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FED vs ECB: Which matters most for Visegrad economies? Evidence from a Bayesian VAR model

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Abstract

We use a Bayesian VAR with economically interpretable structural restrictions and zero restrictions on lags, to analyse the transmission channels of external shocks to an extended set of Central European markets. In particular, we study to what extent monetary policy shocks originating from the US and from the EU can explain fluctuations on countries in the Visegrad Group. We find that the US monetary policy influences the Central European macroeconomic variables at least as much as its EU counterpart, often independently, without being mediated through Germany. Furthermore, the findings indicate that the income absorption effect dominates, leading to a contraction in output of small open economies.

Keywords: EU; Monetary Policy; US; Visegrad Group; V4.

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1 Introduction

There exists considerable evidence that large economies' monetary policy shocks are an important source of variations in key economic indicators of many small open economies (SOE) around the world. For instance, this appears to be the case of countries exhibiting strong economic linkages to the US, such as the Latin American ones. By extension, one might conjecture that the same applies to the Central European countries with reference to EU members, and notably Germany. Should the conjecture hold true, then one might also expect the effect of a US monetary policy shock on these countries to be of secondary importance when compared to one generated by the German Bundesbank and later on by the ECB.

The argument behind this conjecture is straightforward. As representatives of the Central European countries we choose the Czech Republic, Hungary, Poland and the Slovak Republic. This group of countries is known as the Visegrad Four (V4) and Germany is the major trading partner for them. It is attracting almost one third of the total exports from each of the V4, which are also substantial importers of goods produced in Germany. These relationships are quantitatively not reciprocal, which characterises the V4 as SOE relative to Germany. In fact, most studies on how foreign monetary policy impacts V4 macro variables seem to implicitly embrace this idea, as they typically consider Germany as the source of the exogenous shocks.

Following an analogous scheme and identifying Germany as a SOE relative to the US, the german economy may be exposed to the US monetary shocks.[1] This complicates the conjecture implying that the US monetary policy shock may be also important for the V4. Our aim is to assess how much of the movements in

[1] Since the US is an important export partner for Germany, covering a 7 percent export share, but not vice versa, Germany might be regarded as a small open economy (SOE) relative to the US.

the key macroeconomic variables of the V4 are generated by US monetary policy shocks, how much by their German counterparts, and how much of the former might be due to changes in German aggregate demand in response to the US shocks. We show that unlike the conjecture suggests, Germany is not necessarily the main source of V4 variations: even if we control for the US impact through Germany (by including German variables), the strength of the effects of both shocks on V4 variables are at least comparable.

In order to examine whether US monetary policy shocks might have a significant influence on the V4 macro variables, we construct three different estimations. The first two are is in line with the existing literature and estimate the direct influence of either a German Bundesbank/ECB (hereaftger, for brevity, ECB) or a FED monetary policy shock on a set of key V4 economic indicators. This estimation suggests that ECB and FED shocks have an impact on key V4 variables of similar magnitude. One may argue, however, that the impact of US monetary policy on the V4 macro variables could be generated, at least partially, by the effect that the former exercises on German economic indicators, which in turn would have a significant impact on the V4 variables via their strong economic linkages. The second estimation controls for such a potential indirect channel by simultaneously considering two large economies, Germany and the US, where it is assumed that Germany is open towards the US and closed towards the V4. The objective is to investigate how much of a monetary policy shock generated by the FED is merely absorbed by Germany, and how much is instead transmitted to the V4. As a result, one may expect that the effect of the US shock is significantly weaker than the one generated by ECB. But the estimations suggest otherwise: even if we control for the US impact through Germany (by including German variables), the strength of the effects of both shocks on V4 variables are comparable.

V4 countries share similar characteristics. Their economic transition has started in the early 1990's and enabled to open their economies rapidly to Western trade and investment. For these countries the early 90's were characterised by higher inflation especially in Hungary and Poland caused by the price liberalisation. During the late 1990's, they all have already adopted flexible exchange rate regimes, the main part of the transition was finished and the economy system of these countries stabilised.

A vast literature analyses exogenous disturbances generated at home or abroad and their impact on other macroeconomic variables. Several studies, including Uhlig (2005) and Canova and Gambetti (2003), investigate the US monetary policy shock and its impact on the US macroeconomic variables. Similarly, Kim (1999) studies the effects of domestic monetary policy shocks in individual G-7 countries and Kim (2001a) shows the effect of the (domestic) monetary policy shock on the trade balance in small European countries such as France, UK and Italy, using German and US interest rate as a proxy for a world-wide short term interest rate. Furthermore, various authors study the impact of foreign shocks on SOE. Kim (2001b) analyses the effect of US monetary policy on the exchange rate and foreign trade balances on other G-6 countries. He shows that an expansionary US monetary policy shock generates positive spillover effects. Canova (2005) studies the transmission of US shocks on Latin countries and finds that the foreign monetary policy shock produces more fluctuations than real demand and supply shocks generated abroad. Additionally, Mackowiak (2007) finds that US monetary shocks are an important source of macroeconomic fluctuations for small emerging markets in South East Asia and Latin America. These shocks explain more of the variation of real aggregate output and the price level in those countries than the domestic monetary shocks.

Some authors also investigate the effect of monetary policy shocks on V4. For example, Anzuini and Levy (2007) examine the effects of an V4 domestic monetary policy shock in a given V4 on its own key macroeconomic variables. Mackowiak (2006) studies the effect of ECB monetary policy shocks on those variables. Our work is closely related to these two papers; we are investigating a new channel of foreign monetary policy influence. Using a method similar to Kim (2001b) and Canova (2005), we are interested in the impact of US monetary policy shocks on macroeconomic variables on the V4. we use Mackowiak's (2006) argument that these countries are open to exogenous disturbances and show that a monetary shock that originates in the US can explain at least the same amount of V4 macroeconomic fluctuations as a shock generated by the European Central Bank (and previously by the Deutsche Bundesbank).

The methodology, adopted in this paper, relates to the methodology used by Kim (2001 and 2001b), Canova (2005) and Mackowiak (2006, 2007). The long-run zero restrictions for SOE are based on different findings from Cushman and Zha (1995), Kim and Roubini (2000) and Kim (1999). The sign restrictions are generated in a similar fashion as in Canova (2005) and Scholl and Uhlig (2005), using an algorithm developed by Ramirez *et al.* (2010). Finally, we impose the prior in our model using artificial observations following the work from Banbura *et al.* (2008).

Testing the impact of monetary and fiscal policy is not a new idea. For example, Anderson and Jordan (1964) investigate the impact of a change in the monetary base on real GNP using a simple autoregressive model. However, their approach was criticized by Sims (1980) because of the missing feedback between GNP and the monetary base. This author went on proposing a vector autoregressive (VAR) model to analyse the monetary policy shock and its impact on endogenous variables.

The structure of this paper is as follows. Section 2 gives more details about the model adopted for the estimations. Section 3 describes the structural analysis for each country, including the data describtion and the results (impulse response functions, forecast error variance decomposition (FEVD) and historical decomposition). Finally, Section 4 concludes.

