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Givers or Recipients? Co-Movements between Stock Markets of CEE-3 and Developed Countries

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Abstract: In this paper, time-varying co-movements between the stock markets of Poland, the Czech Republic, Hungary, and the capital markets of developed countries in stable and crisis periods are studied. The parameters of the VAR-AGDCC-GARCH (Vector Autoregressive-Asymmetric Generalized Dynamic Conditional Correlation—Generalized Autoregressive Conditional Heteroscedasticity) model are estimated, and volatility spillovers are calculated. The evidence suggests that the level of correlation between stock return shocks of Central and Eastern European countries increased significantly in the period of financial turmoil and was high in the period of the US sub-prime crisis, as well as during the euro area sovereign debt crisis. After the announcement of the OMT (Outright Monetary Transactions) program, the evolution of the stock market indices in Central and Eastern Europe countries (CEECs) have followed different paths. An analysis of the volatility spillovers indicates that CEECs are the recipients of volatility. In the period of 2004–2019, they received much volatility—from Germany and the US, in particular. They also received much volatility from Spain during the euro area sovereign debt crisis. After 2012, volatility transmission to Poland, the Czech Republic, and Hungary dropped significantly.

Keywords: VAR-AGDCC-GARCH; volatility spillover; Central and Eastern Europe

1. Introduction

Financial integration critically affects the functioning of any economy at both the micro and macro levels. Financial markets that are well interconnected with regional and global financial centers allow for better capital allocation and consumption smoothing, and they result in smaller dependence on domestic savings for investment purposes [1]. From firms' perspectives, well-interconnected financial markets provide an easier sourcing of capital. Identifying international linkages among markets and analyzing their variability over time is very important, since it is a condition for the effective management of risk that is associated with the potential negative influence of global capital markets [2]. Understanding the time-varying nature of correlations among stock markets would help decision-makers to react in a timely manner to financial shocks through adequate policies, especially during turbulent periods, when financial markets are stressed. An analysis of the level of integration of financial markets is also important from the perspective of investors. Since the seminal paper of Markowitz [3] and the empirical evidence provided by Grubel [4], it has been recognized that the international diversification of portfolios reduces total risk. Increased co-movements between asset returns can diminish the advantage of internationally diversified investment portfolios [5].

Poland, the Czech Republic and Hungary (henceforth referred to as the CEE-3: Central and Eastern European: the Czech Republic, Hungary and Poland) joined the European Union in May 2004 and are committed to adopting the euro at some point. Their stock markets are still less developed than markets in industrialized countries. However, the CEE-3 stock markets are characterized by higher development levels compared to other Central and Eastern Europe countries (CEECs) [6,7]. Moreover, the Czech Republic, Hungary and Poland significantly contribute to the GDP of the European Union (more than 5%). GDP growth rates in these countries significantly exceed the European Union (EU) average and, with respect to further European integration, their joining the euro area seems to be important [8]. However, joining the euro area without a sufficient degree of financial market integration can lead to problems in terms of common shocks and typical monetary policies [9]. In the case of a high degree of financial market integration, euro-area -wide shocks dominate, since common monetary policies can be effectively applied to react to common shocks. In the case of weak financial market integration, country-specific shocks prevail, so the effectiveness of common monetary policies is limited. Therefore, from the point of view of the whole European Union, as well as in regard to its new member states, an analysis of the alignment of their markets, including the financial ones, with those of the euro area countries seems to be crucial.

An analysis of stock returns performance, as well as correlations between stock returns, is important from an economic perspective. However, an analysis of volatility spillovers among stock markets seems to be important as well. Understanding the mechanism of the transmission of volatility in tranquil and turbulent times could significantly help policymakers. The policymakers of countries receiving volatility from other stock markets should introduce measures in the case of a sharp increase in the volatility of the stock market transmitting such volatility. The appropriate monitoring of the performance of stock markets interconnected with the domestic market could enable the domestic market to function better and provide an easier sourcing of capital.

Though there are numerous studies devoted to the interconnectedness of stock markets in CEE-3 countries with developed ones, these are mainly devoted to the performance of stock indices, as well as to the analysis of the time-varying correlations between stock market returns of emerging countries with developed ones. There is still an important gap, which is addressed in this paper. Firstly, longer time series are used in this empirical analysis. Previous research studies have concentrated on the impact of the EU accession, US sub-prime crisis, and the euro area sovereign debt crisis on stock markets in CEE-3 countries [10–13]. These studies have not taken into account important political events that have been observed in recent years (from 2010 in Hungary, 2015 in Poland, and 2018 in the Czech Republic). The illiberal turn, which has been identified as a very important event in the politics of the European Union in recent years [14], might have had a significant impact on the performance of stock markets in CEE-3 countries, as well as their integration with the markets of developed economies. The identification of this impact seems to be crucial from the point of view of policy of the European Union, as well as from the perspective of the future enlargement of the euro area. Secondly, apart from an analysis of correlations, an analysis of the volatility transmission mechanism seems to be important for international investors and policy makers. Studies of the performance of stock markets in CEE-3 countries based on the predictive directional measurement of volatility spillovers [15] seem to be neglected. Thirdly, many research studies (e.g., [16,17]) have been based on the estimation of the DCC-GARCH (Dynamic Conditional Correlation—Generalized Autoregressive Conditional Heteroscedasticity) model, assuming that positive and negative shocks have a symmetrical impact on market uncertainty. In this paper, the AGDCC-GARCH (Asymmetric Generalized Dynamic Conditional Correlation—Generalized Autoregressive Conditional Heteroscedasticity) framework (see [18]) is used, and an asymmetric impact of shocks on stock markets in CEE-3 countries is identified. Fourthly, on the basis of the methodology used for testing changes in the unconditional variance of financial time series [19,20], different states of stock markets in CEE-3 countries are identified. CEE-3 countries are compared in terms of moments of structural breaks. Correlations between shocks, as well as predictive directional volatility spillovers, are compared across sub-periods.

