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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 that is based on dynamic factor models subject to drifting parameters and exogenous information. We show that exogenous shocks to the euro/USD account for over 50% of the nominal euro/USD exchange rate fluctuations in more than 1/3 of the quarters over the past six years – especially in turning points periods. Our main results indicate that headline inflation in euro area countries, and in particular its energy-related component, has significantly become more affected by these exogenous exchange rate shocks since the early 2010s, in particular, for the largest economies of the region. While such increasing sensitivity relies solely on a sustained surge in the degree of comovement for headline inflation, it is also based on a higher region-wide effect of the shocks for the case of energy inflation. Instead, purely exogenous exchange rate 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.

Keywords: exchange rate, inflation, factor model, structural VAR model.

JEL classification: E31, F3, F41.

Resumen

Este artículo estudia la evolución a lo largo del tiempo de la traslación a la inflación en los distintos países del área del euro de perturbaciones puramente exógenas al tipo de cambio del euro. Esta evolución se descompone en un factor específico de país y en otro común a toda el área. Para ello, se propone un enfoque empírico flexible, basado en un modelo de factores dinámico con parámetros cambiantes en el tiempo e información exógena. Se encuentra que, para más de un tercio del tiempo en los seis últimos años, y especialmente en sus puntos de giro, más del 50 % de las fluctuaciones del tipo de cambio nominal EUR/USD se han debido a perturbaciones puramente exógenas del tipo de cambio. Los principales resultados de este artículo apuntan a que la inflación total en los países del área del euro, y particularmente su componente energético, se ha visto significativamente más afectada por estas perturbaciones exógenas del tipo de cambio desde comienzos del 2010, especialmente en el caso de las mayores economías de la región. Mientras que esta mayor sensibilidad de la inflación total descansa exclusivamente en el superior comovimiento estimado entre las inflaciones de los países, en el caso de la inflación energética se debe también a una mayor respuesta a dichas perturbaciones del tipo de cambio del factor común del área del euro. Sin embargo, el componente de la inflación que excluye alimentos y energía no responde de forma significativa a las perturbaciones cambiarias y, además, muestra un menor grado de correlación entre los países del área.

Palabras clave: tipo de cambio, inflación, modelo de factores, modelo VAR estructural.

Códigos JEL: E31, F3, F41.

1 Introduction

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

From a policymaker standpoint, assessing the impact that currency movements have on price inflation is crucial for the design of monetary policy frameworks. A clearer understanding of its transmission channels may improve the ability to predict its impact, as well as 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 analyzing the degree to which a country's import, producer or consumer prices change in response to its exchange rate fluctuations – commonly known as exchange rate pass-through (ERPT henceforth).[1] The literature on ERPT covers from seminal theoretical studies (Krugman (1987), Dornbusch (1987) and Corsetti el al. (2008)), which showed that the ERPT to prices was incomplete due to imperfect competition and pricing-to-market, to cross-country empirical evidence (Campa and Goldberg (2005, 2010)), focusing on slow-moving structural determinants, such as changes in the composition of imports. Recently, there has been more effort to identify the factors behind the evolution of the ERPT over time from a micro data perspective on firm pricing (Gopinath et al. (2010), Berger and Vavra (2013), Devereaux et al. (2015), and Amiti et al. (2016)). These works highlight drivers such as the role of invoicing currency, whether the transactions take place between or within firms, the frequency and dispersion of prices adjustments and the role of competition in final products markets.

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

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 UK 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 fluctuations in the exchange rate (i.e., whether it is due to domestic demand, global demand, domestic monetary policy, global supply shocks, domestic productivity, etc.), finding that domestic monetary policy shocks are those with relatively higher reponse of prices relative to that of the exchange rate. A similar result was found for the euro area by Comunale and Kunovac (2017), with the same methodology. Their estimates point to a large but volatile pass-through to import prices and overall 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 it. 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 remains silent about 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 to the different economies (country-specific).

This paper builds from the literature of shock-dependent exchange rate pass-through and elaborates further on the time variation and cross-country differences in the response of alternative price components to exchange rate changes in the euro area. Among all sources of exchange rate fluctuations, this paper focusses only on exogenous exchange rate shocks. This is partly motivated to try to mimic as much 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

[2] Using reduced-form approaches (not shock-dependent), a body of empirical literature have 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 (2019) and references therein such as Hahn (2003), Ösyurt (2016) and Jasová et al. (2016).

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 variation in the nominal euro/USD exchange rate - around 65% since 1995 to be precise. There is, however, an increased role of exogenous exchange rate shocks in unanticipated nominal exchange rate movements not only in the last years but also during turning point periods. Our results indicate that they are behind more than 50% of the nominal euro/USD exchange rate fluctuations in more than 1/3 of the quarters over 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 the headline inflation of 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 to control for past inflation dynamics, the exchange rate shocks are measured by ϵ_t^{ER}, and $v_{i,t}$ represents an error term.[3] Notice that in equation (1), our object of interest is the dynamics of $\beta_{i,t}$, which measures the changing sensitivity of inflation to the shocks to the exchange rate.[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 country i. Instead, the other part is common across all countries that belong to the euro area. 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. Such decomposition can be illustrated with the following equation,

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

where $IDI_{i,t}$ denotes the idiosyncratic, country-specific component while COM_t denotes the common, region-wide component. The information contained in equation (2) can be useful for policy makers to understand up to which extent movements in inflation of a given

[3]The lag operator is denoted by L.

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

country, induced 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 from 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 stylized facts, we base our identification scheme on sign and exclusion restrictions, along the lines of Shambaugh (2008), Comunale and Kunovak (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 across (i) countries, (ii) subcomponents, and (iii) time.

The main results show that the sensitivity of headline inflation to exogenous exchange rate shocks has increased since the early 2010s. That is, 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. This finding may seem in contradiction with the literature that estimates lower ERPT now than in previous decades in advanced economies, including those in the euro area (see Ortega and Osbat (2019) and references therein). Instead, by focusing on one type of shocks only, we coincide with the recent shock-dependent ERPT literature above that finds sizeable price-exchange rate comovement for each of the structural shocks that moves the exchange rate, which may partially compensate 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 to the aggregate euro area inflation, has remained relatively stable over time. Instead, the country-specific component has exhibited

[5]The euro area (19) monetary union gathers the following European Union (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.

[6]See the related similar discussion in Ortega and Osbat (2019)

a substantial increase since the early 2010's. This implies that the increasing sensitivity of headline inflation to exchange rate shocks heavily relies on a sustained surge in comovement between the inflation rates of euro area countries exhibited in recent years.

When applying the proposed empirical framework to different subcomponents of headline inflation, that is, energy, food and core components, the results indicate some similarities. For the case of the energy component of inflation, its sensitivity to exogenous exchange rate shocks has also significantly increased in recent years. However, unlike the case of headline inflation, such increasing sensitivity relies equally on both the country-specific and common components. For food-related inflation rates, the pattern is similar to the case of headline inflation, although with less significance. The case of core inflation is somehow different. Core inflation across countries does not seem to be meaningfully affected by exogenous exchange rate shocks, along the lines of what the empirical literature finds (Ortega and Osbat (2019)).

The structure of the paper proceeds as follows. Section 2 sets out the empirical approach. Section 3 discusses the main results and pays special attention to the assessment of inflation commonalities across countries. Section 4 concludes.

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 able to fulfill four main features. 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 propagate across the different countries in the euro area. Third, to provide information about the potential changes over time in the sensitivity of each country to those socks. Fourth, to decompose such changing sensitivity into its country-specific and region-wide counterparts.

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

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

2.1 Structural VAR Model

We employ a structural vector autoregression (SVAR) model to investigate the exchange rate sensitivity of euro area inflation by taking into account how different theory-based shocks may impact the exchange rate and prices. More specifically, we are interested in assessing the effects of five shocks to 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, which rely on open-economy DSGE models and have also been widely used in the related literature.

Under such a setting, if an euro appreciation is mainly driven by a positive euro area demand shock, domestic market and domestic prices are expected to increase, partly compensated by cheaper imported products following the euro appreciation.[8] Such an appreciation is theoretically expected to be associated to a counter-cyclical monetary policy response and to 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 extert downward domestic price and wage pressures, supporting price decreases.These would be partially compensated by the stronger domestic demand for foreign exporters, which would normally increase import prices. Consintently with previous 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 expect a negative correlation between the 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 to an increase in GDP and HICP. Given that the demand growth in the rest of the world would be higher, the corresponding tightening of monetary policy would likely be stronger than in the domestic economy, which would actually loosen monetary policy in relative terms.

If instead the euro appreciation responds to a relative tightening of monetary policy in the euro area with respect to that of the US Federal Reserve, which promotes a higher relative assets yields in euros, 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

[8]The higher weigth of domestic against imported goods (home bias) in the demand of most European economies guarantees that cheaper imported inflation does not dominate over the inflationary effect of the positive demand shock.

measured in euros, thus intensifying the fall in prices caused by the monetary restriction. Similarly, if the euro appreciation is due to a purely exogenous change, to a risk premium shock not based on fundamentals regarding real activity nor monetary policy, import prices are expected to fall and therefore, although to a lesser extent, so will consumer prices. In this case, monetary policy is expected to loose 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 agree that currency values of commodity exporters contain information about future commodity price movements as showed 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)). Under such a setting, supply shocks driving the euro/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 correlation between oil prices and exchange rates. Instead, we acknowledge its influence in a wider 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 US, euro/dollar nominal exchange rate (FX), the relative euro area activity share with respect to the US (EA/US), and an aditional 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, $\mathbf{u}_t = \mathbf{B}\epsilon_t$.

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

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

To identify the structural shocks of interest following the above explained macroeconomic relations, we impose sign restrictions in 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 on domestic output and the relative euro area activity share, while it leads to inflation, interest rates and foreign exchange rate reductions.[12] Instead, a positive domestic demand shock, $\epsilon_t^{Dom\_Dem}$, would be associated to higher output and relative euro area activity, higher HICP inflation, higher interest rates, and euro appreciation. An unexpected tightening in the monetary policy stance, $\epsilon_t^{Mon\_Pol}$ that increases the short term interest rate, is assumed to be associated to lower inflation, output growth and relative share of euro area activity with respect to the US. We also assume that an unexpected appreciation of the euro, $\epsilon_t^{Exo\_ER}$ that increases the amount of USD per euro, would lead to declines in inflation and the interest rate.[13] Finally, we assume that a positive shock in global demand, $\epsilon_t^{Glo\_Dem}$ that reduces the relative size of the euro area economy with respect of the world economy (proxied by the US), exerts upward pressures on the euro area output and inflation, but would lead to a relatively looser monetary policy in the euro area than in the US, whose demand expansion is larger after the positive global demand shock. All these restrictions can be formalized as follows,

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

where the entries with an "$*$" in the impact multiplier matrix indicates that such a relation is left unrestricted. This combination of sign restrictions constitutes the minimum number of theory-based economic restrictions allowing us to both identify the shocks of interest and to guarantee their orthogonality.[14]

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

[12] A reduction of the FX is defined as a reduction in the USD in exchange for 1 euro, that is, a euro depreciation.

[13] For robustness sake, an alternative identification scheme concerning an unexpected appreciation of the nominal exchange rate of the euro (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 robustness checks of the estimation methodology is discussed in the Online Appendix. The obtained estimates are qualitatively similar to the ones obtained with our benchmark specification in equations (3)-(4).

We estimate the SVAR-X model, described in equations (3)-(4), using quarterly data for the euro area and the US over the period from 1995Q1 to 2019Q2 on the following six variables: (i) 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 by the European Commission (Eurostat); (iii) relative short term interest rates between the euro area and the US. For the zero lower bound period, we use shadow rates that are based on quarterly averages of monthly estimates from Krippner (2013);[15] (iv) quarterly average of monthly nominal US dollar/euro reference exchange rate provided by the European Central Bank. Our SVAR-X model results are robust to an alternative estimation accounting for the nominal effective exchange rate of the euro against its main 38 trade partners (NEER - 38 countries). Some caveats arise, though. Those variables proxying global demand and relative monetary policy are measured only in relation with the US, not the entirely set of 38 countries used in the NEER definition;(v) relative euro area activity is computed as the ratio between euro area and US GDP, based on GDP data provided by the European Commission (Eurostat) and the Bureau of Economic Analysis; (vi) world oil prices are based on the quarterly average of monthly Europe Brent spot prices FOB publised by the 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 characterize the degree of comovement in the dynamics of prices from different levels of disaggregation. A couple of 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 provide a global perspective of synchronized inflation dynamics across industrialized countries. Here, we make use of this tool to provide

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

a comprehensive assessment of the exchange rate effects on euro area inflation countries from a unified perspective.

