries. Figure 5 shows the estimated time-varying loadings of the common component into each country's inflation of Equation (5), that is, the *country-specific* component of the *total* sensitivity. Accordingly, the dynamics of $\gamma_{i,t}$ measure the

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[20] The impact of monetary policy shocks on HICP inflation and its components has also been analysed under the same empirical strategy, although it is beyond the scope of this paper. Empirical findings point to a decreasing path of sensitivity of inflation to these shocks.

changing contemporaneous relationship between country-specific inflation measures and their common factor. As expected, the figure reflects sustained increases over time in the synchronisation of headline inflation dynamics for most countries.

The TVP-DFX framework is also used to model the subcomponents of headline inflation - core, food and energy components - across euro area countries We start by analysing the core component of headline inflation. Figure 6 plots the common core inflation factor, showing that, although the factor and euro area core inflation follow a similar pattern, their similarity is not as marked as in the case of headline inflation. This points to a potentially lower degree of comovement in the core component of inflation. Moreover, Figure 7 shows that the effect of exchange rate shocks on core inflation across countries is both negligible and very uncertain. This is also the case when assessing the effect of the shocks on aggregate euro area core inflation, proxied by the extracted common factor (see Figure 8(a)). Also, Figure 8(b) shows that the persistence of core inflation has remained steady. As expected, the pattern of core inflation comovement across countries is more heterogeneous than in the case of headline inflation, which is inferred from the estimated time-varying factor loadings shown in Figure 9. Although some countries, such as Italy or France, have displayed increasing degree of comovement, most countries have shown a relatively stable or even decreasing pattern, as in the case of Latvia.

Next, we apply the same framework to the food and energy subcomponents of inflation. Figures 10 and 14 show the estimated food and energy inflation factors, respectively, along with the corresponding euro area aggregate inflation. Here also, as in the case of headline inflation, the path is strikingly similar. While the increase in the effect of exchange rate shocks on inflation, occurred since 2010, has been significant for food prices (see Figure 11), it has been rather weak and more uncertain for energy inflation (see Figure 15). As the degree and development of comovement experienced by food and energy inflation rates have been relatively similar, as shown in Figures 13 and 17, the difference between the sensitivity of food and energy inflation relies on the impact that exchange rate shocks have on the corresponding euro area aggregates, that is, the *region-wide* component. Thus, the effect of exogenous exchange rate shocks on euro area food inflation has not changed substantially over time, but the sensitivity of aggregate energy inflation to unexpected exchange rate movements has increased considerably since 2009, as shown in Figures 12(a) and 16(a) respectively.

Based on the findings obtained with the multivariate framework in equations (5)-(9), it is important to emphasise that both channels of transmission of exchange rate shocks to countries' inflation, that is, *country-specific* and *region-wide* channels, are relevant, and that their relative importance largely depends on the type of price component being assessed. Also note that an important feature of the proposed multivariate framework is that it is able to both (i) estimate and (ii) decompose the sensitivity of inflation to exchange rate shocks.

In order to verify that the ERPT dynamics across countries estimated using the proposed multivariate framework do not represent an artifact solely driven by the degree of comovement, measured by the time-varying factor loadings, we perform a robustness exercise that omits any information on inflation comovement in the euro area. In particular, we estimate the effect of exchange rate shocks on inflation for each country, independently, based on the following univariate regression model subject to parameter time-variation:

$$\pi_{i,t} = \hat{\phi}_i(L)\pi_{i,t-1} + \hat{\beta}_{i,t}\epsilon_t^{ER} + \hat{v}_{i,t}, \tag{11}$$

for $i = 1, 2, ..., n$, and where the element of interest is given by the dynamics of the ERPT coefficient $\hat{\beta}_{i,t}$.[21]

The estimated time-varying ERPT across countries associated with headline inflation is plotted in Figure 20 of Appendix B to save space. The findings indicate that the ERPT obtained from the univariate models closely tracks the dynamics of the ERPT obtained from the proposed multivariate approach. This is the case for almost all the euro area countries, with the only exceptions being Malta and Finland. In the case of core inflation, although the estimates obtained from the two approaches do not always look similar, the ERPT estimates from the univariate models point to the same message as that provided by the multivariate model. That is, that the sensitivity of core inflation to exchange rate shocks tends to be of

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[21] Each univariate time-varying parameter regression is estimated independently with Bayesian methods, assuming $L = 1$ for consistency with the multivariate approach. The estimation algorithm follows the corresponding simplified version of the one described in Appendix A.1, and follows the same number of Gibbs sampling iterations and corresponding priors.

a smaller magnitude and, what is more important, the estimates tend to be more uncertain (Figure 21). Lastly, regarding the food and energy subcomponents of headline inflation, the estimates from univariate models also follow a similar path to the estimates from the multivariate model, as shown in figures 22 and 23, respectively. These findings evidence that while independent univariate regressions can only measure the degree of sensitivity of euro area countries' inflation to exogenous exchange rate shocks, the proposed factor model is able to perform the same task, while also providing a decomposition of that sensitivity into *country-specific* and *region-wide* effects.

Such a decomposition could be extremely useful for policymakers, as it provides a timely assessment of whether movements in inflation in a given country, brought about by exchange rate shocks, are mainly driven by the country's exclusive and intrinsic economic performance or by the overall performance of all monetary union partners. This type of decomposition is in line with that proposed by Ozdagli and Weber (2017) based on spatial autoregressions. In particular, the authors focus on decomposing the total effect of monetary policy shocks on a given asset price into: (i) a *direct effect*, which would be the equivalent of our *country-specific* component; and (ii) an *indirect effect*, which takes into account the joint interaction of that given asset with the other assets in the economy, i.e. the network effect, which could be interpreted as our *region-wide* component.

4 Concluding remarks

This paper proposes an innovative approach that should improve our ability to assess the effect of exchange rate fluctuations on prices across countries - especially from a time-varying and cross-country unified perspective - and by taking into account the source of exchange rate changes.

To this end, we decompose into a country-specific and region-wide component the time-varying effect that unexpected movements in the EUR/USD nominal exchange rate have on different measures of inflation in the euro area countries. Of all the sources of exchange rate fluctuations, this paper focuses only on exogenous exchange rate shocks. This is partly because we seek to imitate insofar as possible the concept of exchange rate pass-through in a shock-dependent context: we isolate the transmission to prices of ”pure” exchange rate shocks from the joint reaction of prices and exchange rates to other structural shocks such as demand, supply or monetary policy shocks.

We propose an econometric framework that relies: (i) on a SVAR model to identify purely exogenous exchange rate shocks; and (ii) on a dynamic factor model subject to drifting coefficients and exogenous information to identify the pass-through to inflation of such exogenous exchange rate shocks. Our findings suggest that exogenous shocks to the EUR/USD are paramount. They are behind more than 50% of the nominal EUR/USD exchange rate fluctuations in more than a third of the quarters of the past six years, especially in turning point periods.

Our main findings indicate that headline inflation, and in particular its energy component, has become significantly more affected by these exogenous exchange rate shocks since the early 2010s, especially in the largest economies of the region. While in the case of headline inflation this increasing sensitivity is solely reliant on a sustained surge in the degree of comovement, in the case of energy inflation it is also based on a higher region-wide effect of the shocks The effect of exogenous exchange rate shocks in food inflation is similar to, but much lower than, the impact on headline inflation. By contrast, purely exogenous shocks do not seem to have a significant effect on the core component of headline inflation, which also displays a lower degree of comovement across euro area countries.

The framework described here is not intended or able to capture structural differences across countries that are key to explaining different impacts of exchange rate movements, such as the role of invoicing currency, whether the transactions take place between or within firms, the frequency and dispersion of price adjustments, integration in Global Value Chains or the role of competition in final product markets, but it still adds an important new dimension to the standard approach for analysing ERPT. Decomposing the effect of pure exogenous exchange rate shocks on euro area countries’ inflation into country-specific (*idiosyncratic*) and region-wide (*common*) components from a time-varying perspective should improve our understanding, to allow us to better assess the impact of currency movements and, as a result, help central banks set appropriate monetary policy.

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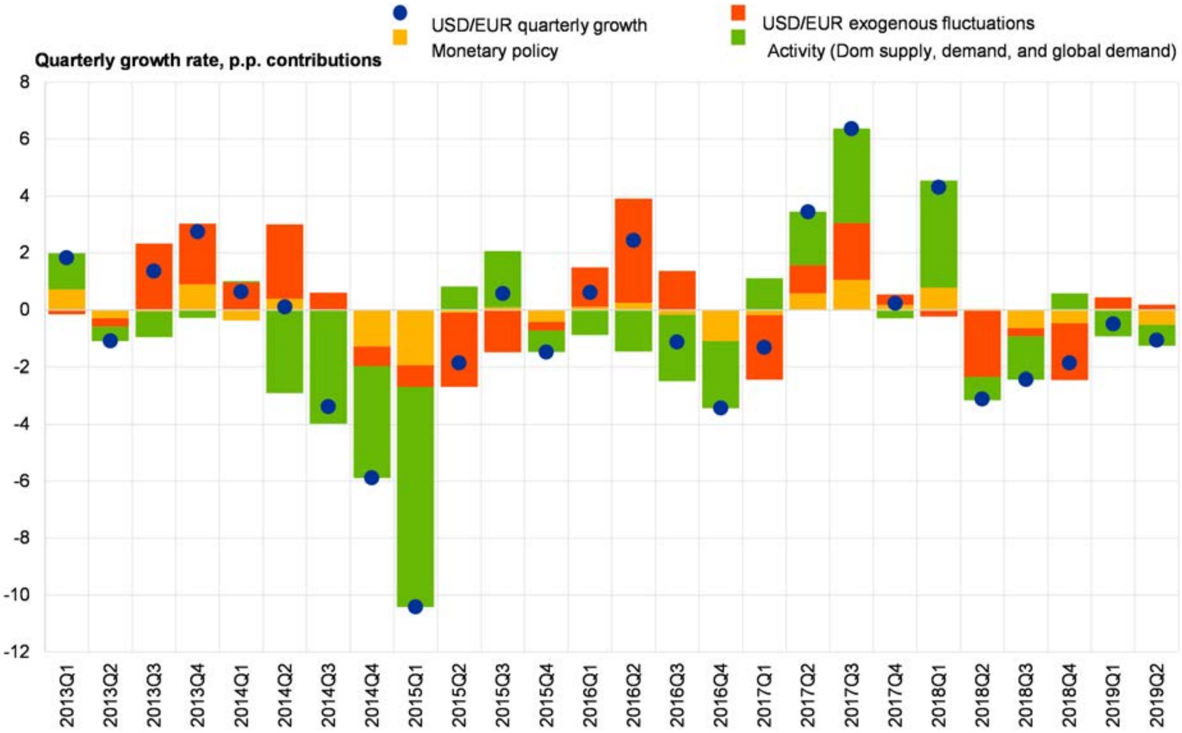
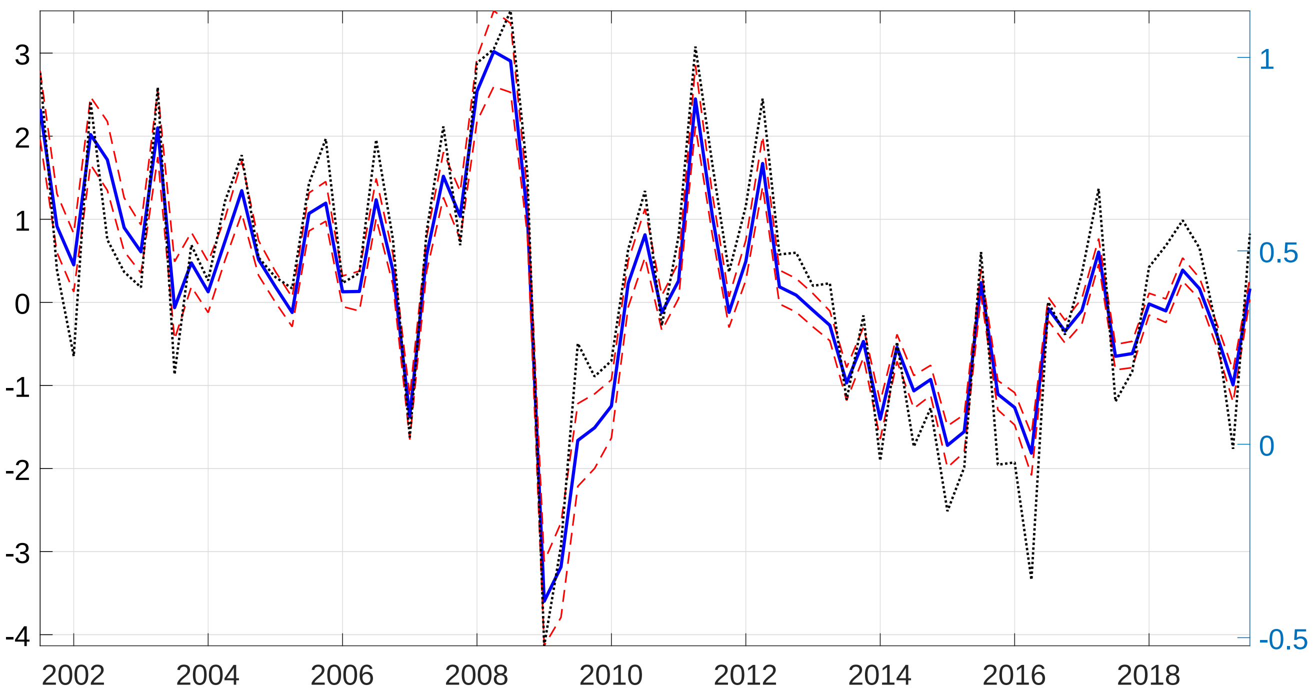
Figure 1: Historical decomposition of nominal exchange rate EUR/USD