In this paper, co-movements between the stock markets of CEE-3 and developed countries are studied. Predictive directional volatility spillovers are measured, and an analysis of the volatility transmission is conducted. Apart from the stock markets in the Czech Republic, Poland, and Hungary, the main stock indices of developed and crisis-affected countries (the United States, Germany, and Spain) are used in the analysis. The period May 2004–June 2019 is considered. The differences in the volatility spillover mechanism among different sub-periods are studied as well. Moreover, based on the results, recommendations for policymakers and investors are provided.

The paper is structured as follows. In the second section, the literature review is provided. In the third section, materials and methods are presented. In Section 4, results of the estimation are presented and discussed. The fifth section concludes the study.

2. Literature Review

In the 20th century, the CEE-3 capital markets were poorly integrated with the markets of developed economies, and so to reduce investment risk, assets from post-transition economies were included in investors' portfolios [21]. The very low degree of global integration of the CEEC's stock markets before the EU's accession was identified by, among others, Mateus, Maneschiold and Nielsson [22–24]. An analysis of the sensitivity of the CEE-3 stock markets to external shocks during the dotcom crisis has indicated that the emerging European stock markets remained calm and did not tend to begin moving more similarly to the world market in the case of negative news [25].

The evidence of growing integration between emerging European stock markets and developed ones has been provided based on the analysis of data encompassing the EU-accession period [6]. The structural increase in the co-movements between stock returns in Central and Eastern European countries and the analogous returns of developed economies after the EU accession was identified by, among others, Grabowski [7]. However, the results obtained by Bein and Tuna [25] indicated that after the announcement of the CEE-3 countries' EU membership, all analyzed stock markets started to show the same level of volatility reactions to both positive and negative news that had the same magnitude. This result has been interpreted as an increase of confidence for investors after the announcement of the accession of CEECs to the European Union. The accession of the countries under consideration to the European Union on May 1, 2004, attracted the interest of many investors who had earlier refrained from investing in these countries because of political, corporate governance, and liquidity risks [26,27]. With a higher level of integration, a significant decrease in the benefits from using the portfolio diversification strategy was observed [28].

The role of the sub-prime crisis in shaping stock prices in Visegrad countries has been broadly discussed in the economic literature. The collapse of Lehman Brothers was identified as the most significant shock transmitted to CEECs' stock markets [5]. In Harkmann's article [17], it was reported that CEECs had exhibited increasing financial integration with Western European markets over time, with the peak corresponding to the Lehman Brothers' collapse. The findings of Syllignakis and Kouretas [16] suggested that the contagion transmission from the major stock markets to CEECs in the period of financial turmoil and the subprime crisis was a result of increased financial liberalization, as well as increased participation of foreign investors in the Central and Eastern European stock markets. As Bein and Tuna [25] noticed, during the financial turmoil, as well as during the subprime crisis, the stock markets of Poland, the Czech Republic, and Hungary tended to overreact to negative news. A strong contagion effect for emerging markets in Europe (Poland, the Czech Republic, and Hungary, among others) during the global financial crisis was identified by Das, Kannadhasan, Tiwari and Al-Yahyaee [29]. Their evidence indicated the coexistence of a contagion and a permanent change in the correlation structure. In Moagăr-Poladian, Clichici and Stanciu's article [30], it was reported that a significant increase in the volatility of correlations between CEECs and developed countries occurred after 2008. They noticed that the countries of Central and Eastern Europe were volatility takers in turbulent times, when the volatility spillovers were uncommonly high.

On the other hand, studies devoted to the impact of the sovereign debt crisis on stock markets in CEECs seem to be rare. The analysis of dynamic correlations conducted in Bein and Tuna's article [25] indicated that all the CEE-3 stock markets have been highly correlated with the finance-led markets of GIIPS (Greece, Ireland, Italy, Portugal, Spain), as well as with the EU3 (Germany, France, the United Kingdom), during the euro area sovereign debt crisis. Moreover, with the exception of the Greek market, a significant spillover effect from the peripheral euro-area countries to the CEE-3 markets has been noticed. Among the three stock markets in Visegrad countries, the Polish market has shown a significantly higher level of weighted average conditional correlation as compared to Hungary and the Czech Republic. Moreover, Bein and Tuna [25] noticed that Spain and Italy had higher levels of correlations with the CEE-3 countries in comparison with Greece, Ireland, and Portugal. However, volatility transmission between the mature (GIPSI and EU3) countries and the CEE-3 countries hardly changed during the sovereign debt crisis. Moreover, during the euro-area sovereign debt crisis (in comparison with the subprime crisis), stock markets in the CEE-3 countries became more resistant, and the financial spillover was less consequential [6]. Some findings in the literature devoted to the propensity of stock markets in Visegrad countries to external shocks have pointed out their asymmetric impact [6,7]. This result has been interpreted as a possibility of information asymmetry and the presence of agents with superior knowledge [31].

Interesting findings have been reported for the period of stability, starting with the announcement of the OMT (Outright Monetary Transactions) program. As Grabowski [7] noted, after the introduction of the OMT program, in Visegrad countries, the sensitivity of the stock market returns to external shocks became weaker, not only in comparison with the crisis period but in comparison with the pre-crisis period as well. Moreover, as Moagăr-Poladian, Clichici and Stanciu [30] noted, after 2012, the evolution of the stock market indices in Poland, the Czech Republic, and Hungary has followed different paths. The level of integration between stock markets in the CEE-3 countries has decreased significantly. Due to the lower level of market uncertainty, volatility spillovers have weakened. A significant decrease of a within-group integration of stock markets has been observed as well. A downward trend, with discrepancies between market returns observed after 2012, has generated opportunities for portfolio diversification [28].

Though the results of empirical studies have indicated that there are similarities in terms of the reaction of the stock markets of the CEE-3 countries to external shocks, as well as very large linkages among them, there have been some findings that show differences among countries from the group under consideration. The conclusions from these studies are mixed. For example, Pietrzak, Fałdziński, Balcerzak, Melzuin and Zinecker [2] found the existence of differences in time in the reaction of the stock markets of Poland and Hungary to changes in the situation on the stock market in Germany. The delayed reaction on the Hungarian stock market has been interpreted as a continuous adaptation of this market to the situation in the group that encompasses the stock markets of the Visegrad countries, Germany, and Austria. Grubel [4], utilized a Bayesian dynamic factor model to uncover the global, regional, and country factors driving the co-movement of rates of return of stock indices. The role of the global factor was found to be smaller in Poland than in the Czech Republic and Hungary. On the other hand, Poland was found to be characterized by the highest share of variation, as explained by the regional factor. The share of the country factor in the variation of rates of return was the lowest for Hungary.