We use the exogenous exchange rate shocks extracted from the structural VAR model above to assess their effect on the inflation of the n euro area countries. Since we are primarily interested in assessing changes over time in the exchange rate sensitivity of inflation, we rely on a multivariate framework subject to time-varying coefficients, following the line of Ductor and Leiva-Leon (2016).

Consider the standardized 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, which is 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 $\omega_t \sim N(0, 1)$. Notice that Equation (5) decomposes the country-specific inflation, $\pi_{i,t}$, into a common component, f_t, and an idiosyncratic component, $u_{i,t}$. Instead, Equation (6) assumes that the common factor follows autoregressive dynamics, and that is also influenced by exogenous information, in particular, by the exogenous exchange rate shocks, $\epsilon_t^{Exo\_ER}$.

The parameters of the model 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 $\vartheta_{\phi,t} \sim N(0, \nu_\phi^2)$. Very 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.

When plugging Equation (6) into Equation (5), we remain with the following expression for country i inflation dynamics,

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

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 $\tilde{v}_{i,t} = \sigma_{i,inf}(\gamma_{i,t}\omega_t + u_{i,t})$. Notice 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, that is, $\tilde{\beta}_{2,i,t}$ and $\beta_{i,t}$, respectively.

The main advantage of the proposed TVP-DFX model is that it allows to decompose the effect of exchange rate shocks on inflation, $\tilde{\beta}^i_{2,t}$, into two components. The country-specific, $\gamma_{i,t}$, and the euro area-wide one, λ_t, which would correspond to the terms $IDI_{i,t}$ and COM_t, respectively, from Equation (2). The term λ_t provides information about the changing effect that exchange rate shocks have on the euro area inflation dynamics, proxied by the factor f_t. Instead, the term $\gamma_{i,t}$ provides information about the changing propagation of those shocks throughout the different countries of the euro area.

Equation (10) is estimated first on headline HICP inflation across euro area economies. Section 3.2 discusses those results, as well as the estimation of Equation (10) on the three components of HICP inflation: food, energy and core, that is, total HICP excluding food and energy prices.

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 euro/USD and euro area consumer prices. We analyse what types of shocks have driven the euro exchange rate fluctuations over the period 1995Q1-2019Q2 by examining historical shock decompositions from the SVAR-X detailed in Section 2[16]. To begin with, in Figure 1 we report the corresponding historical decomposition of quarter-on-quarter euro/USD exchange rate dynamics to better understand if the relative weight of different shocks significantly vary over time. An increase (reduction) is defined as an increase (reduction) in the USD in exchange for 1 euro, that is, a euro appreciation (depreciation) vis-à-vis the USD. 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 the rest of the world demand); (ii) relative monetary policy shocks and, (iii) exogenous exchange rate shocks not directly linked to fundamentals nor monetary

[16]Estimates for 2019Q2 are based on data available at the time of the cut-off date (Sept, 2019).

policy. As discussed before, these exogenous factors reflect most notably changes in the confidence, sentiment, or perception (optimism or pessimism) among traders operating on foreign exchange markets and proxy risk premia shocks. They are usually sudden, strong and difficult to predict.

A quick glance at Figure 1 suggests that there are relevant differences in the sources of euro/USD movements at different points in time. This decomposition clearly suggests that structural shocks other than exogenous exchange rate shocks account for an important share of the variation in the exchange rate - 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, in particular if the mix of shocks driving the exchange rate varies over time as discussed in Section 1. There is, however, an increased role of exogenous exchange rate shocks in unanticipated nominal exchange rate movements not only in the last years but also in turning point periods. Our results indicate that they are behind of more than 50% of the exchange rate fluctuations in more than 1/3 of the quarters over the past six years, as shown in Figure 1.

For example, according to our analysis, the appreciation of the euro between 2017Q2 and 2018Q1 could have been driven by at least three factors sorted by higher weight. First, due to a higher relative growth of the euro area. Secondly, exogenous factors are found to be a key driver as well, given relative higher confidence in the euro over the second half of 2017. Finally, the perception that the ECB's monetary policy was somewhat less loose at the end of 2017, in relative terms to the Fed's, than in previous quarters (in 2016Q4-2017Q1 it was the other way round) also contributed to the euro appreciation. Those shocks leading to greater GDP growth in the euro area would have exerted an inflationary pressure. However, this positive effect on inflation would have been partly offset by the deflationary effect of the change in perceived monetary policy tone and of 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[17]. Coeuré (2017) is an example of how shock-dependent estimates of the exchange rate-prices nexus are affecting the monetary pocliy debate. However, as argued in Ortega and Osbat (2019), it has to be borne in mind when estimating the quantitative contribution of different shocks to the

[17]In particular, he pointed out that there were three forces, of roughly equal strength, that helped to 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.

evolution of the exchange rate at a specific point in time, 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 Feb 2018 identify exogenous, risk premium shocks as a key driver. To be clear, several global events such as global uncertainties on the US trade tariffs policy, the Brexit process, the recent fall of oil prices or the Chinese economy slowdown have likely been behind those unexpected, exogenous exchange rate shocks. In addition, these results suggest that, to a lesser extent, the relative lower 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 results were sensitive to: alternative identification strategies, different lag orders and sign restriction periods, a time-varying parameter approach to the SVAR (TVP-SVAR). The robustness results are summarized in the Online Appendix and show no remarkable differences neither in the historical decomposition of exchange rate shocks nor 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 evaluate the effect of exchange rate shocks to inflation (i) over time, (ii) across countries, and (iii) through price components.

We begin by focusing on the case of headline inflation. The common factor extracted from the headline inflation across countries of the euro area is plotted in Figure 2. This is f_t in Equation (5) estimated using total HICP data for euro area countries. It shows a strikingly similar pattern to the actual headline inflation for the euro area. Therefore, the estimated common factor f_t can be interpreted as a proxy for the euro area headline inflation dynamics.

Figure 3 plots the *total* estimated time-varying sensitivity of 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 particularly acute for the largest economies. In particular, France, Germany and Italy, exhibited a sensitivity of around 0.1, before 2010, but since then it kept increasing, until reaching a value of 0.2. For the case of Spain, the increase is even larger, going from 0.2, before 2010, to around 0.4 after that time. Some smaller economies, such as, Portugal, Finland or Malta, have also experienced an increasing sensitivity, but with a smaller persistence.

Since the estimated common factor is a good proxy for the euro area headline inflation, the time-varying parameter λ_t in Equation (6) can be interpreted as the changing effect of exchange rate shocks to aggregate euro area inflation rate. The left Chart in Figure 4 plots the dynamics of the *region-wide* component of the *total* sensitivity, λ_t, showing that, in general, it has remained steady with the only exception of the Great Recession period, when exogenous exchange rate shocks did not seem to have a significant effect on the euro area headline inflation. In particular, a 1% exogenous appreciation of the euro would be associated with a EA HICP inflation fall around 0.15% on impact.[18] Instead, the right Chart of Figure 4 shows 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.

Having increasing sensitivity across countries along with a relatively stable sensitivity for the aggregate euro area, can be rationalized through an increasing degree of commonality in headline inflation across countries in the area. 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 changing contemporaneous relationship between country-specific inflation measures and their common factor. As expected, the figure reports sustained increases over time in the synchronization of headline inflation dynamics for most countries.

The TVP-DFX framework is also applied to model the subcomponents of headline inflation across euro area countries, that is, core, food and energy components. We start analyzing the case of the core component of headline inflation. Figure 6 plots the common factor on core inflation, showing that, although the factor and the 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

[18]The impact of monetary policy shocks on HICP inflation and its components has also been analysed under the same empirical strategy, being out of the scope of this paper. Empirical results point to a decreasing path of sensitivity of inflation to these shocks.

effect of the shocks on the aggregate euro area core inflation, proxied by the extracted common factor, see Chart A of Figure 8. Also, Chart B of Figure 8 shows that the persistence of the core inflation has remained steady. As expected, the pattern of core inflation comovement across countries is more heterogenous than for the case of headline inflation, which is inferred from the estimated time-varying factor loadings shown in Figure 9. Although some countries have exhibited increasing degree of comovement, such as Italy or France, most countries have shown a relatively stable, or even decreasing pattern, such as 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 factor of food and energy inflation, respectively, along with the corresponding euro area aggregate inflation, showing also a strikingly similar path, as in the case of headline inflation. While the increase in the effect of exchange rate shocks on inflation, occurred since 2010, has been significant for energy-related prices (see Figure 11), it has been rather weak and more uncertain for food-related prices (see Figure 15). Since the degree and evolution of comovement experienced by the inflation rates associated to these two categories of HICP has been relatively similar, as it is 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. Meaning that, the effect of exogenous exchange rate shocks on euro area food inflation has not substantially changed over time, while the sensitivity of aggregate energy inflation to unexpected exchange rate movements substantially increased since 2009, as show in Charts A of figures 12 and 16.

Based on the results obtained with the multivariate framework in equations (5)-(9), it is important to emphasize that both channels of transmission of exchange rate shocks to countries inflation, that is, *country-specific* and *region-wide*, are relevant, and that their relative importance heavily depends on the type of price component being assessed. Also notice that an important feature of the propose 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 validate that the ERPT dynamics, across countries, estimated with 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 about the 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 $\hat{\beta}_{i,t}$.[19]

The estimated time-varying ERPT across countries associated to the case of headline inflation is plotted in Figure 20 of Appendix B, to conserve space. The results indicate that the ERPT obtained from univariate models closely track the dynamics of the ERPT obtained from the proposed multivariate approach. This is the case for almost all the countries, with only a couple of exceptions, given by Malta and Finland. For the case of core inflation, although the estimates obtained from both approaches do not look always similar, the ERPT estimates from univariate models point to the same message as the one gathered from the multivariate model. That is, the sensitivity of core inflation to exchange rate shocks tends to be of smaller magnitudes, and more importantly, estimated with large uncertain, as it is shown in 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 it is shown in figures 22 and 23, respectively. These results corroborate that while independent univariate regressions can only measure the degree of sensitivity of euro area countries inflation to exogenous exchange rate shocks, the propose factor model is able to perform the same task, but in addition, it provides a decomposition of such sensitivity into the *country-specific* and *region-wide* effects.

Such a decomposition could be of high importance for policy makers, in that it helps to evaluate, in a timely fashion, whether movements in inflation of a given country, induced by exchange rate shocks, are mainly driven by its exclusive and intrinsic economic performance or by the overall performance of all monetary union partners. This type of decomposition goes in line with the one proposed by Ozdagly and Webber (2017), which is based 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 to our *country-specific* component, and (ii) an *indirect effect*, which takes

[19]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.

into account the joint interaction of that given asset with the rest of assets in the economy, that is, 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 in a time-varying and cross-country unified perspective - and by taking into account the source of exchange rate changes.

To this end, we decompose the time-varying effect that unexpected movements in the euro/USD nominal exchange rate have on different measures of inflation of the euro area countries into a country-specific and region-wide component. Among all sources of exchange rate fluctuations, this paper focusses only on exogenous exchange rate shocks. This is partly motivated to try to mimic as much 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 of such exogenous exchange rate shocks into inflation. Our results suggest that exogenous shocks to the euro/USD are paramount. They are behind more than 50% of the nominal euro/USD exchange rate fluctuations in more than 1/3 of the quarters over the past six years - especially in turning points periods.

Our main results indicate that headline inflation, and in particular its energy-related component, has significantly become more affected by these exogenous exchange rate shocks since the early 2010s, in particular, for the largest economies of the region. While such increasing sensitivity relies solely on a sustained surge in the degree of comovement for headline inflation, it is also based on a higher region-wide effect of the shocks for the case of energy inflation. For the case of food inflation, the effect of exogenous exchange rate shocks is similar to that of headline inflation, but to a much lower extent. Instead, 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 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 the transactions take place between or within firms, the frequency and dispersion of price adjustments, the integration in Global Value Chains or the role of competition in final products markets - but 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 assess the impact of currency movements and, as a result, help Central Banks to set an appropriate monetary policy.