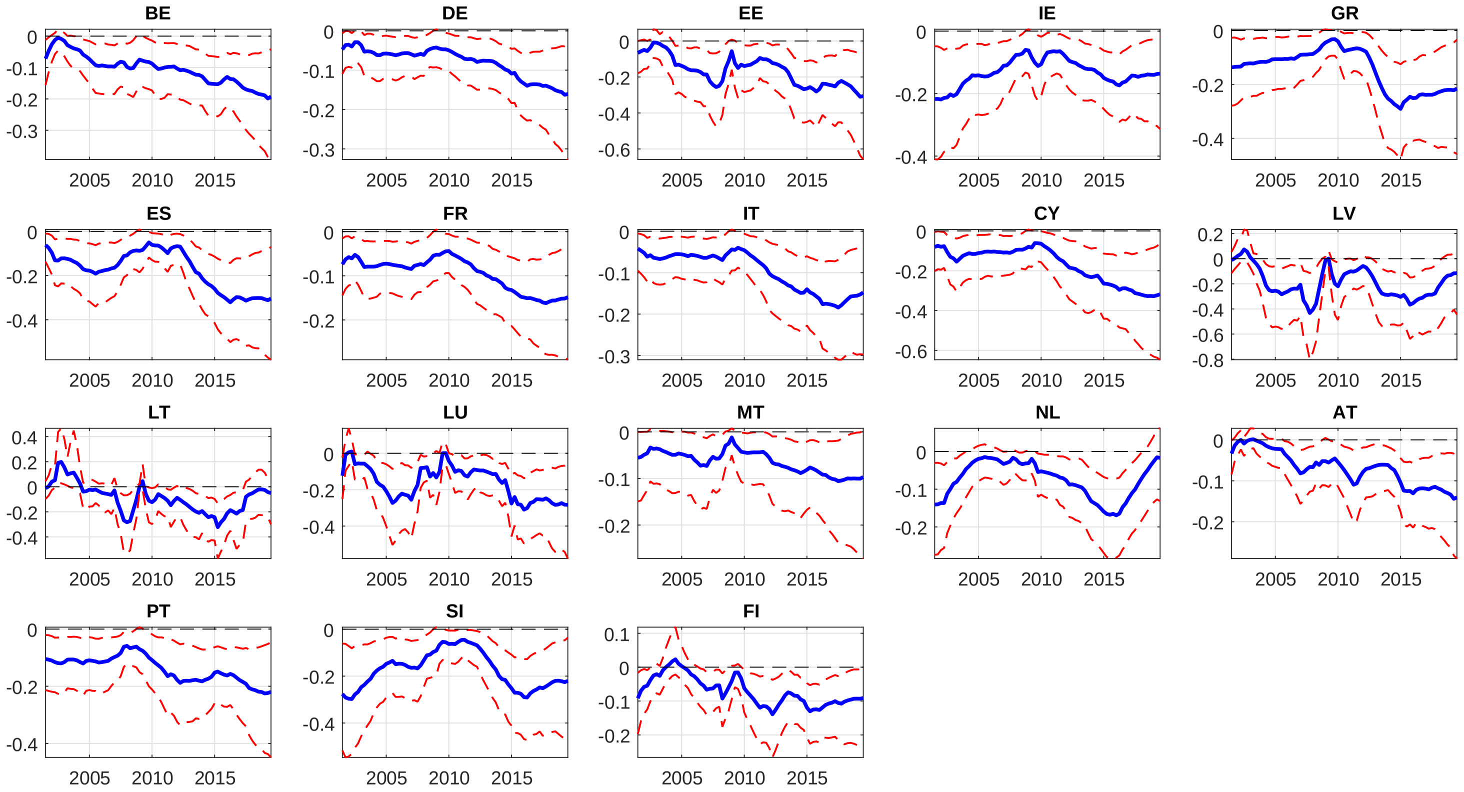
Notes: Estimates based on the quarterly SVAR model of the EUR/USD exchange rate described in Section 2, where shocks are identified via sign restrictions. Estimates for 2019Q2 are based on data available at the time of the cut-off date (Sept, 2019). Data for US and euro area GDP in 2019Q2 are based on flash estimates. The USD exchange rate movements refer to the quarterly rates of changes of the respective quarters. The figure depicts the average contribution of the 10.000 historical decompositions obtained from the saved iterations of the estimation algorithm.

Figure 2: Euro area headline inflation factor (f_t)



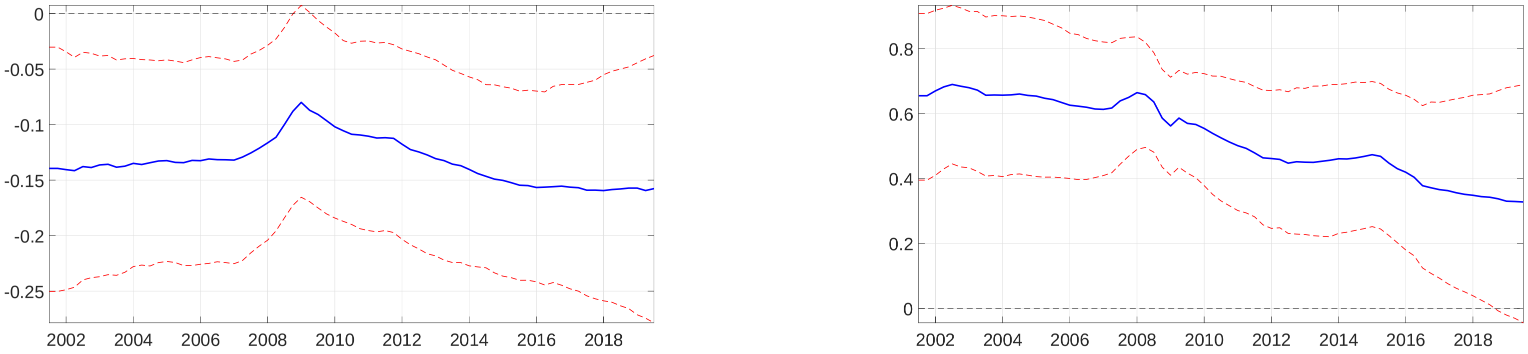
Note: Blue solid (red dashed) line, aligned with left axis, makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Black dotted line, aligned with right axis, make reference to the euro area headline inflation.

Figure 3: Time-varying sensitivity of headline inflation of the euro area countries based on a multivariate model ($\tilde{\beta}_{i,2,t}$)



Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the multivariate model.

Figure 4: Time-varying coefficients of model for headline inflation

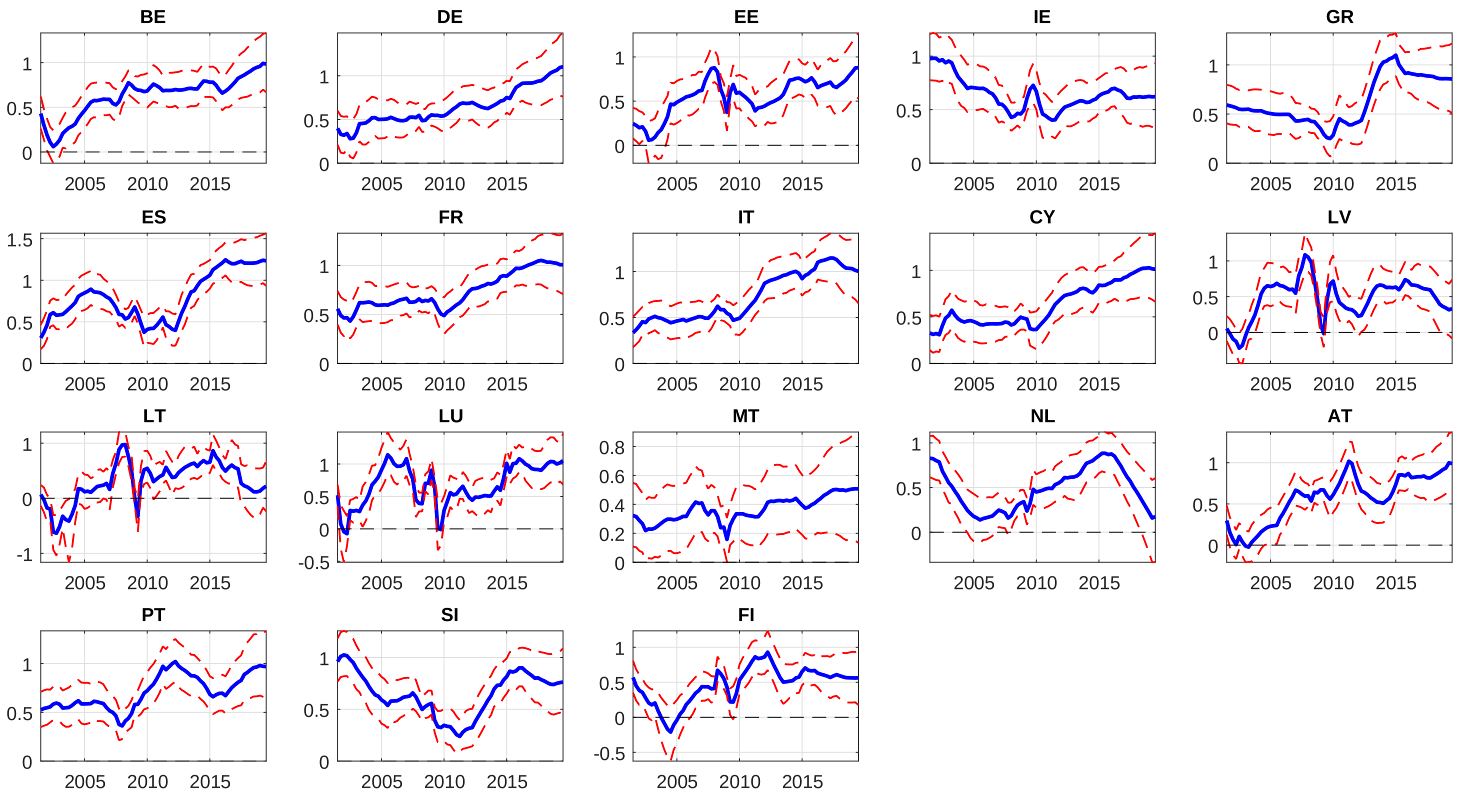


(a) Sensitivity of headline inflation of the euro area (λ_t)

(b) Persistence of the euro area headline inflation factor (ϕ_t)

