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VOLATILITY SPILLOVER BETWEEN GERMANY, FRANCE, AND CEE STOCK MARKETS

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Abstract. The CEE stock markets are more and more integrated in the European financial markets. The growth of the integration of financial markets favours the volatility and return spillover between them. The current study analyses the volatility spillover among the stock markets in the countries from Central and East Europe (CEE) and Germany and France with the aim to identify the possibilities of reduction of a portfolio risk. A special attention is granted to the analysis during the pandemic caused by COVID-19. The time-varying parameter vector autoregressive (TVP-VAR) model on which is based the methodology proposed by Antonakakis and Gabauer (2017) is used to estimate the evolution in time of volatility spillover. The empirical results obtained for the period January 2001 – September 2021 highlight the increase in volatility spillover between the countries analysed when the pandemic caused by COVID-19 was confirmed. The lack of volatility integration of the markets analysed enables the making of arbitrages in order to reduce the risk of a portfolio. The results obtained are important in the management of financial asset portfolios.

Keywords: stock markets, emerging markets, risk, volatility transmission, TVP-VAR, spillover index.

JEL Classification: C58, D53, G15, O57.

Introduction

The growth of financial markets integration, accentuated by the globalization phenomenon, allowed the quicker transmission of risk and return between the national markets both during the financial and economic crisis periods and during the economic growth periods. For this reason, the risk management of international portfolios is both a continuous focus and a significant challenge for both academia and practitioners.

The practitioners, the managers of institutional or individual portfolios adjust the allocation of assets in reaction to the volatility spillover from one market to another one or

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from one type of financial asset to another. At the same time, policy makers need to take into account volatility spillover to mitigate contagion risk when making decisions (Yousaf & Ali, 2020). The academia, in its attempt to respond to practitioners' questions regarding volatility spillover, met the challenge by creating various quantitative methods and models (Škrinjarić & Šego, 2020).

The studies of volatility spillover are conducted during the economic and financial crisis periods. The research undertaken on this topic used especially heteroscedastic univariate models (Aktan et al., 2010; Ajayi et al., 2018), quantile regression (Andrieș & Galasan, 2020), MGARCH (Multivariate Generalized Autoregressive Conditional Heteroskedasticity) (Chirilă & Chirilă, 2020; Beirne et al., 2013), VAR (Vector AutoRegression). The research has been given new impetus once the methodology developed by Diebold and Yilmaz (2009, 2012) was published, which allows the quantification of the intensity of shock spillover in the system by means of some indices. At the same time, the methodology of spillover indices enables the evaluation both of a total spillover and of the dynamic spillover. The method was improved later on by Antonakakis et al. (2020) who use a full-fledged time-varying parameter vector autoregressive (TVP-VAR). If by using the first two versions of the spillover indices method some information was lost due to the size of the rolling-window, the improvement proposed by Antonakakis et al. (2020) doesn't cause loss of information anymore.

Thus, firstly, the study focuses on the empirical analysis of the evolution of volatility spillover between the largest stock markets in Central and Eastern Europe, Poland, Czech Republic, Hungary and Estonia, Latvia, and Lithuania (less approached) and between some of the most developed stock markets in the European Union, Germany and France. Secondly, the study of these stock markets allows the analysis of volatility spillover both between emerging stock markets (Estonia, Latvia, Lithuania, Poland, Czech Republic and Hungary) and between emerging stock markets and developed stock markets. The results obtained provide information about the risk characteristics and risk transmission which represent elements needed when considering the insurance of the international diversification of portfolios. Moreover, a gap was identified in the specialty literature regarding the application of spillover indices in the study of spillovers stock markets volatility in the CEE countries, gap which enables time comparisons, and this paper comes to fill it in. The methodology used allows subsequent comparisons to be made regarding the transmission of volatility between stock markets, an element in addition to previous methodologies that were non-comparable with each other. The methodology proposed by Antonakakis et al. (2020) will be used in what follows.

Our paper improves the existing literature in the following way: firstly it analyses during a long period of time the volatility spillover between the CEE stock markets and Germany and France during a time when CEE countries were marked by significant changes determined by the EU adherence, by the 2008 financial crisis, the 2010 sovereign debt crisis and the sanitary crisis caused by the Covid-19 virus. Secondly, we use a methodology which allows to conduct comparisons in relation to future studies. And thirdly, even if the countries, Estonia, Latvia and Lithuania are also members of the European Monetary and Financial Union (EMU), the study of the stock markets of these countries, in terms of return and volatility spillover, is less approached. Therefore, this paper will fill this gap in the literature. In the fourth place, the recent sanitary crisis determined the increase in volatility spillover on a global level which brings to the forefront of the research the identification of those stock markets allowing the diversification of international portfolios and risk reduction.

This research is a step forward in comparison with the paper performed by Ajayi et al. (2018) who studied the main research topic on a sample made up of Nordic-Baltic States and major advanced markets. The results obtained by this paper cuantify the intensity of volatility spillover between the markets under study, subsequently enabling comparisons with other countries and providing a clear image of this spillover during the recent period when countries have been affected by the COVID-19 virus.

The paper is structured as follows: the second part describes the specialty literature and the research hypotheses while the third part comprises the methodology used. The next sections present the data and the empirical results, ending with conclusions, limits of research and future directions.

1. Literature review and research hypothesis

Volatility spillover is studied on stock markets (Okorie & Lin, 2021; Spulbar et al., 2020; Gabauer, 2021), on exchange rate markets (Wei et al., 2020, Căpraru & Ignatov, 2012), on stocks from different economic sectors (Shahzad et al., 2021; Chatziantoniou et al., 2022), on different types of financial assets and on crude oil markets (Liu & Gong, 2020; Balcilar et al., 2021).