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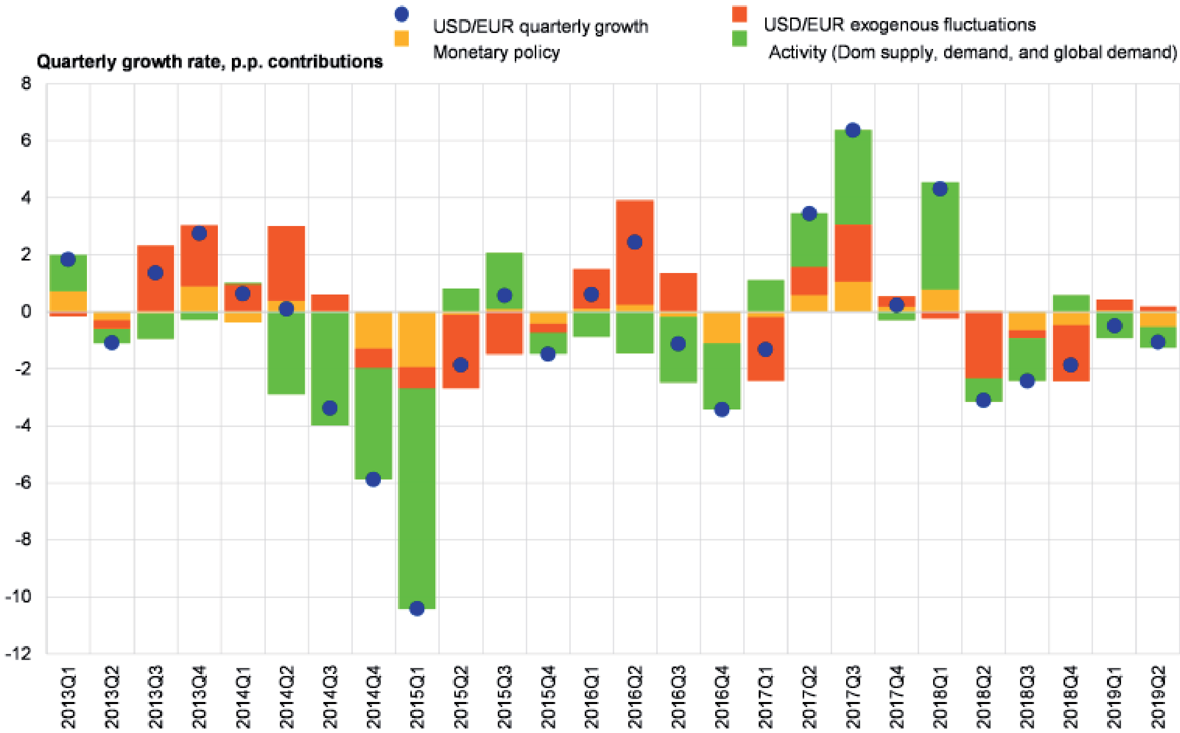
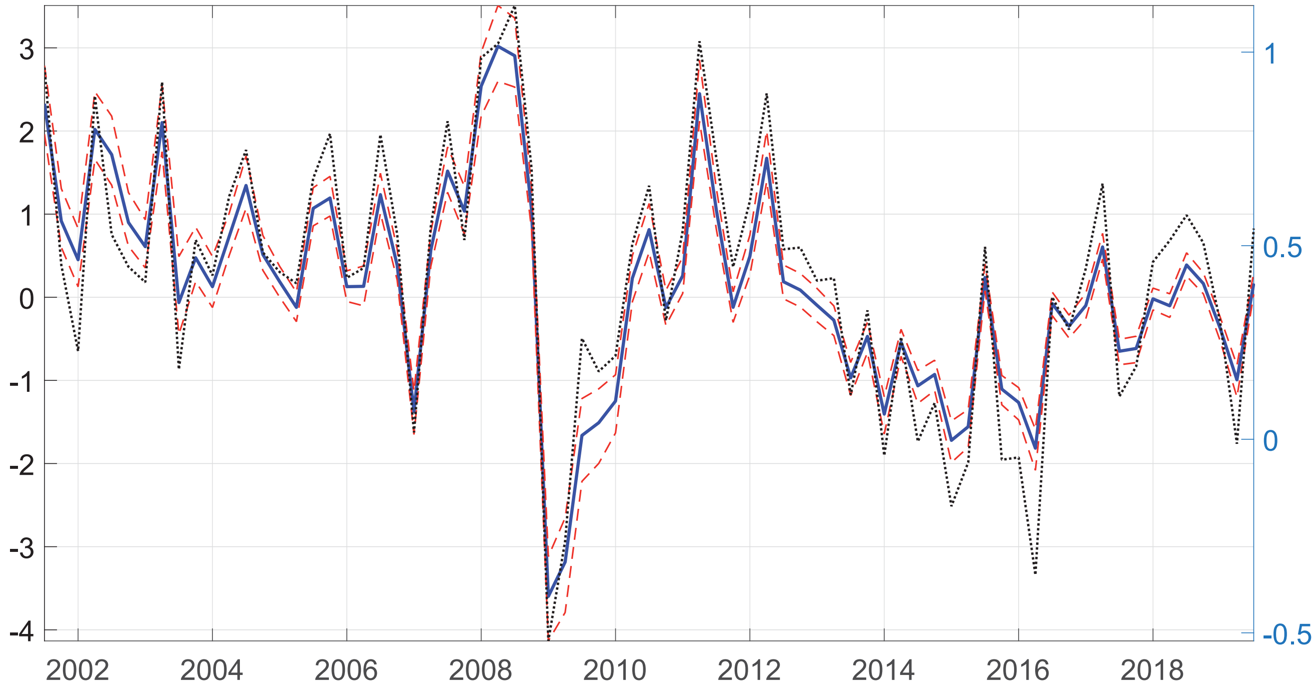
Figure 1: Historical decomposition of nominal exchange rate USD/EUR



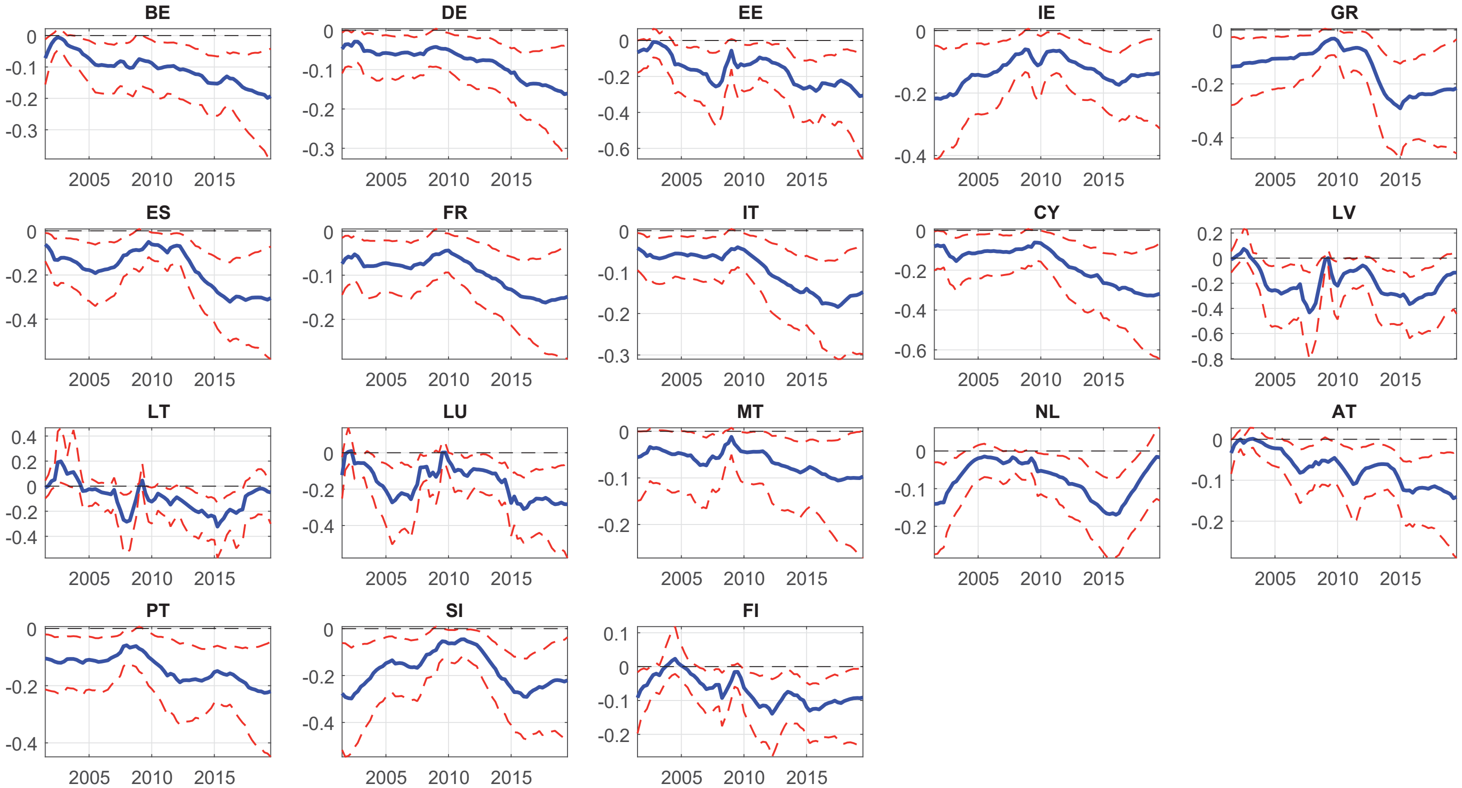
Notes: Estimates based on the quarterly SVAR model of the USD/EUR exchange rate described in Section 2, where shocks are identified via sign restrictions. Estimates for 2019Q2 are based on data available at the time of the cut-off date (Sept, 2019). Data for US and euro area GDP in 2019Q2 are based on 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.

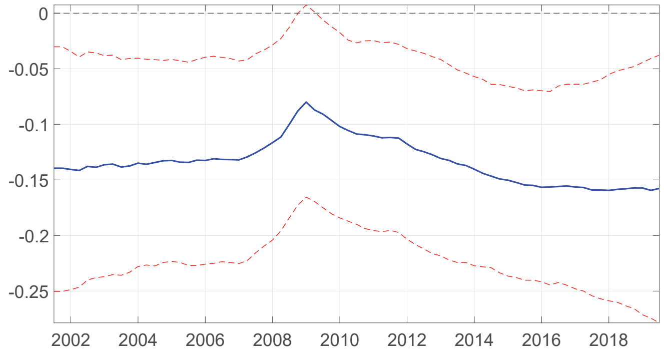
Figure 3: Time-varying sensitivity of headline inflation of the euro area countries based on a multivariate model ($\tilde{\beta}_{i,2,t}$)



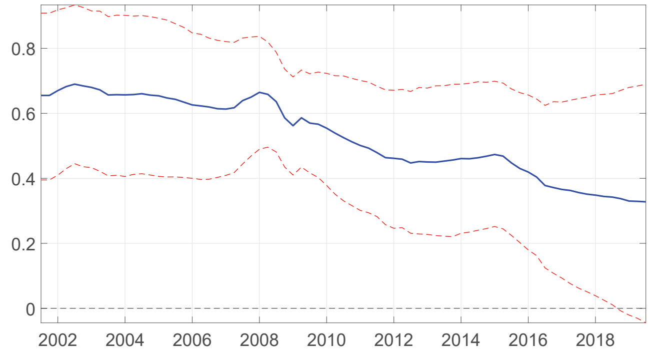
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the multivariate model.