2 Methodology

To estimate the impact of foreign monetary policy on the V4 economic variables we use a structural vector autoregressive (SVAR) model

$$Y_t = BX_t + Ae_t.$$

where e_t is an orthogonal white noise vector following from $\epsilon_t = Ae_t$ with an identity variance-covariance matrix given by

$$\begin{aligned} E[e_t e_s'] &= I_m \text{ if } t = s, \\ E[e_t e_s'] &= 0 \text{ if } t \neq s. \end{aligned} \tag{1}$$

We orthogonalise the shocks by using restrictions derived from an economic interpretation of the model by following Canova (2007). It follows that

$$E[Ae_t e_t' A'] = AA' = \Sigma.$$

In the contemporaneous period, the sign restrictions are implemented in such a way that the model is consistent with the economic theory, mainly to avoid a misspecification of the monetary policy shock that, if positive, should lead to a contemporaneous increase in interest rate and a contemporaneous fall in output and inflation. In this respect, we follow an algorithm provided by Ramirez *et al.* (2010) to compute a structural impact matrix $\tilde{A}$, so we can write

$$\begin{aligned} \Sigma &= AQQ'A' \\ \Sigma &= \tilde{A}\tilde{A}'. \end{aligned} \tag{2}$$

It is important that the matrix $\tilde{A}$ satisfies the sign restrictions set out below and it still holds that $\epsilon_t = \tilde{A}e_t$. Furthermore we impose contemporaneous zero values restrictions as to ensure that the SOE does not influence the large economy contemporaneously. The dots correspond to freely estimated parameters.[2] The identification schemes can be found in Appendix B.

Beside the contemporaneous restrictions, we impose restrictions on lags. Note that the model can be divided into two parts, a first part with a $m_1 \times 1$ vector of the foreign large economy variables (Y_t^*), and a complementary $(m - m_1) \times 1$ vector of domestic SOE variables (Y_t^{V4})

$$Y_t = \begin{pmatrix} Y_t^* \\ Y_t^{V4} \end{pmatrix}, \epsilon_t = \begin{pmatrix} \epsilon_t^* \\ \epsilon_t^{V4} \end{pmatrix}. \tag{3}$$

Therefore, the matrix $B(j)$, $j = 1, ..., p$, can be rewritten as

$$B(j) = \begin{pmatrix} B_{11}(j) & B_{12}(j) \\ B_{21}(j) & B_{22}(j) \end{pmatrix}. \tag{4}$$

Following Cushman and Zha (1995), we impose zero restrictions on the prior beliefs

[2] For a critical survey on contemporanous restrictions, see Fry and Pagan (2011).

in matrix $B_{12}(j)$ is $(m - m_1) \times m_1$, which coefficients demonstrate the impact of domestic SOE variables on the variables in the large economy.

In the whole system, only the foreign monetary policy shock is of our interest. The impulse-response functions, the FEVD as well as the historical decomposition are calculate through the matrix $\tilde{A}$, estimated using Bayesian estimation method with Gibbs sampling. It is worth mentioning that the $\tilde{A}$ matrix is not unique. That is, it is possible to find different $\tilde{A}$ matrices that satisfy the sign restrictions. One of the options to deal with this is to draw $\tilde{A}$ matrix 100 times and choose the one closest to the median. This is the matrix, which we use for analysing the impulse response functions, FEVD and historical decomposition.

We incorporate a prior belief with zero restrictions and thus, we opt for an independent normal inverse Wishart prior. Technically, we impose this prior by following Banbura *et al.* (2008) and incorporate additional artificial data. For more details about priors we refer to Appendix C. To carry out the Bayesian inference, we use a Gibbs sampling procedure, which is a posterior Markov chain Monte Carlo (MCMC) simulation mechanism. We iterate the Gibbs algorithm M times producing draws for B and Σ. Each iteration requires sampling from the conditional posterior distribution, which after the burn-in draws are discarded converges to the marginal distribution. Samples from the beginning of the chain, the first J draws are discarded to remove the influence of starting values. Once draws from the posterior distribution are obtained, we implement a structural analysis to ensure that the sign restrictions hold.

3 Empirical Analysis and Results

As representatives of the SOE, we selected the Visegrad four countries, namely the Czech Republic, Hungary, Poland and the Slovak Republic. These countries have similar characteristics and underwent similar development paths after the their Soviet-imposed regimes collapsed. They all initially experienced rapid GDP growth and in the last two decades, developed from being classified as emerging markets to fully industrialised parts of the European Union. We use a small scale model with three domestic variables for each country. Regressions are run for the period 1996 - 2019 for each country separately in combination with either US or German variables, or both. Because of the limited number of observations, we restrict the analysis only to the most important macroeconomic data such as GDP growth, CPI inflation and the nominal exchange rate for each country. The source of the data is Datastream and the details are given in Appendix A. Given the quarterly data, both criteria, the Akaike and Swarz confirm that two lag VAR estimation fits best.

We run three groups of estimations. First, we estimate the impact of a US monetary shock directly on the SOE macroeconomic variables. The goal here is to assess the direct impact of US monetary policy shocks on V4 markets. Second, we compare this impact with the direct impact of the Deutsche Bundesbank's interest rate (after 2001, the ECB's). This estimation is parallel to that from Mackowiak (2006), who claims that, since Germany is by far the most important trade partner for all of the countries included in the estimation (with export shares ranging from 25 to 30 percent), the innovation in German monetary policy should play a major rule for V4. Finally, the third group of estimations analyse the impact of a US monetary shock on V4 controlling for Germany. Henceforth, the three estimations are in short referred to as: 1) direct US monetary shock (US_V4); 2) direct German monetary shock (GER_V4); and 3) US monetary shock with control for German variables (US_GER_V4).

The impulse responses for the three groups of estimations are given by the median response function for the domestic variables for 12 periods, due to an increase in the interest rate of the large economy by one standard deviation point, and are displayed in a posterior 68% band extracting the 16th and 84th percentile of the simulated impulse response distribution. The impulse response functions for the estimations are presented in Figures 3.1-3.3. It is significant that the pattern of the impulse responses are similar for all the three groups of estimations: the monetary shock generated abroad is followed by a decrease in the GDP growth and a depreciation of the domestic currency in all V4. The impact on CPI inflation is, however, ambiguous.

Figure 3.1 illustrates the direct impact of the US monetary policy shock on the V4. In our sample, the income absorption effect is the weakest in Poland (the largest of the V4), where the GDP growth recovers fully after only three periods (less than one year). Conversely, the biggest effect is on the Slovak Republic (the smallest of the V4), where the impact is as big as on the US GDP rate of growth itself. A contractionary monetary policy leads unambiguously to the appreciation of the dollar relative to all the other currencies in the model. This is in line with the theoretical predictions, and due to the fact that the investors are willing to invest more in US bonds, thereby causing an increase in demand for US dollars. The effect on CPI inflation is ambiguous for two reasons. On the one hand, the slow down in the domestic activity causes the prices to decrease. On the other hand, the depreciation of the domestic currency increases import prices, which generates an increase in the domestic CPI inflation. In the impulse responses, the second effect is clearly stronger in Hungary, but may also dominate in Poland.