The results obtained in Bieńkowski, Gawrońska-Nowak and Grabowski's article [6] indicated decreases in correlations between the stock returns of the CEE-3 countries during the euro-area sovereign debt crisis. In particular, these correlations concern such pairs as WIG-BUX (Warszawski Indeks Giełdowy- Blue Chip Index) and PX-BUX (Prague Index—Blue Chip Index). This may be due to the fact that in the period of the euro-area sovereign debt crisis, problems in Hungary's economy were much deeper than those of the Czech Republic and Poland. The perceptions of investors might have changed, and debt problems in Hungary's economy were not treated as if they were problems in the whole region. Hanousek, Kocenda and Kutan [32] proved that, in the stable period, the stock exchanges in Poland, the Czech Republic and Hungary did not react in a similar way to macroeconomic announcements and shocks from other markets. The results found Cerny and Koblas [33] for the period shortly after EU accession indicated that the stock market in the Czech Republic reacted faster (in comparison with Poland and Hungary) to the transmission of shocks from developed economies. A weaker reaction of the Polish stock market (in comparison with stock markets in the other Visegrad countries) to US macroeconomic announcements was found by Będowska-Sójka [34]. The weaker reactions of the Polish stock market in turbulent periods may have resulted from the fact that the traded volume due to foreign investors was much lower [35]. On the other hand, the results of some studies referring to the euro-area sovereign debt crisis have indicated that in the group of the CEECs, the Polish stock market has shown the highest level of correlation with mature markets [25].

3. Materials and Methods

Since we are interested in the co-movement between the stock market returns of the CEE-3 countries and the stock market returns of developed economies after the EU accession of Poland, the Czech Republic and Hungary, we defined r_t^{PL}, r_t^{CZ}, r_t^{HU} as the logarithmic rates of return on the indices of the WIG, PX, and BUX, respectively. The performance of economies of Central and Eastern Europe strongly depends on the performance of the German economy. Since the business cycles of the CEE-3 countries are strongly synchronized with the business cycles of Germany [36] and because the rates of return on these stock indexes depend on the rate of return on DAX (Deutscher Aktienindex) (e.g., [7]), the major stock market of the European Union (the German stock market) was taken into account. The logarithmic rates of return on the DAX (r_t^{DE}) were included in the analysis. The S&P500 (Standard & Poors 500) is the main index of the NASDAQ (National Association of Securities Dealers Automated Quotations) and the New York Stock Exchange, and it refers to the shock generator during the subprime crisis. Moreover, the importance of the stock market in the United States in influencing the performance of stock market indices all around the world implies that the logarithmic rates of return on the S&P500 (r_t^{US}) had to be included in our empirical study. In order to take into account the transmission of shocks from the crisis-affected countries during the euro-area sovereign debt crisis, the rate of return on the Spanish stock market was included in the empirical investigation. The results of various empirical analyses [6,25] have indicated that the performance of stock markets in CEE-3 countries during the euro-area sovereign debt crisis was strongly influenced by the performance of the Spanish stock exchange. We defined r_t^{ES} as the rate of return on the IBEX (Indice Bursatil Espanol) index. It should be added that our analysis was conducted from the perspective of international investors. Therefore, the values of stock market indices in national currencies were transformed into values in euros. Daily EUR/USD, EUR/PLN, EUR/CZK, and EUR/HUF exchange rates were used for transformation purposes.

In the first part of the empirical investigation, different states of stock markets in the CEE-3 countries were identified. The methodology proposed by Inclán, Tiao, Inclán, Aggarwal and Leal [19,20] was used and on the basis of the statistics:

$$IT = D_{k*}\sqrt{T/2}, \tag{1}$$

moments of significant changes in the unconditional variance were identified. In Formula (1), T denotes the number of observations, and D_{k*} is defined as follows:

$$D_{k*} = \begin{matrix} max \\ k \end{matrix} \ |D_k|, \tag{2}$$

where

$$D_k = \frac{C_k}{C_T} - \frac{k}{T} \tag{3}$$

and C_k is the cumulative sum of squares of a series of uncorrelated random variables. If the statistics provided by Equation (1) exceed the critical value of the limiting distribution (see [19]), then k* represents a statistically significant breakpoint.

The VAR-AGDCC-GARCH(1,1) (Vector Autoregressive-Asymmetric Generalized Dynamic Conditional Correlation—Generalized Autoregressive Conditional Heteroscedasticity) model enabled us to identify both the dependencies among rates of return and volatility spillover, as well as the shock transmission mechanism. It was assumed that current rates of return depend on the lagged rates of return in different markets. Moreover, correlations among shocks are time-varying.

We expected the following VAR(p)-AGDCC-GARCH(1,1) model to explain the performance of stock returns in all markets:

$$\mathbf{r}_t = \sum_{i=1}^{p} \mathbf{\Pi}_i \mathbf{r}_{t-i} + \boldsymbol{\varepsilon}_t \tag{4a}$$

$$E\left(\boldsymbol{\varepsilon}_t \boldsymbol{\varepsilon}_t^T\right) = \boldsymbol{H}_t, \tag{4b}$$

where $\boldsymbol{r}_t$ is the vector of rates of return on stock market indices considered in the previous section, i.e.,

$$\boldsymbol{r}_t = \left[r_t^{PL}\ r_t^{CZ}\ r_t^{HU}\ r_t^{US}\ r_t^{DE}\ r_t^{ES} \right]^T.$$

The covariance matrix was decomposed as follows:

$$\mathbf{H}_t = \mathbf{D}_t \mathbf{R}_t \mathbf{D}_t. \tag{4c}$$

where the matrix $\boldsymbol{D}_t$ consists of squared roots of variances of shocks.

