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Volatility Connectedness on the Central European Forex Markets

Abstract

We provide a comprehensive assessment of volatility connectedness between the currencies of Central European (CE) countries using high-frequency data from 2009 to 2022. We assess asymmetries in connectedness (not investigated for CE currencies before) and document domination of the negative volatility, especially during periods of economic distress. We further bring the first statistical evidence based on a formal bootstrap-after-bootstrap procedure of Greenwood-Nimmo et al. (2023) that increases in connectedness are linked with systematic events, and identify the impact of specific domestic and global shocks. We find that for eight out of eight endogenously selected global events, there was an increase in connectedness within a maximum of one business month from the event's occurrence. Finally, we show that the connectedness is linked with its potential drivers: uncertainty, liquidity, and economic activity whose impacts differ substantially. Our results are robust with respect to a volatility measure and provide direct policy implications for portfolio composition and hedging.

JEL-Codes: C580, F310, F650, G010, G150.

Keywords: volatility connectedness, Central European currencies, asymmetries in volatility connectedness, bootstrap-after-bootstrap procedure, portfolio composition and hedging.

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1. Introduction

Since the 2008 global financial crisis (GFC), propagation of the systematic risk on various segments of financial markets has attracted substantial attention, and the connectedness network approach has become one of its most exploited research tools (Baruník et al., 2017; Diebold and Yilmaz, 2012, 2014; Uluceviz & Yilmaz, 2020). Forex market became no exception, and although the connectedness of the global (Greenwood-Nimmo et al., 2016) and local currencies (Bubák et al., 2011) has been analyzed in considerable detail, the phenomenon of risk propagation from global to local currencies has been studied to a lesser extent. We contribute to the literature by assessing risk contagion towards the Central European (CE) currencies, accounting for asymmetries in volatility spillovers, and statistically testing for major events impacting the CE forex connectedness.

It was evidenced that the financial contagion of the global financial crisis (GFC) and the European debt crisis was transmitted from developed to emerging countries (Gray, 2014). We combine the perspective of both origins and analyze to what extent the US dollar affected the connectedness between emerging currencies (as we use quotations against the euro (EUR)). This background becomes more important because joining the European Union (EU) increased the importance of the Czech koruna, Hungarian forint, and Polish zloty (Hanousek & Kočenda, 2011). Moreover, after the GFC, the currencies of these emerging markets have become important items in the diversification of hedged portfolios (Jotikasthira et al., 2012), as international diversification outperforms industrial diversification within portfolios (Attig et al., 2023).

Many authors have employed the analytical approach of Diebold and Yilmaz (2009, 2012, 2014) for different types of assets. Their published conclusions have shown that connectedness mainly arises in periods of increased uncertainty (Diebold & Yilmaz, 2012; Diebold & Yilmaz, 2014; Uluceviz & Yilmaz, 2020). This approach has been modified by Baruník et al. (2015), who confirmed that connectedness increases in times of economic turbulence and also due to asymmetries in the propagation of volatility. The authors infer that the propagation effects among the six largest currencies change depending on positive or negative volatility (Baruník et al., 2017). This finding is important because of the impact on portfolio returns (Amonlirdviman & Carvalho, 2010). For that, we also explore the extent and dynamics of asymmetries between CE currencies.

Numerous studies indicate an increase in connectedness due to economic or political shocks. However, none of them have addressed the statistical significance of (the value of) individual spikes in connectedness related to specific market events. Only recently has research made contributions in this area. Greenwood-Nimmo et al. (2023) followed up on the process used by Kilian (1998). They created the bootstrap-after-bootstrap procedure to assess the probability that a spike in connectedness is truly linked to a specific event. It is based on bias-corrected confidence intervals and used as an impulse response function. We employ this novel method and compare the orthogonalized and generalized connectedness indices. Using the bootstrap-after-bootstrap procedure, we calculate the probability of an increase in the index value as a response to specific events. We estimate the probability of an increase for five different time horizons after a particular event and distinguish between global and domestic shocks. Our results confirm that for eight out of eight global economic or political shocks, connectedness increased with a 90% or higher probability within the business month after the occurrence of the event. On the other hand, connectedness increased in only two out of four cases in the domestically generated shocks.

Our contribution to the literature is threefold. First, we identify asymmetries in the connectedness of the CE currencies, as so far, they have only been analyzed for global currencies (Baruník et al., 2017). The previous approach was based on daily semivariances calculated from data samples taken every 5 minutes. Our calculations of daily semivariances are calculated using data samples taken every minute. Second, we provide probability-based evidence of an increase in connectedness following a specific shock by employing the bootstrap technique created by Greenwood-Nimmo et al. (2023). This way, we compute the statistical significance of the connectedness response concerning the major economic and financial events. We distinguish between the impact of global and local shocks. This is the first study to apply this method to the forex markets. Third, by using the time span from 2009 to 2022, we cover several important events, including the EU debt crisis, the BREXIT, the COVID-19 pandemic, and the Russian invasion of Ukraine; this way, we extend the period of the CE currencies connectedness assessment beyond that considered by Bubák et al. (2011) and other studies. Finally, we also show that the connectedness is linked with its potential drivers: uncertainty, liquidity, and economic activity whose impacts differ substantially.

The paper is structured as follows: Section 2 reviews recent studies related to connectedness, focused on the European forex market. Section 3: Detailed information about the data and methodology. Sections 4 and 5: Results. Section 6: Conclusions.

2. Literature review

The literature on connectedness related to different asset classes is voluminous, including that linked to foreign exchange (Baruník et al., 2017; Greenwood-Nimmo et al., 2016 etc.). Many studies conclude that volatility connectedness mainly occurs during periods of economic and political shocks (Bubák et al., 2011; Diebold & Yilmaz, 2009; Kočenda & Moravcová, 2019).

The underlying reason for this is that there is a decline in the ability of individuals to predict future outcomes during periods of uncertainty (Bloom, 2009). Uncertainty alters the behavior of individuals, and these changes in behavior affect real variables, such as a country's exports (Baum et al., 2004), the rate of inflation (Haque & Magnusson, 2021), but also affects the labor market (Belke & Setzer, 2003) or foreign direct investment (Killicarslan, 2018). As the degree of uncertainty increases, individuals reduce consumption (Giavazzi & McMahon, 2012) and investment (Baker et al., 2016), but also their future expectations (Boyle & Peterson, 1995) as their aversion to risk increases (Tran, 2019). Subsequently, uncertainty is transmitted through these channels to the entire market (Goodell et al., 2020). Entities may adopt ineffective strategies as they are guided by exaggerated emotion and rebalance their assets held in foreign currencies as they are motivated to protect their portfolios.

Rebalancing increases asset volatility (Wu, 2001), and, in return, this increases exchange rate volatility (Menkhoff, 2013; Fratzscher et al., 2019). Through this transmission mechanism, economic policy shocks spread across countries and increase connectedness (Balcilar et al., 2023). In such a context, portfolio rebalancing is particularly important for the currencies of emerging markets (Menkhoff, 2013; Fratzcher et al., 2019), as countries with their local currency are more exposed to global economic and political shocks (Bubák et al., 2011). According to Kočenda and Moravcová (2019), a deeper understanding of connectedness could help in investment portfolio management and provide portfolio managers with valuable information regarding hedging or diversification strategies. Kanas (2000) proves that volatility connectedness significantly affects portfolio diversification gains.

Bubák et al. (2011) analyzed the connectedness between Central European currencies and the USD/EUR, and they identified significant connectedness between the currencies of the Czech Republic, Hungary, and Poland. They identified the Hungarian forint as the currency most affected by volatility in other currencies between 2003 and 2009. Bostanci and Yilmaz (2020) identified that the Czech koruna had a particularly significant impact on Polish and Hungarian currencies. However, they used currencies quoted against the US dollar even though exchange rates of the CE currencies quoted against the euro would be more appropriate since the CE currencies are substantially more traded with respect to the euro (BIS, 2019).

Baruník et al. (2017) further researched volatility transmission with improvements to the original methodology used by Diebold and Yilmaz (2009, 2012) for the measurement of asymmetry. They analyzed propagation effects for the six most traded currencies, emphasizing distinguishing between positive and negative sources of volatility. Their study confirms the assumption that markets react asymmetrically to volatility. However, recent development did not sufficiently cover emerging currencies, which might be useful as these asymmetries affect portfolio returns (Amonlirdviman & Carvalho, 2010), and these currencies are important in the diversification of portfolios (Jotikasthira et al., 2012)

Greenwood-Nimmo et al. (2023) made further advancements in previous methods used in the examination of volatility by measuring the statistical significance of the connectedness using their bootstrap-after-bootstrap procedure. The authors used the original data from the Diebold and Yilmaz study (2009) to identify which events produced bursts of volatility in the observed markets and the timescale. In the end, for 15 out of 19 events, they determined that there was a 90 percent probability of an increase in connectedness. The timing of the increase was from immediately after the event up to 22 days later. To the best of our knowledge, our paper is the first to analyze asymmetries in the volatility connectedness of CE currencies and to test the statistical significance of forex connectedness in the context of economic and political shocks. Identifying the events that lead to an increase in connectedness is critical because various economic indicators are shown to be subsequently affected via connectedness (labor market - Baum et al., 2004; exports - Belke and Setzer, 2003; inflation - Haque and Magnusson, 2021; foreign direct investment (FDI) - Killicarslan, 2018).

3. Data and methods

In this research, we quantify the volatility connectedness among the Central European currencies (the Czech koruna (CZK), the Hungarian forint (HUF), the Polish zloty (PLN)) and the US dollar (USD); all exchange rates are quoted against the euro. The data covers the daily exchange rates from July 1, 2009, to June 30, 2022, and the daily exchange rate data were obtained from Bloomberg; the descriptive statistics are presented in Table A1.

The data range choice has been motivated by the following reasons. First, the beginning of the data span coincides with the end of the global financial crisis; according to the U.S. National Bureau of Economic Research the GFC ended in June 2009. As such, the data span also coincides with the end of the data set used in an earlier study by Bubák et al. (2011) who analyzed the same set of currencies. Further, the beginning of our data span in July 2009 corresponds to the emergence of the first difficulties related to the EU debt crisis; as we show in our results, the EU debt crisis affected the connectedness among selected currencies. Finally, the end of our data span covers two crucial issues: the peak of the COVID-19 omicron variant affirmed by the World Health Organization (WHO) in January 2022 (WHO, 2022) and the first three months of the Russian invasion of Ukraine.