The impulse responses in Figure 3.2 show the direct impact of German (later, European) monetary shock on V4 variables. Similar to the first estimation, here the effect on GDP growth in Poland is lowest and in the Slovak Republic it

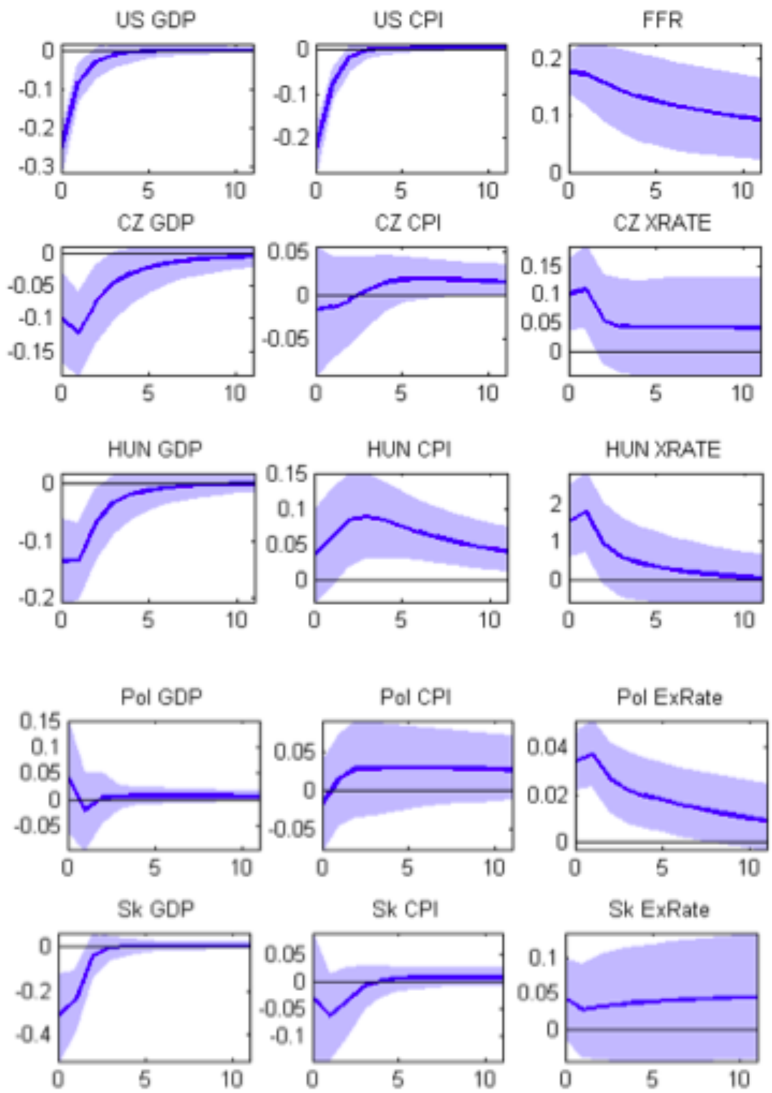

Figure 3.1: Dynamic Effect of a US monetary shock on V4 macroeconomic variables

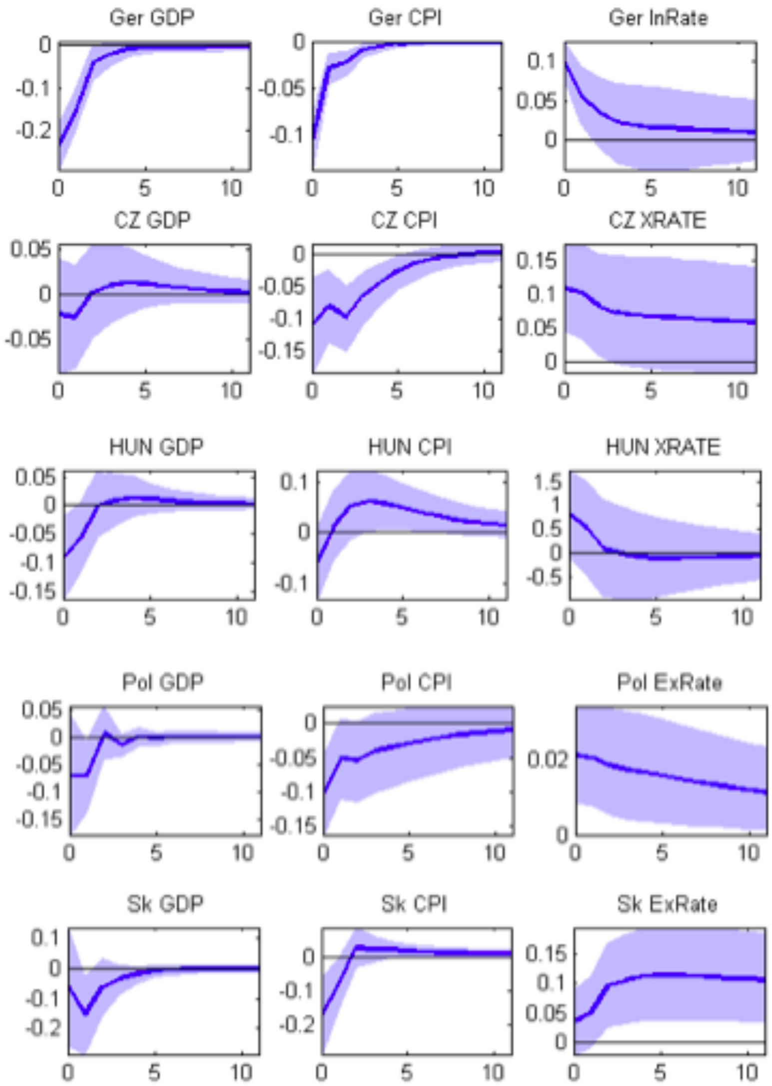

Figure 3.2: Dynamic effect of a ECB monetary shock on V4 macroeconomic variables.

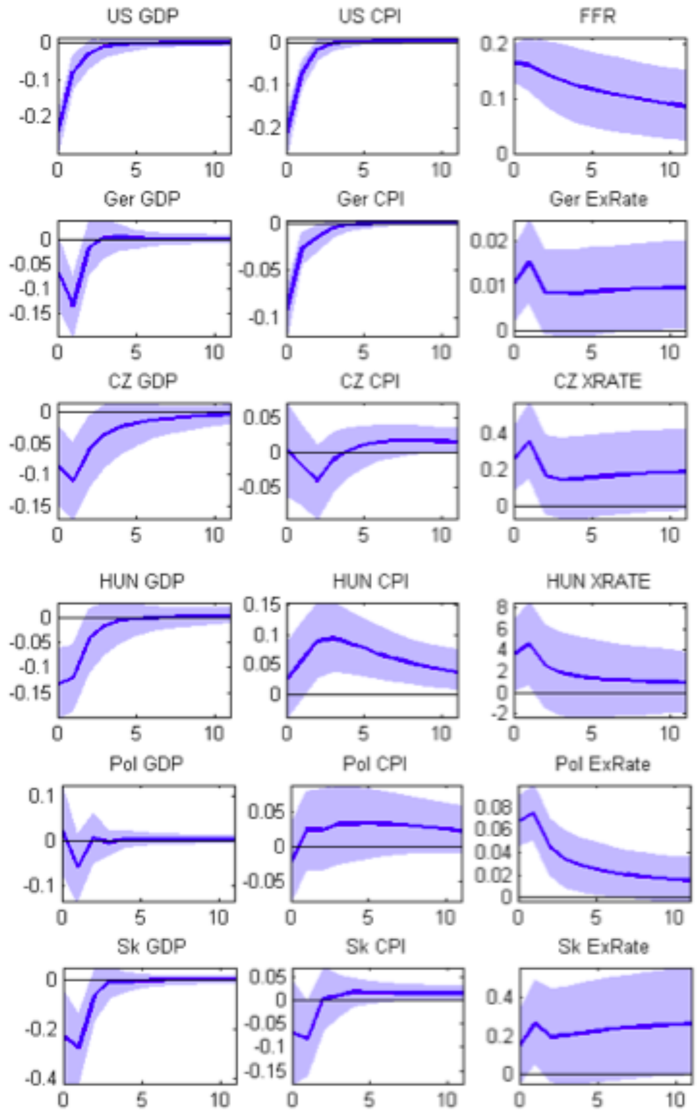

Figure 3.3: Dynamic effect of a US monetary shock on German and V4 macroeconomic variables

is strongest. On the contrary, in all countries, except for the Slovak Republic, GDP growth may increase after a short period (half a year), showing that after a while the income absorption effect may be dominated by the expenditure switching effect. There is no such a positive effect on Slovak output, which is consistent with the fact that the exchange rate is not allowed to depreciate since Slovakia is a member of the Eurozone and therefore only the income absorption effect takes place.