If the volatility and return spillover between the stock markets was long debated, in the case of countries with developed economies (Ben Slimane et al., 2013; Diebold & Yilmaz, 2009, 2012; Kanas, 1998; Theodossiou & Lee, 1993; Yilmaz, 2010; Adekoya & Oliyide, 2021; Zhang et al., 2020), return and volatility spillover both between the capital markets of emerging economies and between the capital markets of developed and developing economies is much less tackled (Chirilă et al., 2015).

1.1. Volatility spillover between the stock markets of emerging countries and the stock markets of developed countries

Beirne et al. (2013) study the volatility spillover from the mature stock markets of 41 emerging countries by means of the GARCH-BEKK models. The period included in the research starts in September 1993 (in the case of emerging countries in Asia) or September 1996 (for the emerging countries in Latin America, Europe and Middle East), in relation to the availability of daily values of the indices of these markets and ends, for all countries, mid-March 2008. The results obtained confirm that the conditional variances in emerging markets are affected by the variances in the mature markets. The volatility spillover is higher, on average, during the troubled stages and, at the same time, the spillover parameters change during these disruptive periods. Latvia is one of the seven countries from the sample considered where this transmission is significantly higher during the unstable periods.

The research conducted by Spulbar et al. (2020) on a sample of twelve countries over five continents (Asia, Africa, Europe, South America and North America) which comprises seven stock markets of developed countries and five stock markets of emerging countries uses symmetrical (GARCH) and asymmetrical heteroscedastic models (EGARCH, GJR). The results highlight that each emerging stock market has a similar evolution with the one of a certain developed country and that, at the same time, volatility spillover is higher during the economic and financial crisis periods.

Another study (Ng, 2000) which tackles volatility spillover between the stock markets of developed countries, Japan (regional factor) and USA (global factor), and emerging markets from the Pacific-Basin (Hong-Kong, Korea, Malaysia, Singapore, Taiwan, Thailand) reaches the conclusion that regional and global shocks are transmitted in a ratio of a maximum of 10% and that the specific factors of a country have the highest influence and are not correlated with the regional factor.

Therefore, our study will test the following hypothesis:

Hypothesis 1 (H1): *Volatility spillover is unidirectional from the developed markets to the emerging markets.*

Hypothesis 2 (H2): *The shocks which occur on the stock markets are spilled to a great extent on their own markets.*

According to the literature, we expect the results to confirm that the CEE countries are influenced to a great extent by specific factors, situation which is often met in countries with emerging stock markets (Kregzde, 2018). Such a result will allow on one hand the possibility to perform the international diversification by means of foreign investments on these markets in order to obtain a high risk-return ratio and on the other hand the increase in the financing sources of firms listed on these markets and the development of emerging capital markets. The increase in the capital flow in the CEE countries may trigger a growth of the firms listed on the stock markets and afterwards, an economic development of the country.

We also expect that during the crisis periods, the volatility spillover between all stock markets considered should rise. The volatility spillover indices will enable us to identify whether the 2008 global financial and economic crisis had a higher effect on spillovers than the crisis determined by the COVID-19 pandemic. The study will highlight what the effect of these crises is on the spillover phenomenon: whether it is persistent or temporary.

The results obtained confirm that there is volatility spillover between the stock markets from the sample studied. Volatility spillover is stronger during the unstable periods, so that, due to the confirmation of the COVID-19 pandemic volatility spillover between markets is more important for a certain period, also maintaining a significantly higher volatility spillover after the event. The markets in Estonia, Latvia, and Lithuania register the lowest volatility spillover unlike the ones from Poland, Czech Republic, Hungary, France and Germany, fact which confirms the likelihood to be considered in the portfolio diversification.

1.2. Volatility spillover between the stock markets of emerging countries

Škrinjarić and Šego (2020) study the volatility spillover on a sample of stock markets from Central, Eastern and South-Eastern Europe (CESEE) during January 2012 – June 2019. The research sample is made up of eight stock markets from Bulgaria, Slovakia, Czech Republic, Slovenia, Ukraine, Croatia and Hungary. VAR and the spillover indices of Diebold and

Yilmaz (2009, 2012) are used, and the authors draw the conclusion that some of the stock markets in this system absorb shocks from the neighboring markets in Central and East Europe (CEE), while others absorb shocks from the neighboring markets in South-Eastern Europe (SEE). This situation will subsequently determine the increase in volatility spillover in each subregion. Škrinjarić (2019) reaches a similar conclusion when he studies the stability of stock markets in CESEE. The results are obtained by means of the quantile regression in order to take into consideration different conditions or events of the markets which vary from extremely negative to extremely positive.

Therefore, this study will test the following hypotheses:

Hypothesis 3 (H3): *There is a bidirectional volatility spillover between emerging markets.*

Hypothesis 4 (H4): *Volatility spillover between the stock markets varies in time.*

1.3. Volatility spillover caused by the COVID-19

The pandemic caused by COVID-19 determined the intensification of research on the topic of dynamic volatility spillover between various markets (Chaudhary et al., 2020; Corbet et al., 2021; Jebabli et al., 2021; Lupu et al., 2021; Fasanya et al., 2021; Gherghina et al., 2021).

Apostolakis et al. (2021) study the dynamic volatility spillover and conclude that on the Greek stock market during COVID-19 there is a higher volatility spillover from mid-cap firms to large cap firms.

Aslam et al. (2021) study the volatility spillover between the European financial markets during COVID-19. The study deals with the spillover before March 11, the moment when the pandemic was confirmed, and after this date. The results obtained on intraday observations show a more stable spillover during the second period. The results confirm that Germany's market has the highest net directional spillovers while the minimum spillovers to other stock markets are in Poland's stock market.