In addition to the daily data, we also collected high-frequency data for the selected currency pairs at a frequency of one minute to allow a measurement of the asymmetric behavior of the volatility connectedness. Based on this data, we distinguish between positive and negative returns and calculate the daily semivariances. The date range of the one-minute frequency data runs from November 14, 2010 (the availability of the dataset) to June 30, 2022. The high-frequency data was downloaded from the HistData.com database. The descriptive statistics for these semivariances are provided in Table A2.

The period from 2009-2022 contains several major economic and political shocks. It includes Fitch's downgrading of Hungary's credit rating to "junk" status (2011), the EU sovereign debt crisis (2012), failed negotiations about the loan from the International Monetary Fund (IMF) to Hungary (2013), the launch of the exchange rate commitment by the Czech National Bank in November 2013 and its subsequent cancellation in April 2017, the credibility scandal of National Bank of Poland (2014), the annexation of Crimea by Russia and the ensuing economic sanctions (2014), the cancellation of the exchange rate commitment by the Swiss National Bank (2015), the BREXIT referendum (2016), a 10 % decline in the S&P500 due to US interest rate hike concerns (2018), US sanctions on Turkish exports (2018), the US-China trade war (2019), and the COVID-19 pandemic of 2020-2021. Finally, the period also covers the first three months of the Russian invasion of Ukraine (2022). We combine events that are country-specific with events endogenously chosen by the method.

In addition, we gathered data to explore the links between connectedness and uncertainty, liquidity, and economic activity. We use the expected future volatility of options, the VSTOXX index for the EU market, as a proxy for uncertainty. The European version of the Treasury-EuroDollar rate (TED) spread is used as a proxy for liquidity in the European market, similar to Baruník and Kočenda (2019). Since the original TED spread was computed as the difference between the 3-month LIBOR and 3-month US treasury yield, we computed a European version of the TED spread as the difference between the 3-month EURIBOR and 3-month German treasury yields. In the second model, we replace the EU TED spread with bid-ask spreads of individual CE currencies since the bid-ask spread has been confirmed as a reliable proxy for measuring market liquidity (Karnaukh et al., 2015). Finally, we employ the stock index (EURO STOXX 50) as a proxy for economic activity, similar to Davis et al. (2022). The above data were downloaded from July 18, 2011 (when the first spillover indices were available) until June 30, 2022; the data were downloaded from Bloomberg.

3.1. Methods

Diebold and Yilmaz (2009, 2012) compute the connectedness index as a variance decomposition from vector autoregressions (VAR), calculating the amount of information that each variable adds to the other in the regression, and it demonstrates how much of the forecast error variance of each variable can be explained by exogenous shocks from the other variables. We compute the actual daily variances ($RV_t = \sum_{i=1}^{p} \phi_i RV_{t-i} + u_t$) as the sum of the variances of the high-frequency intraday data where u_t is a vector of *iid* errors and ϕ_i represents p coefficient matrices. To represent the moving average of the invertible VAR process ($RV_t = \sum_{i=0}^{p} A_i u_{t-i}$), the $N \times N$ matrices with coefficients A_i are obtained from the recursion $A_i = \sum_{j=1}^{p} \phi_j A_{i-j}$, with A_0 being the identity matrix; $A_0 = I_N$ and $A_i = 0$ for $i < 0$. In this context, I_N refers to an identity square matrix with appropriate dimensions used as the initial coefficient matrix in the moving average representation of the VAR process. Computing the moving average allows us to disentangle the forecast errors, which makes it suitable for use as a description of the VAR dynamics.

This method is based on connecting the variance decomposition matrix to the vector autoregression of N-variables. The index value is calculated as the share of forecast errors from the diagonal components of the variance-covariance matrix of the sum of all matrix components. The Diebold-Yilmaz Connectedness Index (DYCI), created by Diebold and Yilmaz (2012), was developed using the generalized VAR approach, defined by Pesaran and Shin (1998), as its foundations where the variance decompositions are independent of the order of variables. This approach allows us to define the proportion of the variance that is part of the H-step forecast errors x_i, the proportion against shocks x_j, and the proportion of the variances between variables is defined as connectedness. Connectedness is understood as the parts of the H-stepped forecast errors contained in the forecast x_i against shocks in the x_j variable ($i,j=1,2,\ldots,N$, while $i \neq j$). The contribution of the j component to the forecast of the error in the i; component j is defined as follows:

$$\theta_{ij}^{g}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} \left(e_i' A_h \Sigma e_j\right)^2}{\sum_{h=0}^{H-1} \left(e_i' A_h \Sigma A_h' e_i\right)} \tag{1}$$

where A_h represents the forecast moving average coefficient at time t. The sum of the components of the decomposed variances of each row is not necessarily equal to 1, $\sum_{j=1}^{N} \theta_{ij}^{g}(H) \neq 1$. σ_{jj} is the standard deviation of the error component and e_j and e_i are the selection vectors (Baruník et al., 2017). Diebold and Yilmaz (2012) normalized each entry with the sum of the rows as the shocks are not strictly orthogonal. Then the authors defined the total connectedness index as the contribution of shocks to the set of variables of the total forecast error variance:

$$S^H = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} S_{i \leftarrow j}^H}{\sum_{i,j=1}^{N} S_{i \leftarrow j}^H} = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} S_{i \leftarrow j}^H}{N} \quad (2)$$

where $\sum_{j=1}^{N} S_{i \leftarrow j}^H = 1$ and $\sum_{i,j=1}^{N} S_{i \leftarrow j}^H = N$. Volatility spillover and contributions from the shocks of variables are normalized using the total forecast error variance decompositions. The connectedness dynamic is captured through a 100-day rolling window from time *t-99* to day *t*. We set the forecast horizon to *H=10* and the VAR lag length to 2 so that our results are directly comparable with those of Bubák et al. (2011); the values also correspond to those used in Baruník et al. (2017).[1]

Diebold and Yilmaz (2012) then defined directional indices to express how the shocks are transmitted to the assets. Using generalized variance decomposition, we can observe the volatility transmission mechanism FROM other assets to a single asset: $S_{i \leftarrow j}^H = \frac{\theta_{i,j}^g(H)}{\sum_{j=1}^{N} \theta_{i,j}^g(H)}$, where we sum all the numbers in rows *j*, with the exception of the numbers that correspond to the impact of the values of the asset itself. The spillover index is defined in a similar way, it measures the spillover TO other assets where $S_{i \to j}^H$ expresses the volatility transmitted by shocks to asset *i* to other assets *j*. As a supplement to these calculations Diebold and Yilmaz (2012) further defined the directional spillover index as the difference between shocks received and shocks transmitted $S_{N,i}^H = S_{i \to j}^H - S_{i \leftarrow j}^H$.

3.2. Asymmetry measurement

We replace the actual volatilities in a VAR model with negative and positive daily semivariances ($RS_t^+ = \sum_{i=1}^{p} \phi_i RS_{t-i}^+ + u_t$; $RS_t^- = \sum_{i=1}^{p} \phi_i RS_{t-i}^- + u_t$). The forecast error variance decomposition matrix is then calculated the same way as shown in Equation 1. Baruník et al. (2017, p. 44) defined the asymmetry of the currencies as the "difference between the directional volatility spillover coming from a positive or negative semivariance", which defines their Spillover Asymmetry Measure (SAM). Employing the asymmetry-measurement method,

[1] We have experimented with the forecast horizons with values of 8, 10, and 12 and VAR lag length ranging from 1 to 3. Results based on the different horizons and lag lengths are not materially different from our benchmark results and do not affect our findings.

the formula for directional spillover from one currency to a set of others is defined as follows (Baruník et al., 2017):

$$S^{H}_{2Ni\to j} = 100 \times \frac{1}{2N} \sum_{\substack{i=1, i\neq j \\ |i-j|\neq N/2}}^{2N} \theta^{g}_{ij}(H) \quad i,j = 1, \ldots, 2N \tag{3}$$

After having calculated the directional spillover index, we can calculate the net asymmetric directional index as the difference between the net spillover transmission from good/bad volatility. Following the approach of Baruník et al. (2017, p. 44), we subtract the impact of “the ($N+i$)-th column of the spillover matrix from the effect of the i-th column":

$$SAM^{H}_{2N,i\to \boldsymbol{j}} = S^{H}_{2N,i\to j} - S^{H}_{2N,(i+N)\to j} \quad i, \ldots, N. \tag{4}$$

Following Baruník et al. (2017), we use the 200-day rolling window from day *t-199* to time *t*. Then, we set the forecast horizon $H=10$ and the VAR lag length to 2. While the calculation from Equation 3, $SAM^{H}_{2N,i\to \boldsymbol{j}}$, gives us information about the connectedness of one currency, Baruník et al. (2017) defined an equation for the calculation of a whole group of currencies. The index SAM^{H}_{2N} represents the differences between the connectedness due to positive and negative shocks for all the selected currencies, defined as $SAM^{H}_{2N} = \sum_{i=1}^{N} S^{H}_{2N,i\to j} - \sum_{i=N+1}^{2N} S^{H}_{2N,i\to j}$. Similar to the measurement of directional asymmetry in Equation 4, SAM^{H}_{2N} gives us information about the asymmetry of shocks from good/bad volatility. If the value of the measure is positive (negative), then the spillover effect from positive (negative) volatility to all assets was stronger than the negative (positive).

3.3. Statistical measurement of connectedness indices

The total connectedness index S^H can be used to provide information about the strength of the links between pairs. However, the value of this index does not give any information about the statistical significance of individual spikes concerning specific events that could be associated with them. We assess the statistical link between the connectedness spikes and underlying events using the bootstrap-based method developed by Greenwood-Nimmo et al. (2023). Bootstrapping is performed twice; the first step generates bias-corrected bootstrap estimates. Greenwood-Nimmo et al. (2023) summarized the method performed on an orthogonalized connectedness index (dependent on variable ordering) as the following steps that need to be performed: (i) to estimate and save the residuals $\hat{u}_t$, (orthogonalized) connectedness index values S^{Ho}, and parameter estimates $\hat{A}_j$; (ii) to retrieve the B, bootstrap samples, from x_t:

$$x^{(b)}_{t} = \sum_{j=1}^{p} \hat{A}_j x^{(b)}_{t-j} + u^{(b)}_{t} \tag{5}$$

where the initial values of p are given and $u_t^{(b)}$ are calculated from the VAR residuals. (iii) when the bootstrap samples of B are estimated, it is used to make a new estimate of the VAR model B times to obtain new estimates for the residuals, connectedness index, and parameters. (iv) it is used to estimate the bias between the bootstrap measurements obtained according to the formula: $\hat{\Upsilon}_o = B^{-1} \sum_{b=1}^{B} S_{Ho}^{(b)} - S_{Ho}$. (v) steps from (ii) to (iv) are repeated to obtain new B estimates through bootstrapping; each time the bias $\hat{\Upsilon}_o$ is subtracted. (vi) all steps (i)-(v) are repeated to provide statistical information for all observations of the rolling sample.