Figure 3.3 illustrates the impact of US monetary shock and its effect on Germany as well as on other countries (though Germany is considered a large economy relative to the V4). The model is detailed in Appendix B. The relevant impulse responses show that an unanticipated increase in the Federal Funds rate leads to a contraction in US macroeconomic variables as well as in those of all other countries. However, adding German macroeconomic variables into the model does not alter the reaction of the V4 variables to the innovation in the Federal Funds rate. Furthermore, comparing the result with the one from second estimation, it is clear that German GDP growth and inflation react similarly to the unanticipated increase in Federal Funds rate than to its own shock.

To summarise, three findings can be identified from our analysis. First, an exogenous contractionary monetary shock reduces output growth in all V4 significantly (except for Poland), regardless the origin of the shock. Second, the effect of the German (later, ECB's) shock on V4 GDP growths is smaller and dies out quicker than the one generated in the United States. Third, both exogenous monetary shocks induce a depreciation in the domestic currency and have an ambiguous effect on domestic inflation.

Tables 3.1 and 3.2 report the median share of the FEVD for forecast horizons of 1 quarter (refer to as the short-run), 4 quarters (1 year, the medium run) and

US_V4

	CZ CPI	Hun CPI	Pol CPI	SK CPI
1	0.75	0.83	0.60	0.63
4	3.59	1.97	1.41	3.10
12	6.98	5.97	3.14	4.38

Ger_V4

	CZ CPI	Hun CPI	Pol CPI	SK CPI
1	5.60	1.37	0.91	0.65
4	9.60	2.40	2.00	2.91
12	12.93	7.41	4.63	4.59

US_Ger_V4

	CZ CPI	Hun CPI	Pol CPI	SK CPI
1	1.33	0.64	0.52	0.60
4	6.20	1.75	1.31	2.96
12	10.98	5.68	3.23	4.38

Table 3.1: Forecasting Error Variance Decompositions (FEVDs) for CPI inflation

12 quarters (3 years, the long-run). Although the contribution of the German shock is higher in the short run, after three years, the contribution of US shocks and German shocks are of similar size for both the V4 output growth as well as inflation.

Table 3.1 compares the FEVD for the CPI inflation for all three groups of estimations, and shows that the German monetary policy shock explains more of

US_V4

	CZ CPI	Hun CPI	Pol CPI	SK CPI
1	13.77	7.20	7.05	0.76
4	22.48	14.58	8.12	10.48
12	22.88	16.29	8.78	11.09

Ger_V4

	CZ CPI	Hun CPI	Pol CPI	SK CPI
1	21.28	11.40	4.30	12.57
4	19.56	10.42	5.55	17.20
12	24.18	13.16	6.74	18.10

US_Ger_V4

	CZ CPI	Hun CPI	Pol CPI	SK CPI
1	12.91	6.12	8.40	0.77
4	19.78	12.12	9.26	10.14
12	19.80	12.94	9.94	10.61

Table 3.2: Forecasting Error Variance Decompositions (FEVDs) for GDP growth

the CPI inflation for all countries than its US counterpart, especially in the short run. The difference is large, especially for the Czech Republic (although, when controlling for Germany, the difference dies out in the long run). Generally, in the long run, the US monetary shock accounts for 3 to 7 percent of the variability of the CPI inflation and when we control for the effect from for Germany, it explains up to 11 percent. The German (later, ECB's) shock explains mostly the Czech inflation, in the long run up to 13 percent. Generally, the exogenous monetary policy shocks explains more of the inflation in the Czech Republic and less of it in Poland. Table 3.2 shows that a sizeable fraction of the variation in real GDP growth can be attributed to external monetary policy shocks. The US generates higher variation in Hungarian and Polish GDP, even when controlled for Germany, whereas the Czech and the Slovak Republic are the countries most exposed to the German (later, ECB's) monetary shock. In general, the exogenous monetary shocks explain more of the GDP the variation than of the CPI inflation in a 12-period horizon.

What would it happen in the absence of any shock but those generated by monetary policy? The historical decomposition shows the contribution of the monetary policy shock to the endogenous variables, and therefore the overall effects of the exogenous monetary policy shock in specific periods. Figures 3.4-3.6 show the detrended variables (represented by the blue line) and its decomposition in the structural shocks to the data, where the red (dark) bars measure the contribution of the monetary policy shock for the estimated model for the period 2005-2012 for all the three groups of estimations. By looking at the specific period, the US monetary shock plays a significant role in explaining the GDP growth in the Czech Republic and Hungary, and less in Poland and the Slovak Republic. The Slovak GDP growth is better explained by the German (later, ECB's) shock. Again, this is consistent with the Slovak Republic joining the Eurozone in 2009. Although the contribution of the exogenous monetary policy shock is relatively small, there are some sub-periods, *i.e.* during the recession, in which these shocks are significant. For example, the bottom-left panel of Figure 3.4 shows clearly that the recession in Poland was driven by the US shock. Similar but weaker results are found for the other countries as well.