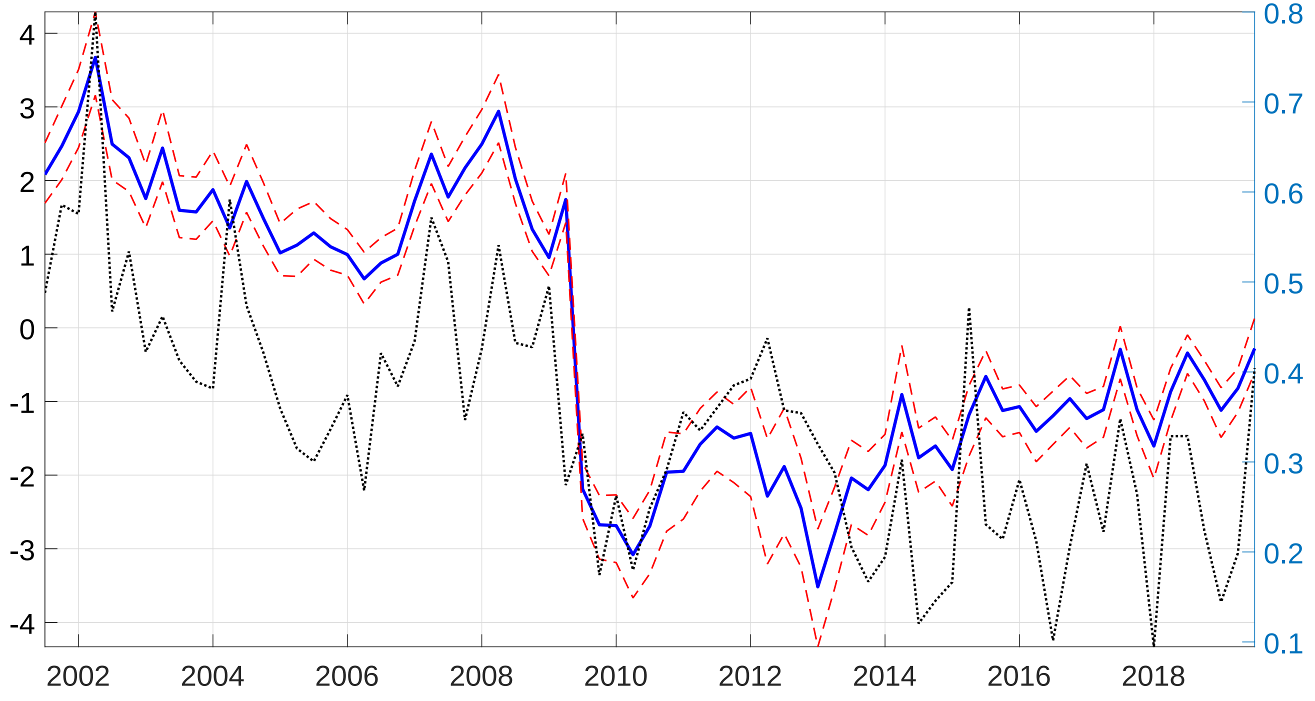
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

Figure 5: Time-varying comovement of euro area countries headline inflation ($\gamma_{i,t}$)



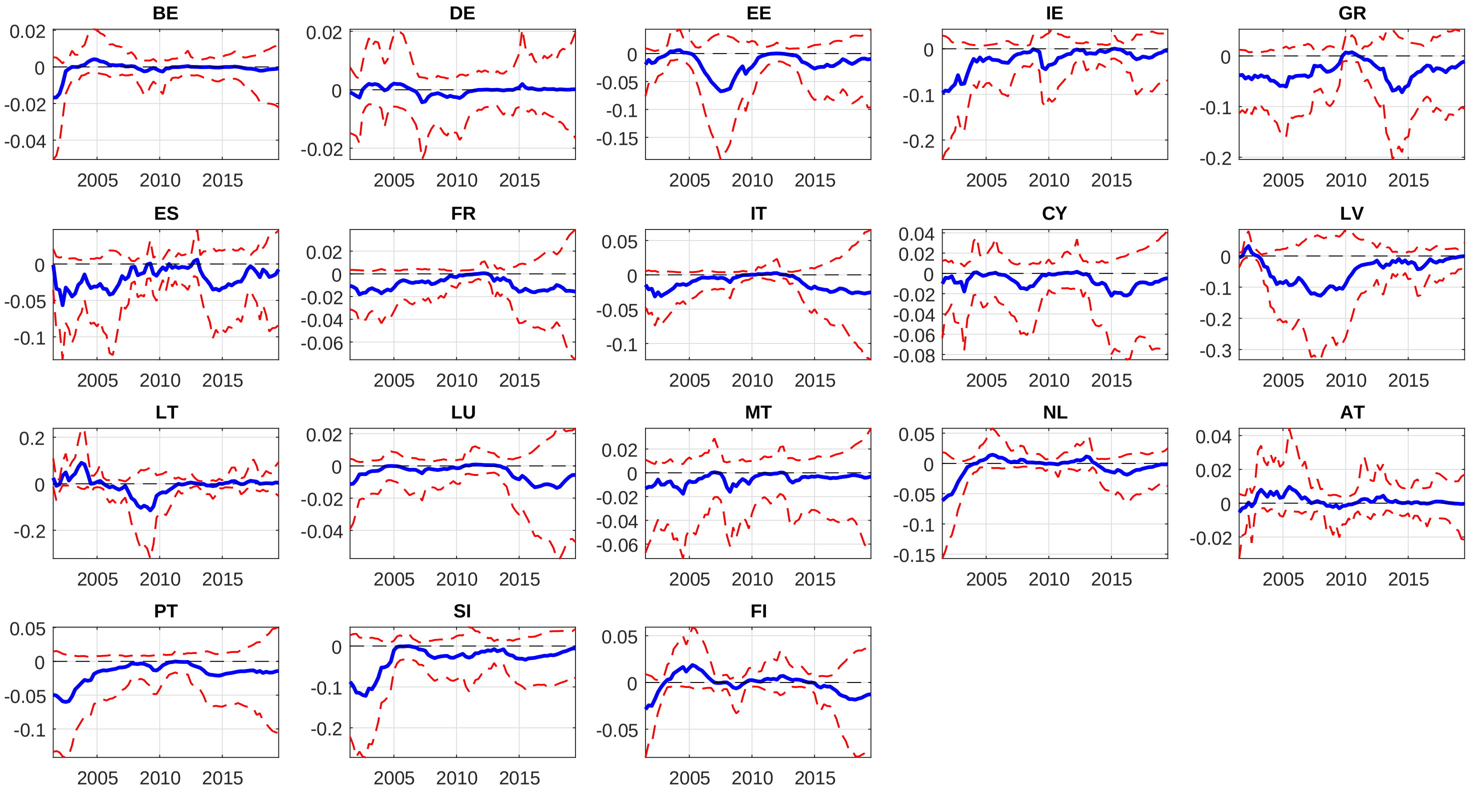
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

Figure 6: Euro area core inflation factor (f_t)



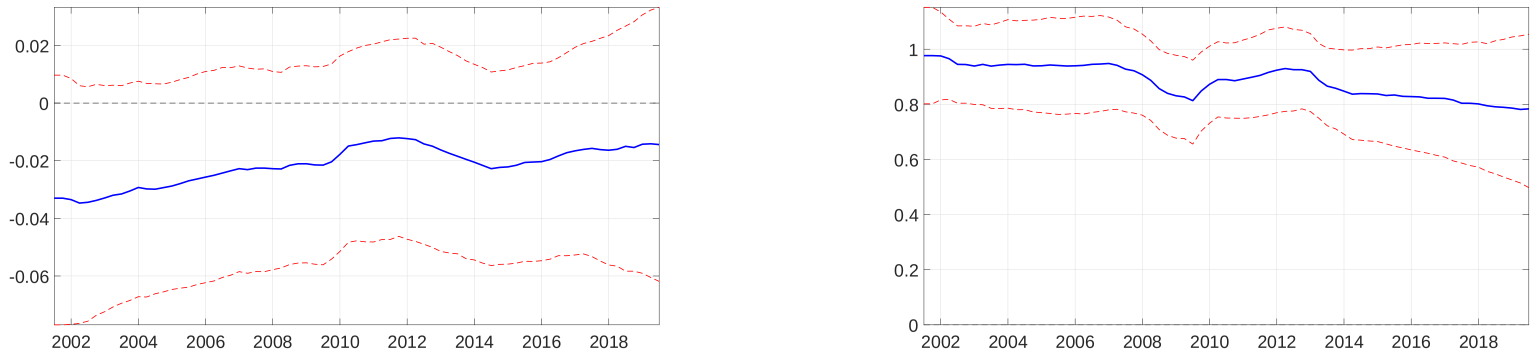
Note: Blue solid (red dashed) line, aligned with left axis, makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Black dotted line, aligned with right axis, make reference to the euro area core inflation.

Figure 7: Time-varying sensitivity of core inflation of euro area countries based on a multivariate model ($\tilde{\beta}_{i,2,t}$)



Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

Figure 8: Time-varying coefficients of model for core inflation

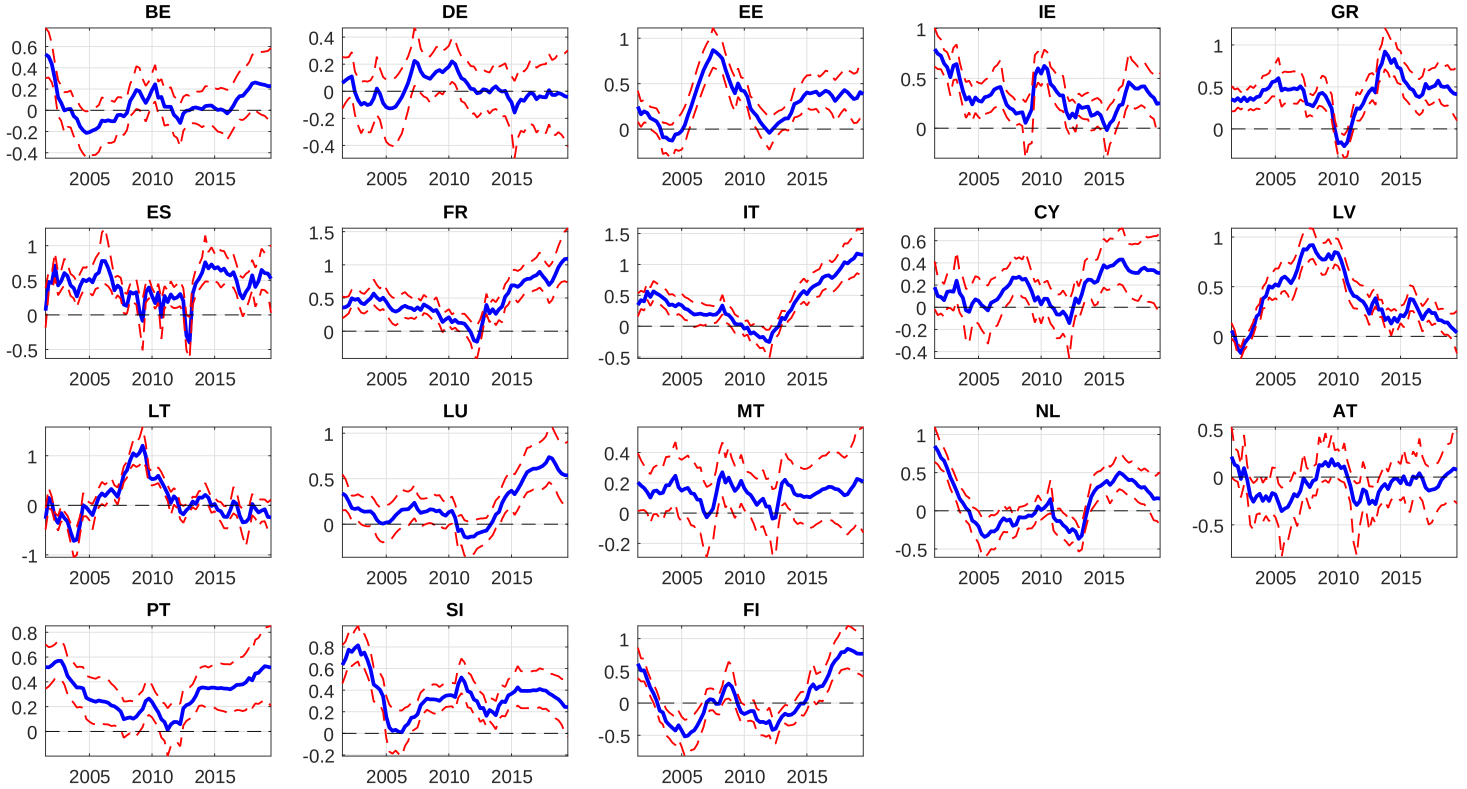


(a) Sensitivity of core inflation of the euro area (λ_t)

(b) Persistence of the euro area core inflation factor (ϕ_t)