For our analysis, we performed the above procedure. We calculated the probability to assess whether a specific event (day) is associated with a specific value (spikes) of the connectedness measurement to a statistically significant level. The calculation based on the generalized connectedness index provides an averaged index value over the selected period before and after the target event to observe the reaction during that specific period, before and after the shock. For the probability analysis, we used a lag value of 2, a 10-step ahead forecast, and a window of 200, as used by Greenwood-Nimmo et al. (2023).

4. Connectedness results

Table A3 shows the calculated contribution of one currency to the variance of another. The explanatory power of the shock to one of the pairs to the increased volatility of one of the pairs can be interpreted using this methodology. Table A3 shows the calculated contribution of the currencies to the volatility of the other currencies during the period analyzed. The "From others" column shows the percentage of volatility received from other currency pairs. The "To Others" row shows the percentage of the volatility of the selected currency pair transmitted to other currency pairs. The "Net spillover" row shows the net percentage of volatility that was received or transmitted by a currency pair.

As we can see in Table A3, the currencies obtain 60-80 % of volatility from their past values and 0-23 % from the volatilities of other currencies. Further, this statistical analysis shows that the exchange rate of the US dollar only transmits or receives a small amount of volatility from the Central European currencies. The following figures identify the events during which the highest volatility was transmitted. It is essential to recognize that the USD/EUR transmits very little volatility (Table A3) to the Central European currencies. This represents the volatility that the US dollar transfers (currencies quoted against the euro). A significant percentage of shared volatility exists between the Central European currencies.

Other Central European currencies are more vulnerable to shocks from other currencies. The largest carrier of volatility is the Polish zloty, the largest economy within the Visegrad Group (OECD, 2022c). However, it is also more volatile than, for instance, the Czech koruna (Figure A1). The Czech Republic has a larger economy than Hungary (OECD, 2022b). However, the Czech National Bank's (CNB) exchange rate commitment to maintaining the CZK/EUR exchange rate above 27 korunas per euro was in place from 2013 to 2017 (Kočenda & Moravcová, 2019). For this reason, over a substantial proportion of the sample period, the Czech koruna exhibits a lower degree of volatility (Figure A1).

An important finding is that the volatility connectedness between the currencies of the Czech Republic, Hungary, and Poland is substantial (Table A3). This is consistent with the findings of Bubák et al. (2011). The connectedness of the Czech koruna, Hungarian forint, and Polish zloty appears to be vital for the whole period studied. The net volatility transmission over the whole period reflects the sizes of the individual economies - the Polish zloty was the largest volatility transmitter, and the Czech koruna was a net transmitter of volatility to the Hungarian forint. This finding differs from that of Bostanci and Yilmaz (2020), who note that the Czech koruna was the only transmitter of volatility. However, since the size of the economy affected exchange rate dynamics (Karras, 2006), our results seem to be more realistic as they reflect the respective sizes of the three economies (OECD, 2022a, 2022b, 2022c). The connectedness table (Table A3) also reflects the economic links between European countries and between the Central European countries and the US (IMF, 2022).

4.1. *Volatility connectedness analysis using a dynamic rolling sample with probabilistic analysis of the events*

The dynamics of the total connectedness index between all selected currencies are presented in Figure 1. We are interested in establishing if these effects only appear when there is global/local uncertainty or if there is a stable regime so that connectedness does not change over time. Other studies have already indicated a link between increases in connectedness and stressful events (e.g., Diebold and Yilmaz, 2009; Greenwood-Nimmo et al., 2016). However, the contribution of this work is that we are the first for the currency markets to uncover the extent to which the increase was associated with a specific event. As shown in Figure 1, in the absence of any significant shock to the market, connectedness ranges from 10% to 40%. Periods when there are economic policy shocks also tend to have higher volatility connectedness between the currencies under consideration. This is consistent with the finding that market uncertainty and economic-policy shocks increase currency volatility (Beckmann & Czudaj, 2017; Bartsch, 2019; Liming et al., 2020). Rebalancing portfolios is one of the factors that increases volatility when investors attempt to minimize foreign exchange risk (Camanho et al., 2022). Portfolio rebalancing commences with selling assets denominated in foreign currencies, especially emerging markets' currencies (Bubák et al., 2011).

We have chosen eight global and six local events that recently influenced European or world economic and financial developments as the subject of probability analysis. By employing the bootstrap-after-bootstrap technique developed by Greenwood et al. (2021), we are able to assign a probability of whether an increased connectedness is statistically related to a specific event. First, with the technique of Greenwood et al. (2021), we endogenously selected dates at which connectedness increased with a probability of 90% and more. Then, we identified the events that occurred on the selected dates and analyzed how persistent the increase in connectedness was for up to 22 days after the event day. Second, we expanded our sample of shocks by exogenously including important country-specific events to observe how their impact on connectedness differs from global shocks.

4.1.1. Global economic and political shocks

The first date (July 26, 2012) for the global shock marks the day that the former governor of the European Central Bank (ECB), Mario Draghi, declared a willingness to do "whatever it takes" to save the euro during the EU sovereign debt crisis (Fiordelisi & Ricci, 2016). This event has since become the subject of research that has demonstrated the solid impact of the statement on markets "along many dimensions" (Alcaraz et al., 2018, p. 1). This was the peak of the EU debt crisis, confirmed by Figure 1. Further, it can be linked to increased connectedness between the CE currencies and the US dollar with a probability of 90% or more, with an impact lasting for five to ten days and up to one business month (Table 1).

Another major economic-political event that impacted multiple asset classes was the Russian annexation of Crimea (Costola & Lorusso, 2022). For this event, we chose the date (December 18, 2014) the EU imposed and strengthened sanctions on investment, services, and trade with Crimea and Sevastopol. Regarding the results for volatility connectedness, this event increased connectedness for the following business month (Table 1).

Then, in 2016, the result of the BREXIT referendum (June 23, 2016) came as a shock to the markets and impacted multiple sectors and industries (Kierzenkowski et al., 2016). However, to the best of our knowledge, no study has provided an estimate of its significance, to what extent, and for how long the referendum's result affected forex connectedness. Table 1 provides empirical evidence that connectedness increased one, five, ten, and twenty-two days after the referendum. When quoted against the euro (observing the influence of the US dollar), the probability of an increase in connectedness was above 90%, even on the event day.

Another shock was the most significant daily point decline in the S&P500 index and its largest percentage decline since 2009. This decline can be attributed to the (at that time) expected economic slowdown in 2018 and the forecast interest rate hikes by the Fed (United Nations, 2017). However, since the event was more related to the US economy, it has greater significance for the CE currencies and the US dollar. Although the chart (Figure 1) shows only a tiny spike, Table 1 confirms that it affected the connectedness of currencies five to twenty-two days ahead. Also, this finding further underscores the importance of this novel probabilistic analysis, as other studies have addressed the implications of the findings based only on the spikes on the graph. This is particularly important because connectedness then influences multiple variables, as explained in the Literature review.

The US sanctions on Turkish exports have lasted for several years. However, on August 10, 2018, President Trump declared that relations with Turkey "are not good" and that he would double the current import tariffs on Turkish commodities. This step substantially impacted Turkey since, for example, 13% of its steel was exported to the United States (International Trade Administration, 2019). That same month, a sell-off in other emerging currencies was also associated with these particular sanctions (Reid, 2018). In the context of this event, the connectedness significantly increased between ten days and up to a business month after the event (Table 1).

Another market shock was the trade war between the US and China (Figure 1). On March 12, 2019, the media reported that trade negotiations between the US and China were at a "critical stage" (Garver, 2019). This event significantly increased volatility connectedness, but only for ten days and up to one month after the announcement (Table 1). Then, on January 30, 2020, the World Health Organization (WHO) publicly declared the outbreak of the COVID-19 virus. We can see a statistically significant association of volatility with the announcement date and the next business month (Table 1). The currency dynamics presented earlier (Figure A1), and the figure that illustrates connectedness (Figure 1), suggest that during 2020 the transmitted volatility was very high. Later on, when the WHO declared the covid infection was a pandemic (March 11, 2020), the virus had already spread across many countries, and the markets had already priced in the earlier declaration of an outbreak by the WHO (January 30, 2020). Uncertainty prevailed within the markets because of the lack of experience with such events, and the markets could not price in the expectation of future lockdowns. This market uncertainty affected all emerging currencies (ECB, 2020). Our last event is the day that Russia invaded Ukraine (February 24, 2022). The dynamic evidence presented in Figure 1 indicates the increased risk propagation. Then, the results in Table 1 demonstrate a significant increase in the connectedness of currencies quoted against the euro for five, ten, and twenty-two business days after the event. Connectedness within this currency group increased from 10% to 60% (Figure 1).

These early results highlight the very first finding – connectedness increased within a month for eight out of the eight events. Such a result confirms our hypothesis that connectedness increases precisely in the context of risk aversion-induced portfolio rebalancing. Further, the finding that there is a lag of 22 business days offers an opportunity for portfolio hedging after the events occur. This is important because the identification of lag in the context of connectedness has yet to be identified for currency markets.

4.1.2. Country-specific events

The first country-specific stressful event was a downgrade of Hungary's rating by Fitch to "junk" status (January 6, 2012). This event was exogenously chosen to analyze domestic shocks as well (Szakacs & Dunai, 2012). During this one, Hungary asked the IMF for help with a credit lifeline, and later on January 10, 2013, these negotiations failed (Than and Peto, 2013). We added both shocks; however, none of them had an impact on the connectedness (Table 1). This follows the results of Figure 2, where the Hungarian forint obtains volatility but does not transmit. Further, it confirms the theoretical assumption that global shocks drive connectedness as investors rebalance their portfolios (Camanho et al., 2022).

Then, the beginning (November 7, 2013) and end (April 6, 2017) of the exchange rate commitment by the CNB represents a regime change for one of the three CE currencies. This expands on the findings shown in Table A3, which indicates that the CZK/EUR is, to a minor extent, a receiver of volatility. The rolling sample (Figure 1) proves that the effects were more substantial before 2013 and much greater after 2017. From 2017 onwards, connectedness increased over most of the period of study. On the other hand, the rolling sample provides evidence of an increase in connectedness in November 2013 as the Czech National Bank announced the exchange rate commitment (Figure 1), but it was only a short-term spike. Even though we can see an increase in the connectedness value, this spike is not significantly connected to the selected domestic event (Table 1). Thus, it did not significantly impact the volatility connectedness of the set of currencies. This finding is reasonable since the exchange rate commitment reduced currency volatility (Figure A1) and only affected one of the three currencies. However, the end of the exchange rate commitment affected the connectedness of selected currencies for the following business month (Table 1). From 2017 onwards, connectedness increased over most of the study period. This makes sense as the volatility of the Czech koruna increased by 80% (Figure A1). Table 1 further confirms that the end of the CNB's exchange rate commitment increased connectedness one business month ahead. As Figure 1 indicates, the shared volatility between the Central European currencies increased rapidly in 2018 as the CZK/EUR continued to float after the end of the exchange rate commitment.