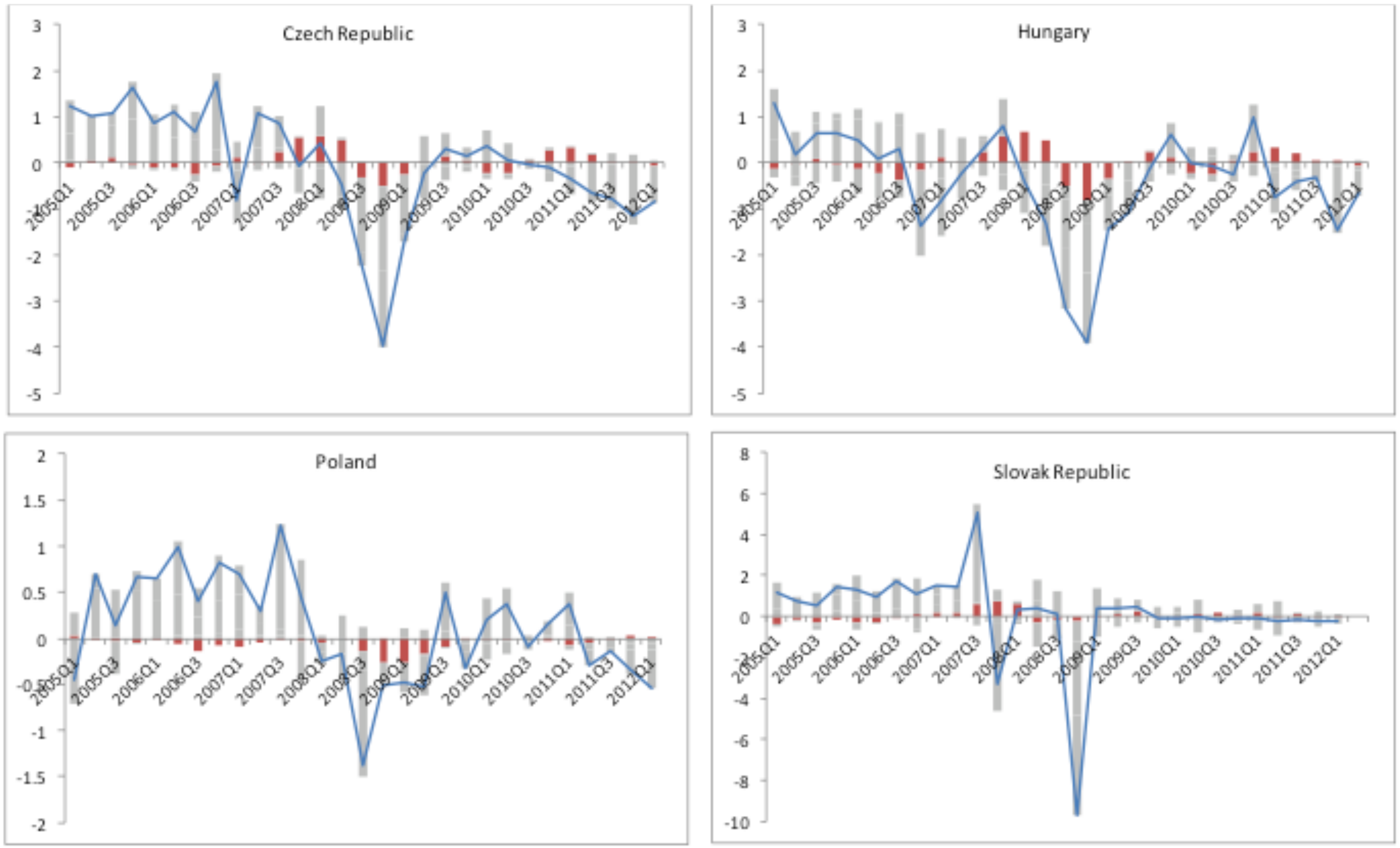

Figure 3.4: Contribution of a US monetary policy shock to the V4 GDP Growth

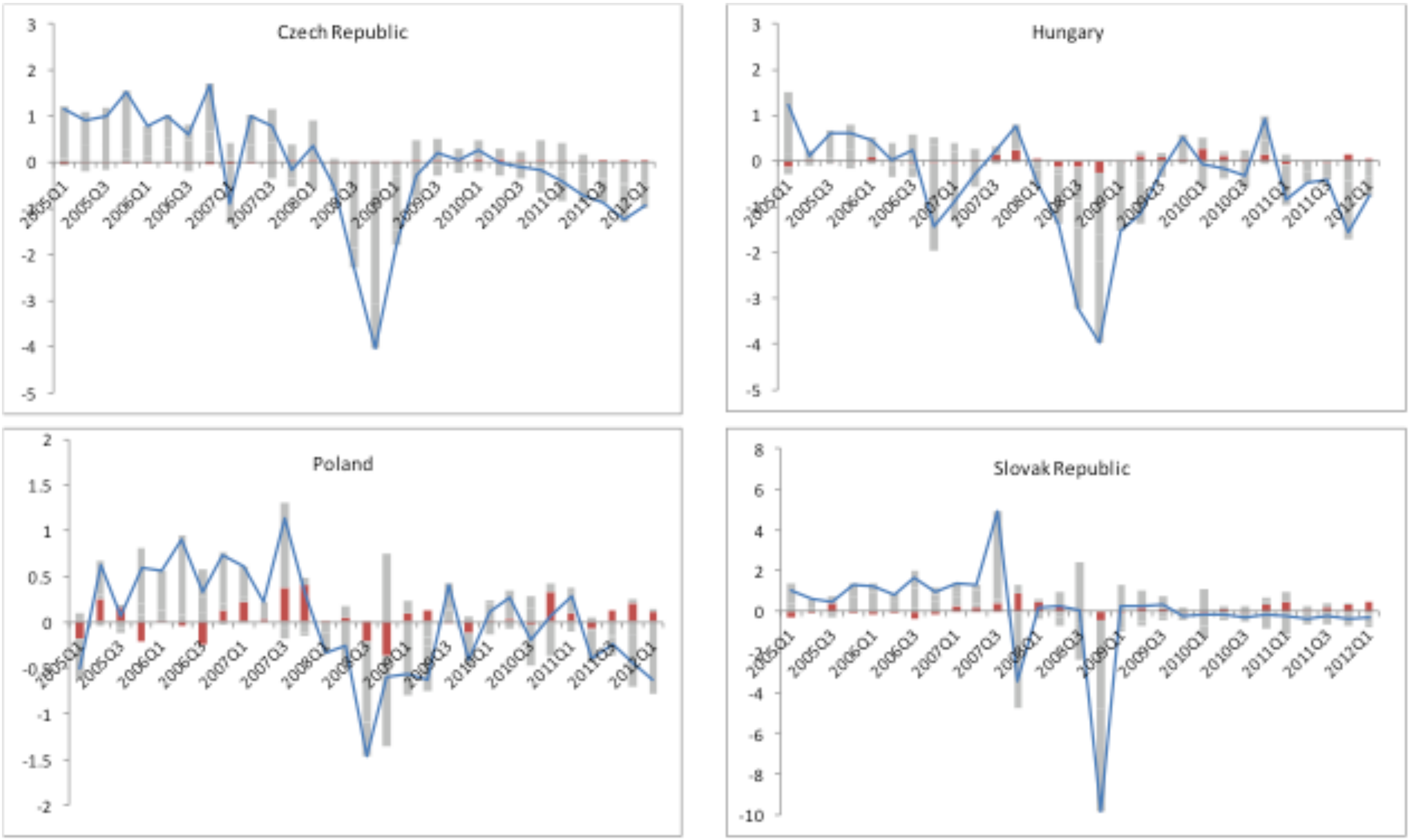

Figure 3.5: Contribution of a ECB monetary policy shock to the V4 GDP Growth

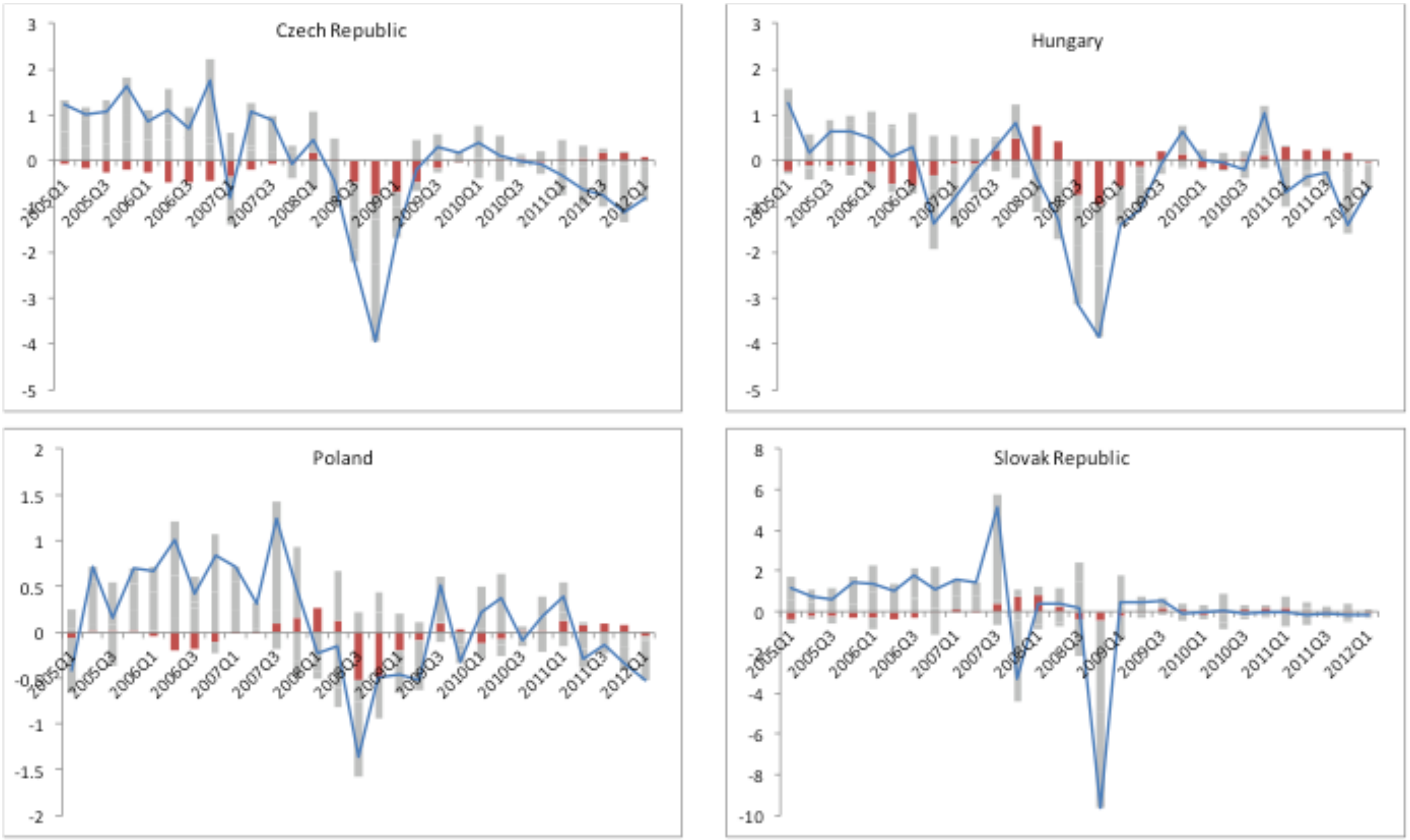

Figure 3.6: Contribution of a US monetary policy shock to the German and V4 GDP Growth

4 Conclusion

The results of our VAR estimation suggests that a foreign contractionary shock leads to a decrease in output, with an ambiguous effect on inflation. According to the mainstream theory, represented by the Dornbush-Mundell-Fleming (DMF) model, under a flexible exchange rate regime, a monetary contraction in a large economy, represented by an increase in the interest rate, has two contradictory effects on the variables of a small open economy (SOE): the expenditure switching effect and the income absorption effect.

The findings point out that the income absorption effect dominates, leading to a decline in SOE output. This is consistent with the results in Kim (2001), who shows that an expansion in the US monetary policy leads to a boom in G6 countries. The findings are also in line with the theory of Betts and Devereux (1999). These authors argue that, if exports are priced in the foreign currency (and imports in the domestic one), then no expenditure switching effect happens, thus the income absorption effect naturally drives the economic dynamics. The appreciation in the domestic currency worsens the terms of trade in both the small and the large economy, and outputs of both countries decrease proportionally.

It is worth drawing a parallel with the findings reported in Junicke (2019). The results of DSGE estimation discussed there are suggestive of the expenditure switching effect overweighting the income absorption effect. The reason is twofold. On the one hand, currency invoicing is neglected, hence the expenditure switching effect plays a role in the determination of the equilibrium dynamics. On the other hand, our estimations suggest that the small open economy central bank is at most mildly concerned with exchange rate targeting. In this latter case, the SOE currency is bound to depreciate, and this leads to an increase in SOE output. For the findings of our VAR analysis to hold, by contrast, the SOE central bank must be strictly targeting the exchange rate, or committed to a peg with the large economy's currency. In this case, the income absorption effect would dominate its expenditure switching counterpart.[3] Further investigation of the dichotomy between the two results may become an interesting topic for further research. All the more so if one considers this issue in conjuction with the central claim raised by Betts and Devereux, *i.e.*, that the currency invoicing becomes a critical point in explaining the dynamics of the macroeconomic variables. In this respect, investigating the effect of currency invoicing on the monetary policy transmission mechanism from the US to the V4, with particular regard to the degree of exchange rate tightening, appears to be a promising subject for future research.