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

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

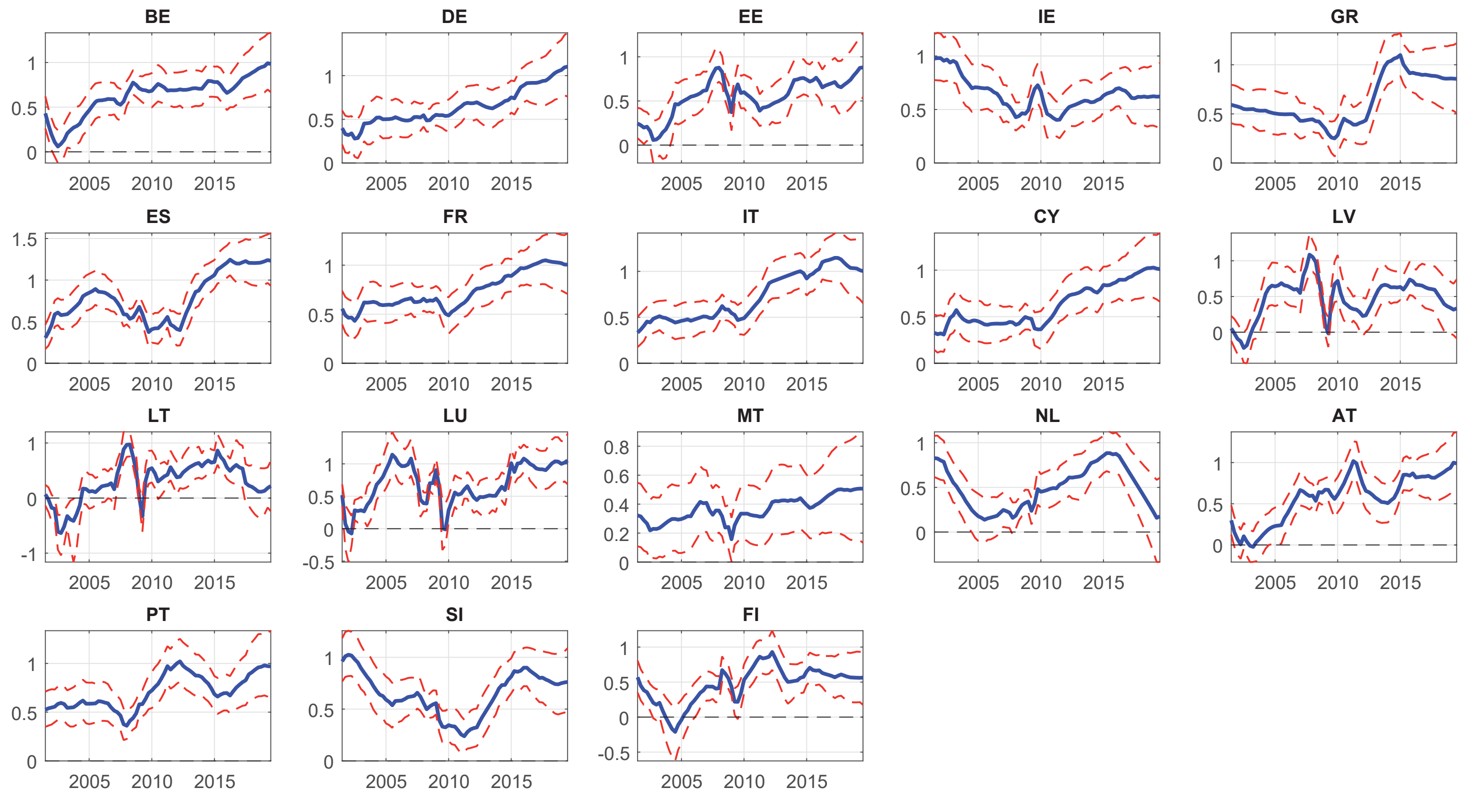


(b) Persistence of the euro area headline inflation factor (ϕ_t)



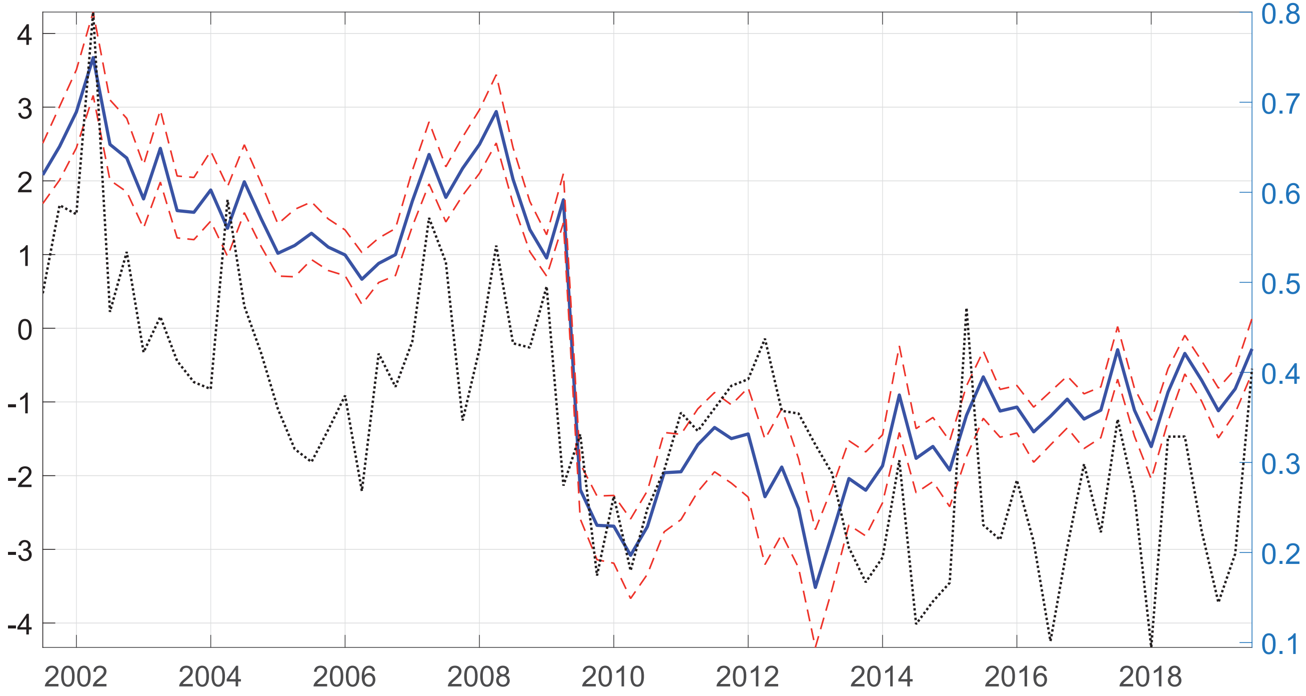
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

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



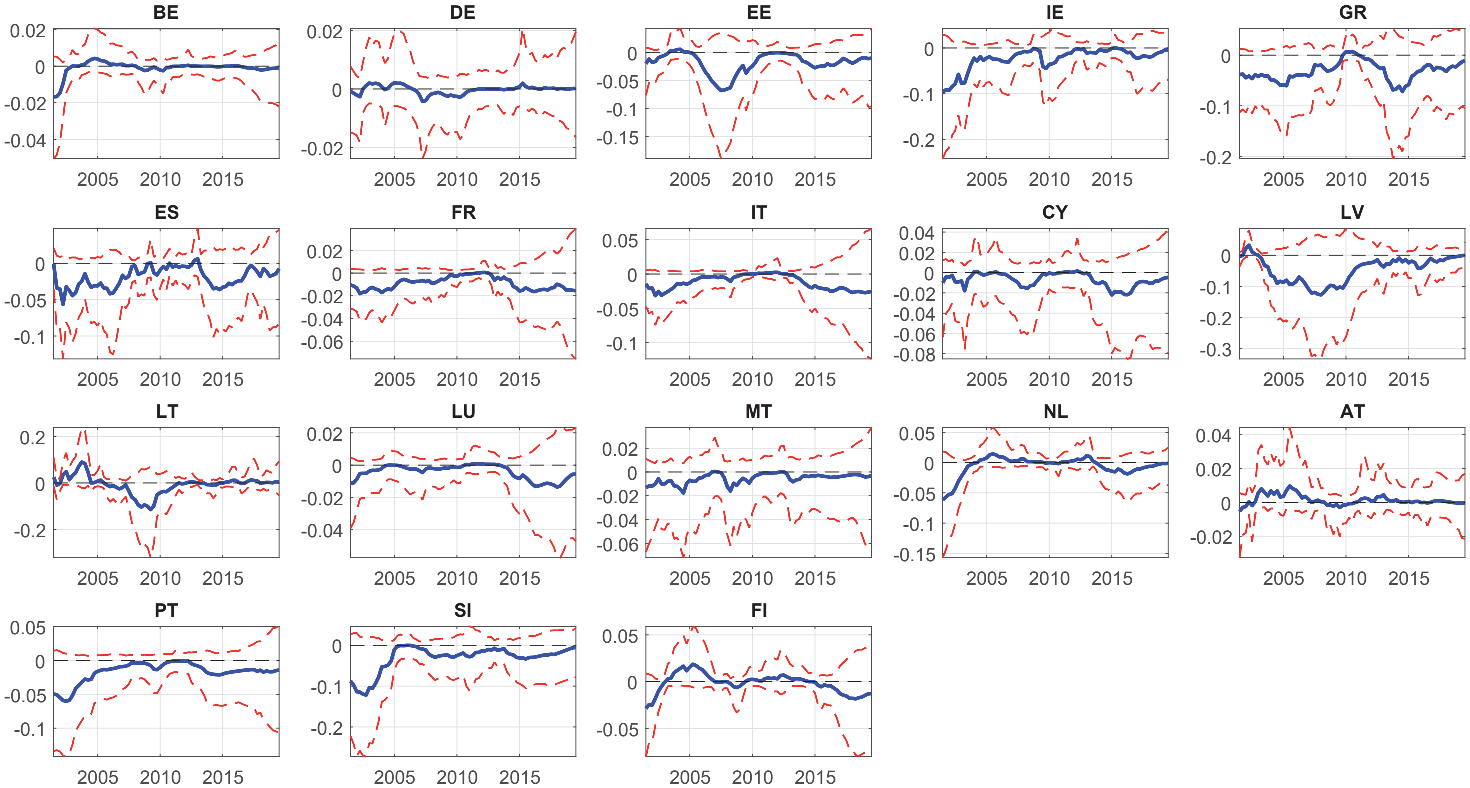
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

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.

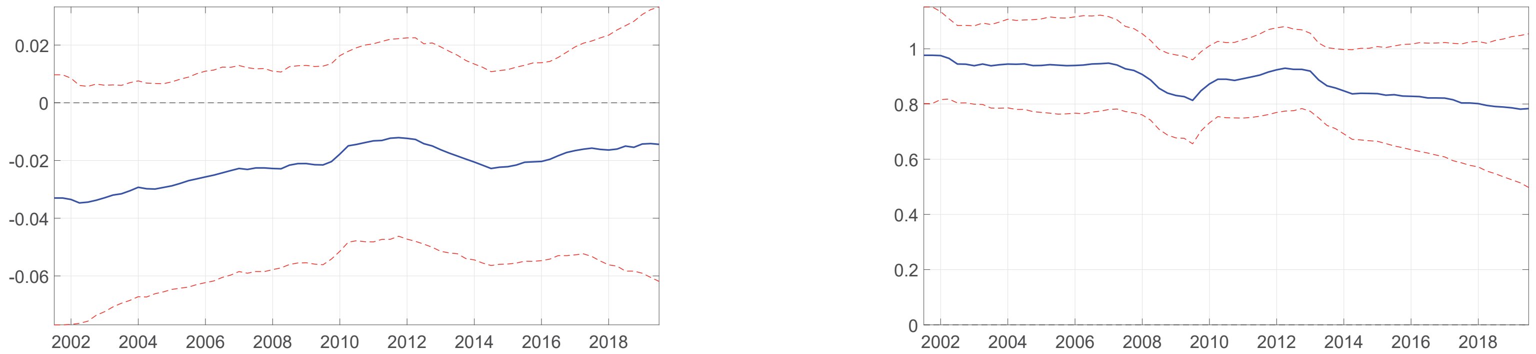
Figure 7: Time-varying sensitivity of core inflation of euro area countries based on a multivariate model ($\tilde{\beta}_{i,2,t}$)



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.