On June 16, 2014, the Polish zloty was affected by the NBP stability issue linked to its governor due to released recordings undermining the credibility of NBP. As a result, there was pressure on the governor to resign from his position, which was linked to the depreciation of the Polish zloty at that time (Rybacki, 2019). Although Figure 1 indicates an increase in connectedness associated with this scandal, Table 1 does not confirm its impact.

The next event, the exchange rate commitment by the Swiss National Bank (January 15, 2015), might be considered a global shock. We interpret it as a country-specific shock as it was closely tied to Poland and Hungary. This event is one of two that impacted every one of the dates ahead, as shown in Table 1. This is because Poland and Hungary had indexed a substantial part of their loans to the Swiss franc, which hit market expectations hard when the Swiss National Bank (SNB) removed the franc exchange rate cap (Białowolski & Węziak-Białowolska, 2017).

The results of this chapter imply a connectedness between the currencies that ranged from 10 % to 60 % (Figure 1). Connectedness increased primarily due to economic or political shocks coming from global events, not local ones, which is confirmed by the probability analysis results. Connectedness between the CE currencies and the US dollar significantly increased in eight of our test cases using the selected shocks for one business month after the event occurred (Table 1). Further, it is crucial to notice that the only four events not significantly affecting connectedness were exogenously chosen country-specific shocks. These findings confirm our hypothesis that connectedness increases mainly in the context of global economic turbulence. This indicates that the investors rebalance their portfolios and move away from emerging markets to avoid the risk of uncertain market conditions (Tran, 2019). The commented results highlight the importance of examining the association between a given shock and an increase in the index. Past studies have commented on index increases and linked them to events during a given period. Again, index increases could be attributed to events

(Figure 1), but probabilistic analysis confirmed these associations only for global shocks. The analysis in the following subsections provides more detail.

4.2. Analysis of net volatility spillovers

Looking at Figure A2, the CZK/EUR rate is a net transmitter of volatility towards Central European currencies, albeit only to a minor extent and particularly after the end of the exchange rate commitment. This is in line with the findings of previous studies (Bostanci & Yilmaz, 2020; Bubák et al., 2011) and further expands on them, as they did not look beyond 2017. A comparison of the net volatility spillovers between the Czech koruna and the US dollar shows that they appear to be more sensitive to economic distress, as the most significant rises in net transmitted volatility took place at the beginning of the exchange rate commitment (10 %) and the Russian annexation of Crimea followed by the end of Swiss franc cap by SNB (almost 20 %) as the rapid appreciation of Swiss franc affected Polish and Hungarish mortgages indexed in this currency (Białowolski & Węziak-Białowolska, 2017). Further, we can see (Figure A2) increases after the CNB unwound the exchange rate commitment (40%) and during the COVID-19 crisis (30%). In connection with the same events above, the Czech koruna versus the US dollar (quoted against the euro) is also a net volatility transmitter (Figure A2), but to a lesser extent (a maximum transmitted volatility of 20 %).

The Hungarian forint is considered by Bostanci and Yilmaz (2020) to be a volatility receiver, but their study was conducted considering the HUF/USD exchange rate. However, apart from the COVID-19 pandemic, the HUF/EUR seems fairly neutral regarding volatility connectedness (Figure A2). The volatility received by the Hungarian forint mainly came from the Czech and Polish currencies. In Figure 2, we show the net spillover in more detail. The volatility received is highest during periods of economic or political shocks, specifically the EU debt crisis (2010-2012), the beginning of the CNB exchange rate commitment (2013), and the annexation of Crimea in 2015 (Figure A2).

Further spikes are visible in connection with the US sanctions on Turkey (2018), the COVID-19 pandemic (2020), and the Russian invasion of Ukraine (2022). This could be linked to outflows to the US dollar, as the shocks are generally associated with European countries. These results are partially confirmed by Table 2, where we estimate the impact of uncertainty, liquidity, and economic performance on volatility connectedness.

Figure A2 shows that the Polish zloty received volatility from other currencies, mainly in 2016, in connection with the BREXIT referendum. If we exclude this period, the Polish zloty is a net volatility transmitter to other CE currencies (Figure A2). Peaks in transmitted volatility can be seen in response to the events surrounding the EU debt crisis and then the Russian annexation of Crimea (up to 10 %). Subsequently, it peaked during the COVID-19 pandemic and when Russia invaded Ukraine (15%). Thus, our results confirm and expand on the previous findings that the Polish zloty is a transmitter of volatility during economic or political shocks (Bubák et al., 2011). A closer examination of the direct link between the Czech and Hungarian currencies (Figure 2) provides evidence that the Czech koruna continued to transmit volatility, even after the exchange rate commitment was cancelled in 2017. This transmission is meaningful in the context of the evidence that the size of an economy produces an impact on exchange rate dynamics (Karras, 2006): the two larger economies (the Czech Republic and Poland) transmit volatility to a smaller one (Hungary). In this context, the connectedness table (Tabel A3) reflects the economic links between European countries and then that between the Central European countries and the US (IMF, 2022). However, previous studies do not address the issue of the lag between the event and the increase of connectedness, which is very important as it affects hedging and diversification strategies (Kanas, 2000; Jotikasthira et al., 2012).

A more detailed analysis of directional spillovers indicates a greater degree of volatility propagation when the US dollar is included in the sample. The direction of these transmissions suggests that they are outflows from portfolios seeking to move into the US dollar as a global currency. Such a proposition is supported by a study by Camanho et al. (2022), who identified a link between forex volatility connectedness and investor portfolio rebalancing. Further, Kočenda and Moravcová (2019) confirmed that connectedness increases, especially during economic turbulence, which agrees with our results.

4.3. Asymmetries in total connectedness

The results from the previous subchapters have not accounted for asymmetries between currencies. In this part of the paper, we compute the actual semivariances when differentiating between bad and good volatility. The calculated semivariances are based on data with a one-minute frequency and we compute the daily variances from the volatility of that data. In Table A4, we present the dynamic connectedness intended to identify positive or negative volatility. Table A4 estimates connectedness using the semivariances of the Central European currencies and the US dollar.

The difference between positive/negative volatility is about 10 % in the context of shocks, but Table A4 is based on a static sample. In the dynamic estimates for the sample with the US dollar, we observe (Figure A3) that spillovers are more prevalent for negative volatility in a period of economic distress. These results are similar to those of Baruník et al. (2017), who identified that during economic turbulence, connectedness from negative volatility was dominant compared to that from positive volatility. The authors observed this phenomenon between the seven most traded currencies, and we can further confirm these findings for the Central European currencies. When connectedness is dominated by positive volatility, the CE currencies appreciate against the euro (Figure A3). This is in line with the findings of Menkhoff (2013) and Fratzcher et al. (2019), who argue that emerging currencies are more vulnerable during economic turbulence. Camanho et al. (2022) explain that the vulnerability of emerging currencies in response to a crisis is caused by portfolio rebalancing. Further, Tran (2019) empirically confirmed that during periods of market uncertainty, there is an increase in risk aversion.

The pattern of asymmetries correlates with economic or political shocks (Table A5). We can see prevailing positive connectedness asymmetries in 2011 and 2012 when the EU debt crisis peaked. Then we can observe those effects linked to the annexation of Crimea (December 18, 2014), followed by the lifting of the exchange rate cap by the SNB (January 15, 2015), the BREXIT referendum (June 23, 2016), and then on April 6, 2017, when the Czech National Bank ended its exchange rate commitment (Figure A3). Following this event, the volatility of the CZK/EUR pair increased by 80 % (Figure A1). Further, in connection with the US sanctions on Turkish exports, asymmetries increased by 6 %. Then, the connectedness from negative volatility prevailed over positive volatility by 6% with the outbreak of COVID-19, recording its all-time low value. Finally, the asymmetric volatility connectedness due to adverse shocks (2 %) peaked around February 2022, likely linked to the Russian invasion of Ukraine (Figure A3). We observe that for the set of the CE currencies with the US dollar, asymmetry in volatility connectedness reaches the highest values during periods of economic distress, but the pattern is more mixed.

4.4. Asymmetries in directional connectedness

In Figure A4, we further expand our results with the dynamic spillover asymmetries. Figure A4 compares the effects of positive and negative shocks for each CE currency and the US dollar. For much of the observed period, the asymmetries in volatility transmission ranged from -1 % to +1 % (Figure A4). As was also seen in Figure A3, the CE currencies individually transmit negative volatility (depreciation of CE currencies) during economic policy shocks. A 4 %

impact can be seen at the beginning of 2012 when the former governor of the ECB, Mario Draghi, announced that the ECB intended to help eurozone member countries with "whatever it takes" (Fiordelisi & Ricci, 2016). We interpret this directional asymmetry as a strong reaction to a positive shock, which led to a rise in the euro against the CE currencies as the EU debt crisis was partially tamed. The speech by the former governor acted as a positive shock to the market, and in response, the CE currencies dropped against the euro (Figure A1). The transmission of negative volatility prevailed in 2018 for the PLN/EUR and HUF/EUR pairs when there was an economic deceleration in European countries. The Czech National Bank (2021) explained that during 2018, the CZK/EUR rate did not correlate with other emerging currencies as it was trying to find equilibrium after the change of regime in 2017.

The volatility received from weakening CE currencies (negative volatility) peaked in 2020. When Covid broke out, the connectedness from negative volatility prevailed over the connectedness from positive volatility, in the case of the Czech koruna, by 5%. In 2022, harmful volatility transmission was more significant than 1% for the dataset (Figure A4). This indicates that these emerging currencies were negatively affected by the conflict in Ukraine (Figure A1). These results indicate that the CE currencies have greater exposure to adverse volatility shocks. The evidence shows that asymmetric directional spillover mainly occurs during periods of economic turbulence, and negative connectedness prevails over positive connectedness during periods of market uncertainty. In directional spillover, negative asymmetries indicate that the CE currencies are falling against the euro.