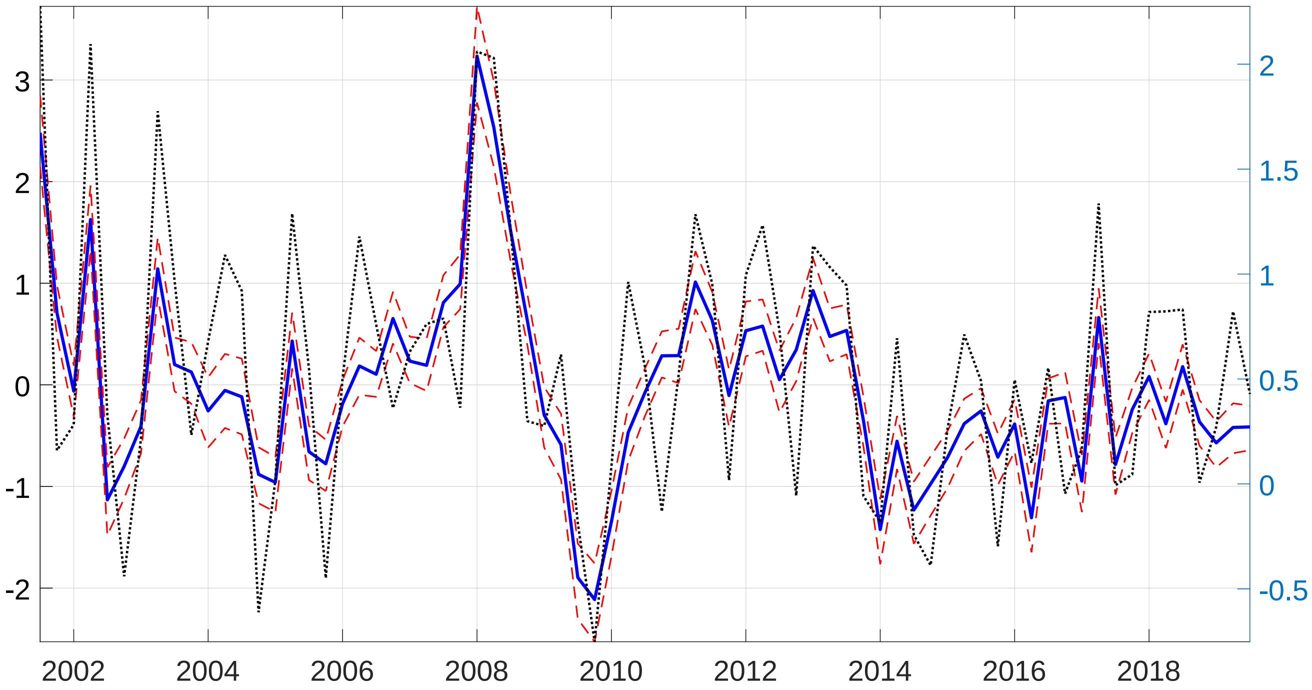
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

Figure 9: Time-varying comovement of euro area countries core inflation ($\gamma_{i,t}$)



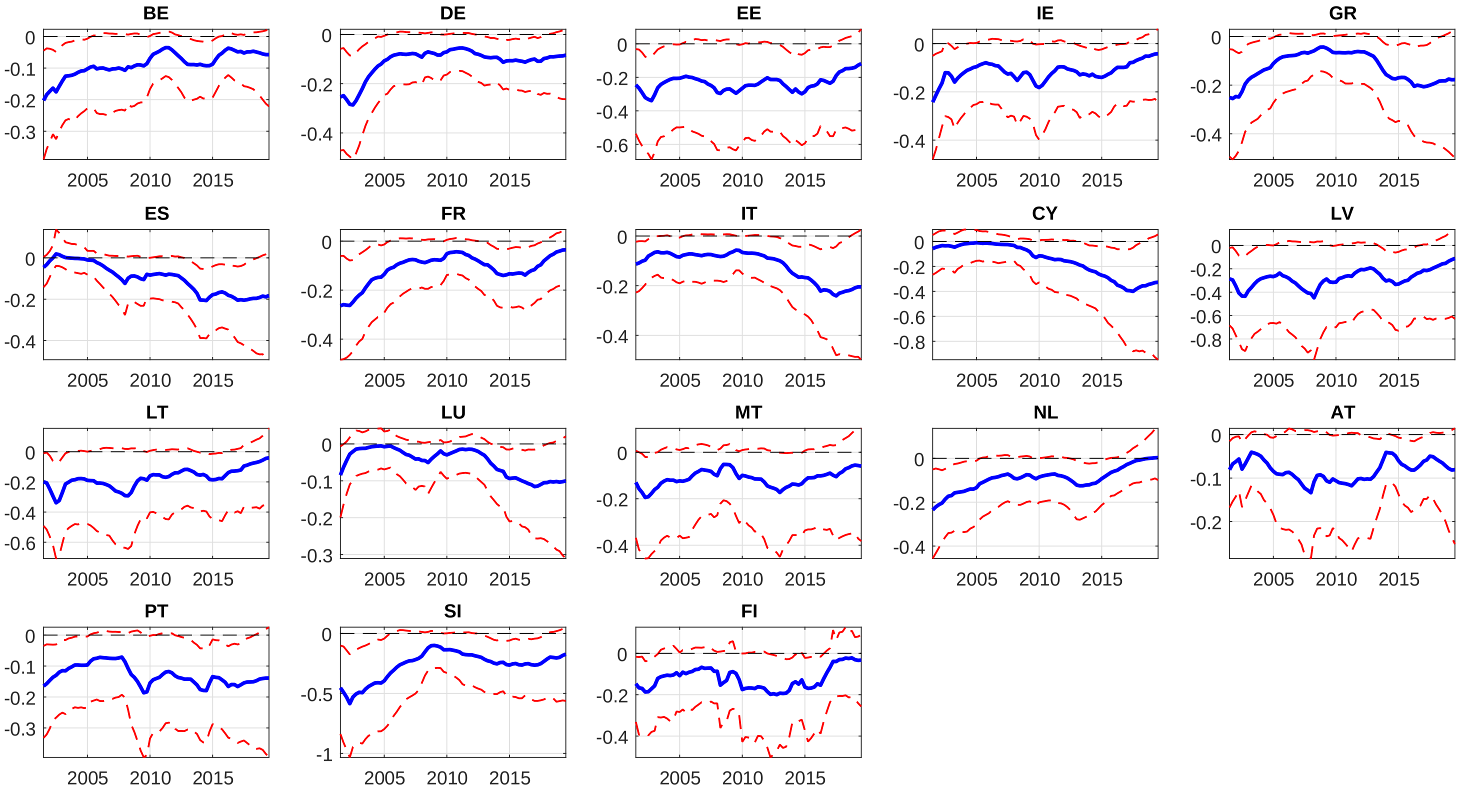
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

Figure 10: Euro area food-related inflation factor (f_t)



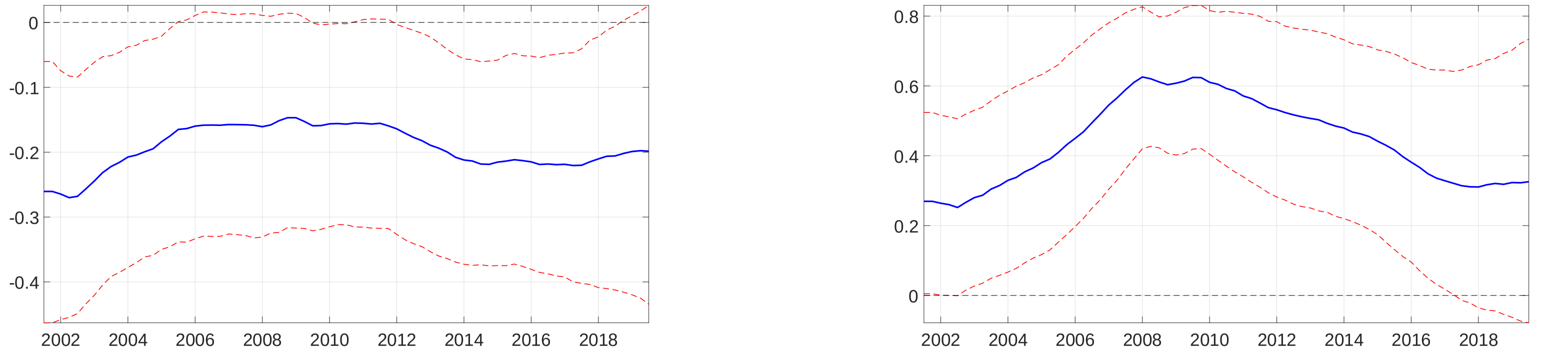
Note: Blue solid (red dashed) line, aligned with left axis, makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Black dotted line, aligned with right axis, make reference to the euro area food-related inflation.

Figure 11: Time-varying sensitivity of food-related inflation of euro area countries based on a multivariate model ($\tilde{\beta}_{i,2,t}$)



Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

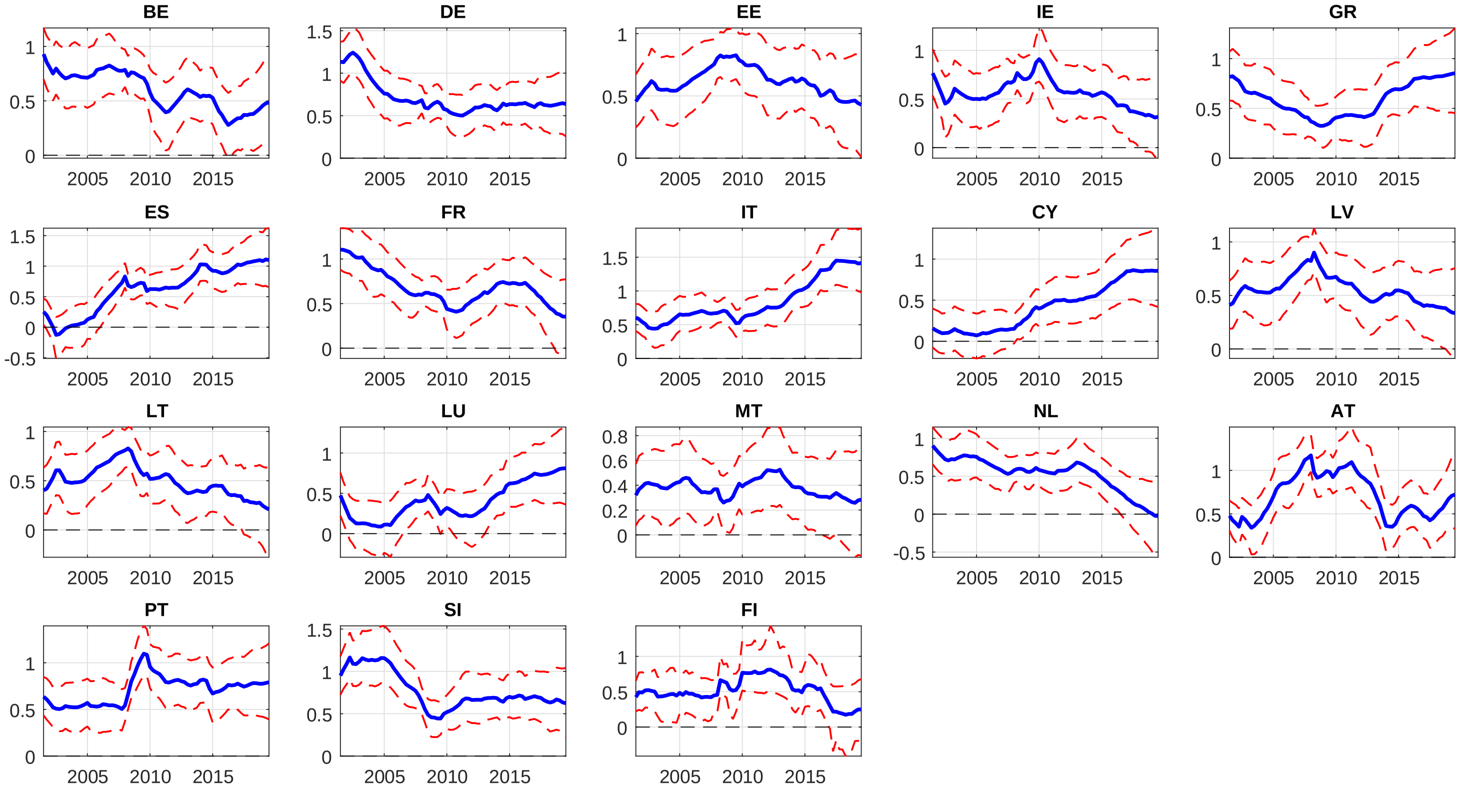
Figure 12: Time-varying coefficients of model for food-related inflation


(a) Sensitivity of food-related inflation of the euro area (λ_t)

(b) Persistence of the euro area food-related inflation factor (ϕ_t)