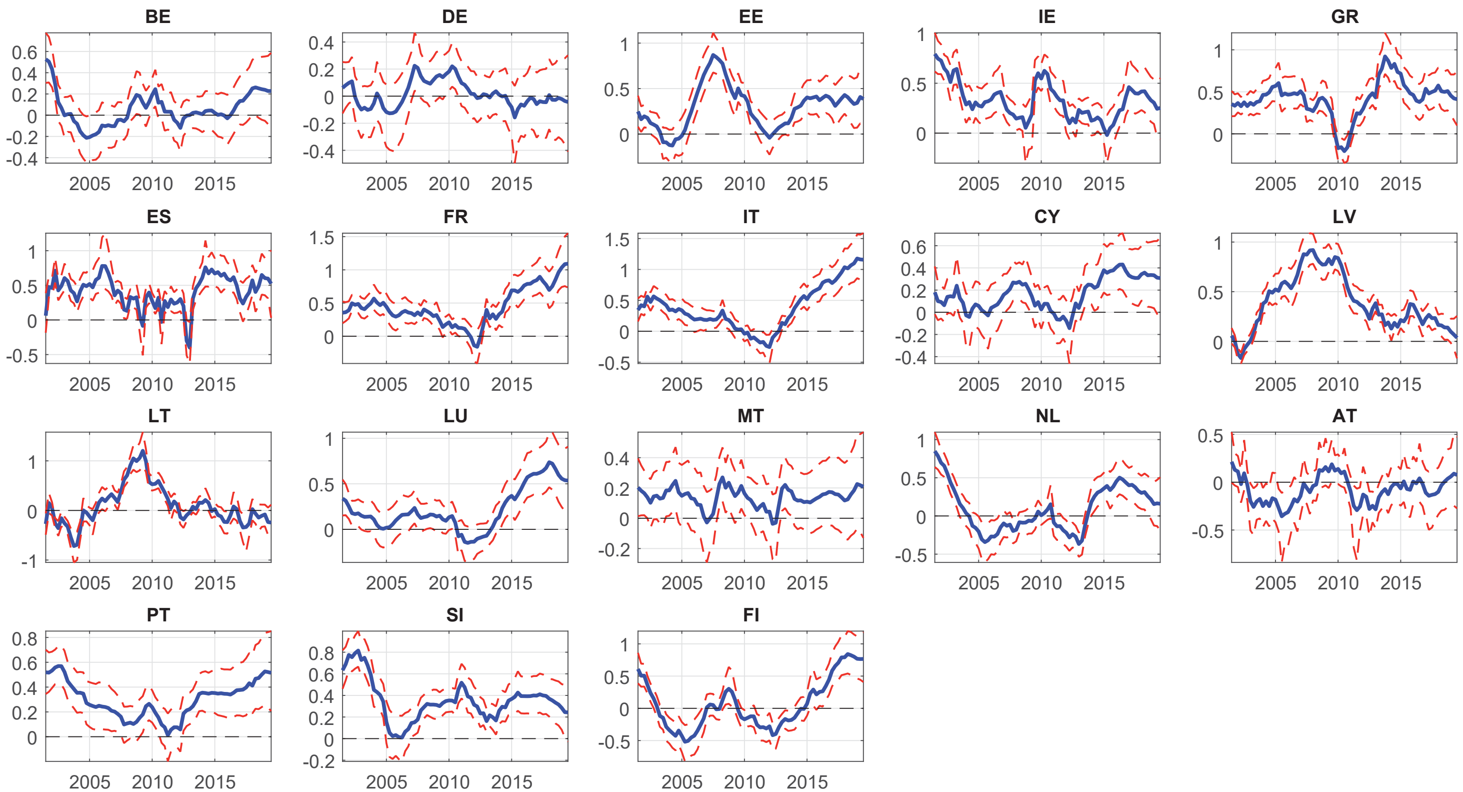
Figure 8: Time-varying coefficients of model for core inflation

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



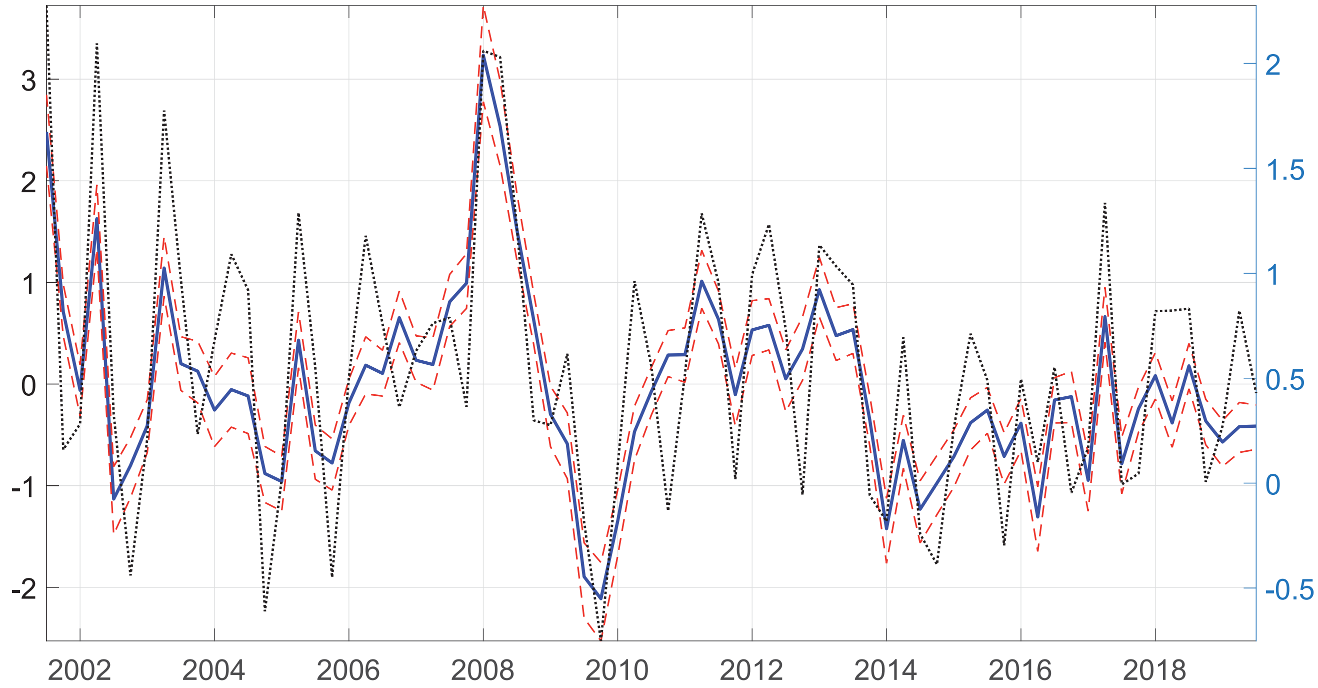
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

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



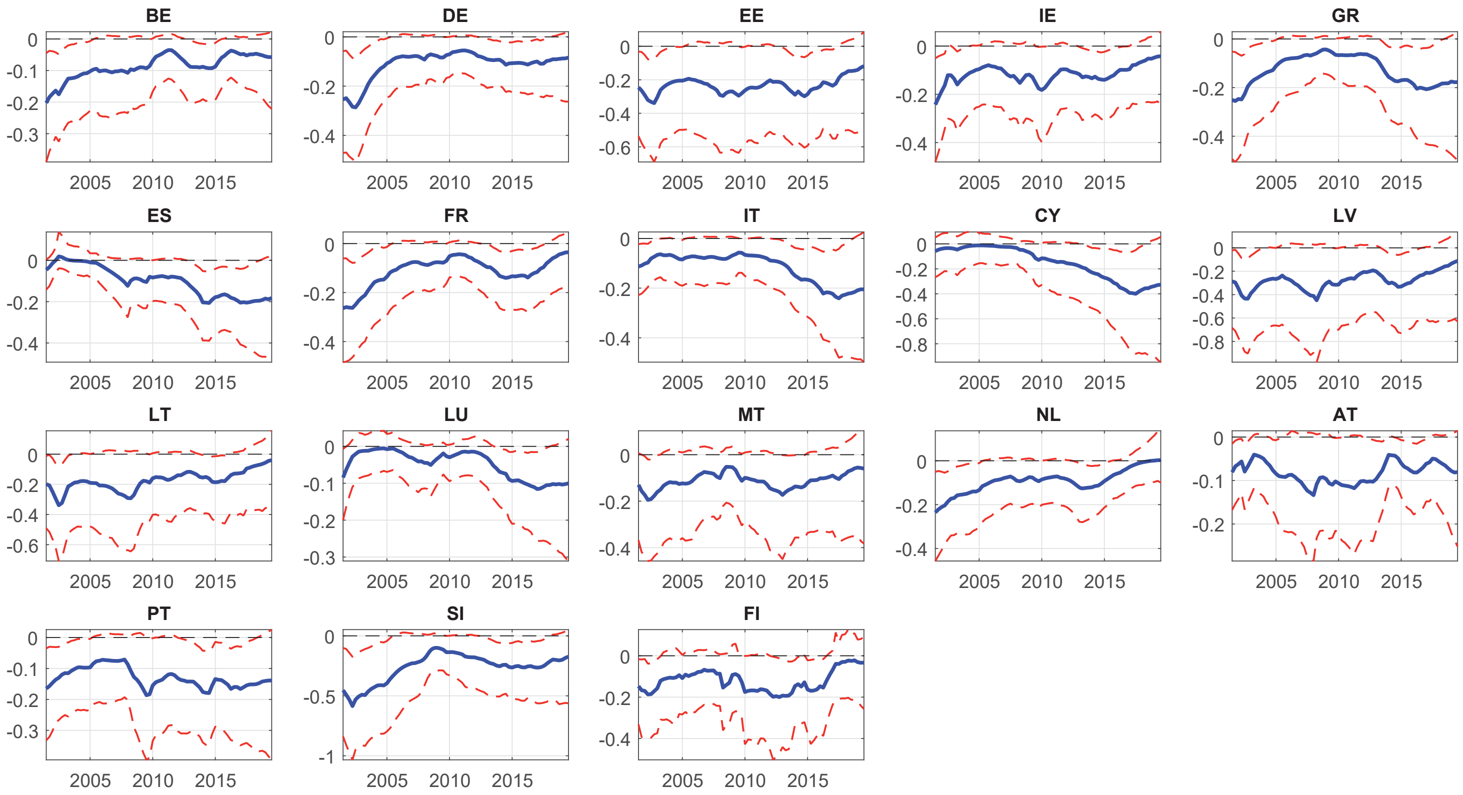
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

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.

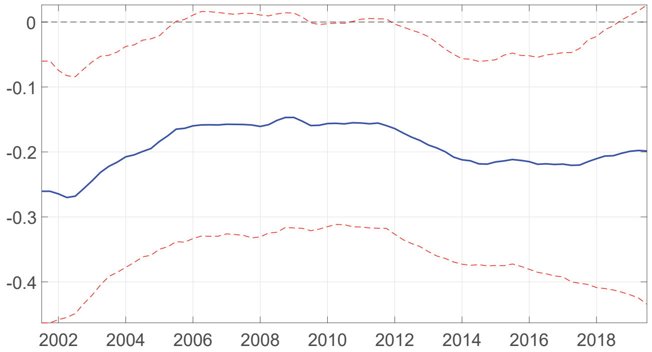
Figure 11: Time-varying sensitivity of food-related inflation of euro area countries based on a multivariate model ($\tilde{\beta}_{i,2,t}$)



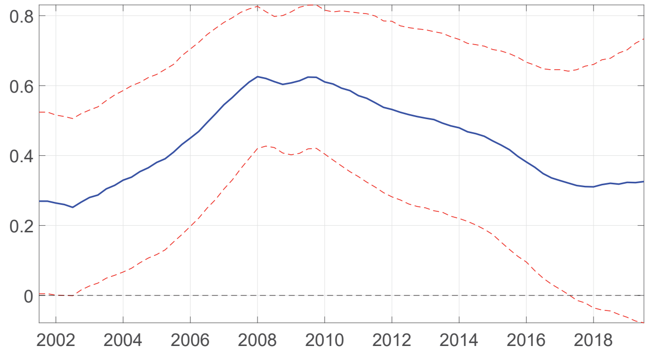
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