This study investigated the impact of US monetary policy shock on countries of the Visegrad Group, namely the Czech Republic, Hungary, Poland and the Slovak Republic, using a SVAR methodology. The structural VAR process is identified using two types of restrictions. We impose sign restrictions to ensure that a contractionary monetary policy shock in the large economy causes a decrease both in its inflation and output and zero restrictions on the channels feeding back from the small open economy to the large economy, in order to guarantee that the economic variables of the former has no influence on those of the latter.

We find that a contractionary monetary policy in the large economy significantly reduces output growth in all V4, independently of whether the large economy is represented by the US or Germany. In particular, US monetary policy appears to influence V4 macroeconomic variables at least as much as its German (later, ECB's) counterpart, even after controlling for the indirect effect of the

[3] To assess whether the DMF theory could rationalise the findings in Junicke (2019), we have also run the relevant estimations using a higher and tighter prior on parameter ϕ_S. In this case, the estimated output decreases (*i.e.*, in the opposite direction relative to the benchmark estimation). It should be stressed, however, that comparing the marginal data densities of the two models suggest that lower value of ϕ_S fits the data better.

former through German macroeconomic variables.

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Appendix A

We use data starting in 1996, thus, the number of observations is limited. Therefore we restrain the number of variables too, by focusing on the movement in key macroeconomic variables such as CPI inflation and GDP growth.

For the analysis, Macrobond was a source for following data:

- As an indicator of monetary policy shock:
  - US Money market rate - federal funds rate (USI60B..)
  - Day to Day money market rate monthly average (BDSU0101R)

  - Exchange rate, used in percentage logarithm values
  - German Mark to US $ (USWGMRK)
  - Czech Koruna to US $ (USCZECK)
  - Hungarian Forint to US $ (USHUNGF)
  - Polish Zloty to US $ (USPOLZL)

- Slovak Koruna to US $ (SXUSDSP)

The FRED database was used as a source for following time series:

- As a measure of aggregate price level, seasonally adjusted and in the first difference of the logarithm values
  - Consumer Price Index of All Items in United States (USACPIALLQINMEI)
  - Consumer Price Index of All Items in Germany (DEUCPIALLQINMEI)
  - Consumer Price Index: All Items for the Czech Republic (CZECPIALLMINMEI)
  - Consumer Price Index: All Items for Hungary (HUNCPIALLMINMEI)
  - Consumer Price Index: All Items for Poland (POLCPIALLMINMEI)
  - Consumer Price Index: All Items for the Slovak Republic (SVKCPIALLQINMEI)

- As a measure of real GDP activity, seasonally adjusted and in the first difference of the logarithm values
  - Real Gross Domestic Product for US (GDPC96)
  - Current Price Gross Domestic Product in Germany (DEUGDPNQDSMEI)
  - GDP Implicit Price Deflator in Germany (DEUGDPDEFQISMEI)
  - Current Price Gross Domestic Product in Czech Republic(CZEGDPNQDSMEI)
  - GDP Implicit Price Deflator in Czech Republic (CZEGDPDEFQISMEI)

– Current Price Gross Domestic Product in Hungary (HUNGDPNQDSMEI)

– GDP Implicit Price Deflator in Hungary (HUNGDPDEFQISMEI)

– Current Price Gross Domestic Product in Poland (POLGDPNQDSMEI)