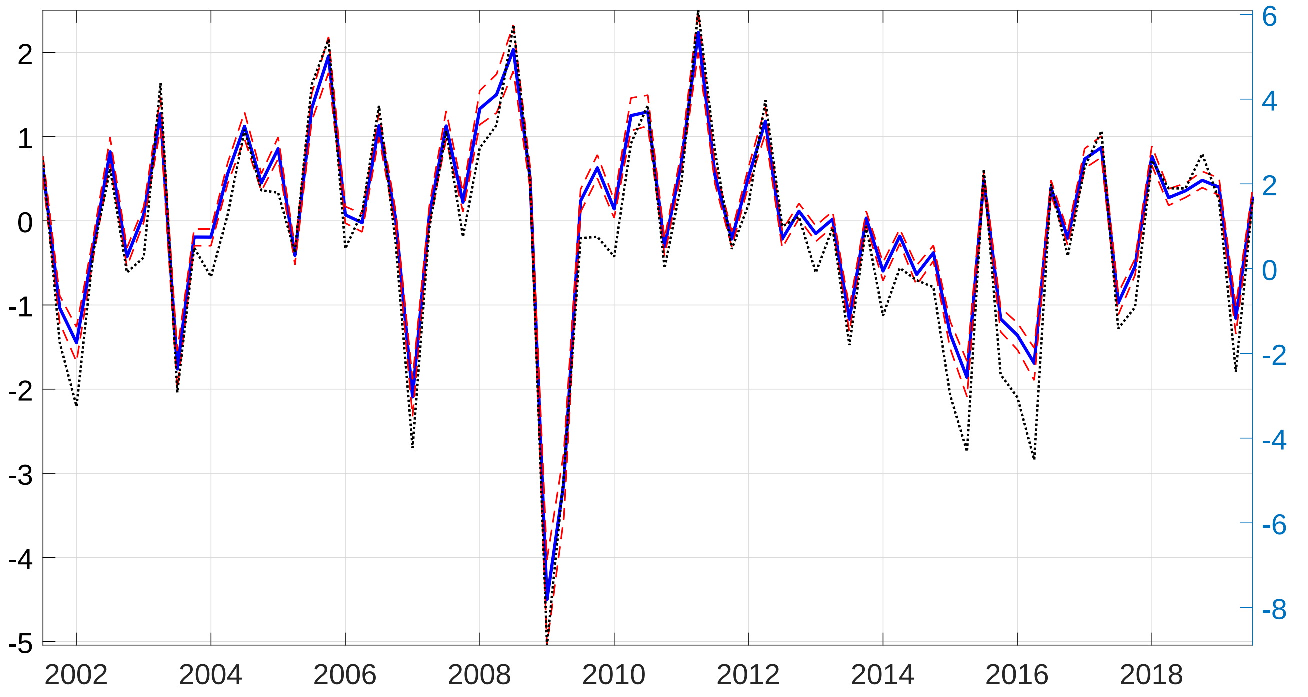
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

Figure 13: Time-varying comovement of euro area countries food-related inflation ($\gamma_{i,t}$)



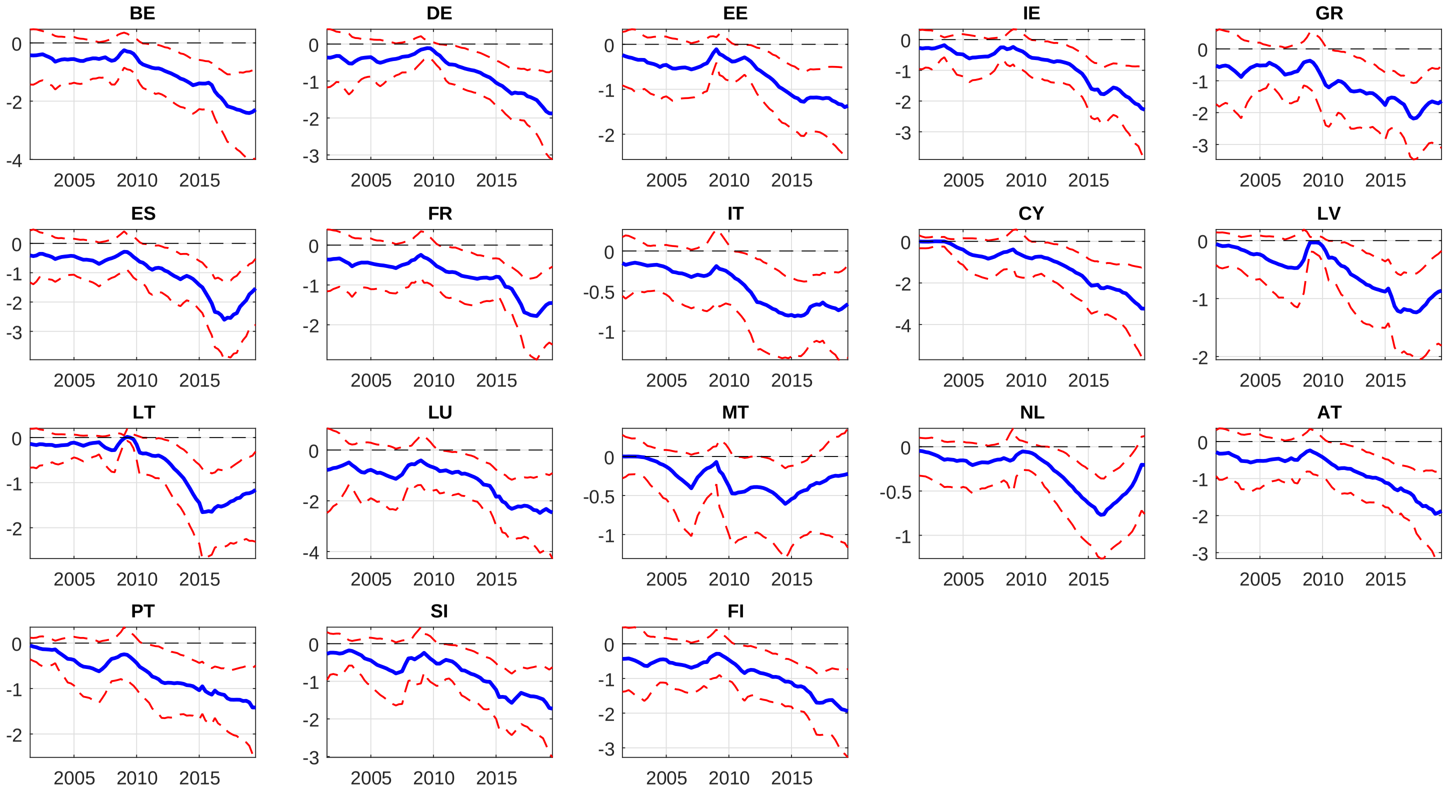
Note: Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

Figure 14: Euro area energy-related inflation factor (f_t)



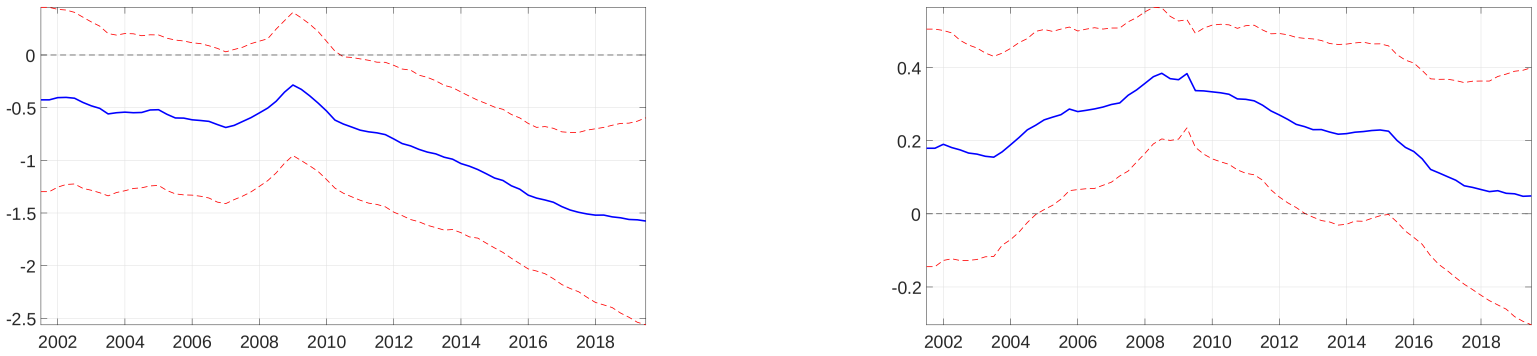
Note: Blue solid (red dashed) line, aligned with left axis, makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Black dotted line, aligned with right axis, make reference to the euro area energy-related inflation.

Figure 15: Time-varying sensitivity of energy-related inflation of euro area countries based on a multivariate model ($\tilde{\beta}_{i,2,t}$)



Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

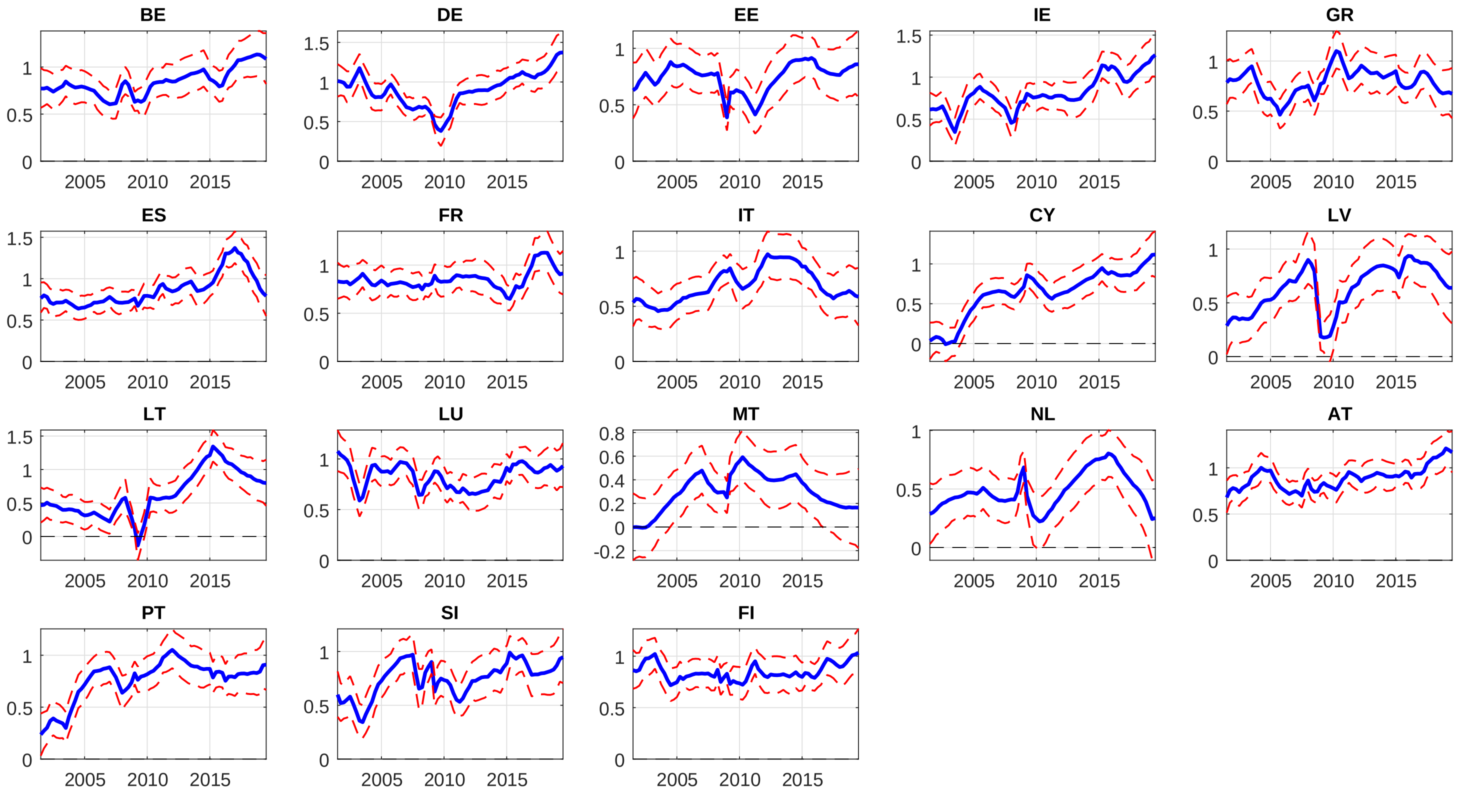
Figure 16: Time-varying coefficients of model for energy-related inflation


(a) Sensitivity of energy-related inflation of the euro area (λ_t)

(b) Persistence of the euro area energy-related inflation factor (ϕ_t)

Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

Figure 17: Time-varying comovement of euro area countries energy-related inflation ($\gamma_{i,t}$)



Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

A Online Appendix

A.1 Estimation of TVP factor model with exogenous information

The proposed estimation algorithm relies on Bayesian methods, in particular, we use the Gibss sampler to approximate the posterior distribution of parameters and latent variables involved in the time-varying parameter factor model with exogenous information (TVP-DFX). Let the vectors of observed variables defined as $\widetilde{\pi}_T = \{\pi_{1,t}, ..., \pi_{n,t}\}_{t=1}^T$, $\widetilde{x}_T = \{\epsilon_t^{Exo\_ER}\}_{t=1}^T$, and the vectors of latent variables as, $\widetilde{f}_T = \{f_t\}_{t=1}^T$, $\widetilde{\lambda}_T = \{\lambda_t\}_{t=1}^T$, $\widetilde{\phi}_T = \{\phi_t\}_{t=1}^T$, and $\widetilde{\gamma}_T = \{\widetilde{\gamma}_{1,T}, ..., \widetilde{\gamma}_{i,T}, ..., \widetilde{\gamma}_{n,T}\}$, where $\widetilde{\gamma}_{i,T} = \{\gamma_{i,t}\}_{t=1}^T$, for $i = 1, ..., n$. The parameters of the model, which consists of the variances associated to the different innovation processes, are given by $\Sigma = diag(\sigma_1^2, ..., \sigma_n^2)$, $\Omega = \{\nu_1^2, ..., \nu_n^2\}$, $\Pi = diag(\nu_\lambda^2, \nu_\phi^2)$, and can be collected in $\Theta = \{\Sigma, \Omega, \Pi\}$ to simplify notation. The algorithm consists of the following steps:

- ***Step 1***: Sample $\widetilde{f}_T$ from $P(\widetilde{f}_T|\widetilde{\pi}_T, \widetilde{x}_T, \widetilde{\lambda}_T, \widetilde{\phi}_T, \widetilde{\gamma}_T, \Theta)$

We cast the proposed factor model a in state space representation, with measurement equation given by,

$$\begin{bmatrix} \pi_{1,t} \\ \vdots \\ \pi_{n,t} \end{bmatrix} = \begin{bmatrix} \gamma_{1,t} \\ \vdots \\ \gamma_{n,t} \end{bmatrix} f_t + \begin{bmatrix} u_{1,t} \\ \vdots \\ u_{n,t} \end{bmatrix}, \tag{12}$$

and transition equation defined as,

$$f_t = \mu_t + \phi_t f_{t-1} + \omega_t , \tag{13}$$

where $\mu_t = \lambda_t \epsilon_t^{Exo\_ER}$, and similarly to other parameters of the state space model, are observed in this step of the algorithm. The innovations are assumed to be Gaussian, $(u_{1,t}, ..., u_{n,t})' \sim N(0, \Sigma)$, and $\omega_t \sim N(0, 1)$. Notice that the variance ω_t is set to one, this restriction is assumed for identification of the factor model. Conditional on the time-varying parameters being observed, the Carter and Kohn (1994) simulation smoother is applied to generate inferences of the latent factor, f_t.

- ***Step 2***: Sample $\widetilde{\gamma}_T$ from $P(\widetilde{\gamma}_T|\widetilde{\pi}_T, \widetilde{f}_T, \Omega, \Sigma)$

Given that Σ is a diagonal matrix, we sample the time-varying factor loadings associated to each observable independently from each other by employing the following state space representation

$$\begin{aligned} \pi_{i,t} &= \gamma_{i,t}\ f_t\ + u_{i,t}, \\ \gamma_{i,t} &= \gamma_{i,t-1} + \vartheta_{i,t}, \end{aligned}$$

where $u_{i,t} \sim N(0, [\Sigma_{ii}])$ and $\vartheta_{i,t} \sim N(0, \nu_i^2)$, for $i = 1, ..., n$. Conditional on the factor, f_t, being observed, the Carter and Kohn (1994) simulation smoother is applied to generate inferences of the factor loadings, $\gamma_{i,t}$.

- ***Step 3***: Sample Ω from $P(\Omega|\widetilde{\gamma}_T)$

We sample the elements of $\Omega = \{\nu_1^2, ..., \nu_n^2\}$ conditional on the dynamics of the time-varying factor loadings by relying on a prior inverse Gamma distribution, $IG(\underline{\eta}, \underline{v})$, with $\underline{\eta} = \kappa \times T$, and $\underline{v} = 0.01 \times (\underline{\eta} - 1)$. The coefficient κ measures the degree of uncertainty about the prior belief of the innovations variance of the factor loadings. The larger (smaller) the κ the smaller (larger) the uncertainty about the prior belief. If there is a relatively high (low) degree of underlying comovement, a factor model would be more (less) suitable for the data, and the uncertainty about the dynamics of the factor loadings would be smaller (larger). Therefore, we set $\kappa = 0.1 \times std^{-1}$, where std measures the median, cross-sectional and over time, of the squared differences of inflation between two countries, which provides a simple measures of overall comovement in the data. Accordingly, draws are sampled from independent posterior distributions

$$\nu_i^2 \sim IG(\bar{\eta}, \bar{v}),$$

with $\bar{\eta} = \underline{\eta} + T$, and $\bar{v} = \underline{v} + (\gamma_{i,t} - \gamma_{i,t-1})'(\gamma_{i,t} - \gamma_{i,t-1})$, for $i = 1, ..., n$.

- ***Step 4***: Sample Σ from $P(\Sigma|\widetilde{\pi}_T, \widetilde{f}_T, \widetilde{\gamma}_T)$

We sample the elements of $\Sigma = diag(\sigma_1^2, ..., \sigma_n^2)$ conditional on the observed data, factor and time-varying factor loadings by relying on a prior inverse Gamma distribution, $IG(\underline{\eta}, \underline{v})$. Hence, draws are sampled from independent posterior distributions

$$\sigma_i^2 \sim IG(\bar{\eta}, \bar{v}),$$

with $\bar{\eta} = \underline{\eta} + T$, and $\bar{v} = \underline{v} + (\pi_{i,t} - \gamma_{i,t} f_t)'(\pi_{i,t} - \gamma_{i,t} f_t)$, for $i = 1, ..., n$.

- ***Step 5***: Sample $\widetilde{\lambda}_T, \widetilde{\phi}_T$ from $P(\widetilde{\lambda}_T, \widetilde{\phi}_T | \widetilde{f}_T, \widetilde{x}_T, \Pi)$

We sample jointly the time-varying coefficients, $\widetilde{\lambda}_T, \widetilde{\phi}_T$, by using the following state space representation

$$\begin{aligned} f_t &= \begin{bmatrix} f_{t-1} & \epsilon_t^{Exo\_ER} \end{bmatrix} \begin{bmatrix} \phi_t \\ \lambda_t \end{bmatrix} + \omega_t, \\ \begin{bmatrix} \phi_t \\ \lambda_t \end{bmatrix} &= \begin{bmatrix} \phi_{t-1} \\ \lambda_{t-1} \end{bmatrix} + \begin{bmatrix} \vartheta_{\phi,t} \\ \vartheta_{\lambda,t} \end{bmatrix}, \end{aligned}$$

where $\omega_t \sim N(0,1)$ and $(\vartheta_{\phi,t}, \vartheta_{\lambda,t})' \sim N(0, \Pi)$. Conditional on the dynamics of the factor and the exogenous variable being observed, the Carter and Kohn (1994) simulation smoother is applied to generate inferences of the time-varying coefficients.

- ***Step 6***: Sample Π from $P(\Pi | \widetilde{\lambda}_T, \widetilde{\phi}_T)$

We sample the elements of $\Pi = diag(\nu_\lambda^2, \nu_\phi^2)$ conditional on the dynamics of the corresponding time-varying coefficients by relying on a prior inverse Wishart distribution, $IW(\underline{\eta}, \underline{V})$, with $\underline{V} = I_2 \times \underline{v}$. Hence, draws are sampled from the posterior distribution

$$\Pi \sim IW(\bar{\eta}, \bar{V}),$$

with $\bar{\eta} = \underline{\eta} + T$, and $\bar{V} = \underline{V} + (\xi_t - \xi_{t-1})'(\xi_t - \xi_{t-1})$, where $\xi_t = (\phi_t, \lambda_t)'$.

To approximate the posterior distribution of both the parameters and latent variables involved in the model, each step of the algorithm is recursively repeated $M = 20,000$ times, discarding the first $m = 10,000$ iterations.

A.2 Robustness checks: Alternative SVAR specifications

With the aim of assessing if our results reported Section 3.1 are robust to different specifications, we summarize a series of extensions and sensitivity checks. First, to alternatively identify the structural shocks with regards to the unexpected appreciation of the euro, we rely on imposing a different set of sign restrictions in some of the entries of the impact multiplier matrix. Second, we analyse any effect of changes in the SVAR-X dynamic properties such as model lag orders and timing of sign restrictions. Third, we evaluate the differences across the shocks extracted from our baseline VAR model and a version of the same specification, but subject to time-varying parameters (TVP-VAR).

A.2.1 Alternative Identification Strategies

Let us now assume that an unexpected appreciation of the euro, $\epsilon_t^{Exo\_ER}$, would lead to declines in inflation, along with further appreciation of the euro and a rise in output (through confidence channels) and in the global demand. In the baseline scenario, monetary policy is expected to loose the interest rate in line with An and Wang (2012). However, an alternative identification strategy relaxing the latter assumption is imposed (i.e., with no assumption about whether the interest rate is unchanged or lowered). All these restrictions can be formalized as follows,

$$\begin{bmatrix} u_t^{GDP} \\ u_t^{INF} \\ u_t^{INT} \\ u_t^{FX} \\ u_t^{EA/US} \end{bmatrix} = \begin{bmatrix} + & + & - & + & + \\ - & + & - & - & + \\ - & + & + & * & * \\ - & * & * & + & * \\ + & + & - & + & - \end{bmatrix} \begin{bmatrix} \epsilon_t^{Dom\_Sup} \\ \epsilon_t^{Dom\_Dem} \\ \epsilon_t^{Mon\_Pol} \\ \epsilon_t^{Exo\_ER} \\ \epsilon_t^{Glo\_Dem} \end{bmatrix},$$

where the entries with an "$*$" in the impact multiplier matrix indicates that such a relation is left unrestricted. As shown in Figure 1S, the historical decomposition of shocks is little changed with respect to the baseline identification strategy (Figure 1).

A.2.2 Alternative SVAR Dynamics

As an additional set of robustness check, we analyse any effect of changes in the SVAR-X specification, in terms of lag orders and timing of sign restrictions in the vein of Forbes et al. (2018). The results in Table 1 (columns 2-4) show no remarkable differences by changing the lag structure compared to our baseline results (lag of order 2). In addition, our results do not seem to be sensitive to imposing longer sign restrictions of 2 or 4 quarters (columns 5 and 6)

A.2.3 Time-Varying Parameter SVAR

The dynamic properties of those series accounted for in our shock-dependent approach might not be constant over time. For this reason, we assess whether our main results are robust to a specification that allows both the estimated coefficients and the residuals covariance matrix to change over time. Let Y_t be a $n-$vector of time series satisfying:

$$\mathbf{Y}_t = A_{0,t} + A_{1,t}\mathbf{Y}_{t-1} + ... + A_{p,t}\mathbf{Y}_{t-p} + \epsilon_t, \tag{14}$$

where ϵ_t is Gaussian white noise mean and time-varying covariance matrix Σ_t and $A_{j,t}$ are matrices of coefficients (n x n). For the law of motion of the VAR parameters let $A_t = [A_{0,t}, A_{1,t}, ..., A_{p,t}]$ and $\theta_t = vec(A_t')$, where:

$$\theta_t = \theta_{t-1} + \omega_t \tag{15}$$

where ω_t is Gaussian white noise with zero mean and covariance Ω. In addition, let the covariance matrix be: $\sum_t = F_t D_t F_t'$ where F_t is lower triangular and D_t a diagonal matrix. Finally, the law of motion of the covariance matrix is defined as follows. First, let σ_t be the $n-$vector of the diagonal elements of $D_t^{1/2}$ and let $\phi_{i,t}$, with $i = 1, ..., n-1$, be the column vector formed by the non-zero and non-one elements of the $(i+1) - th$ row F_t^{-1}. We assume that:

$$\log \sigma_t = \log \sigma_{t-1} + \xi_t \tag{16}$$

$$\phi_{i,t} = \phi_{i,t-1} + \psi_{i,t} \tag{17}$$

where ξ_t and $\psi_{i,t}$ are again Gaussian white noises with zero mean and covariance matrix Ξ and $\Psi_{i,}$, respectively. Let us also assume that ξ_t, $\psi_{i,t}$, ω_t, and ϵ_t are mutually orthogonal at all leads and lags.