5. Drivers of connectedness and a robustness analysis

5.1. *Drivers of connectedness*

As a next step, we analyze the links between connectedness and its potential drivers. In the literature, three key factors are considered from both theoretical and empirical perspective as potentially affecting connectedness on the forex market: uncertainty and liquidity as market-specific factors (Baruník et al., 2017; Baruník & Kočenda, 2019), and economic activity representing broader economic conditions (Baruník & Kočenda, 2019; Uluceviz & Yilmaz, 2020; Davis et al., 2022).

First, uncertainty plays a crucial role in shaping investor behavior (Bloom, 2009). High uncertainty can lead to increased risk aversion, which prompts investors to adjust their portfolios and trading strategies (Albrecht et al., 2022). This, in turn, affects the correlations and interactions between currencies in the forex market (Camanho et al., 2022). Second, liquidity is a fundamental characteristic of financial markets. In the forex market, where currencies are traded continuously, liquidity can vary significantly across different time periods (Baruník et al., 2017). Changes in liquidity levels can impact the ease with which traders can execute orders, influencing the speed and intensity of price movements (Uluceviz & Yilmaz, 2020). Third, economic activity provides the underlying foundation for currency movements (Peksen & Son, 2015). Changes in economic conditions, such as GDP growth, inflation, and employment, can signal shifts in monetary policy, trade balances, and overall market sentiment (Peksen & Son, 2015; Khan et al., 2019). These factors directly influence forex market dynamics. However, all three factors also impact forex market dynamics in terms of combined effects. Various types of shocks increase uncertainty about future outcomes of the economy (Boyle & Peterson, 1995). As a result, investors try to sell assets denominated in foreign currencies and by doing so they decrease market liquidity (Baruník et al., 2017; Baruník & Kočenda, 2019). Further, due to shocks investors are more risk averse, which decreases economic activity (Tran, 2019; Davis et al., 2022). For Central European currencies the impact of shocks should be further multiplied due to generally lower liquidity on emerging currencies markets and higher exposure of these economies to uncertainty (Menkhoff, 2013; Fratscher et al., 2019).

By considering the three drivers, our analysis takes into account both market-specific factors (uncertainty and liquidity) and broader economic conditions (economic activity), providing a comprehensive framework for understanding the dynamics of connectedness in the forex market. In Table 2, we show that volatility connectedness is driven by uncertainty, liquidity, and economic activity but that their impacts differ. Our results further corroborate earlier findings that volatility connectedness increases due to economic or political shocks.

Uncertainty is proxied with the expected future volatility of options (the VSTOXX index for the EU market) and exhibits a positive effect on connectedness values (Table 2). This suggests that the results are robust; we argue that connectedness increases as a consequence of economic or political shocks. If there is a shock to the economy, uncertainty increases, and entities start to rebalance the portfolios they hold in foreign currencies due to increased risk aversion (Camanho et al., 2022). Such rebalancing subsequently increases the volatility in currency markets, and shocks are transmitted across countries (Balcilar et al., 2023).

The liquidity is first proxied by the Treasury-EuroDollar (TED) rate. An impact of the EU_TED rate shows how liquidity affects connectedness between CE currencies and that it depends on the US dollar. The association of a negative coefficient with the EU_TED rate suggests that the effects of liquidity shocks on connectedness cause the connectedness between

CE currencies and the US dollar to increase when the rate of funding liquidity falls. This may stem from the character of connectedness - the characteristic of the connectedness of the group of CE currencies with the US dollar exhibits many peaks, and it hits extreme levels when a shock occurs (Figure 1). While the EU_TED spread is a reliable indicator of liquidity in the market (Baruník & Kočenda, 2019), its value is derived from bond yields. Therefore, in the second model, we use bid-ask spreads of the CE currencies, which also reliably measure market liquidity (Karnaukh et al., 2015) and are derived from currency markets. In any case, each of the three bid-ask spread estimates among the CE currencies significantly impacted the connectedness between these currencies in this study (see Table 2). Finally, no matter how the liquidity is measured, its impact is larger than that of uncertainty. In terms of market-specific factors, liquidity seems to dominate uncertainty as a connectedness driver.

Following the approach of Davis (2022), we explore broader economic conditions and quantify the economic activity with a proxy of the aggregate equity index; in our case, it is the EURO STOXX 50. In Table 2, we show the impact of economic activity on a static sample covering twelve years. For both groups of currencies, we show that the interconnectedness of currencies intuitively increases as economic activity increases. The finding resonates well with the idea that all drivers impact connectedness jointly as other studies have confirmed the link between uncertainty and equity indices (Albrecht et al., 2022; Tiwari et al., 2019) or the link between connectedness and portfolio rebalancing that occurs due to changing liquidity (Camanho et al., 2022). Finally, the impact of economic activity on CE forex connectedness seems to be more important than that of market-specific factors.

5.2. Robustness analysis

In the next step, we performed a robustness check of our earlier probability analysis, presented in Section 4.5. Instead of using daily volatilities, we now averaged the volatilities over five days to capture a slightly longer perspective. In Table A6, we present (robustness) results based on a five-day volatility average to test if a given shock affects future connectedness and the probability it will have an effect. The dataset (Table A6) exhibits very similar results compared to earlier ones (Table 1). For seven of eight global events, there is a probability of 90% (or higher) that connectedness will increase within one business month. Estimates of the probability of an increase in connectedness differ after the speech made by the governor of the ECB, Mario Draghi. The result was that the connectedness increased in all models for five or more days in the initial results (Table 1). The robustness check (Table A6) gave slightly different results, with a lower likelihood than the orthogonal models. The imposition of US sanctions on Turkish exports is assessed with a greater likelihood (at 90 %) of higher connectedness after ten or more days, which aligns with our initial results (Table 1). Following the results of the robustness check (Table A6), the likelihood of an increase in connectedness is 78% to 88%.

We obtained very similar results for country-specific shocks where the probability of the association between a given shock and an increase of connectedness was above 90 %, only for two events out of six. Further, one of these two events with a significant impact is the end of the exchange rate commitment by the SNB, which had both – local and global influence. However, we considered it a local shock due to its impact on loans in Hungary and Poland. The robustness of the results is essential in the context of the finding that international diversification is more effective than cross-industry diversification within a country (Attig et al., 2023).

6. Conclusions

We provide a comprehensive assessment of the volatility connectedness among currencies of the Central European countries over two decades from 2009 to 2022. In our analysis, we are the first to identify the asymmetric volatility propagation for this group of currencies, which has previously only been investigated for global currencies (Baruník et al., 2017). Specifically, using high-frequency intraday data, we show that connectedness from bad volatility is stronger than from good volatility, especially during economic turbulence.

Further, we provide the first quantification of the statistical probability that increasing volatility connectedness is associated with a specific economic or political shock on a forex market. Previous approaches have identified the dynamics of volatility connectedness in financial markets (e.g., Diebold and Yilmaz, 2012; Greenwood-Nimmo et al., 2016) but have not estimated the significance of the extent to which index spikes were related to economic or political shocks. With a probability of 90% or higher, we found that for eight out of eight of the endogenously selected global events and two out of six of the exogenously selected local events, connectedness increased within the business month after the event occurred. This indicates that connectedness among emerging currencies increases in the context of global shocks, not local ones. Further, the likelihood of an increase in connectedness on the same day as the event occurred was only more significant than 90 % in only two cases out of the fourteen. This suggests that there is a lag in the response of the DYCI index to stressful events, which may offer an opportunity to hedge foreign exchange risk.

A distinct policy implication emerges when we combine (i) the finding that the Czech koruna and Polish zloty transmit volatility to the Hungarian forint with (ii) the finding that volatility connectedness often increases for up to a business month after a global economic or political shock. Based on the above, the implication for portfolio management is that investors have a twenty-two business day window to hedge a portfolio denominated in the Hungarian forint after the occurrence of a global economic or political shock.

Since volatility connectedness and spillover asymmetries on forex markets impact portfolio returns, our contributions are highly relevant to using CE currencies as valuable components in the diversification of hedged portfolios. In future research, we intend to use our approach to assess the importance of connectedness in the context of quantitatively identified specific events on global currencies.

List of Abbreviations:			
BIS	Bank for International Settlements	HUF	Hungarian forint
CE currencies	Central European currencies	IMF	International Monetary Fund
CNB	Czech National Bank	OECD	Organisation for Economic Co-operation and Development
CZK	Czech koruna	PLN	Polish zloty
DYCI Index	Diebold-Yilmaz Connectedness	SAM	Spillover Asymmetry Measure
EU	European Union	SNB	Swiss National Bank
EUR	Euro	TED	Treasury-EuroDollar rate
ECB	European Central Bank	USD	US dollar
FDI	Foreign direct investment	VAR	Vector autoregression
GFC	Global financial crisis	WHO	World Health Organization