Li (2021) studies volatility spillover between the stock markets from US, Japan, Germany, UK, France, Italy, Canada, China, India and Brazil. He draws the conclusion that during the recession caused by COVID-19 volatility spillover is maintained at an extremely high level and the main receivers of risk are the emerging markets.

As a consequence, the study will test the following hypotheses:

Hypothesis 6 (H6): *The pandemic caused by COVID-19 determined an increase in volatility spillover between the stock markets.*

Hypothesis 7 (H7): *Volatility spillover is higher during disruptive times.*

2. Methodology

When evaluating the spillover, which varies in time, the methodology proposed by Diebold and Yilmaz (2009) allowed the development of research on this topic. The original methodology was improved by Diebold and Yilmaz (2012, 2014) and Antonakakis and Gabauer (2017). In the current research, we will use the methodology proposed by Antonakakis and Gabauer (2017), namely the time-varying parameter vector autoregressions (TVP-VAR). Antonakakis and Gabauer (2017) specify two great advantages of this method in comparison with the original method: first of all, it doesn't need rolling-window and implicitly, there is no need to specify its size and secondly, there are no more lost observations (determined by the rolling-window specification). Thus, the method can be also used in the case of smaller samples of observations and its results are not influenced by the presence of outliers.

The estimated TVP-VAR model is presented in the Eqs (1) and (2).

$$y_t = B_t x_{t-1} + \varepsilon_t \qquad \varepsilon_t \left| F_{t-1} \sim N\left(0, \in_t\right)\right.; \tag{1}$$

$$vec\left(B_t\right) = vec\left(B_{t-1}\right) + \upsilon_t \qquad \upsilon_t \left| F_{t-1} \sim N\left(0, S_t\right)\right., \tag{2}$$

where:

$$x_{t-1} = \begin{pmatrix} y_{t-1} \\ y_{t-2} \\ \vdots \\ y_{t-m} \end{pmatrix} \text{ and } B_t = \begin{pmatrix} B_{1t} \\ B_{2t} \\ \vdots \\ B_{mt} \end{pmatrix},$$

y_t is $n\times1$ dimensional vector; x_{t-1} is a $nm\times1$ dimensional vector; F_{t-1} represents the information available at the moment *t*–1; B_t is a $n\times nm$ dimensional time-varying coefficient matrix; ε_t is a $n\times1$ dimensional error vector; $\in_t$ time-varying variance-covariance matrix $n\times n$; $vec\left(B_{t-1}\right)$, $vec\left(B_t\right)$ and ϑ_t $n^2m\times1$ dimensional vectors; S_t is a $n^2m\times n^2m$ dimensional vector.

The choice of the lag for the VAR model presented is performed by selecting the minimum values of the information criteria Akaike, Schwarz, Hannan-Quinn. When the minimum values of the information criteria do not coincide, Lütkepohl (2005, p. 148–152) states that the choice of the lag is performed based on the Schwarz information criterion which provides consistent estimates of the true lag order.

VAR is transformed in a vector moving average representation (VMA) in order to be able to calculate the generalized impulse response functions (GIRF) and the generalized forecast error variance decomposition (GFEVD) (Koop et al., 1996; Pesaran & Shin, 1998). The result is presented in Eq. (3) and Eq. (4).

$$y_t = \sum_{j=0}^{\infty} L' Q_t^j L \varepsilon_{t-j}; \tag{3}$$

$$y_t = \sum_{j=0}^{\infty} A_{it} \varepsilon_{t-j}, \tag{4}$$

where: $\boldsymbol{L} = \left[\boldsymbol{I_n}, \ldots, 0_{\boldsymbol{p}}\right]'$ is a $nm\times n$ dimensional matrix; $\boldsymbol{Q} = \left[\boldsymbol{B_t}; \boldsymbol{I_{n(m-1)}}, 0_{\boldsymbol{n(m-1)\times n}}\right]$ is a $nm\times nm$ dimensional matrix; $\boldsymbol{A_{it}}$ is a $n\times n$ dimensional matrix.

The values for GIRF represent the responses of all variables which were subjected to a shock that occurred in the *i* variable. The shock response determined within the i variable is calculated as a difference between a *J*-step-ahead forecast for the situation where the *i* variable is subjected to the shock and a *J*-step-ahead forecast for the situation where the *i* variable is not subjected to the shock. The calculation method of *GIRF* is presented in Eq. (5) while the relationship for *GIRF* is presented in Eq. (6):

$$GIRF_t\left(J,\gamma_{j,t},F_{t-1}\right)=E\left(Y_{t+J}\left|\varepsilon_{j,t}=\gamma_{j,t},F_{t-1}\right.\right)-E\left(Y_{t+J}\left|\varepsilon,F_{t-1}\right.\right); \tag{5}$$

$$\Psi_{j,t}^{g}\left(J\right)=\in_{jj,t}^{-\frac{1}{2}}A_{j,t}\in_t\varepsilon_{i,t}\ , \tag{6}$$

where: $\Psi_{j,t}^{g}\left(J\right)$ is GIRF for the variable *j*; *J* is the forecast horizon; $\gamma_{j,t}$ is a vector which has the value o on the j^{th} position and zero otherwise; F_{t-1} represents the information available at the moment *t*–1.