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

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

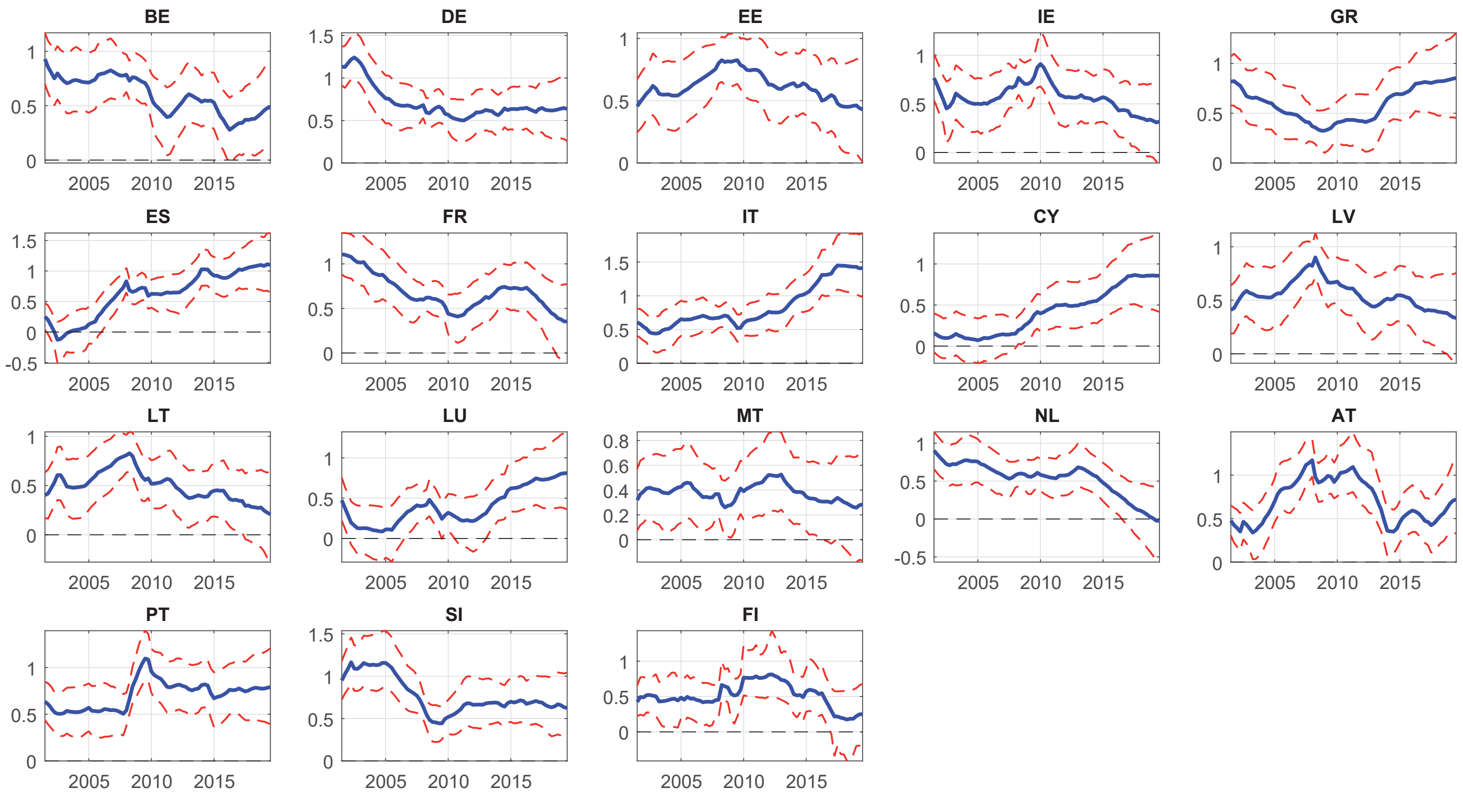


(b) Persistence of the euro area food-related inflation factor (ϕ_t)



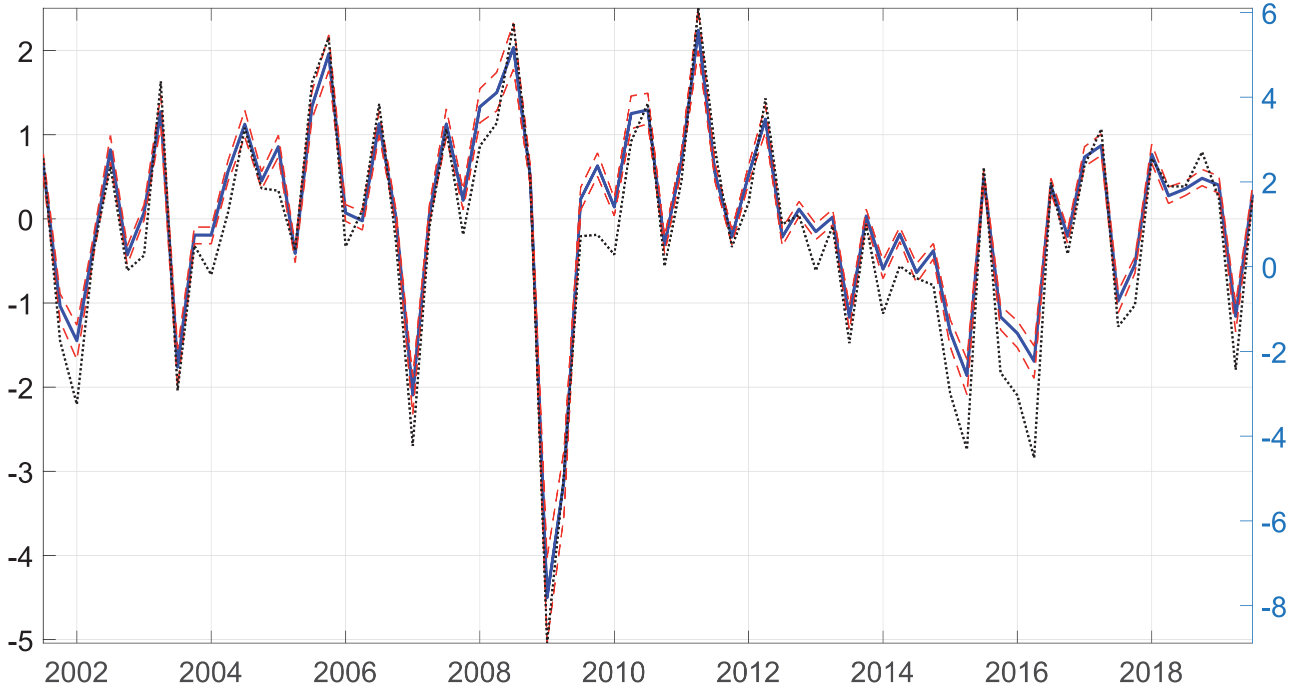
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

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



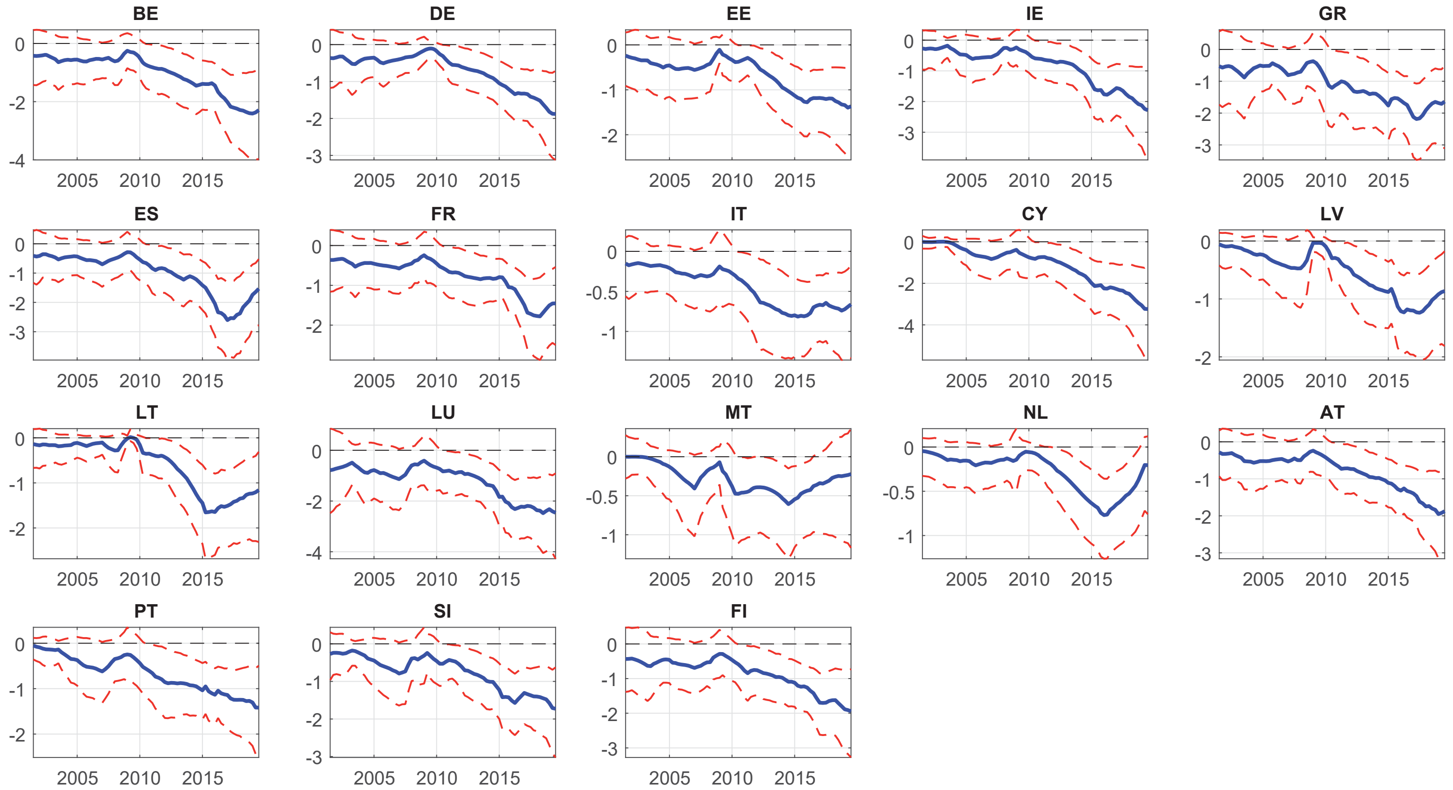
Note: Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

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.

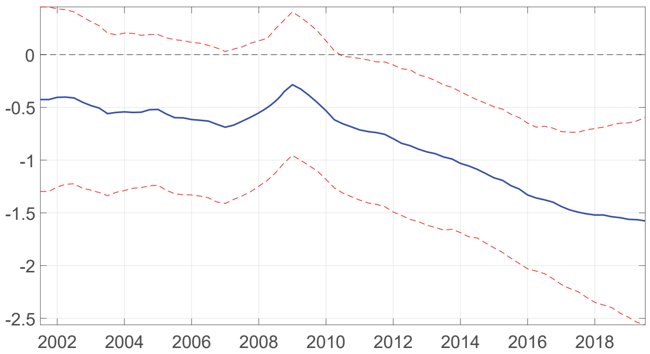
Figure 15: Time-varying sensitivity of energy-related inflation of euro area countries based on a multivariate model ($\tilde{\beta}_{i,2,t}$)



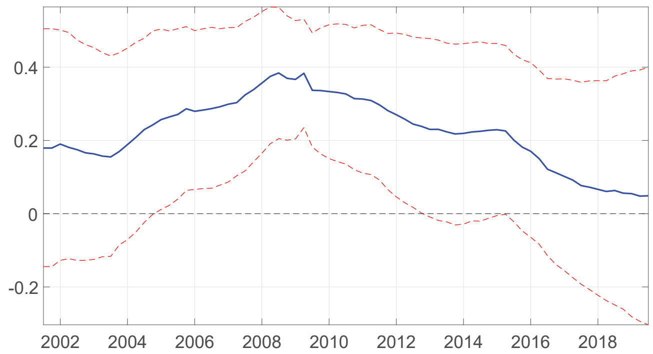
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model.