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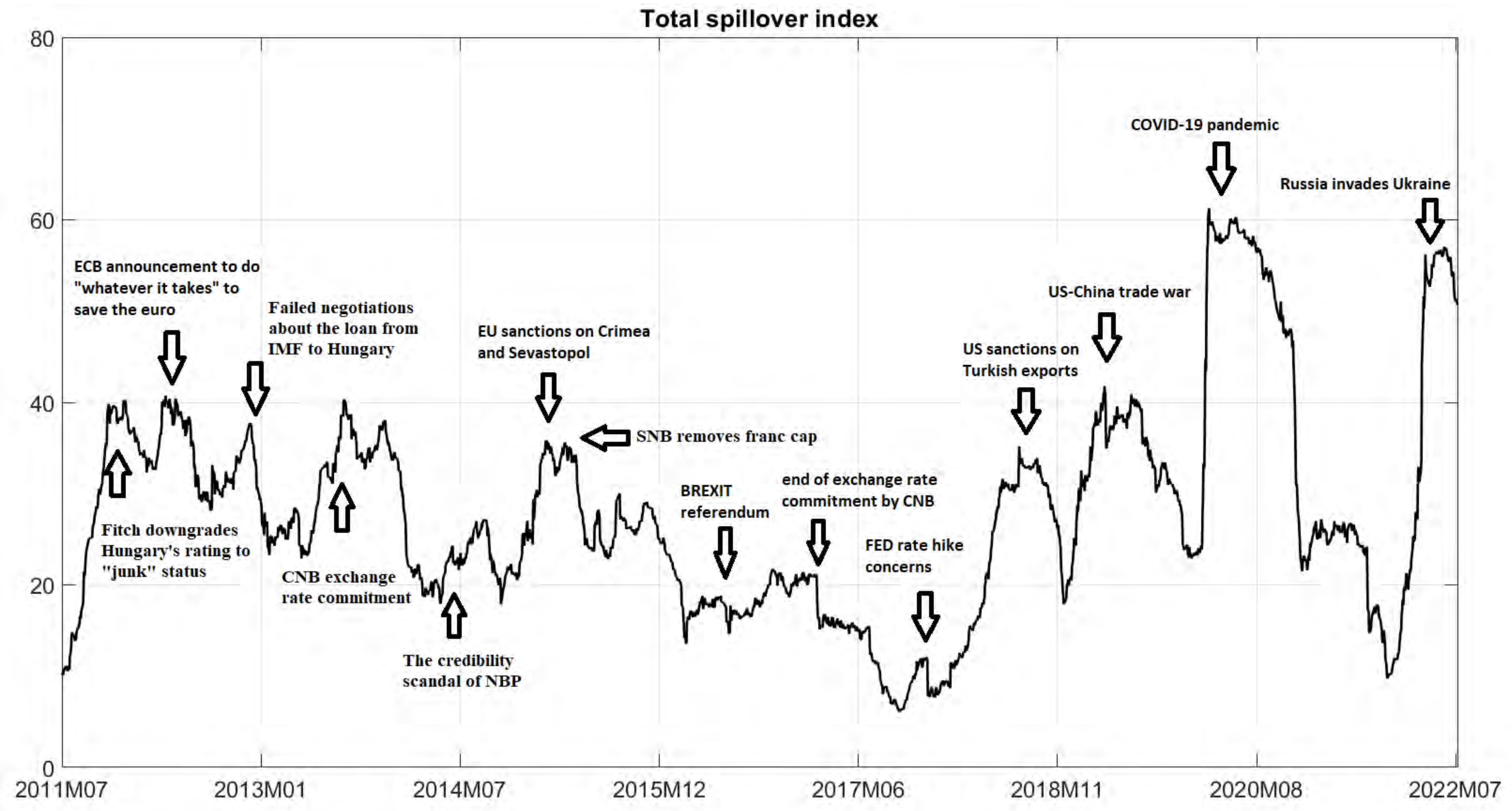
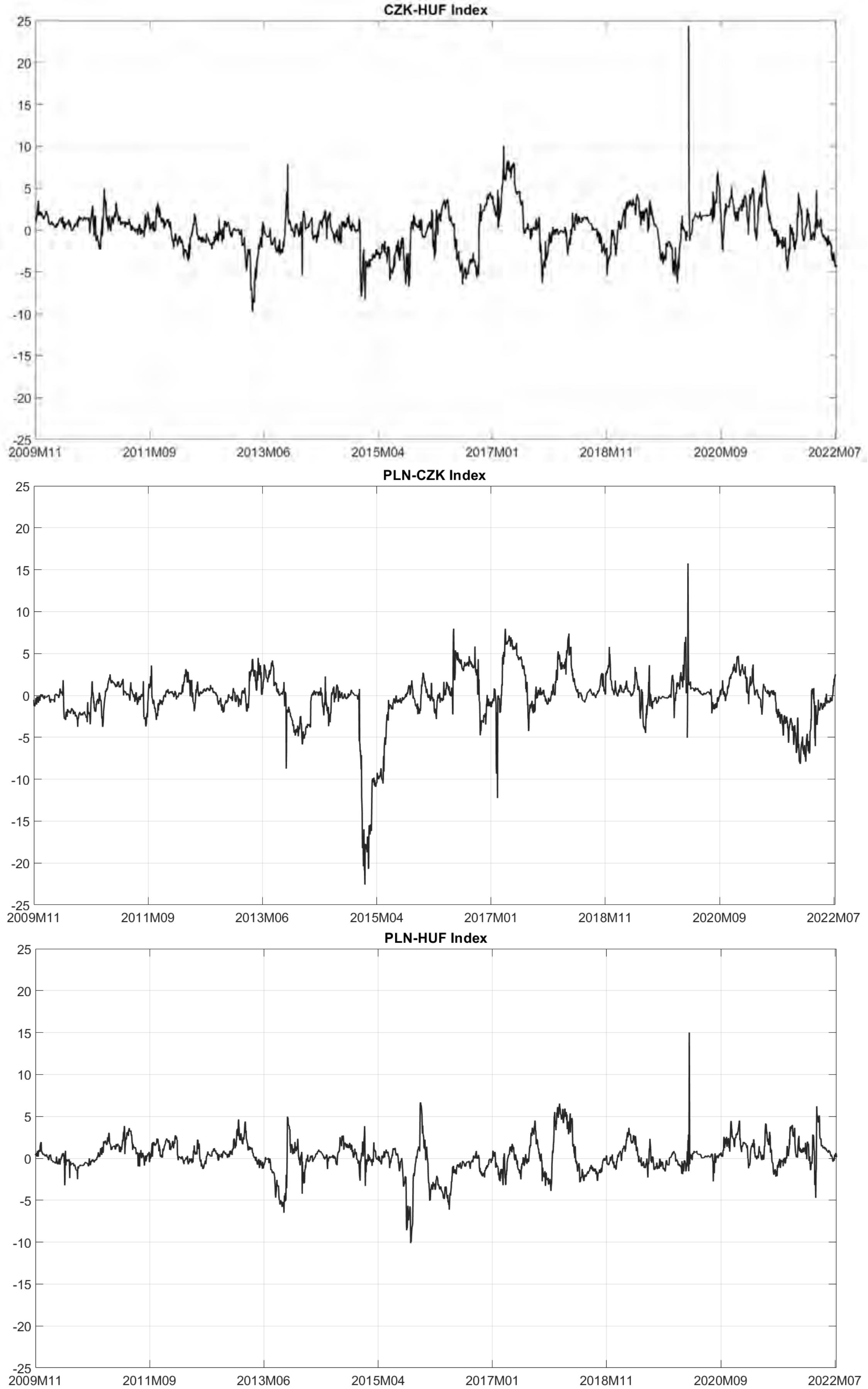
Figure 1: The total volatility connectedness measured between Central European currencies and the US dollar



Note: the y-axis could be interpreted as the percentage of shared volatility between the sample set of currencies. The results of this table are for the currency pairs CZK/EUR, HUF/EUR, PLN/EUR, and USD/EUR

Figure 2: Net volatility spillover between two currencies

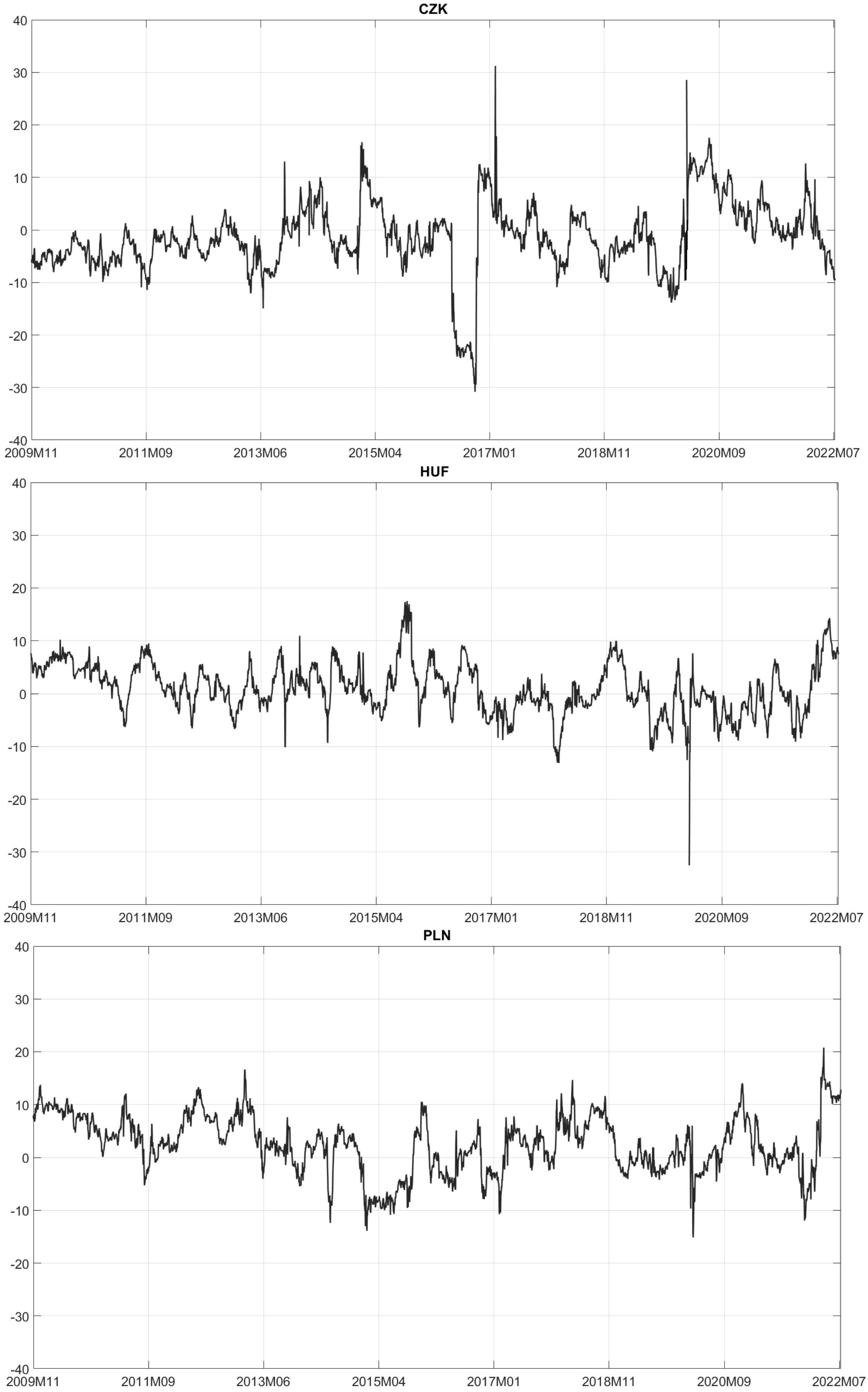


Note: The calculated indices represent the share of volatility transmitted to other currencies in comparison to the received volatility.