$$\mathbf{D}_t = \mathrm{diag}\left(\sqrt{h_{11,t}}, \ldots, \sqrt{h_{NN,t}} \right). \tag{4d}$$

These variances of shocks are modelled using the GARCH(1,1) model:

$$h_{nn,t} = \alpha_{0n} + \alpha_{1n} \varepsilon_{n,t-1}^2 + \beta_{1n} h_{nn,t-1}, n = 1, 2, \ldots, N. \tag{4e}$$

Correlations between shocks are time-varying and depend on positive and negative shocks.

$$\mathbf{R}_t = (\mathrm{diag}(\mathbf{Q}_t))^{-1/2} \mathbf{Q}_t (\mathrm{diag}(\mathbf{Q}_t))^{-1/2} \tag{4f}$$

$$\boldsymbol{Q}_t = \left(1 - \widetilde{\alpha}_1 - \widetilde{\beta}_1\right)\overline{\boldsymbol{Q}} + \widetilde{\gamma}_1\left(\overline{\boldsymbol{Q}} - \overline{\boldsymbol{Q}^-}\right) + \widetilde{\alpha}_1 \boldsymbol{u}_{t-1} \boldsymbol{u}_{t-1}^T + \widetilde{\beta}_1 \boldsymbol{Q}_{t-1} + \widetilde{\gamma}_1 \boldsymbol{u}_{t-1}^- \left(\boldsymbol{u}_{t-1}^-\right)^T. \tag{4g}$$

The elements of vector $\boldsymbol{u}_t$ were defined as follows:

$$u_{n,t} = \frac{\varepsilon_{n,t}}{\sqrt{h_{nn,t}}}, \tag{4h}$$

where $\boldsymbol{u}_{t-1}^-$ consists of zero-threshold standardized errors and the matrixes $\overline{\boldsymbol{Q}}$ and $\overline{\boldsymbol{Q}^-}$ are the unconditional covariance matrix of vectors $\boldsymbol{u}_t$ and $\boldsymbol{u}_t^-$, respectively.

The moving-average representation of the rates of return is as follows:

$$\boldsymbol{r}_t = \sum_{i=0}^{\infty} \boldsymbol{A}_i \boldsymbol{\varepsilon}_{t-i}, \tag{5a}$$

where the coefficient matrices $\boldsymbol{A}_i$ obey the recursion:

$$\boldsymbol{A}_i = \mathbf{\Pi}_1 \boldsymbol{A}_{i-1} + \mathbf{\Pi}_2 \boldsymbol{A}_{i-2} + \ldots + \mathbf{\Pi}_p \boldsymbol{A}_{i-p}, \tag{5b}$$

with $\boldsymbol{A}_0$ being an identity matrix and with $\boldsymbol{A}_i = 0$ for $i < 0$.

The calculation of variance decompositions required orthogonal innovations, while innovations from model (1.a) were contemporaneously correlated. In order to circumvent this problem, the generalized VAR framework of Koop, Pesaran and Potter [37], as well as Pesaran and Shin [38], was exploited. As a result, invariants to the ordering variance decompositions were produced [15].

According to the approach proposed by Diebold and Yilmaz [15], own variance shares are defined as the fractions of the L-step-ahead error variances in forecasting r_{it} that are due to shocks to r_{it}, for i = 1, 2, ... , N, while cross-variance shares (spillovers) are defined as fractions of the L-step-ahead error variances in forecasting r_{it} that are due to shocks to r_{jt} for i,j = 1, 2, ... , N such that $i \neq j$. We denoted the L-step-ahead forecast error variance decompositions by $\theta^g_{ij}(L)$, for L = 1, 2, ... These time-varying decompositions were calculated according to the following formula:

$$\theta^g_{ij,t}(L) = \frac{h^{-1}_{jj,t} \sum_{l=0}^{L-1} \left(e_i^T A_l H_t e_j \right)^2}{\sum_{l=0}^{L-1} \left(e_i^T A_l H_t A_l^T e_j \right)}, \tag{6}$$

where $h_{jj,t}$ denotes the j-th diagonal element of the matrix $\boldsymbol{H}_t$, and $\boldsymbol{e}_i$ is the selection vector, with one as the i-th element and zeros otherwise. Next, each entry of the variance decomposition matrix was normalized by the row sum:

$$\widetilde{\theta}^g_{ij,t}(L) = \frac{\theta^g_{ij,t}(L)}{\sum_{j=1}^{N} \theta^g_{ij,t}(L)}. \tag{7}$$

On the basis of normalized contributions defined according to Formula (7), the total volatility spillover index was constructed as follows:

$$S^g_t(L) = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \widetilde{\theta}^g_{ij,t}(L)}{\sum_{i,j=1}^{N} \widetilde{\theta}^g_{ij,t}(L)} * 100 = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \widetilde{\theta}^g_{ij,t}(L)}{N} * 100. \tag{8a}$$

The directional volatility spillovers received by market i from all other markets were calculated according to the formula:

$$S^g_{i*,t}(L) = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} \widetilde{\theta}^g_{ij,t}(L)}{N} * 100, \tag{8b}$$

while the directional volatility spillovers transmitted by market i to all other markets were measured as follows:

$$S^g_{*i,t}(L) = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} \widetilde{\theta}^g_{ji,t}(L)}{N} * 100. \tag{8c}$$

If a country receives volatility from other markets, the value of the quantity (Formula (8b)) is high. On the other hand, in the case of countries transmitting volatility to other markets, the value of the quantity (Formula (8c)) is large.

The net volatility spillover from market i to all other markets was calculated according to the following formula:

$$S^g_{i,t}(L) = S^g_{i*,t}(L) - S^g_{*i,t}(L) \tag{8d}$$

Countries that are volatility givers are characterized by a positive value of this quantity.

In order to examine the net pairwise volatility spillovers, the following formula was used:

$$S^g_{i,t}(L) = \left(\frac{\widetilde{\theta}^g_{ji,t}(L) - \widetilde{\theta}^g_{ij,t}(L)}{N} \right) * 100 \tag{8e}$$

In a pair of two countries, a positive or negative value of this quantity informs which market gives and which receives more volatility.