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

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

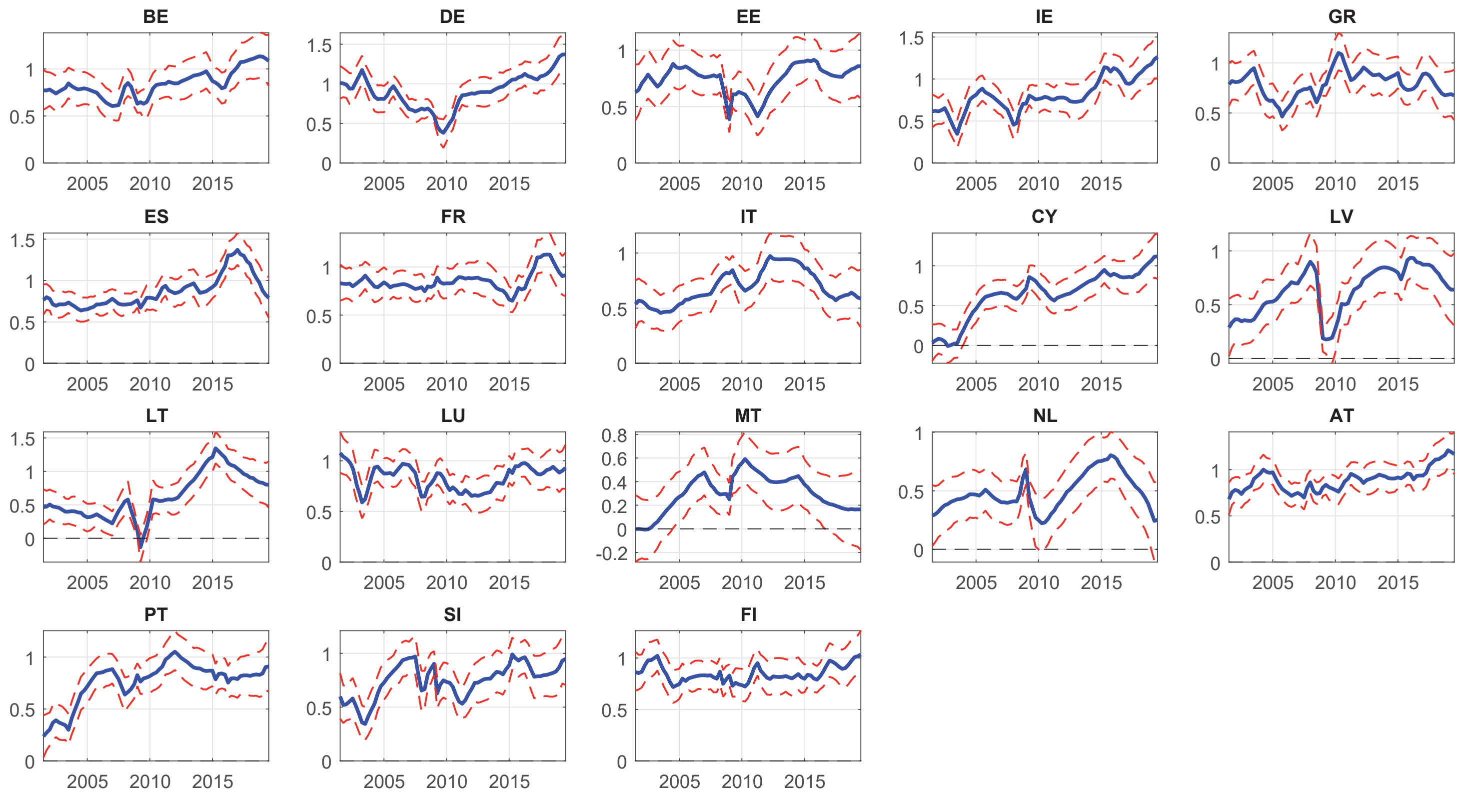


(b) Persistence of the euro area energy-related inflation factor (ϕ_t)



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 $p(\Omega|Y^T, \theta^T, \sigma^T, \phi^T, \Xi, \Psi)$

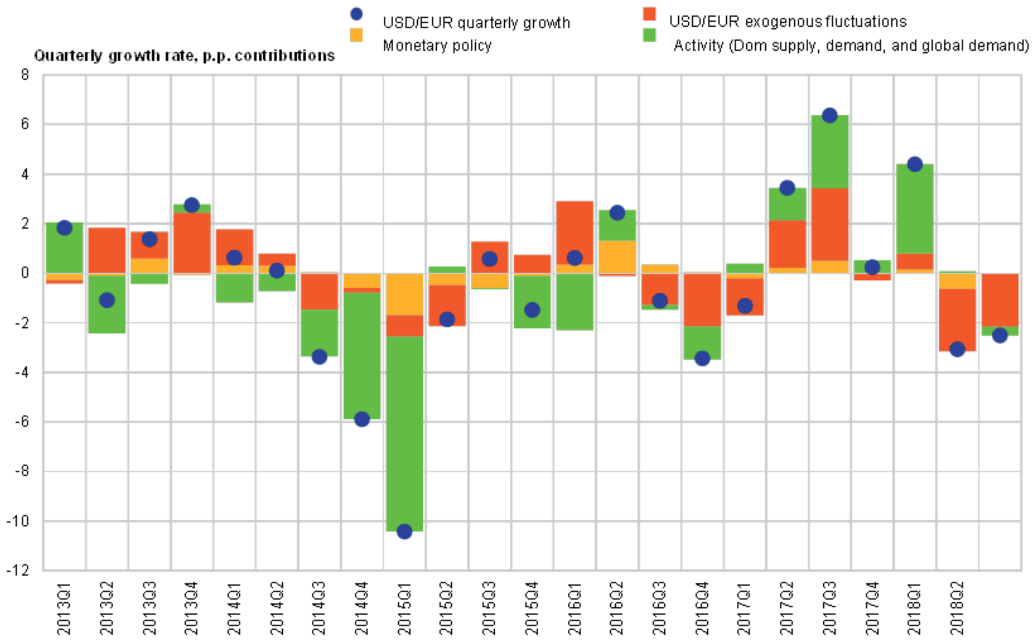
Step 5: Sample Ξ from $p(\Xi|Y^T, \theta^T, \sigma^T, \phi^T, \Omega, \Psi)$

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.

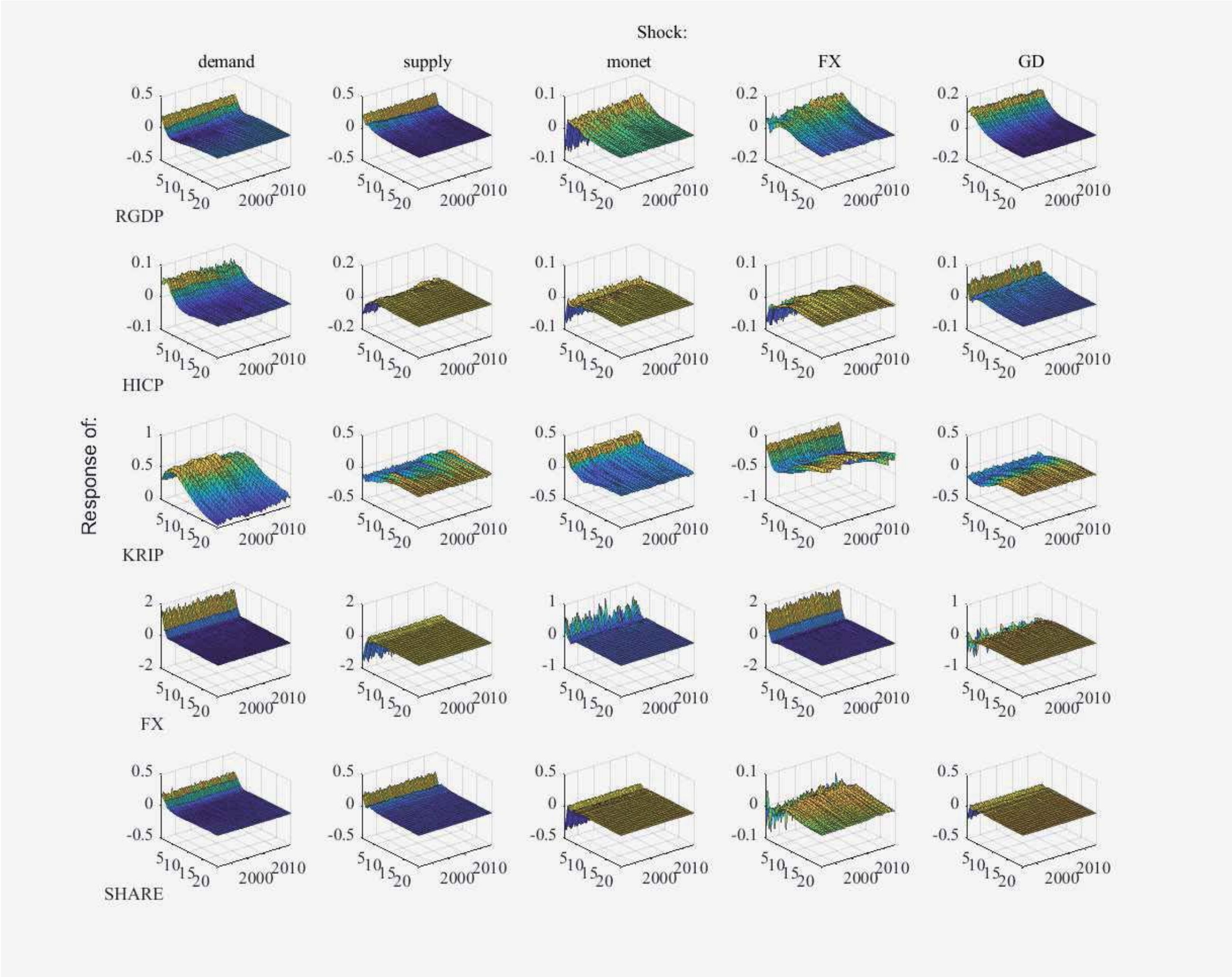
B Online Appendix: Figures and Tables

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



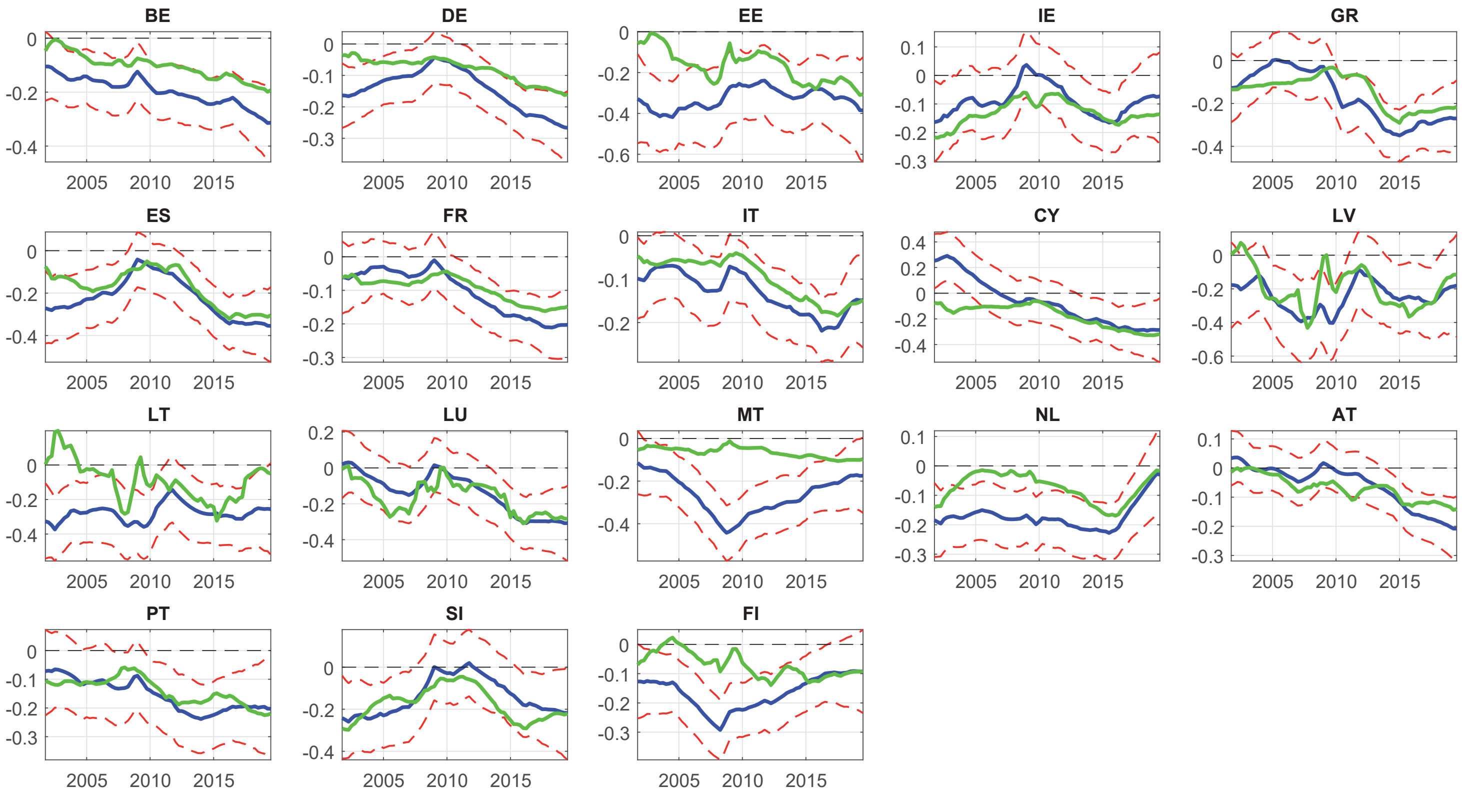
Notes: Estimates based on a quarterly SVAR model of the USD/EUR exchange rate where shocks are identified via sign restrictions defined in the Online Appendix Section.