Appendix

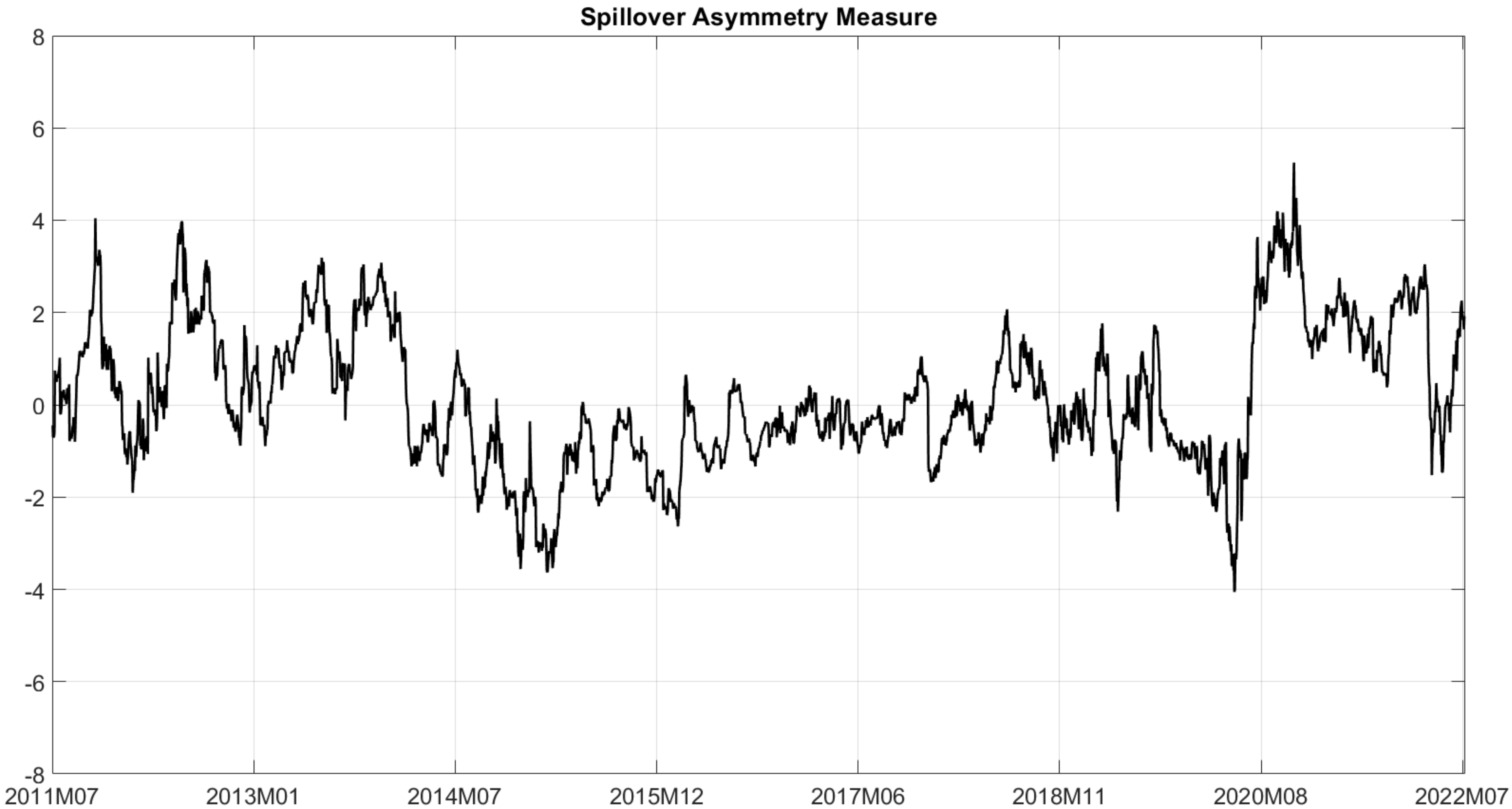
Figure A1: Dynamics of Central European currencies quoted in EURs

Figure A2: Net volatility spillover (with the US dollar)



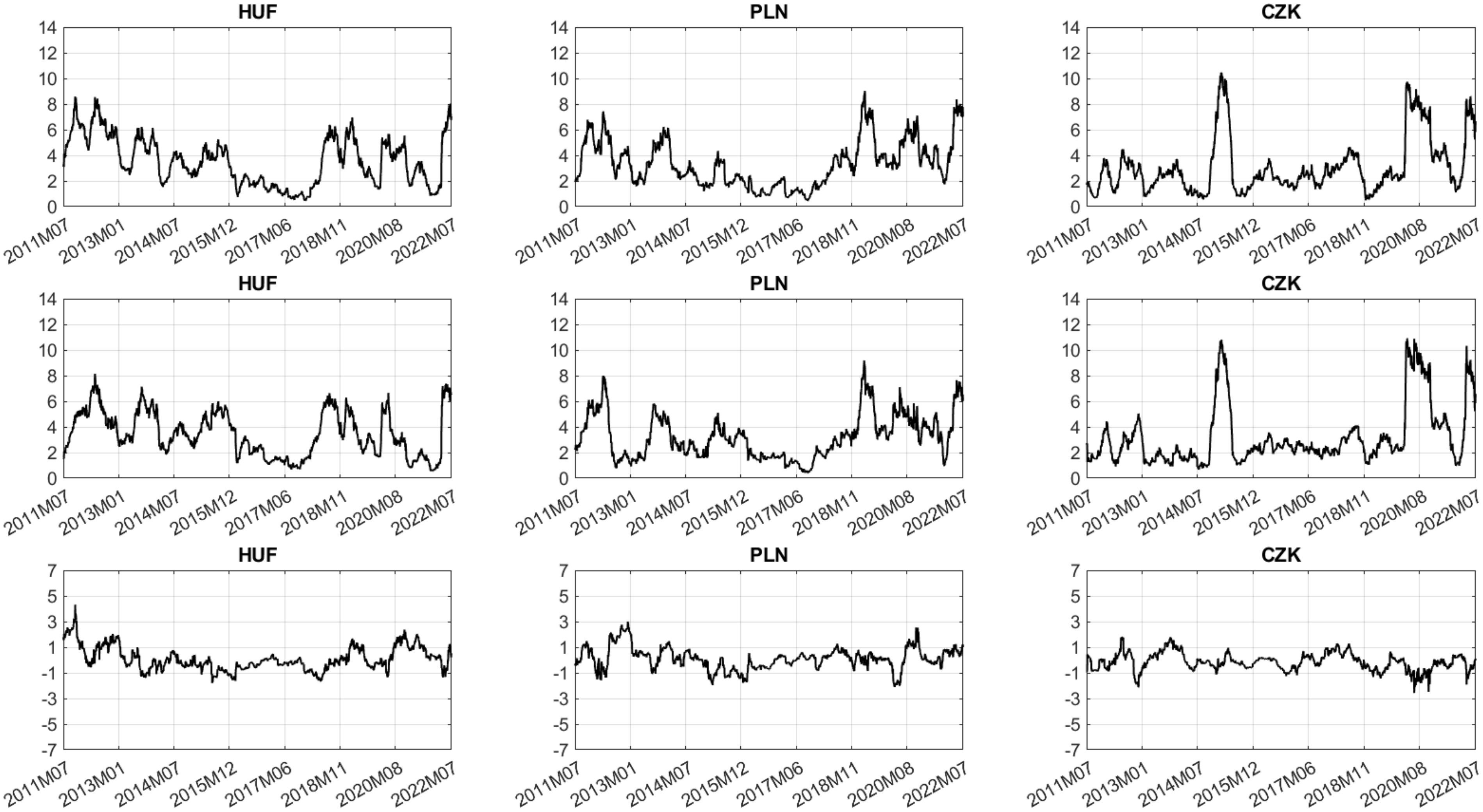
Note: The calculated indices represent the share of volatility transmitted to other currencies in comparison to the received volatility. These results are for the currency pairs CZK/EUR, HUF/EUR, PLN/EUR, and USD/EUR.

Figure A3: The spillover asymmetry measure: Central European currencies and the US dollar



Note: The spillover asymmetry measure compares the total spillover from good volatility with the total spillover from bad volatility between four currencies. These results are for the currency pairs CZK/EUR, HUF/EUR, PLN/EUR, and USD/EUR.

Figure A4: Directional spillover from good/bad volatility and measured asymmetry



Note: The top panel represents direct spillover comparing the TO and FROM directions of good volatility; the middle panel represents direct spillover TO and FROM bad volatility, and the bottom panel represents direct asymmetry measurements of spillovers. These results are for the currency pairs CZK/EUR, HUF/EUR, PLN/EUR, and USD/EUR.

Table 1: Empirical Probability of an Increase in Spillover Activity after Selected Events, in Percent

Event	Description of the shock	r_e+0		r_e+1		r_e+5		r_e+10		r_e+22	
		OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD
	Global shocks										
1	Mario Draghi “whatever it takes” speech	40.0	38.7	40.7	39.2	**92.6**	**94.7**	**90.5**	**92.8**	88.7	**90.9**
2	EU Council meeting strengthening sanctions on investment, services and trade with Crimea and Sevastopol	40.0	35.5	39.0	35.7	49.9	45.1	71.6	71.7	**100.0**	**100.0**
3	BREXIT referendum	87.6	**92.0**	**100.0**	**99.9**	**99.8**	**99.8**	**100.0**	**100.0**	**100.0**	**100.0**
4	S&P 500 10% decline due to FED rate hikes concerns	45.6	46.4	50.8	51.9	**92.0**	**97.1**	88.4	**94.7**	**97.3**	**99.0**
5	US sanctions on Turkish export	72.3	74.5	**100.0**	**100.0**	**93.6**	**95.1**	86.3	89.6	85.3	**90.3**
6	US-China trade war peak	52.2	51.3	47.6	47.0	81.3	79.6	89.0	**90.6**	**96.7**	**97.6**
7	WHO declares COVID-19 outbreak	45.1	43.9	72.0	72.8	70.9	70.0	63.5	65.3	**99.8**	**99.9**
8	Russian invasion to Ukraine	49.4	50.2	48.7	49.4	48.8	50.8	**100.0**	**100.0**	**100.0**	**100.0**
	Local shocks										
1	Fitch downgrades Hungary’s rating to “junk” status	42.9	45.7	45.8	47.1	48.9	49.3	59.3	58.5	61.2	56.3
2	Failed negotiations about the loan from IMF to Hungary	44.4	46.0	42.6	44.4	46.0	52.6	41.0	39.6	1.9	1.6
3	Beginning of the exchange rate commitment by CNB	49.5	50.9	46.9	47.0	27.3	26.5	27.9	29.8	27.0	26.8
4	The credibility scandal of National Bank of Poland	45.0	49.8	49.7	55.2	46.2	53.2	54.2	55.9	2.5	8.1
5	SNB removes franc cap	**100.0**	**100.0**	**99.9**	**100.0**	**96.5**	**97.1**	**91.9**	**92.3**	**99.7**	**99.6**
6	End of the exchange rate commitment by CNB	48.1	49.7	42.5	43.5	45.2	48.9	77.9	78.8	78.7	**90.3**

Note: the table reports the empirical probability that the value of the connectedness index exceeds the mean of the connectedness index during the specified r_e+j days using bootstrap samples in a rolling sample. The results under the "OVD" and "GVD" headings denote the calculated probabilities for the connectedness indices using the orthogonalized and generalized forecast error variance decompositions. The results follow the process used by Greenwood-Nimmo et al. (2023), we performed 1000 bootstrap-after-bootstrap non-parametric replications. These results are for the currency pairs CZK/EUR, HUF/EUR, PLN/EUR, and USD/EUR.