As a robustness check, the parameters of the factor model were estimated. Yields on German bunds (y^{DE}) were used as the risk-free rate of return.

4. Results and Discussion

On the basis of the literature review and the introduction section, we set the following hypotheses:

H1. *The stock markets of CEE-3 countries were volatility takers.*

H2. *The intensity of volatility spillovers to the CEE-3 stock markets is stronger in turbulent periods than in tranquil periods.*

H3. *The reaction of stock markets in the CEE-3 countries to external shocks is characterized by asymmetry.*

Table 1 presents dates of significant (at the 0.01 level of significance) changes in the unconditional variance.

Table 1. Identification of the days of a statistically significant breakpoints.

Country	Dates
Poland	08/07/2007; 09/15/2008; 10/09/2009; 07/27/2012
the Czech Republic	08/08/2007; 09/12/2008; 10/08/2009; 07/25/2012
Hungary	08/09/2007; 09/11/2008; 10/09/2009; 07/26/2012

The results of the analysis indicates that similar dates of structural breaks in the Polish, Czech and Hungarian stock market were identified. On the basis of the obtained results, the following five phases could be distinguished:

period of stability on the financial markets (05/01/2004–08/08/2007)—Phase I,
period of financial turmoil (08/09/2007–09/12/2008)—Phase II,
period of the subprime crisis (09/15/2008–10/09/2009)—Phase III,
period of the euro area sovereign debt crisis (10/10/2009–07/26/2012—Phase IV,
post-crisis period (07/27/2012–06/30/2019)—Phase V.

Table 2 presents the results of the selection procedure of the optimal lag length for the VAR-AGDCC-GARCH model. The results indicated that the model with 1 lag was an optimal choice.

Table 2. Choosing lag length for the VAR-DCC-GARCH (Vector Autoregressive-Dynamic Conditional Correlation- Generalized Autoregressive Conditional Heteroscedasticity) model.

Lag Length	AIC
1	−2497.32
2	−2495.98
3	−2495.13
4	−2494.87

Table 3 presents the results of the estimation of the parameters of the VAR(1)-AGDCC-GARCH(1,1) model.

Table 3. Results of the estimation of the parameters of the VAR(1)-AGDCC-GARCH model.

	r_t^{US}	r_t^{DE}	r_t^{ES}	r_t^{PL}	r_t^{HU}	r_t^{CZ}
			Mean equation			
r_{t-1}^{US}	−0.061 ***	0.097 ***	0.027 **	0.037 ***	0.034 **	0.053 ***
r_{t-1}^{DE}	0.090 ***	−0.041 *	0.037 ***	0.040 ***	0.054 ***	0.078 ***
r_{t-1}^{ES}	−0.001	0.009	−0.008	0.008	−0.018	0.068 ***
r_{t-1}^{PL}	0.037	0.039 *	0.020	0.029	0.065 ***	0.065 ***
r_{t-1}^{HU}	−0.013	−0.014	−0.001	−0.039 **	−0.055 ***	0.000
r_{t-1}^{CZ}	−0.012	0.020	0.017	0.041 **	0.013	−0.099 ***
			Variance equation			
ε_{t-1}^2	0.056 ***	0.049 ***	0.059 ***	0.049 ***	0.059 ***	0.064 ***
σ_{t-1}^2	0.929 ***	0.936 ***	0.928 ***	0.928 ***	0.924 ***	0.919 ***
			Covariance equation			
$\widetilde{\alpha}_1$				0.011 ***		
$\widetilde{\beta}_1$				0.975 ***		
$\widetilde{\gamma}_1$				0.008 ***		
			Correlations			
corr($\varepsilon_t^{US}, \varepsilon_t^{DE}$)	0.532 ***	corr($\varepsilon_t^{DE}, \varepsilon_t^{ES}$)	0.765 ***	corr($\varepsilon_t^{ES}, \varepsilon_t^{HU}$)	0.441 ***	
corr($\varepsilon_t^{US}, \varepsilon_t^{ES}$)	0.458 ***	corr($\varepsilon_t^{DE}, \varepsilon_t^{PL}$)	0.571 ***	corr($\varepsilon_t^{ES}, \varepsilon_t^{CZ}$)	0.417 ***	
corr($\varepsilon_t^{US}, \varepsilon_t^{PL}$)	0.333 ***	corr($\varepsilon_t^{DE}, \varepsilon_t^{HU}$)	0.486 ***	corr($\varepsilon_t^{PL}, \varepsilon_t^{HU}$)	0.569 ***	
corr($\varepsilon_t^{US}, \varepsilon_t^{HU}$)	0.288 ***	corr($\varepsilon_t^{DE}, \varepsilon_t^{CZ}$)	0.414 ***	corr($\varepsilon_t^{PL}, \varepsilon_t^{CZ}$)	0.477 ***	
corr($\varepsilon_t^{US}, \varepsilon_t^{CZ}$)	0.263 ***	corr($\varepsilon_t^{ES}, \varepsilon_t^{PL}$)	0.524 ***	corr($\varepsilon_t^{US}, \varepsilon_t^{DE}$)	0.431 ***	
			Degrees of freedom			
cons				8.713 ***		

*, **, and *** denote significance at the 0.1, 0.05, and 0.01 levels of significance, respectively.

The results of the estimation indicated that the analyzed stock markets are characterized by a very high level of persistence. The estimation of the parameter $\widetilde{\beta}_1$ was close to 1, which informs us about the very high persistence of covariances between shocks. A very high level of average correlation between shocks was observed for the Germany–Spain pair. Since both countries are representatives of the eurozone, shocks, especially during the euro-area sovereign debt crisis, had a significant impact on the performance of stock returns on the IBEX and DAX. Among the three CEE countries, the Polish stock market has shown a significantly higher level of conditional correlation with the Spanish, German, and American stock markets compared to Hungary and the Czech Republic. Similar findings were obtained by Bein and Tuna [25]. The high level of conditional correlation between shocks generated by Germany and the US is not surprising. Major stock markets react similarly to important shocks. In particular, negative shocks generated in the US stock market during the subprime crisis have resulted in similar reactions in the major European stock market [6]. The estimate of the parameter $\widetilde{\gamma}_1$ indicates that reaction of stock markets in the CEE-3 countries to external shocks is characterized by asymmetry, which is in line with the H3hypothesis.