The generalized forecast error variance decomposition (GFEVD) can be calculated according to Eq. (7) and represents the variance share one variable has on the others:

$$\breve{\varphi}_{ij,t}^{g}=\frac{\sum_{t=1}^{j-1}\Psi_{ij,t}^{2,g}}{\sum_{j=1}^{n}\sum_{t=1}^{j-1}\Psi_{ij,t}^{2,g}}, \tag{7}$$

therefore, we have

$$\sum_{j=1}^{n}\tilde{\varphi}_{ij,t}^{g}\left(J\right)=1\text{ and}\sum_{j=1}^{n}\tilde{\varphi}_{ij,t}^{n}\left(J\right)=n. \tag{8}$$

Total connectedness index is calculated according to Eq. (9) by means of GFEVD as follows:

$$C_t^{g}\left(J\right)=\frac{\sum_{i,j=1,i\neq j}^{n}\tilde{\varphi}_{ij,t}^{g}\left(j\right)}{n}\cdot 100, \tag{9}$$

and it shows how a shock on a variable spills overs other variables.

Total directional connectedness to others can be determined based on Eq. (10):

$$C_{i\to j,t}^{g}\left(J\right)=\frac{\sum_{j=1,i\neq j}^{n}\tilde{\varphi}_{ij,t}^{g}\left(j\right)}{\sum_{j=1}^{n}\tilde{\varphi}_{ij,t}^{g}\left(j\right)}\cdot 100, \tag{10}$$

and describes how a shock on a variable *i* spills over all the other *j* variables.

Total directional connectedness from others represents the shock spillover from variable j to variable i and it is determined by means of the relation presented in Eq. (11).

$$C_{j\to i,t}^{g}\left(J\right)=\frac{\sum_{j=1,i\neq j}^{n}\tilde{\varphi}_{ij,t}^{g}\left(j\right)}{\sum_{i=1}^{n}\tilde{\varphi}_{ij,t}^{g}\left(j\right)}\cdot 100. \tag{11}$$

Total net directional connectedness presented in Eq. (12) is obtained as a difference of Eqs. (10) and (11) as follows:

$$C_{i,t}^{g}=C_{i\to j,t}^{g}\left(J\right)-C_{j\to i,t}^{g}\left(J\right). \tag{12}$$

If the value obtained for total net directional connectedness is negative, then the variable is a net receiver in the system while if the value for total net directional connectedness is positive, then it is a net transmitter in the system.

Net pairwise directional connectedness is determined in order to identify the bidirectional relationship according to Eq. (13):

$$NPDC_{ij}\left(J\right)=\frac{\breve{\varphi}_{ij,t}^{g}-\breve{\varphi}_{ji,t}^{g}}{T}\cdot 100, \tag{13}$$

where: $NPDC_{ij}\left(J\right)$ is net pairwise directional connectedness.

In order to decompose the spillover between two stock markets, a particular focus should be granted on one hand to the extent in which the spillover is performed within the stock market analysed and on the other hand to the extent in which the spillover is conducted from one stock market to the other one. The decomposition for k stock markets can be performed as follows:

$$\Phi\left(J\right)=\left|\breve{\varphi}^{g}\right|_{ij,t}\left(J\right)=\begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1k} \\ C_{21} & C_{22} & \cdots & C_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ C_{k1} & C_{k2} & \cdots & C_{kk} \end{bmatrix}, \tag{14}$$

where: $\mathbf{C}_{ii}$ represents the spillover within the stock market; $\mathbf{C}_{ij}$ represents the spillover from an i stock market to a j stock market.

If we consider $diag(\boldsymbol{C}_{ii})$ = 0 we can calculate:

- Total spillover of the *i* stock market to the other stock markets, as per Eq. (15):

$$TO_{ij}=\sum_{n=1}^{k}C_{ij,nm}. \tag{15}$$

- Total spillover of the *i* stock market received from the other stock markets as per Eq. (16):

$$FROM_{ij}=\sum_{m=1}^{k}C_{ji,nm}. \tag{16}$$

- Net spillover as per Eq. (17):

$$NI_{ij}=TO_{ij}-FROM_{ij}=\sum_{n=1}^{k}\sum_{m=1}^{k}C_{ij,nm}-\sum_{n=1}^{k}\sum_{m=1}^{k}C_{ji,nm}. \tag{17}$$

3. Data and empirical results

If previous studies usually took into consideration market systems from the same geographical area (Škrinjarić & Šego, 2020) or with the same features (developed or emerging markets) (Yilmaz, 2010) our study analyses the connection between volatilities between stock markets in CEE (Central and East Europe) and two countries with developed markets from the Euro zone. The choice was performed so that the results should present the connection of stock markets' volatility from these different regions and with different features. Thus, the empirical analysis considers the CEE countries Czech Republic, Poland Hungary, Latvia, Lithuania, Estonia, and two developed stock markets from the Euro zone, Germany and France. For the study of volatility spillover we took into consideration the following stock indices: OMX Riga_GI (Latvia), OMX Vilnius_GI (Lithuania), OMX Tallinn_GI (Estonia), PX (Czech Republic), WIG 20 (Poland), BUX (Hungary), DAX (Germany) and CAC 40 (France). The daily values of indices are recorded during the period January 1st, 2001 – September 21st, 2020, comprising 5407 observations for each index based on which 5406 daily returns were determined.

The return rate of each stock market was calculated according to the relationship:

$$r_t = \ln\left(\frac{I_t}{I_{t-1}}\right), \tag{18}$$

where: r_t – log-the return of the stock market considered at the moment t; I_t, I_{t-1} – the value of the index of the stock market at the moment t and the moment t–1, respectively.

The daily returns are used to calculate the monthly standard deviations based on which we will analyse the volatility spillover between the selected stock markets as in the study conducted by Škrinjarić (2019). Thus, during the period under consideration, there are 248 monthly values available.

The descriptive statistical indices for all the standard deviations are presented in Table 1. This table shows us that the highest means of the standard deviation during the analysed period are in Poland, Hungary, Germany and France (0.0130, 0.0127, 0.0127 and 0.0123, respectively) while in Lithuania and Estonia there are the lowest values of the standard deviation (0.0072 and 0.0081, respectively). Therefore, Lithuania and Estonia have the lowest values of stock markets' volatility.