Finally, the estimation procedure is based on Bayesian MCMC methods (Gibbs sampler) in order to obtain the draws of the coefficients from the posterior distribution with the same identification strategy than previously mentioned. Let the vector ϕ_t a vector containing all the $\phi_{i,t}$, $i = 1, ..., n-1$, and σ^T containing $\sigma_1, \sigma_2, ..., \sigma_T$. The posterior distribution is unknown but not the conditional posteriors:

Step 1: Sample σ^T from $p(\sigma^T|Y^T, \theta^T, \phi^T, \Omega, \Xi, \Psi)$

Step 2: Sample ϕ^T from $p(\phi^T|Y^T, \theta^T, \sigma^T, \Omega, \Xi, \Psi)$

Step 3: Sample θ^T from $p(\theta^T|Y^T, \sigma^T, \phi^T, \Omega, \Xi, \Psi)$

Step 4: Sample Ω from $p(\Omega|Y^T, \theta^T, \sigma^T, \phi^T, \Xi, \Psi)$

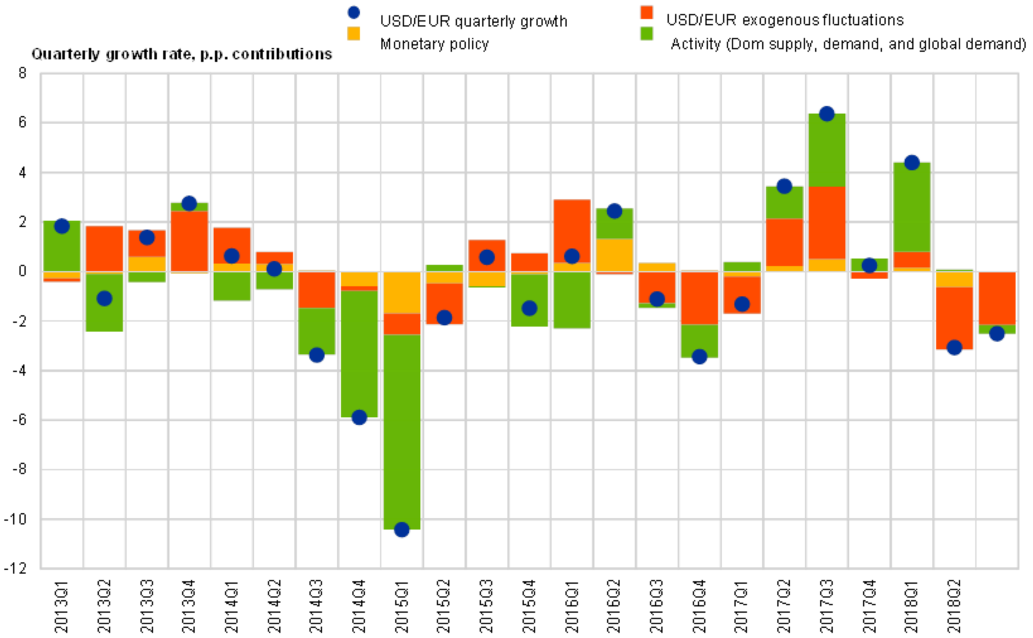
Step 5: Sample Ξ from $p(\Xi|Y^T, \theta^T, \sigma^T, \phi^T, \Omega, \Psi)$

Step 6: Sample Ψ from $p(\Psi|Y^T, \theta^T, \sigma^T, \phi^T, \Omega, \Xi)$

We generate $M = 10,000$ iterations, and discard the first $m = 1,000$ iterations. Time-varying impulse response functions computed at each quarter do not significantly vary over the sample period, as it is shown in Figure 19. Also, historical decomposition of shocks suggest that there are no serious grounds for parameter instability to change our main results. To summarize, purely exogenous exchange rate shocks extracted from all three different SVAR approaches (i.e., SVAR, SVAR-X, TVP-SVAR) show little variation, since their statistical correlation is higher than 0.9.

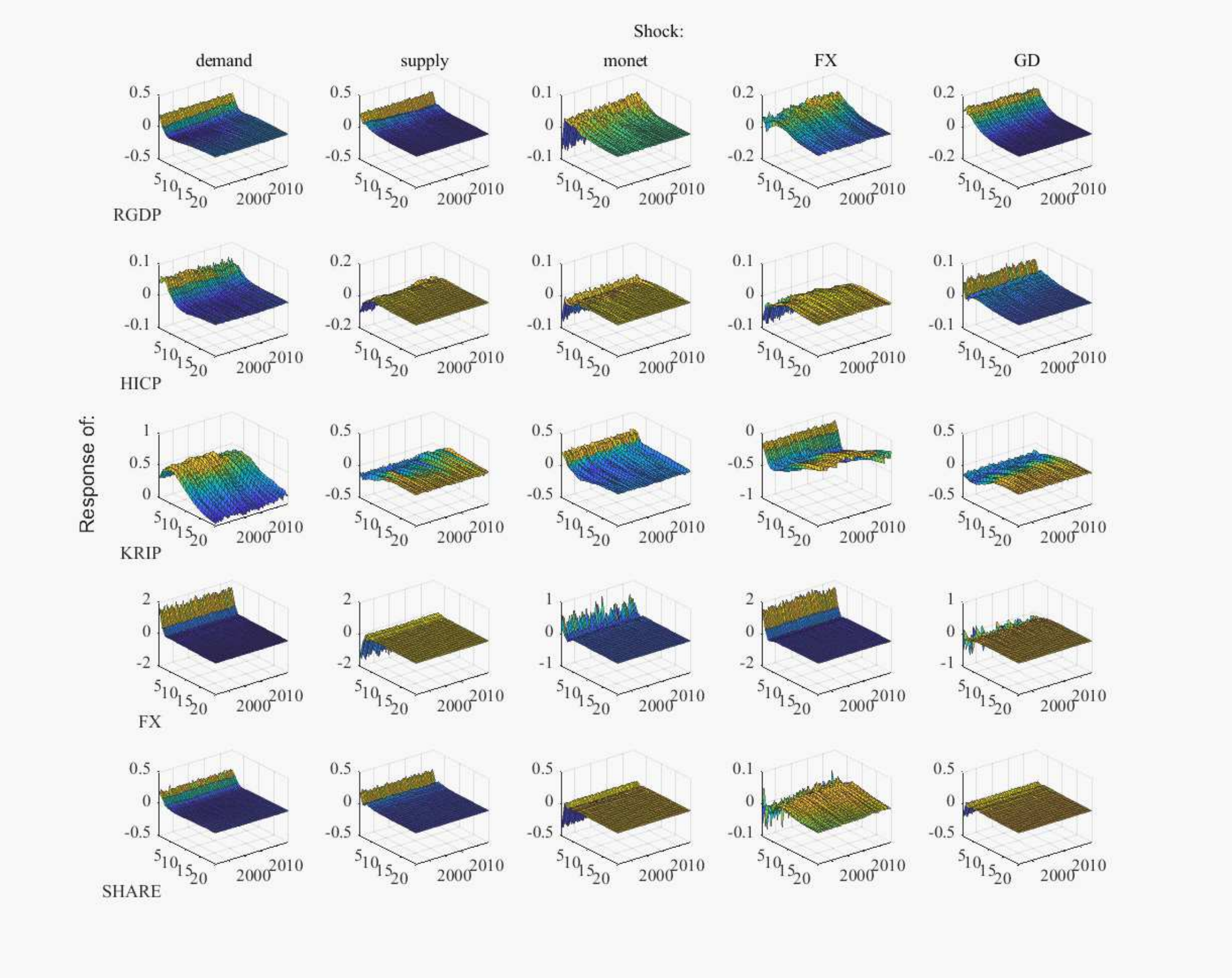
B Online Appendix: Figures and Tables

Figure 18: Historical decomposition of nominal exchange rate EUR/USD: Alternative SVAR Identification Strategy



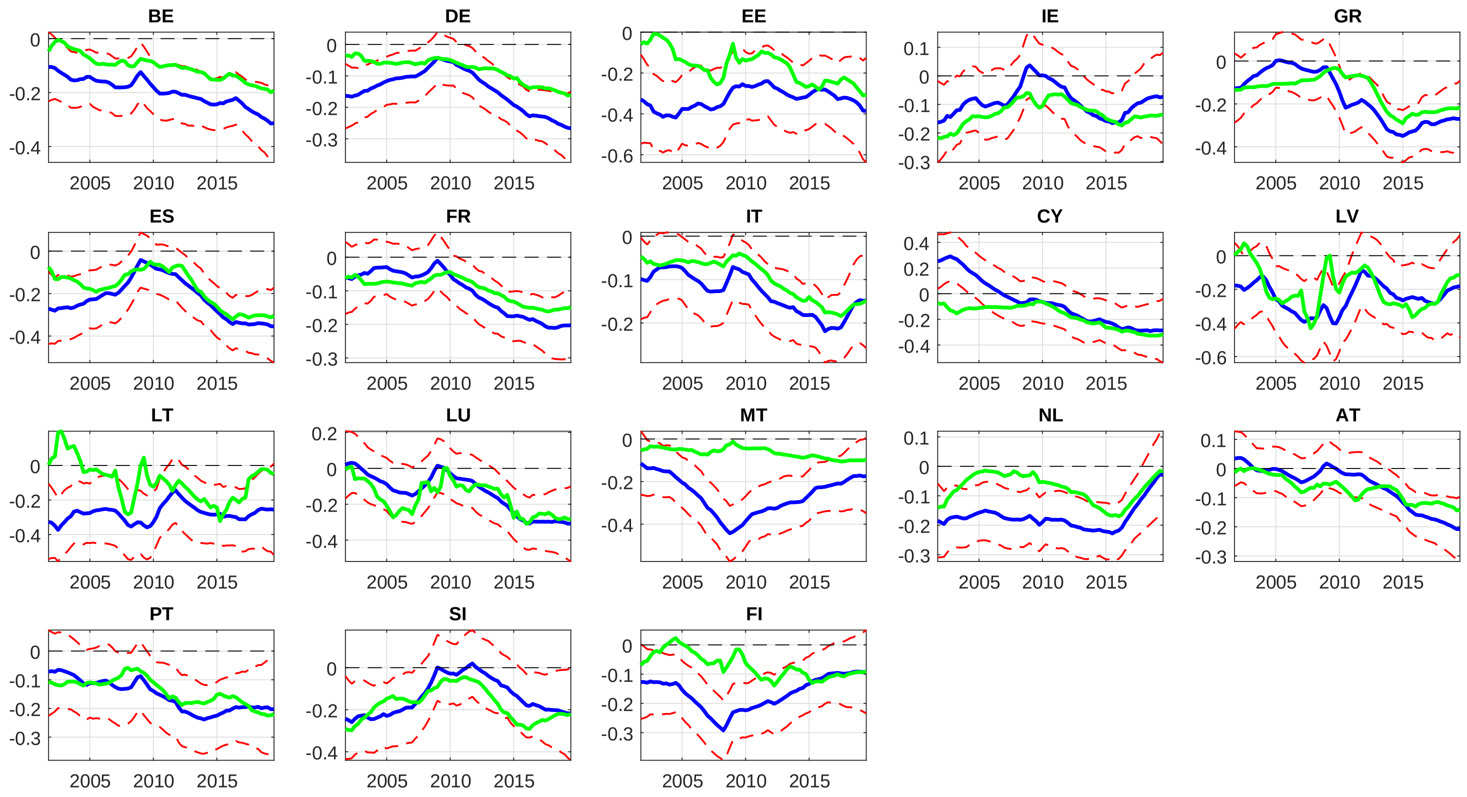
Notes: Estimates based on a quarterly SVAR model of the EUR/USD exchange rate where shocks are identified via sign restrictions defined in the Online Appendix Section.