The results of the empirical investigation are in line with the findings of other studies. However, some differences are observed as well. These differences may be due to the longer time horizon of the research (data covering the period until June 2019 are used) and the taking of the perspective of an international investor. Significant and positive estimates of parameters measuring the impact of lagged rates of return of the S&P500 on the rates of return in Poland, the Czech Republic, and Hungary were in line with expectations. They inform us about the very important impact of the US stock market on the euro-area and transition countries. On the other hand, stock returns in the US were dependent only on stock returns in Germany. This result is not surprising because the United States is a global economic player, and the condition of the stock market in that country does not depend on the situation in transition economies or the situation in the Spanish capital market. It should be added that at the beginning of trading sessions on the stock exchanges in Europe, investors' moods are based on the performance of stock exchanges in countries located in other time zones. However, this impact is not the same for all countries in Central and Eastern Europe. The Czech stock market proved to be the most affected in the analyzed group. A similar result concerning the sensitivity of stock markets in the CEE-3 countries was obtained by Bieńkowski, Gawrońska-Nowak and Grabowski [6], who found that the Czech stock market reacted more strongly to fluctuations of the rates of return on the S&P500 than the stock markets in Poland and Hungary. Moreover, the impact of the rates of return of the DAX index on fluctuations of the rates of return on the BUX, WIG, and PX proved to be strong and significant. Due to very strong linkages between the German economy and the economies in the Visegrad countries, the level of synchronization of the business cycle in the Visegrad countries with the German business cycle is very high. Therefore, stock markets in CEE countries are very sensitive to fluctuations in stock returns in Germany. The lagged rates of return on the IBEX proved to be significant in the equation that explained rates of return on the PX. The intense flight to quality was proven by significant linkages among the rates of return of the CEE-3 countries. Problems and dips in one of the markets in the CEE-3 countries were treated as if they signaled adverse financial conditions in the region. However, the estimate of the parameter for the variable r_{t-1}^{HU} in the equation that explained r_t^{PL} proved to be negative. This result may be explained by differences in the business cycle in these two countries in the last few years [7]. In the period of the euro-area sovereign debt crisis, problems in Hungary's economy were much deeper than in the Czech Republic and Poland. The perceptions of investors changed, and the debt problems in Hungary's economy were not treated as if they were problems in the whole region. On the other hand, the pension system reform of 2013 in Poland, as well as political tensions in 2016, had a negative impact on the performance of the Polish stock exchange. In 2016, the BUX grew by 44%, while the WIG declined by 10%. The negative estimate of the parameter for the variable r_{t-1}^{HU} in the equation that explained r_t^{PL} may be interpreted as a possibility of shifts in portfolios of investors in recent years. When problems in Hungary's economy have been deep-rooted, international investors have gotten rid of assets from this country and have bought equities in Polish companies. On the other hand, in periods of political tension in Poland, the equities of Hungarian firms have been treated as an appropriate alternative to the stocks of Poland.

Figure A1 (Appendix A) presents the performance of variances of shocks for developed countries, while the variances of shocks for the CEE-3 countries are shown in Figure A2 (Appendix A).

Figure A1 shows that after Lehman Brothers was declared bankrupt, a significant increase in the volatility of shocks was observed in the case of all three developed stock markets. Volatility patterns proved to be very similar in the case of the American and German stock markets. The Spanish stock market has been characterized by a significant increase in volatility of shocks in periods of financial turmoil, as well as in the most turbulent moments of the euro-area sovereign debt crisis. This result is not surprising since, as Grabowski and Stawasz-Grabowska [39] showed, credit rating downgrades and negative news concerning the real economy, economic growth, and the sustainability of public finances resulted in very significant increases of uncertainty during the euro-area sovereign debt crisis. Since the largest intensity of negative news concerning Spain was observed in the middle of 2010, in the autumn of 2011 and the first half of 2012, a significant increase in the volatility of shocks generated by Spain in these periods was in line with expectations. After the announcement about the OMT program by the European Central Bank in July 2012, the situation of the financial markets in the peripheral euro-area countries calmed down, which is in agreement with findings of other studies [40–43].

An analysis of Figure A2 indicates that in all three CEE stock markets, a substantial increase of uncertainty was noticed after Lehman Brothers was declared bankrupt. The beginning of the second sub-period was characterized by a very large increase of uncertainty worldwide. However, the sensitivity of stock markets in the CEE-3 countries proved to be different during the euro-area sovereign debt crisis. Since the Polish stock market has been characterized by the highest level of stock market capitalization in comparison with Hungary and the Czech Republic [2], and has been more integrated with the mature markets of the peripheral euro-area countries during the debt crisis [25], stronger reactions of the rates of return on the WIG to external shocks were recorded between 2010 and 2012. In the group that encompasses the Czech Republic and Hungary, the volatility of shocks generated by the Czech stock market seems to be more synchronized with the volatility of shocks generated by Spain. Though the total capitalization of the Budapest stock exchange exceeds the capitalization of the Prague stock exchange, problems in Hungary's economy have been much deeper than in the Czech Republic and Poland, so the sensitivity of the Hungarian stock market to external shocks between 2010 and 2012 was weaker.

Figure A3 (Appendix A) presents the conditional correlations between shocks in the group of CEE-3 countries, while conditional correlations between shocks in the group of developed countries are shown in Figure A4 (Appendix A). In Figure A5 (Appendix A), conditional correlations between shocks from the CEE-3 and developed countries are provided.