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



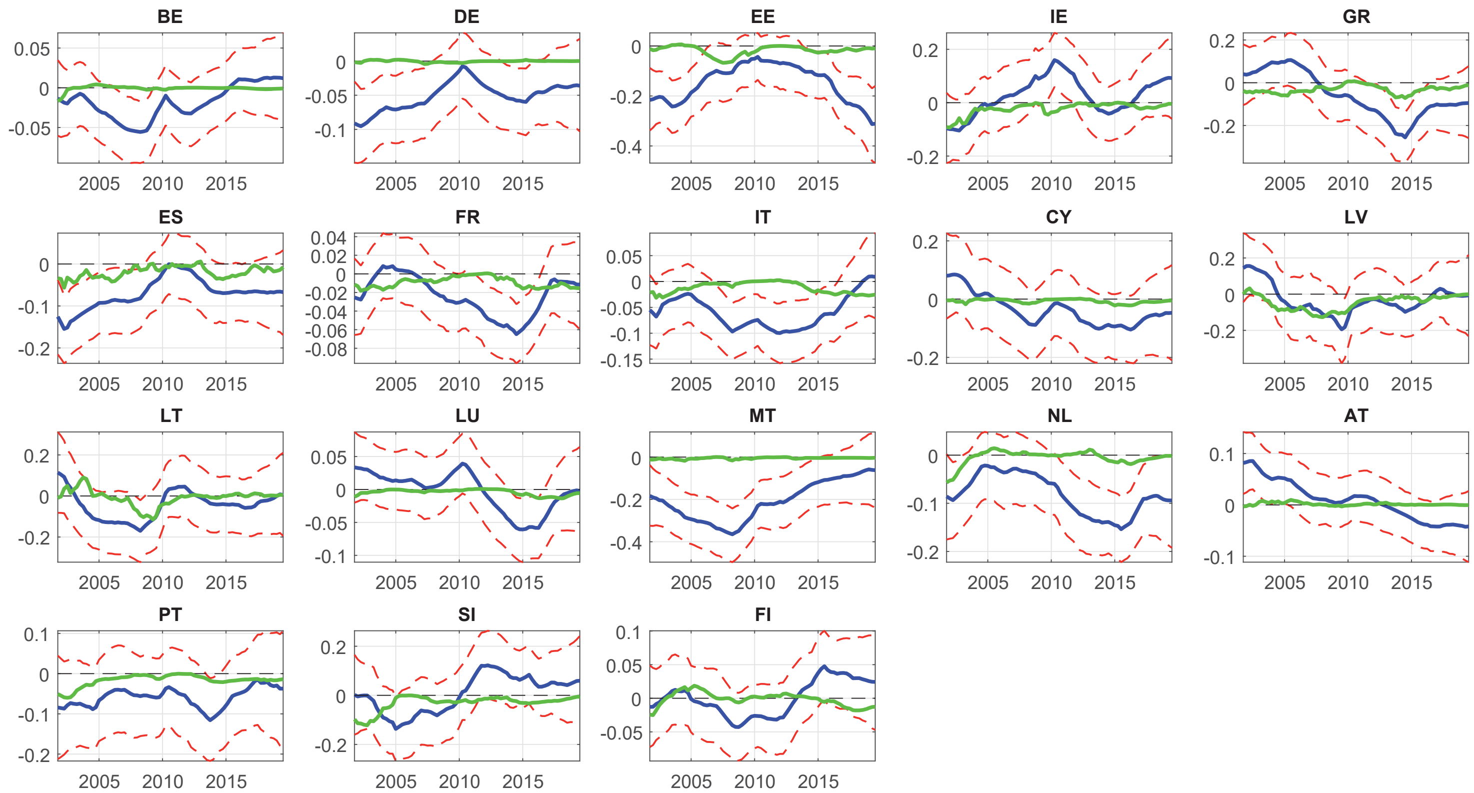
Notes: Estimates based on a quarterly TVP-SVAR model of the USD/EUR exchange rate where shocks are identified via sign restrictions. RGDP refers to euro area GDP growth, HICP refers to consumer prices inflation, KRIP refers to relative monetary policy rates for the euro area and the US as of Krippner (2013), FX refers to the nominal USD/EUR 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 ($\hat{\beta}_{i,2,t}$)



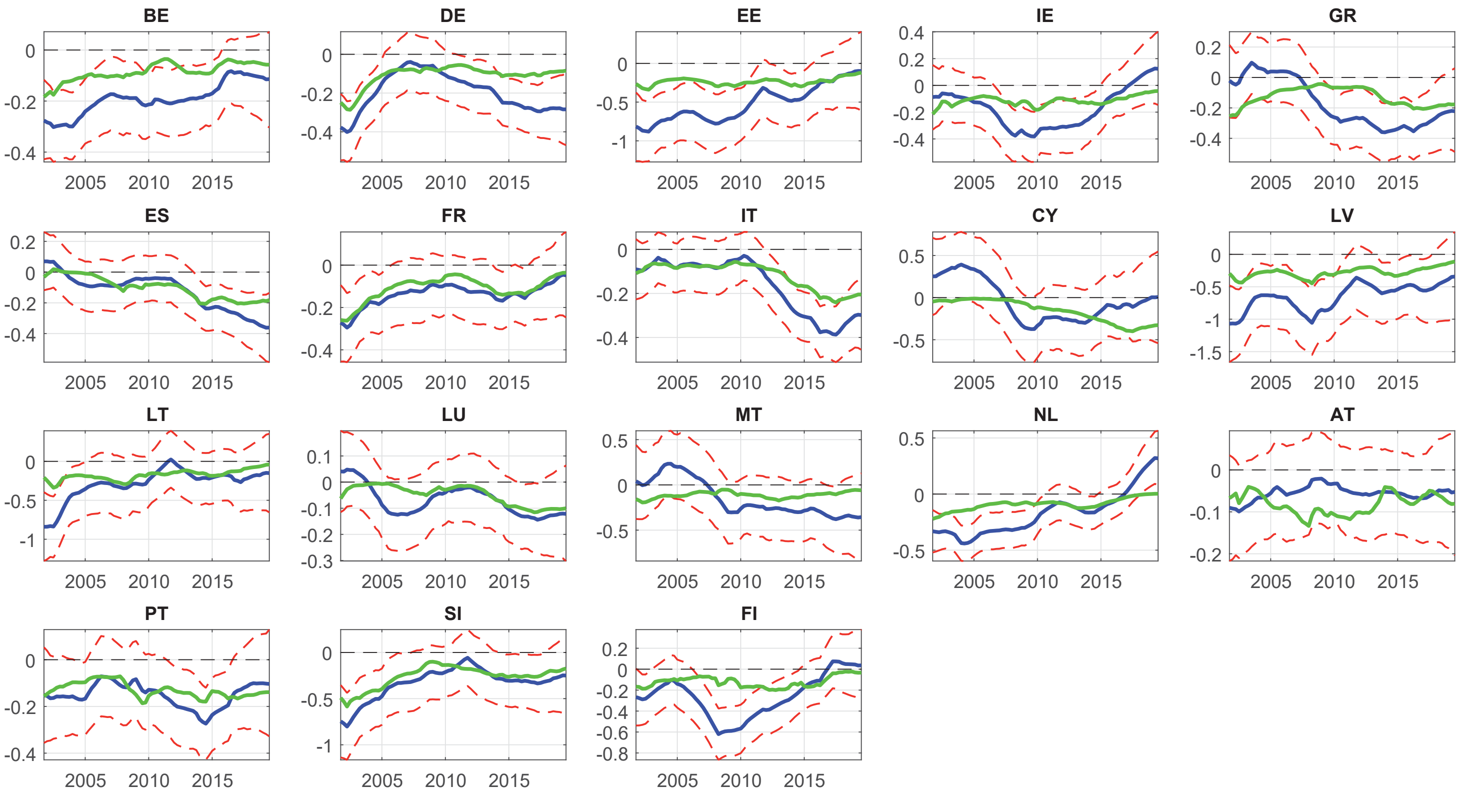
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Green solid line reports the median estimate obtained with the multivariate model for comparison purposes.

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



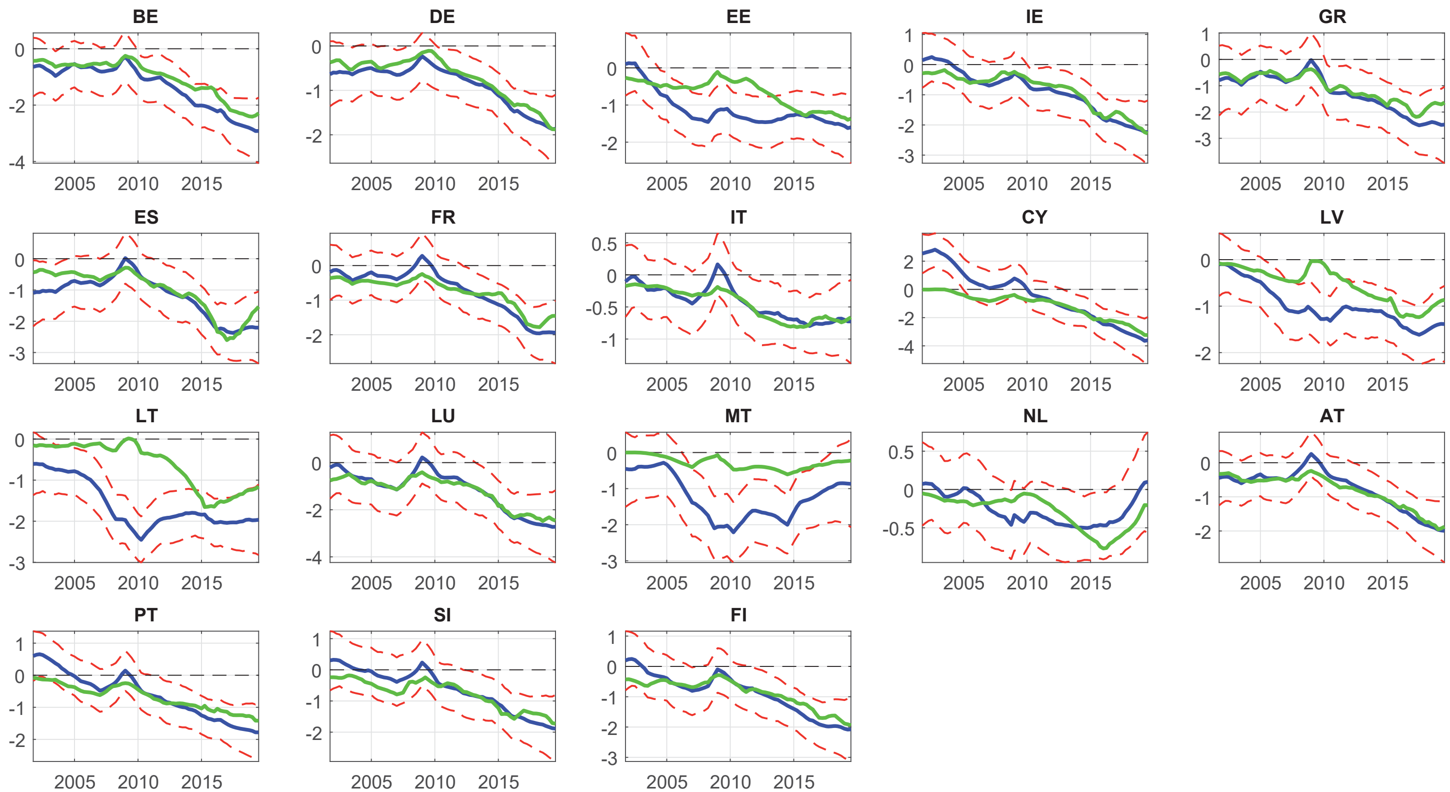
Note: Blue solid (red dashed) line makes reference to the median (16th and 84th percentile) of the posterior distribution estimates obtained with the univariate model. Green solid line reports the median estimate obtained with the multivariate model for comparison purposes.

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 USD/EUR for different lag orders and sign restriction p

	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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