Table 1. Descriptive statistical indicators for the stock markets' volatility

Std. deviation	Mean	Median	Maximum	Minimum	Std. Dev.	Coefficient of variation (%)
Latvia	0.010606	0.008299	0.072537	0.003522	0.008045	75.85
Lithuania	0.007247	0.005566	0.050483	0.001882	0.005398	74.48
Estonia	0.008175	0.006663	0.035535	0.001337	0.005328	65.17
Czech Republic	0.010756	0.008832	0.074338	0.003611	0.006977	64.86
Poland	0.013072	0.011632	0.048473	0.004329	0.005758	44.04
Hungary	0.012780	0.011013	0.061276	0.005012	0.006571	51.41
Germany	0.012710	0.010764	0.049133	0.003874	0.007192	56.58
France	0.012378	0.010695	0.051675	0.003752	0.007089	57.27

Note: Results obtained by the authors.

The variation coefficient of all standard deviations has higher values than 50%, which indicates a very high variation of these distributions, being a characteristic of financial time series. The exception is represented by Poland.

For the computation of volatility spillover indices, the VAR model is estimated. Before estimating the VAR model, the stationarity of all standard deviation series is tested (by means of which the volatility of the stock markets was quantified). The Augmented Dickey-Fuller (ADF) (1979), the Phillips-Perron (PP) (1988) test, the modified Augmented Dickey-Fuller breakpoint unit root test (Perron, 1989) and ERS test (Elliot et al., 1996) confirm the existence of series' stationarity.

Table 2. The values of information criteria for the choice of the VAR model lag (source: Results obtained by the authors)

Lag	FPE	AIC	SC	HQ
0	1.75e-39	–66.53991	–66.42389	–66.49316
1	2.69e-40	–68.41004	–67.36585*	–67.98931*
2	2.57e-40*	–68.45873*	–66.48637	–67.66402
3	2.90e-40	–68.34208	–65.44155	–67.17338
4	3.84e-40	–68.06999	–64.24129	–66.52730
5	4.75e-40	–67.86866	–63.11179	–65.95199

Note: FPE – final prediction error, AIC – Akaike information criterion, SC – Schwarz information criterion, HQ – Hannan-Quinn information criterion, * – lag order selected by the criterion.

The estimation of the VAR(p) model implies the choice of the size of the optimal lag. The lag determination is made by means of the information criteria and the final prediction error. If the values of information criteria indicate different lags, we will favour the Schwarz criterion. According to the results presented in the Table 2, the lag order which is selected is equal to 1. A VAR (1) model is estimated.

Table 3. Granger causality test results for VAR model (source: Results obtained by the authors)

Cause	Test value	Probability
Latvia	7.359072	0.3925
Lithuania	25.66312	0.0006
Estonia	11.36203	0.1236
Czech Rep.	18.36076	0.0104
Poland	7.692719	0.3605
Hungary	15.96597	0.0254
Germany	5.707674	0.5743
France	3.749591	0.8081

In the estimated VAR(1) model Granger-causality is tested. Table 3 presents the results obtained. According to these, only the volatility of the stock markets in Lithuania, Czech Republic and Hungary is Granger-caused by the volatility from other stock markets. But the results obtained through this analysis are static. That is the reason why we will estimate the volatility spillover indices according to the methodology proposed by Antonakakis and Gabauer (2017).

In the volatility spillover of stock markets, we will focus on the unidirectional spillovers of each stock market, the total spillover to and from a stock market and on the net directional spillover of each individual stock market. The net directional spillover can have a positive or a negative value. It is calculated as a difference between the total contribution received by a market from the other markets and the total contribution spilled to other markets. If the net directional spillover has a positive value, then that stock market is a net shock transmitter and if the net directional spillover has a negative value, then the stock market is a shock receiver.

Table 4 presents the average spillover for the period under study based on the generalised forecast error variance decomposition. The results presented by rows, in Table 4, show what % of the generalized forecast error variance of the stock market volatility is caused by the shocks in the volatilities of stock markets within the system. Thus, in the case of the stock market from Latvia, 37.15% of the generalised forecast error variance of stock market volatility is due to its own shocks on volatility, 10.23% is caused by the shocks of volatility of Lithuanian stock market, 8.74% is due to the shocks of Estonia's volatility and so on and so forth.

According to the estimated results presented in Table 4 there is quite a high spillover effect of volatility shocks between the stock markets, all these giving and receiving significant volatility shocks. The total spillover index takes the value 73.98%, which shows that the volatility shocks from the system are spilled over other volatilities in the system in a ratio of 73.98%. This result suggests a very high connection between the volatilities of the markets considered due to a very high spillover.

Table 4. Spillover table (Results obtained by the authors)

	Latvia	Lithuania	Estonia	Czech Rep.	Poland	Hungary	Germany	France	From others
Latvia	37.15	10.23	8.74	9.86	9.67	8.08	8.26	8.01	62.85
Lithuania	6.05	28.43	12.32	14.24	11.06	13.69	7.05	7.15	71.57
Estonia	6.51	12.55	24.24	13.22	11.78	12.63	8.53	10.53	75.76
Czech Republic	3.80	10.92	9.31	22.45	13.41	17.07	10.20	12.84	77.55
Poland	5.11	11.05	9.90	15.36	21.39	14.86	10.46	11.87	78.61
Hungary	3.67	11.41	9.63	17.60	13.13	22.79	10.18	11.58	77.21
Germany	4.03	6.69	6.70	11.64	9.76	11.68	28.03	21.46	71.97
France	4.22	6.49	8.30	13.67	11.24	12.44	19.94	23.69	76.31
TO others	33.40	69.34	64.91	95.60	80.06	90.44	74.63	83.46	591.83
NET	–29.44	–2.24	–10.84	18.05	1.45	13.23	2.65	7.15	73.98