– GDP Implicit Price Deflator in Poland (POLGDPDEFQISMEI)

– Current Price Gross Domestic Product in Slovak Republic (SVKGDP-NQDSMEI)

– GDP Implicit Price Deflator in Slovak Republic (SVKGDPDEFQIS-MEI)

Appendix B

We restrict the model by imposing specific signs and zero values in a way that the identification scheme for a model with two countries takes the following form

$$\begin{pmatrix} \epsilon\left\{IR^{*}\right\} \\ \epsilon\left\{\Delta GDP^{*}\right\} \\ \epsilon\left\{\Delta CPI^{*}\right\} \\ \epsilon\left\{\Delta GDP^{V4}\right\} \\ \epsilon\left\{\Delta CPI^{V4}\right\} \\ \epsilon\left\{XR^{V4}\right\} \end{pmatrix} = \begin{pmatrix} + & . & . & 0 & 0 & 0 \\ - & . & . & 0 & 0 & 0 \\ - & . & . & 0 & 0 & 0 \\ . & . & . & . & 0 & 0 \\ . & . & . & . & . & 0 \\ . & . & . & . & . & . \end{pmatrix} \begin{pmatrix} e\left\{IR^{*}\right\} \\ e\left\{\Delta GDP^{*}\right\} \\ e\left\{\Delta CPI^{*}\right\} \\ e\left\{\Delta GDP^{V4}\right\} \\ e\left\{\Delta CPI^{V4}\right\} \\ e\left\{XR^{V4}\right\} \end{pmatrix}.$$

The vector $a_j \in R^m$ is called an impulse vector if there is some matrix $\tilde{A}$ such that $\tilde{A}\tilde{A}' = \Sigma$ holds and a_j is the jth column of $\tilde{A}$. The impulse vector yields the instantaneous impulse response of all variables to the structural shock associated with that vector and, in our specification needs to have the following signs: $a_{11} > 0$, $a_{21} < 0$, and $a_{31} < 0$. In other words, the sign restrictions on large economy variables ensure that positive shocks in the interest rate implies a fall in

GDP growth and inflation in the US. The impulse responses for the rest of the variables remain unrestricted on sign.

The identification is completed by using zero restrictions on contemporaneous structural parameters so as to ensure that the SOE does not influence the large economy contemporaneously. The dots correspond to freely estimated parameters.[4]

Following (4), some prior coefficients B_0 are restricted to zero on lags. The prior for coefficient matrix $B(j)$ has therefore the form given as

$$B_0(j) = \begin{pmatrix} B_{11}^0(j) & 0 \\ B_{21}^0(j) & B_{22}^0(j) \end{pmatrix},$$

and incorporates the belief that the coefficients of matrix $B_{12}^0(j)$ for all $j = 1, ..., p$ are close to zero. To ensure that these restrictions are also fulfilled for the posterior, so that the appropriate parameters stay close to zero, we set the elements of the prior variance H matrix belonging to these coefficients very close to zero. For the remaining coefficients, regarding the first lag $j = 1$, the prior mean on its own lag is set equal to 0.95, *e.g.,* the diagonals of matrices $B_{11}(1)$, $B_{22}(1)$ and $B_{33}(1)$ equals 0.95. For all other elements of matrix $B(1)$, the elements are set to be zero. The vector $\tilde{C}$ is a zero vector and matrix $B(j)$, $j = 2, ...p$, is a zero matrix. The elements of the prior variance H correspond to all the coefficients except those for $B_{12}(j)$, $B_{13}(j)$ and $B_{23}(j)$, which are set to be sufficiently large that these coefficients are mainly determined within the model. To summarise, H is a $((m \times (m \times p + 1)) \times (m \times (m \times p + 1)))$ diagonal matrix, with near-zero elements for coefficients which are believed to be zero, and large elements for the remaining coefficients.

[4] For a critical survey on contemporanous restrictions, see Fry and Pagan (2011).

In the particular case of three countries, *e.g.*, the US, Germany and a (domestic) V4 like the Czech Republic, the matrix $B(j)$ can be written as

$$B(j) = \begin{pmatrix} B_{11}(j) & 0 & 0 \\ B_{21}(j) & B_{22}(j) & 0 \\ B_{31}(j) & B_{32}(j) & B_{33}(j) \end{pmatrix}, \tag{5}$$

where $B_{12}(j)$, $B_{13}(j)$ and $B_{23}(j)$ are zero matrices with $m \times (m \times p + 1)$ parameters, meaning that V4 variables have impact on neither German nor the US economy, and where $B_{31}(j)$ and $B_{32}(j)$ respectively give the direct impact of US and German variables on the V4. The first line represents US economy.

The identification scheme has the following form

$$\begin{pmatrix} \epsilon\left\{FFR^{US}\right\} \\ \epsilon\left\{\Delta GDP^{US}\right\} \\ \epsilon\left\{\Delta CPI^{US}\right\} \\ \epsilon\left\{\Delta GDP^{G}\right\} \\ \epsilon\left\{\Delta CPI^{G}\right\} \\ \epsilon\left\{XR^{G}\right\} \\ \epsilon\left\{\Delta GDP^{V4}\right\} \\ \epsilon\left\{\Delta CPI^{V4}\right\} \\ \epsilon\left\{XR^{V4}\right\} \end{pmatrix} = \begin{pmatrix} + & . & . & 0 & 0 & 0 & 0 & 0 & 0 \\ - & . & . & 0 & 0 & 0 & 0 & 0 & 0 \\ - & . & . & 0 & 0 & 0 & 0 & 0 & 0 \\ . & . & . & . & 0 & 0 & 0 & 0 & 0 \\ . & . & . & . & . & 0 & 0 & 0 & 0 \\ . & . & . & . & . & . & 0 & 0 & 0 \\ . & . & . & . & . & . & . & 0 & 0 \\ . & . & . & . & . & . & . & . & 0 \\ . & . & . & . & . & . & . & . & . \end{pmatrix} \begin{pmatrix} e\left\{FFR^{US}\right\} \\ e\left\{\Delta GDP^{US}\right\} \\ e\left\{\Delta CPI^{US}\right\} \\ e\left\{\Delta GDP^{G}\right\} \\ e\left\{\Delta CPI^{G}\right\} \\ e\left\{XR^{G}\right\} \\ e\left\{\Delta GDP^{V4}\right\} \\ e\left\{\Delta CPI^{V4}\right\} \\ e\left\{XR^{V4}\right\} \end{pmatrix}.$$

For VAR(2), the model has the following form

$$Y_t = B_1 Y_{t-1} + B_2 Y_{t-2} + C + \epsilon_t.$$

The prior mean for $vec\left(B_0\right)$ is set to be equal 0.95 for coefficients on own first lags and equal zero on all other remaining coefficients. The VAR(2) model under the prior can be written as

$$\begin{pmatrix} Y_t^{US} \\ Y_t^{G} \\ Y_t^{V4} \end{pmatrix} = \begin{pmatrix} diag(0.95) & 0 & 0 \\ 0 & diag(0.95) & 0 \\ 0 & 0 & diag(0.95) \end{pmatrix} \begin{pmatrix} Y_{t-1}^{US} \\ Y_{t-1}^{G} \\ Y_{t-1}^{V4} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} Y_{t-2}^{US} \\ Y_{t-2}^{G} \\ Y_{t-2}^{V4} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} \epsilon_t^1 \\ \epsilon_t^2 \\ \epsilon_t^3 \end{pmatrix},$$

where Y_t^{US} is a 3×3 matrix of US variables, the interest rate, GDP growth and CPI inflation, Y_t^G and Y_t^{V4} are 3×3 matrices of German and V4 variables respectively, namely the GDP growth, CPI inflation and nominal exchange rate.