Conditional correlations for developed markets are higher and have different paths than the correlations for the CEE-3 countries. Between 2004 and 2006, the stock markets of Poland, the Czech Republic, and Hungary were relatively weakly integrated with the stock markets of developed economies. The level of conditional correlations for US–Spain, US–Germany, and Germany–Spain was high, even between 2004 and 2006. The faster reaction of the Prague stock market (in comparison with markets in Warsaw and Budapest) to the transmission of shocks from developed economies shortly after the EU accession is in line with results obtained in Savva and Aslanidis's article [44]. In 2007 and 2008, a significant increase in conditional correlations for all pairs was recorded. The results that showed an increase in stock market co-movements of the CEE-3 countries with the mature stock markets after EU accession are in line with the findings obtained by the authors of [10]. However, the conditional correlations between the stock market returns of CEE-3 countries and developed ones decreased after the end of the US sub-prime crisis. This finding is consistent with the results of Pietrzak, Fałdziński, Balcerzak, Melzuin and Zinecker's article [2], who noted a slower process of integration of the CEE-3 markets with the developed ones. Due to the difference in terms of both the size of the economy and the exchange rate regimes, there was a substantial difference in the reaction to external shocks by the Baltic and CEE-3 countries [45]. During the global financial crisis, the former became fully integrated with the financial markets of developed countries.

The stock markets in the CEE-3 countries proved to be sensitive to external shocks during the euro-area sovereign debt crisis. This finding has been confirmed by a significant increase in conditional correlations between shocks for the IBEX–WIG, IBEX–BUX, and IBEX–PX pairs in 2011 and 2012. In the case of the Czech Republic, the stock market of this country proved to be more integrated with the Spanish stock market during the euro-area sovereign debt crisis than with the American market during the sub-prime crisis. However, in general, the level of sensitivity of the CEE-3 stock markets to global shocks decreased in the period of the euro-area sovereign debt crisis in comparison with the sub-period of the sub-prime crisis [7].

Since 2013, a significant drop in conditional correlations between shocks generated by CEE-3 countries and shocks generated by mature markets has been observed. It turned out that after the introduction of the OMT program, the sensitivity of the stock market returns in Poland, the Czech Republic, and Hungary to external shocks became weaker, not only in comparison with the crisis period but also in comparison with the pre-crisis period [7]. Moreover, after 2013, a significant decrease in conditional correlations between shocks for pairs in the group of CEE-3 countries has been recorded. This finding is confirmed by the results obtained by, among others, the authors of [30], who noted that the evolution of the stock indices in the CEE-3 countries followed different paths after 2012.

In order to evaluate the shock transmission mechanism, the Diebold–Yilmaz volatility spillover index (DYVSI), as well as directional volatility spillovers received by markets and transmitted from markets, Formulas (3), (4) and (8a)–(8c) were applied. Since the variances of shocks and the covariances between them are time-varying, the value of the index proposed by Diebold and Yilmaz [15], as well as the quantities of Formulas (8b) and (8c), differ across time. Therefore, the average values of the Diebold–Yilmaz volatility spillover index, as well as the average directional volatility spillovers, were calculated. Table 4 presents the performance of the Diebold–Yilmaz volatility spillover index, as well as directional volatility spillovers for all six countries.

Table 4. Performance of the Diebold-Yilmaz volatility spillover index (DYVSI) and volatility spillovers.

	Phase I	**Phase II**	**Phase III**	**Phase IV**	**Phase V**
DYVSI	0.49	0.65	0.70	0.62	0.53
Spillover to the US	0.40	0.52	0.53	0.38	0.39
Spillover from the US	0.66	0.83	0.85	0.78	0.67
Spillover to Germany	0.59	0.70	0.72	0.69	0.62
Spillover from Germany	0.60	0.72	0.73	0.69	0.65
Spillover to Spain	0.58	0.70	0.71	0.66	0.60
Spillover from Spain	0.54	0.64	0.66	0.69	0.59
Spillover to Poland	0.52	0.69	0.70	0.68	0.55
Spillover from Poland	0.43	0.56	0.57	0.51	0.42
Spillover to Hungary	0.48	0.67	0.69	0.65	0.49
Spillover from Hungary	0.40	0.58	0.60	0.50	0.40
Spillover to the Czech Republic	0.42	0.64	0.69	0.64	0.48
Spillover from the Czech Republic	0.36	0.60	0.63	0.53	0.40

Table 5 presents the performance of the net pairwise volatility spillovers for all pairs and all phases. Bold numbers denote net pairwise volatility spillovers for the group that encompasses developed countries. Italic numbers denote net pairwise volatility spillovers between developed and CEE-3 countries. Underlined numbers provide information about the net pairwise volatility spillovers for all pairs that encompass CEE-3 countries.

Table 5. Net pairwise volatility spillovers for all pairs and for all phases.

	The US	**Germany**	**Spain**	**Poland**	**Hungary**	**The Czech Republic**
The US	-	**I 0.043 II 0.057 III 0.093 IV 0.122 V 0.075**	**I 0.027 II 0.049 III 0.099 IV 0.067 V 0.022**	*I 0.099 II 0.110 III 0.158 IV 0.115 V 0.048*	*I 0.093 II 0.101 III 0.207 IV 0.139 V 0.038*	*I 0.038 II 0.076 III 0.124 IV 0.058 V −0.032*
Germany	**I −0.043 II −0.057 III −0.093 IV −0.122 V −0.075**	-	**I 0.035 II 0.060 III 0.077 IV 0.081 V 0.025**	*I 0.036 II 0.145 III 0.161 IV 0.168 V 0.075*	*I 0.109 II 0.188 III 0.243 IV 0.184 V 0.037*	*I 0.023 II 0.080 III 0.116 IV 0.101 V −0.091*
Spain	**I −0.027 II −0.049 III −0.099 IV −0.067 V −0.022**	**I −0.035 II −0.060 III −0.077 IV −0.081 V −0.025**	-	*I 0.051 II 0.135 III 0.077 IV 0.186 V −0.011*	*I 0.084 II 0.129 III 0.113 IV 0.248 V 0.004*	*I 0.040 II 0.004 III 0.114 IV 0.129 V −0.020*
Poland	*I −0.099 II −0.110 III −0.158 IV −0.115 V −0.048*	*I −0.036 II −0.145 III −0.161 IV −0.168 V −0.075*	*I −0.051 I −0.135 II −0.077 IV −0.186 V 0.011*	-	I −0.039 II −0.029 III −0.045 IV −0.094 V −0.027	I 0.072 II 0.069 III 0.058 IV 0.065 V 0.072
Hungary	*I −0.093 II −0.101 III −0.207 IV −0.139 V −0.038*	*I −0.109 II −0.188 III −0.243 IV −0.184 V −0.037*	*I −0.084 II −0.129 III −0.113 IV −0.248 V −0.004*	I 0.039 II 0.029 III 0.045 IV 0.094 V 0.027	-	I 0.068 II 0.080 III 0.093 IV 0.133 V 0.088
the Czech Republic	*I −0.038 II −0.076 III −0.124 IV −0.058 V 0.032*	*I −0.023 II −0.080 III −0.116 IV −0.101 V 0.091*	*I −0.040 II −0.004 III −0.114 IV −0.129 V 0.020*	I −0.072 II −0.069 III −0.058 IV −0.065 V −0.072	I −0.068 II −0.080 III −0.093 IV −0.093 V −0.088	-