On an average, the volatilities in Czech Republic, Hungary and Poland are the highest shock transmitters, the estimated values reaching 95.6%, 90.44% and 80.06%, respectively, while Latvia is a market whose volatility registers the lowest shock spillover (33.40%). The shock spillover from the volatilities of the markets in Lithuania, Estonia, France and Germany are significant, exceeding 50%. But the highest volatility shock- transmitter markets are also the highest shock receivers. It is the case of the market from Poland, Czech Republic and Hungary (78.61%, 77.55% and 77.21%) after which comes Estonia (75.76%) and France (76.31%). The least volatility shock-receiver market from the sample is Latvia (62.85%).

The net spillover provides information for each stock market whether it receives or gives more volatility shocks. The Latvian market is the highest shock receiver from the other markets and it is followed by Estonia (–10.84%) and Lithuania (–2.24%). The markets from Czech Republic, France, Germany, Poland and Hungary are net shock transmitters.

The diagonal axis presents how much of the generalised forecast error variance of volatility is due to shocks within the volatility of its own market. Thus, we can state that the highest influence on the volatility of Latvia, Lithuania and Estonia belongs to its own volatility. The contribution of own volatility in Latvia is 37.18%, in Lithuania is 28.43% followed by Estonia with 24.24%. The other markets have comparable contributions to their own volatility, being comprised between 22–25% with the exception of Germany with 28.03%.

The lowest volatility shock spillovers are noticed from Hungary, Czech Republic, Germany, France, Poland and Estonia to Latvia. Thus, since there are the lowest spillovers of volatility shocks towards the volatilities of the stock market from Latvia, the investors can use this result to reduce their portfolio risk.

The highest spillovers are from the volatility of the stock market in Germany to the volatility of the stock market in France, from the volatility of the stock market in France to the one in Germany, from the volatility of the stock market in Hungary to the one of Czech Republic and respectively, from the volatility of the stock market in the Czech Republic to the volatility of the market in Hungary, from the volatility of the stock market in Lithuania to the volatility of the stock market in Czech Republic and from the volatility of the stock market in Lithuania to the volatility of the stock market in Hungary. We notice the high bilateral connection between the volatilities of the stock markets in Germany and France and between Hungary and Czech Republic, respectively.

Seen in its evolution, the total spillover index, presented in Figure 1, highlights an interesting fact: international crises which occur determine not only an immediate increase in volatility spillover but also the maintenance of the high values of the spillover. It can be observed that the shock on the volatility of the stock markets determined by the 2008 global economic and financial crisis caused a significantly quick increase in spillover, then until

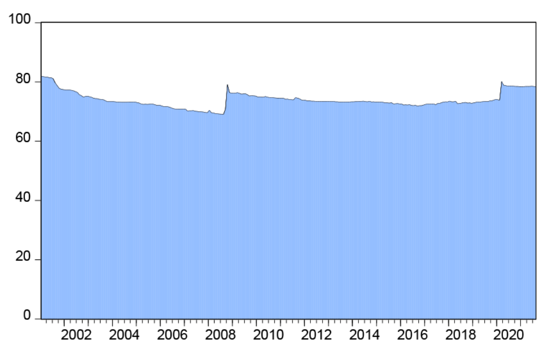

Figure 1. Overall volatility spillovers

the year 2020, it registered a very slow decrease (without reaching the level before the crisis) while the sanitary crisis determined by COVID-19 caused, in its turn, an increase in spillover, rising to a high level and then decreasing very little.

If the quite high volatility spillover from the beginning of the analysis period drops until 2008, that is until the global economic and financial crisis, after the 2008 crisis the volatility spillover drops very little. This increase in the average volatility spillover, in time, between the stock markets can be explained also by the increase in the integration level of the stock markets from the emerging countries in the European Union within the developed stock markets from the European Union (Boțoc & Anton, 2020).

Figure 2 which presents the dynamic connectedness between the volatilities of the markets considered highlights some interesting elements. The volatilities of the markets from Latvia and Estonia, which we identified as being net shock-receivers of volatility, present this feature for the entire period studied but with fluctuating values. On the Latvian market, the value of the spillover index increased since 2009 until 2015 which indicates a drop in received shocks while at the beginning of 2020, since the COVID-19 occurrence, the spillover registers a local minimum value, which shows an increase in receiving shocks.

The volatility of the market in Estonia registers an increase in the net receiving of shocks until the 2008 global economic and financial crisis, after which it is kept at a high level and then the shock receiving drops gradually, with a strong decrease recorded when the COVID-19 pandemic happened. The values of the net volatility spillover index, as an absolute value, registers the highest values in comparison with the other markets.