Figure 19: Time-varying impulse response functions: TVP-SVAR model with sign restrictions



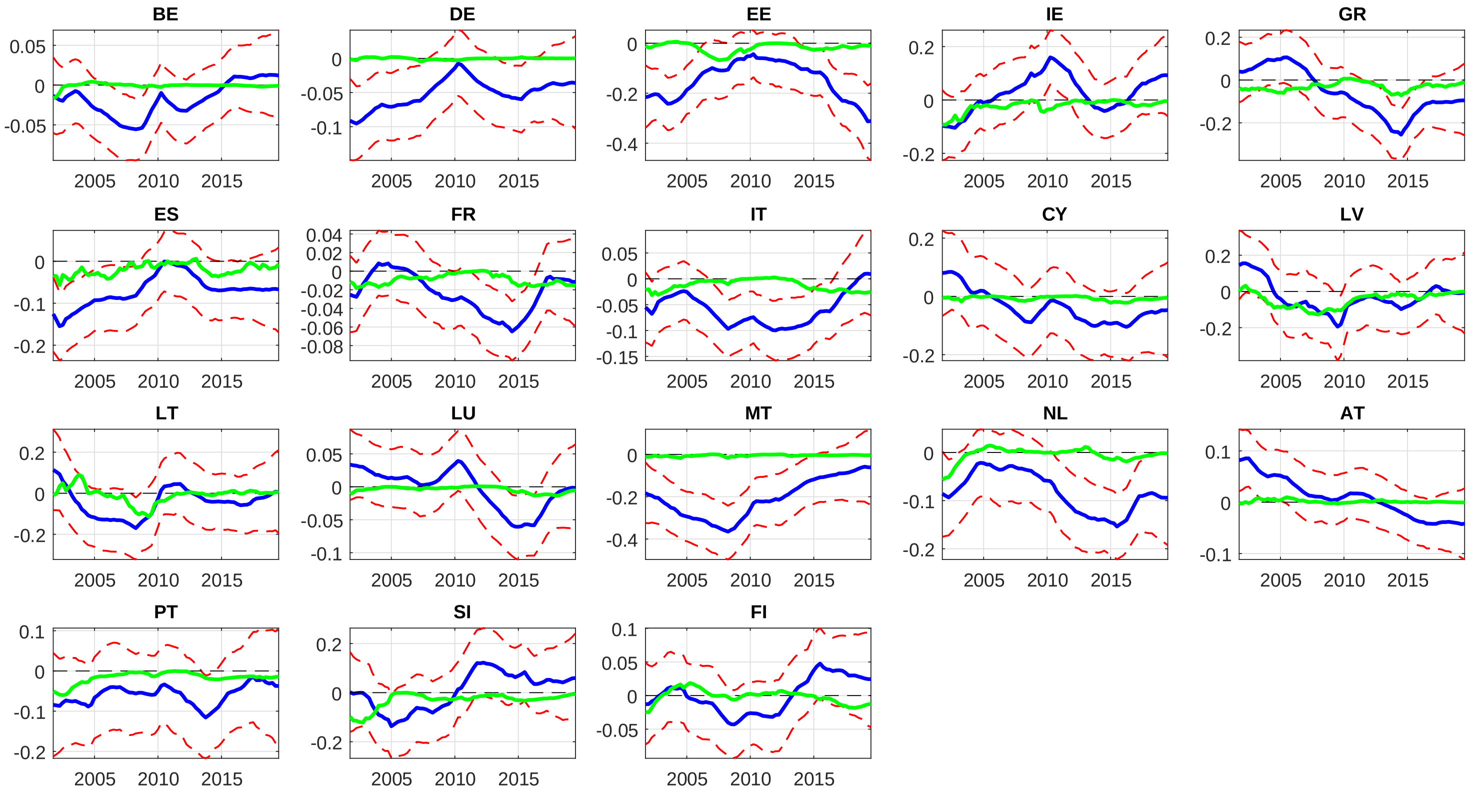
Notes: Estimates based on a quarterly TVP-SVAR model of the EUR/USD exchange rate where shocks are identified via sign restrictions. RGDP refers to euro area GDP growth, HICP refers to consumer prices inflation, KRIP refers to relative monetary policy rates for the euro area and the US as of Krippner (2013), FX refers to the nominal EUR/USD exchange rate and share refers to the relative share of activity growth between the euro area and the US.

Figure 20: Time-varying sensitivity of headline inflation of the euro area countries based on a univariate model ($\hat{\beta}_{i,2,t}$)



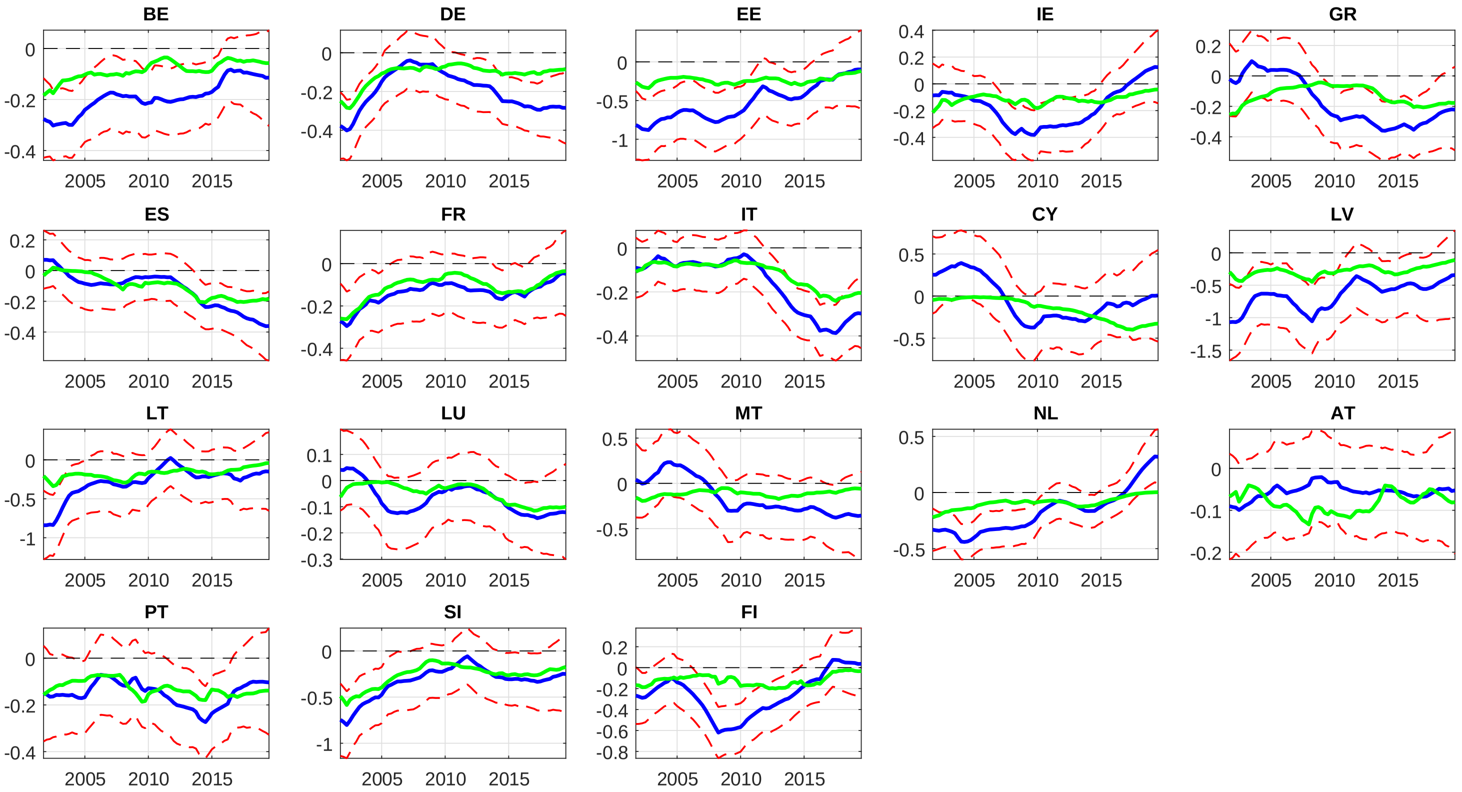
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Green solid line reports the median estimate obtained with the multivariate model for comparison purposes.

Figure 21: Time-varying sensitivity of core inflation of the euro area countries based on a univariate model ($\hat{\beta}_{i,2,t}$)



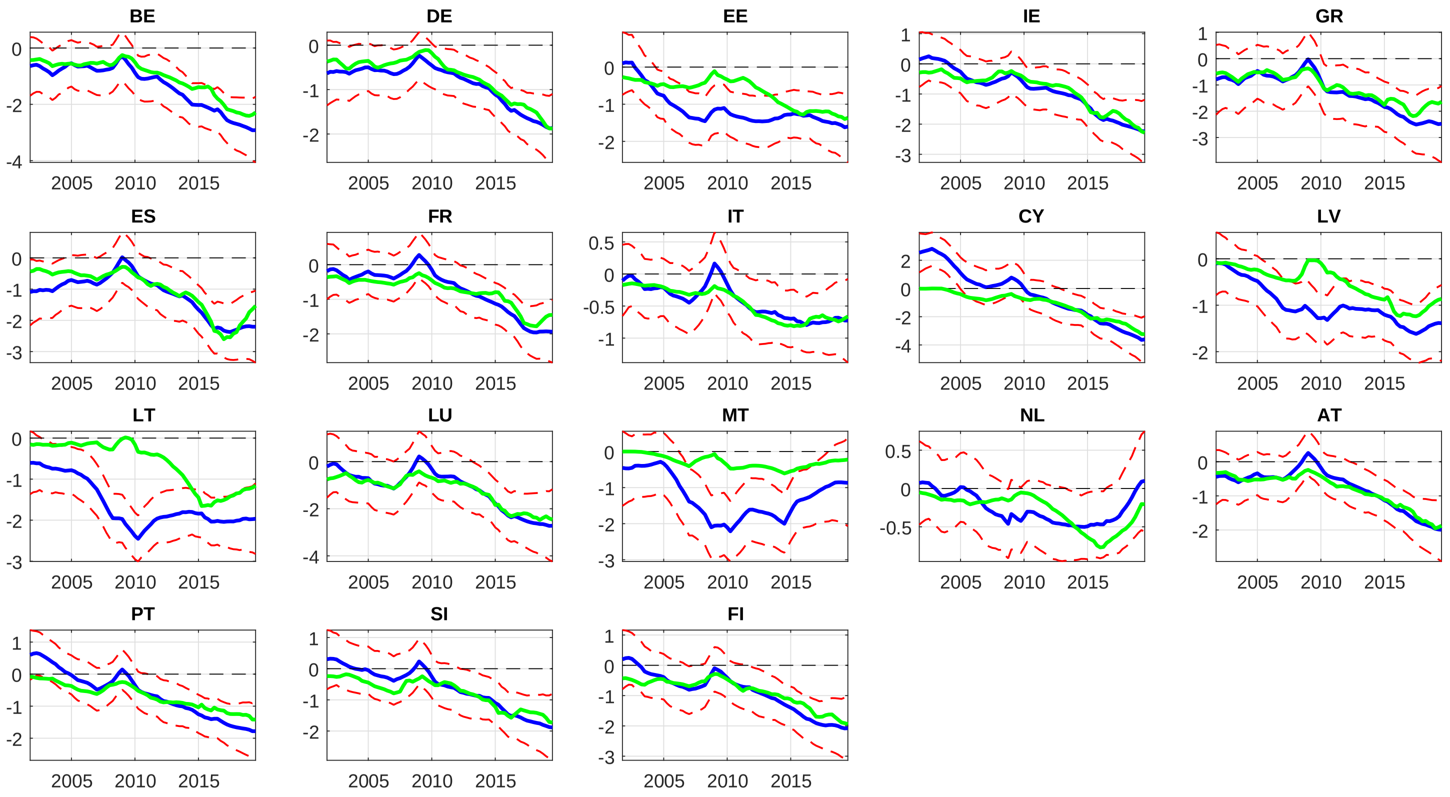
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Green solid line reports the median estimate obtained with the multivariate model for comparison purposes.

Figure 22: Time-varying sensitivity of food-related inflation of the euro area countries based on a univariate model $(\hat{\beta}_{i,2,t})$



Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Green solid line reports the median estimate obtained with the multivariate model for comparison purposes.

Figure 23: Time-varying sensitivity of energy-related inflation of the euro area countries based on a univariate model ($\hat{\beta}_{i,2,t}$)



Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Green solid line reports the median estimate obtained with the multivariate model for comparison purposes.

Table 1: FEVD of the EUR/USD for different lag orders and sign restriction periods

	SVAR estimated with:					
	Baseline	1 lag	3 lags	4 lags	2-per	4-per
	[1]	[2]	[3]	[4]	[5]	[6]
Domestic demand	14%	17%	15%	17%	23%	24%
Domestic supply	31%	29%	32%	31%	27%	30%
Rel monetary policy	16%	15%	13%	13%	11%	14%
Exchange rate	25%	24%	25%	23%	27%	21%
Global demand	15%	15%	15%	16%	12%	11%

Notes: Estimated using SVAR model described in Section 2.1. N-per refers to sign restrictions of N periods

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