Assuming 9 endogenous variables, the prior variance matrix H is a 171×171 diagonal matrix, where diagonal elements are set close to zero for coefficients restricted to zero and large for the remaining coefficients. In particular, with reference to the part of the matrix H corresponding to either matrix $B(j)$, $j = 1, 2$ as given by (5), the elements are all given a very high value (10 000) except for those corresponding to $B_{12}(j)$, $B_{13}(j)$ and $B_{23}(j)$, which are set very low (1/10.000) to impose the prior strictly.

Appendix C

The Bayesian estimation combines a subjective prior together with sample information. It is based on the Bayes' theorem, which states that

$$\text{posterior distribution} \propto \text{likelihood} \times \text{prior distribution}.$$

The likelihood function is taken from the OLS estimation of the data sample.

Equivalently, it can be written as

$$R\left(vec\left(B\right)\backslash\Sigma, Y_t\right) \propto F\left(Y_t\backslash vec\left(B\right), \Sigma\right) \times P\left(vec\left(B\right), \Sigma\right),$$

the posterior distribution $R\left(vec\left(B\right)\backslash\Sigma, Y_t\right)$ is proportional to the product of the prior distribution $P\left(vec\left(B\right), \Sigma\right)$ and distribution of the sample as given by the likelihood function $F\left(Y_t\backslash vec\left(B\right), \Sigma\right)$. The vector $vec\left(B\right)$ is a matrix of regressors B in vector form and Σ the variance-covariance matrix. Because we incorporate a prior belief with zero restrictions, we opt for an independent normal inverse Wishart prior.

It can be assumed, given the nature of the data, that the matrix of coefficients B is normally distributed

$$P\left(vec\left(B\right)\right) \sim N\left(vec\left(B_0\right), H\right), \tag{6}$$

where $vec\left(B_0\right)$ is the $\left(\left(m \times \left(m \times p + 1\right)\right) \times 1\right)$ vector of prior means for the elements of matrix B. The matrix H is a $\left(\left(m \times \left(m \times p + 1\right)\right) \times \left(m \times \left(m \times p + 1\right)\right)\right)$ diagonal matrix, whose elements are the prior variances for each corresponding coefficient from matrix B_0. As discussed earlier, we impose the strong prior belief that the elements of matrices $B_{12}(j)$, $B_{13}(j)$ and $B_{23}(j)$ equal zero. Therefore, the prior variances of the corresponding elements in matrix H are set to be very low.

Following Zellner (1971), the conjugate prior for a positive definite variance-covariance matrix Σ is an Inverse Wishart prior

$$P\left(\Sigma\right) \sim IW\left(\bar{S}, \alpha\right) \tag{7}$$

with the prior scale matrix $\bar{S}$ and prior degrees of freedom α.

Given the fact that conjugate prior on B is normal distributed, it can be shown that the posterior distribution of the coefficients conditional on the variance-covariance matrix Σ is given by

$$R\left(vec\left(B\right)\backslash\Sigma, Y_t\right) \sim N\left(M^*, V^*\right),$$

where M^* and V^* are the mean and the variance of this normal distribution, respectively. As shown in Kadiyala and Karlsson (1997), the mean and the variance of the conditional posterior distribution are respectively given by

$$\begin{aligned} M^* &= \left(H^{-1} + \Sigma^{-1} \otimes X_t' X_t\right)^{-1} \left(H^{-1} vec\left(B_0\right) + \Sigma^{-1} \otimes X_t' Y_t\right) \\ V^* &= \left(H^{-1} + \Sigma^{-1} \otimes X_t' X_t\right)^{-1}. \end{aligned} \tag{8}$$

Note that M^* is a weighted average of the prior mean $vec\left(B_0\right)$ and the OLS estimator, given by $X_t' Y_t$, weighted by the reciprocal of the corresponding variance-covariance matrices. The smaller the values of matrix H elements, the higher the weight on the prior relative to the conditional posterior estimates. In the case where there are no beliefs about the prior, *i.e.* the value of matrix H elements are very large, then the posterior estimates are identical to the maximum likelihood estimator.

Given the prior in equation (7), the posterior distribution for Σ conditional on B is Inverse Wishart

$$R\left(\Sigma\backslash vec\left(B\right), Y_t\right) \sim IW\left(\bar{\Sigma}, T + \alpha\right),$$

where $\bar{\Sigma} = \bar{S} + \left(Y_t - X_t B\right)' \left(Y_t - X_t B\right)$, with T observations and α degrees of freedom.

Technically, we impose this prior by following Banbura *et al.* (2008) and incorporate additional artificial data. The artificial data Y_D and X_D are formed by four independent blocks as follows

$$Y_D = \begin{pmatrix} \frac{diag(\chi_1\sigma_1 ... \chi_m\sigma_m)}{\lambda} \\ 0_{((m\times(p-1))\times m)} \\ -------------- \\ diag\,(\sigma_1...\sigma_m) \\ -------------- \\ 0_{(1\times m)} \\ -------------- \\ \frac{diag(\chi_1\mu_1 ... \chi_m\mu_m)}{\tau} \end{pmatrix},$$

$$X_D = \begin{pmatrix} \frac{J_p \otimes diag(\sigma_1...\sigma_m)}{\lambda} & 0_{(mp\times 1)} \\ ---------------- & ------ \\ 0_{(m\times mp)} & 0_{(m\times 1)} \\ ---------------- & ------ \\ 0_{(1\times mp)} & c \\ ---------------- & ------ \\ \frac{J_p \otimes diag(\chi_1\mu_1 ... \chi_m\mu_m)}{\tau} & 0_{(m\times 1)} \end{pmatrix}.$$

The first block in each matrix imposes the prior beliefs on the autoregressive coefficients. The second block implements the prior for the variance-covariance matrix and the third block reflects the uninformative prior for the intercept. By adding artificial data in the last row, we incorporate the prior that incorporates the belief that the sum of the coefficients on lags of the dependent variable in each equation sum to 1, *i.e.* that each variable has a unit root. The matrix J_p is given as $J_p = diag\,(1...p)$. As in Banbura *et al.* (2008), the variance of the prior distribution is defined by hyperparameters that regulate the variation around the prior. The hyper-parameter $\lambda > 0$ controls the overall tightness of the prior so that as $\lambda \to 0$, the prior is implement more tightly, whereas the larger the value of this parameter the more the posterior approaches an OLS estimation of the VAR model. The hyperparameter τ controls for the degree of shrinkage. If τ is large, the prior is imposed loosely. we set $\lambda = 10$ and $\tau = 10\lambda$, implying that the prior on these data is not very informative. The parameter χ_i measures the persistence of variable i, and follows from the OLS estimation of AR(1). Literally, it is a prior mean for the coefficient on the first lag of dependent variable i. The parameter μ_i is a sample mean of the variable i, and σ_i is a sample standard deviation of error terms. They can both be calculated as sample averages of the time series y_i from the OLS estimation. The matrix Y_D is the $(m\,(p+2)+1) \times m$ matrix and X_D is a $(m\,(p+2)+1) \times (mp+1)$ matrix adding $(m\,(p+2)+1)$ dummies to each time series. These artificial data are mixing with the actual data and the hyperparameters placed on them determine how tightly the prior is imposed. This approach also helps to alleviate the curse of dimensionality in the VAR model.