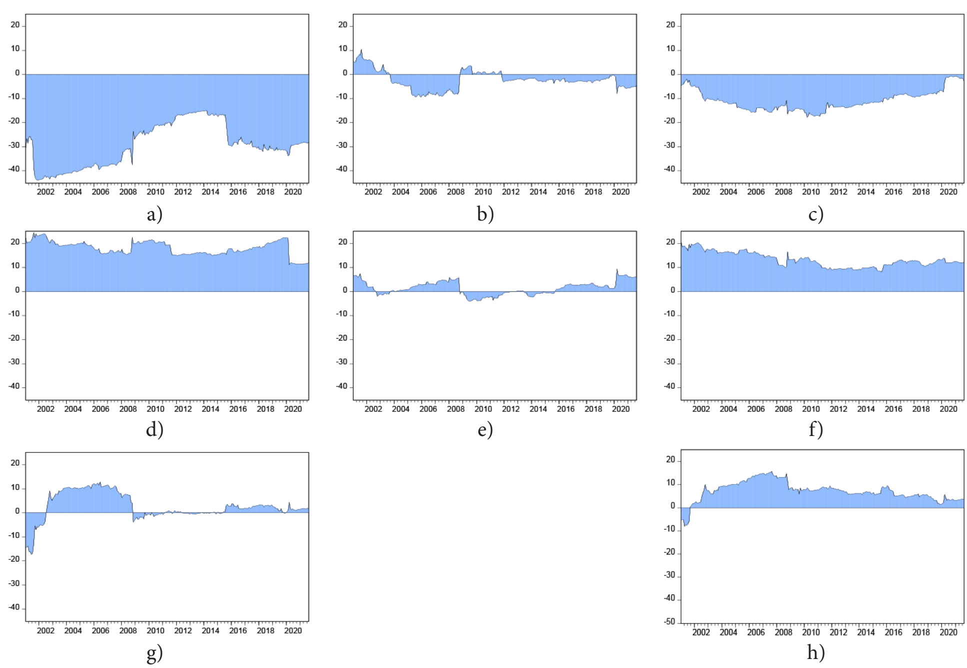

Figure 2. Dynamic Connectedness in the countries: a – Latvia; b – Lithuania; c – Estonia; d – Czech Republic; e – Poland; f – Hungary; g – Germany; h – France (source: results obtained by the authors)

The stock market in Lithuania registers during the period studied both net shock transmitters of volatility and net volatility spillovers. After the 2008 crisis, it becomes a net volatility transmitter for a 3-year period and then it continues to be a net receiver. Both the net volatility shock-receiving periods and the net volatility shock-giving periods are characterized by low values. In the case of Czech Republic and Hungary, Figure 2 shows that they are net volatility shock transmitters for the entire period studied, with high values. A decrease in the net volatility spillover can be observed after the occurrence of COVID-19 in Czech Republic while Hungary registers a local maximum during the same period.

Poland has periods where it is a net volatility receiver and periods when it is a net transmitter. During the 2008 crisis it becomes a net receiver while during the COVID-19 pandemic it is a net transmitter. The stock market volatility in Germany is a net shock receiver after the 2008 global economic and financial crisis until 2015 and then it is a net volatility shock-transmitter even if to a small extent in comparison with the other markets. The pandemic determines a temporary increase in net volatility spillover even if for a very short period of time. The stock market in France is a net volatility shock-transmitter almost during the entire period under study, with the last period registering drops but it presents a local maximum when the sanitary pandemic happened.

Figure 3 highlights the total volatility shocks transmitted by the countries in the system to the volatility of each stock market within the system considered. The stock markets in Latvia,

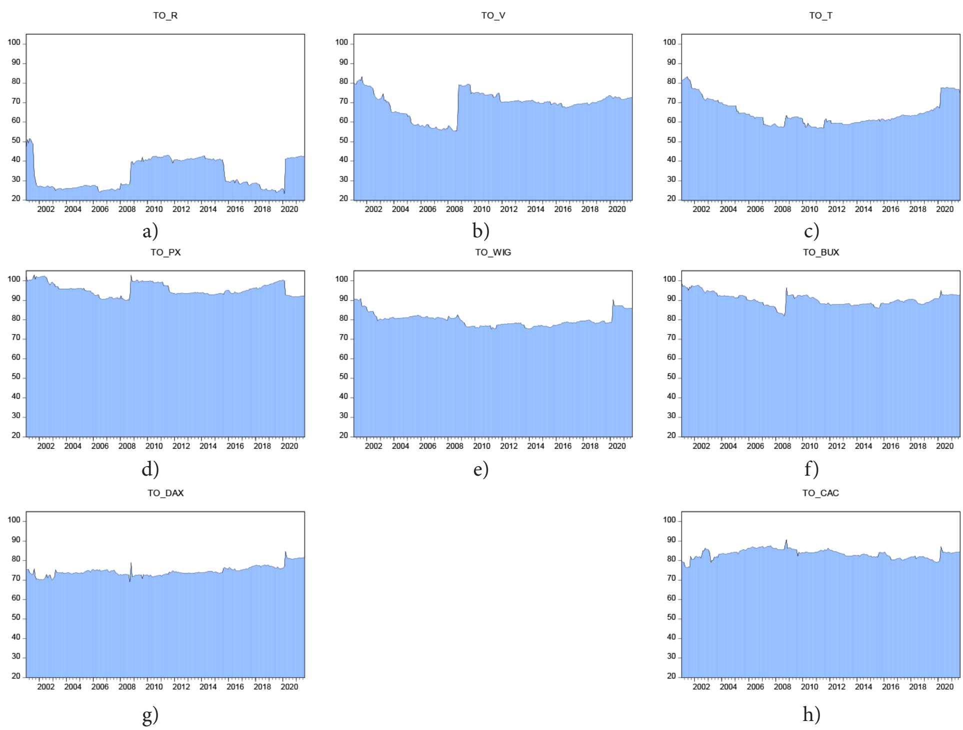

Figure 3. Directional volatility spillovers, to each stock market: a – Latvia; b – Lithuania; c – Estonia; d – Czech Republic; e – Poland; f – Hungary; g – Germany; h – France (source: results obtained by the authors)