Table 2: Connectedness indices in regression with indicators of uncertainty, liquidity, and economic performance

	(1) EU_TED as a proxy for a liquidity	(2) Bid-ask spread as a proxy for a liquidity
Constant	16.9322***	16.3128***
	(0.5956)	(0.6059)
VSTOXX	0.7736***	0.4324***
	(0.0277)	(0.0360)
EU_TED	-14.2663***	-
	(0.8083)	-
ld_EURO STOXX 50	77.0734***	53.7204***
	(15.3694)	(15.6835)
CZK/EUR bid-ask spread	-	8.5041***
	-	(0.7357)
HUF/EUR bid-ask spread	-	2.9483***
	-	(0.6711)
PLN/EUR bid-ask spread	-	-5.3200***
	-	(0.7503)
Observations	2686	2686
R^2 adj.	0.2383	0.2181

Note: *** denotes p-value < 0.01, ** p-value < 0.05, and * p-value < 0.10.

Appendix

Table A1: Descriptive Statistics

Variables	Obs.	Mean	St. Dev.	Min	Mdn	Max	Skewness	Kurtosis	ADF Test
USD/EUR	3380	1.22	0.12	1.04	1.19	1.51	0.44	-1.00	-1.58
CZK/EUR	3380	25.96	0.97	23.91	25.77	28.30	0.14	-0.95	-2.09
HUF/EUR	3380	311.66	28.63	260.97	309.74	402.38	0.52	-0.12	0.30
PLN/EUR	3380	4.26	0.18	3.82	4.25	4.96	0.26	-0.09	-2.09
USD/EUR log diff	3379	0.00	0.01	-0.03	0.00	0.03	-0.09	2.18	-17.59***
CZK/EUR log diff	3379	0.00	0.00	-0.02	0.00	0.05	1.07	18.23	-11.93***
HUF/EUR log diff	3379	0.00	0.01	-0.02	0.00	0.03	0.27	3.06	-13.96***
PLN/EUR log diff	3379	0.00	0.00	-0.03	0.00	0.03	0.12	5.09	-12.30***

Table A2: Descriptive Statistics of positive ($\sqrt{RS^{+}}$) and negative ($\sqrt{RS^{-}}$) realized semivariances

	Variables	Obs.	Mean	St. Dev.	Min	Mdn	Max	Skewness	Kurtosis	ADF Test
$\sqrt{RS^{+}}$	USD/EUR	3374	0.00	0.00	0.00	0.00	0.00	27.59	1078.6	-8.20***
	CZK/EUR	3374	0.00	0.00	0.00	0.00	0.00	12.73	279.87	-5.94***
	HUF/EUR	3374	0.00	0.00	0.00	0.00	0.00	10.23	177.80	-6.85***
	PLN/EUR	3374	0.00	0.00	0.00	0.00	0.00	14.03	304.30	-6.75***
$\sqrt{RS^{-}}$	USD/EUR	3374	0.00	0.00	0.00	0.00	0.00	19.30	493.92	-9.02***
	CZK/EUR	3374	0.00	0.00	0.00	0.00	0.00	10.80	205.78	-6.12***
	HUF/EUR	3374	0.00	0.00	0.00	0.00	0.00	7.10	99.06	-5.60***
	PLN/EUR	3374	0.00	0.00	0.00	0.00	0.00	13.39	280.93	-6.81***

Table A3: Volatility spillover table

	USD/EUR	CZK/EUR	HUF/EUR	PLN/EUR	FROM Others
USD/EUR	85.31	2.01	6.16	5.15	14.69
CZK/EUR	2.08	76.08	9.38	11.92	23.92
HUF/EUR	4.79	8.81	64.40	22.17	35.61
PLN/EUR	4.13	10.80	21.85	63.72	36.28
TO Others	11.32	21.05	38.31	39.82	27.63
NET SPILLOVER	-3.37	-2.87	2.11	3.53	

Note: The values in the table represent the percentage of volatility shared between currencies.

Table A4: Volatility spillover measured by using realized semivariances

		RS⁺				***RS⁻***			
		HUF	**PLN**	**CZK**	**USD**	**HUF**	**PLN**	**CZK**	**USD**
RS⁺	HUF	36.26	9.29	5.88	4.26	25.8	8.48	5.90	4.13
	PLN	10.28	33.99	5.14	5.62	9.63	24.09	5.56	5.69
	CZK	5.85	3.97	41.58	3.64	6.52	4.23	30.89	3.33
	USD	5.70	5.47	3.77	45.09	6.54	5.50	3.93	24.00
RS⁻	HUF	25.5	7.94	6.24	4.89	35.84	8.92	6.37	4.29
	PLN	9.50	24.04	5.41	5.38	10.27	34.13	6.12	5.15
	CZK	6.11	4.26	29.97	4.02	6.86	4.64	40.44	3.69
	USD	5.93	5.56	3.73	26.77	6.01	4.94	3.69	43.37

Note: These results are for the currency pairs CZK/EUR, HUF/EUR, PLN/EUR, and USD/EUR.

Table A5: Dates of specifical events from references

Event	Description of the shock	Global/local	Date	Source
1	Fitch downgrades Hungary's rating to "junk" status	Local	06/01/2012	https://www.reuters.com/article/us-hungary-orban-idUSTRE8050ZP20120106
2	Mario Draghi "whatever it takes" speech	Global	26/07/2012	Fiordelisi and Ricci, 2016
3	Failed negotiations about the loan from IMF to Hungary	Local	10/01/2013	https://www.reuters.com/article/uk-hungary-cbank-insight-idUKBRE9090TF20130110
4	Beginning of the exchange rate commitment by CNB	Local	11/07/2013	Impact of the CNB's exchange rate commitment: pass-through to inflation (bis.org)
5	The credibility scandal of National Bank of Poland	Local	16/06/2014	https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3463072
6	EU Council meeting strengthening sanctions on investment, services and trade with Crimea and Sevastopol	Global	18/12/2014	https://www.consilium.europa.eu/en/meetings/european-council/2014/12/18/
7	SNB removes franc cap	Local	15/01/2015	https://www.reuters.com/article/us-swiss-snb-strategy-idINKBN0KP1YF20150116
8	BREXIT referendum	Global	23/06/2016	EU referendum - GOV.UK (www.gov.uk)
9	End of the exchange rate commitment by CNB	Local	06/04/2017	CNB ends exchange rate commitment - Czech National Bank
10	S&P 500 10% decline due to FED rate hikes concerns	Global	05/02/2018	https://www.npr.org/sections/thetwo-way/2018/02/05/583325123/stocks-extend-losses-with-dow-dropping-more-than-300-points-at-the-open
11	US sanctions on Turkish export	Global	10/08/2018	https://twitter.com/realDonaldTrump/status/1027899286586109955
12	US-China trade war peak	Global	12/03/2019	https://www.voanews.com/a/us-china-trade-talks/4825253.html
13	WHO declares COVID-19 outbreak	Global	30/01/2020	https://www.who.int/news-room/detail/30-01-2020-statement-on-the-second-meeting-of-the-international-health-regulations-(2005)-emergency-committee-regarding-the-outbreak-of-novel-coronavirus-(2019-ncov)
14	Russia invades Ukraine	Global	02/24/2022	Russian forces invade Ukraine (cnbc.com)

Table A6: Robustness of the Empirical Probabilities for the use of a 5-day Average as a Pre-Event Comparator

Event	Description of the shock	r_e+0		r_e+1		r_e+5		r_e+10		r_e+22	
		OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD	OVD	GVD
	Global shocks										
1	Mario Draghi "whatever it takes" speech	39.4	36.3	41.9	36.7	58.6	**91.4**	47.6	89.0	54.1	85.4
2	EU Council meeting strengthening sanctions on investment, services and trade with Crimea and Sevastopol	62.1	59.6	59.8	60.4	64.5	72.6	79.4	89.9	**100.0**	**100.0**
3	BREXIT referendum	79.6	**91.9**	**99.9**	**99.9**	**99.9**	**99.8**	**100.0**	**100.0**	**99.9**	**100.0**
4	S&P 500 10% decline due to FED rate hikes concerns	47.2	45.1	45.2	51.1	85.0	**97.0**	81.5	**94.4**	**93.4**	**98.9**
5	US sanctions on Turkish export	70.8	75.3	**99.9**	**100.0**	89.9	**95.5**	81.7	**90.2**	81.1	**91.1**
6	US-China trade war peak	47.6	51.3	49.6	47.4	70.1	79.7	71.8	**90.7**	84.3	**97.7**
7	WHO declares COVID-19 outbreak	47.4	42.8	60.5	72.0	60.8	68.9	58.9	63.2	**99.8**	**99.9**
8	Russian invasion to Ukraine	51.4	55.8	53.1	57.5	54.4	57.3	**100.0**	**100.0**	**100.0**	**100.0**
	Local shocks										
1	Fitch downgrades Hungary's rating to "junk" status	49.1	45.0	47.0	46.2	47.8	49.0	61.4	57.4	59.1	55.7
2	Failed negotiations about the loan from IMF to Hungary	41.6	41.9	40.4	39.2	41.3	48.9	35.3	34.6	0.5	1.2
3	Beginning of the exchange rate commitment by CNB	47.7	50.1	48.3	45.8	32.0	25.9	31.3	28.7	30.9	26.3
4	The credibility scandal of National Bank of Poland	45.7	44.3	44.4	48.5	44.5	47.1	48.0	50.3	4.4	6.2
5	SNB removes franc cap	**99.9**	**100.0**	**99.2**	**100.0**	**97.4**	**96.8**	**97.1**	**91.8**	**99.5**	**99.6**
6	End of the exchange rate commitment by CNB	57.6	64.1	59.1	55.5	63.9	61.5	78.8	88.1	77.5	**94.0**

Note: the table reports the empirical probability that the value of the connectedness index exceeds the mean of the connectedness index during the specified r_e+j days using bootstrap samples in a rolling sample. The results under the "OVD" and "GVD" headings denote the calculated probabilities for the connectedness indices using the orthogonalized and generalized forecast error variance decompositions. The results follow the process used by Greenwood-Nimmo et al. (2023), we performed 1000 bootstrap-after-bootstrap non-parametric replications. These results are for the currency pairs CZK/EUR, HUF/EUR, PLN/EUR, and USD/EUR