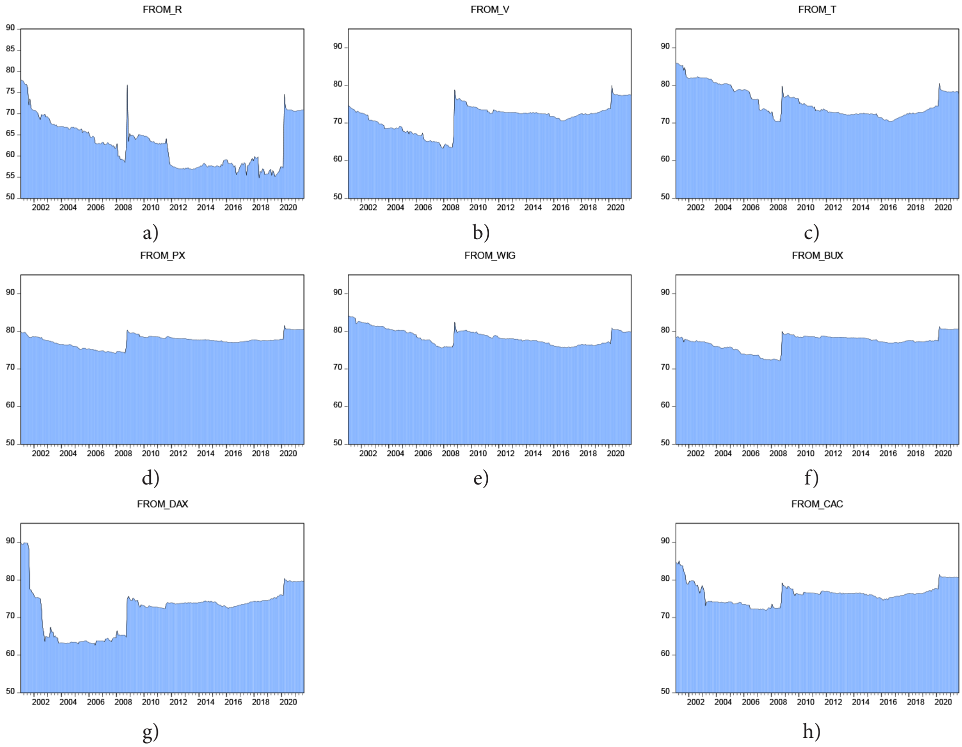

Figure 4. Directional volatility spillovers, from each stock market: a – Latvia; b – Lithuania; c – Estonia; d – Czech Republic; e – Poland; f – Hungary; g – Germany; h – France (source: results obtained by the authors)

Estonia, Poland, Germany and France receive significantly higher volatility shocks during the period when the COVID-19 pandemic started. In contrast, in the case of Czech Republic's market, during the same period, the total shocks received register a decrease. Lithuania and Latvia register very low, almost insignificant increases in the shocks received.

The total shock spillovers from each stock market to the other ones, during the occurrence of COVID-19, follow the same pattern: all of them register a significant increase. The highest increase in volatility spillover, as Figure 4 indicates, is observed on the stock market in Latvia.

Conclusions

In the management of financial asset portfolios, a special attention is granted to return and volatility spillover. This phenomenon is studied on stock markets, on exchange rate markets, on stocks from various economic sectors, on various financial assets and so on and so forth. Volatility spillover was deeply studied during the periods of economic and financial crisis and the methodology allowed the identification of volatility spillover or lack thereof. Gradually, the spillover methodology developed, new methodologies appeared which are being continuously improved. They enabled the study of volatility spillover both during the crisis periods and even after that.

If volatility spillover between the stock markets in the developed countries has the upper hand in this research framework, the emerging markets are less studied. Thus, due to the identification of this gap in the research, the present study analyses volatility spillover between a group of CEE stock markets Czech Republic, Poland, Hungary Latvia, Lithuania, Estonia, and developed stock markets from the Euro zone, Germany and France.

Following the analyses conducted, the research hypotheses presented in the literature review section were validated or rejected.

First of all, volatility spillover between the stock markets is fluctuating which confirms hypothesis H4 for all countries considered in the study: Latvia, Lithuania, Estonia, Czech Republic, Poland, Hungary, Germany and France. This result suggests to the investors that the analysis of volatility spillover needs to be updated continuously and the adjustments in the portfolio asset weights should be performed in compliance with the situation identified in the volatility spillover.

Secondly, volatility spillover is higher during disruptive times, which confirms hypothesis H6. The total volatility spillover index between the stock markets confirms this situation. At the same time, the result is highlighted the volatility spillover from each stock market which is significantly higher during the 2008 Global Financial Crisis, European Debt Crisis and during the COVID-19 pandemic confirmation period. This last result confirms hypothesis H5.

Thirdly, volatility spillover from the developed stock markets in France and Germany to the CEE countries is significant. This result confirms hypothesis H1 of the unidirectional volatility spillover from the developed stock markets to the emerging markets. Also, there is significant bidirectional spillover between the emerging stock markets: Latvia, Lithuania, Czech Republic, Poland and Hungary which confirm hypothesis H3. The lowest spillover from Germany and France is identified for the stock market in Lithuania. This result confirms the possibility for portfolio diversification with the aim to reduce the risk.

And fourthly, the shocks on the stock markets are spilled to a great extent over their own markets confirming hypothesis H2. In the case of the CEE countries, shock spillover on their own markets is significantly higher, which suggests a research follow-up is needed in this direction. The identification of the potential influence economic factors which determine shock occurrence would enable portfolio managers to forecast volatility and volatility spillover. This study has limits determined by the few numbers of stock markets from CEE countries. Future research could also be directed towards the extension of the sample of countries considered for analysis and towards the study of volatility spillover on the stocks of companies from specific economic sectors.

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Author contributions

All authors have contributed to this paper in all phases.

Disclosure statement

The authors declare no competing financial, professional, or personal interests from other parties.

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