Notes: please explain. Bold numbers denote net pairwise volatility spillovers for the group that encompasses developed countries. Italic numbers denote net pairwise volatility spillovers between developed and CEE-3 countries, while underlined numbers provide information about the net pairwise volatility spillovers for all pairs that encompass CEE-3 countries.

The obtained results indicate that the largest value of the Diebold–Yilmaz volatility spillover index was recorded in the most turbulent phases of the global financial crisis. An increase in volatility spillovers between markets at the onset of the financial crisis is in line with expectations. Between 2007 and 2009, stock markets were very sensitive to external shocks, and the performance of a domestic economy had a weaker impact on the rates of return on financial markets. A similar increase in volatility transmission in emerging European currency markets after 2007 was found by, among others, the authors of [46]. During the euro-area sovereign debt crisis, most of the volatility generated in specific stock markets was transmitted to other markets as well. However, in the analyzed group of countries, the level of the volatility transmission mechanism proved to be weaker than during the sub-prime crisis and in the period of financial turmoil. This finding can be explained by the different roles played by the American stock market and the stock markets in peripheral euro-area countries in the global financial system. The results of numerous studies have confirmed the dominant role played by the US equity market in the system of world stock markets [6]. Though Spain is geographically closer than the US, turbulences in the Spanish market have had a weaker impact on volatility spillover in the group that encompasses the countries of Central and Eastern Europe. Moreover, the euro-area sovereign debt crisis mainly concerned bond markets. During this sub-period, the equities of developed and safe countries (the United States and Germany) offered better investment opportunities than the bonds of the peripheral euro-area countries. Due to a very high risk of Grexit and the insolvency of Greece, a stronger panic was observed in the bond and currency market [47]. The stock markets of the euro-area peripheral countries (the Spanish stock market, among others) plunged, but their impact on stock markets in other countries was weaker. It is not surprising that in the last analyzed phase, the level of volatility spillover proved to be much lower than during the global financial crisis. It is commonly known that after the announcement of the OMT program, the situation of the financial markets calmed down, and linkages among stock market returns were much weaker [48,49]. Therefore, the phenomenon of the volatility transmission was much weaker than in the crisis period. The process of increasing the integration of the financial markets of Central and Eastern European countries with developed ones has stopped. A significant decrease in the level of interdependence of the stock markets of the CEE-3 countries with the German and American capital market has been found by other authors in studies that encompass data from 2013–2017 [6,7]. Moreover, a decrease of the Diebold–Yilmaz volatility spillover index in recent years can be justified by the home bias phenomenon, which can be explained by factors such as hedging home risk, barriers to foreign investments, information asymmetries, and behavioral factors [46].

An analysis of the volatility spillovers “from” and “to” indicated that the stock markets of developed countries were the givers of shocks, while the capital markets of the CEE-3 countries were the recipients. Identifying the stock markets of the CEE-3 countries as volatility takers is in line with findings obtained, among others, by Grabowski and Welfe [50]. This tendency was observed in all analyzed phases. However, the level of spillover “from” and “to” differed significantly across sub-periods. For example, volatility spillover from the US was strongest during the period of the financial turmoil and during the sub-prime crisis. It turns out that the influence of shocks coming from the world’s key economic player, which is located a great distance away, is more important than the impact of regional shocks coming from geographically closer countries that may not be so globally important. Volatility spillover from the US weakened in the phase of the euro-area sovereign debt crisis. In this phase, there were no turbulences in the American stock market, so volatility was not transmitted to other countries. However, the phenomenon of volatility spillover from a crisis-affected country (Spain) turned out to be weaker. This may have been for at least two reasons. Firstly, Spain is not a key economic player, and the shocks generated by the stock exchange in this country have a weaker impact on other markets. Secondly, the first wave of the crisis might have provided information regarding which classes of assets were riskier or safer. Therefore, agents investing in the stock markets of the CEE-3 countries were less sensitive to external shocks that arose during the euro-area sovereign debt crisis. The sensitivity of the stock markets in Poland, the Czech Republic, and Hungary decreased significantly after the announcement of the OMT program. Volatility spillover to the Warsaw, Prague, and Budapest stock markets was much weaker after 2013. However, these stock markets became more sensitive to internal shocks. Moreover, in all three analyzed countries, some important internal events affected the performance of financial markets. For example, the contribution of pension funds in Poland had a negative impact on the performance of the Polish stock exchange. Moreover, in recent years, the intensity of press releases concerning political instability in countries from the analyzed group has increased significantly. The illiberal turn turned out to have a negative impact on the level of integration of CEE-3 stock markets with developed ones.

These results are in line with expectations and show that the countries of Central and Eastern Europe were recipients of volatility from major stock markets (American and German), as well as from the stock market of the crisis-affected country, during the euro-area sovereign debt crisis. This result is not controversial because the stock markets in Warsaw, Prague, and Budapest do not play a dominant role in the world's financial system. The obtained result is in line with the Hypothesis H1. The strongest transmission of volatility from the US to Poland, the Czech Republic, and Hungary was noticed in the period of the subprime crisis. When the level of uncertainty in the US stock market was high, an increase in volatility on the stock markets in the CEE-3 countries was immediate. Positive net pairwise volatility spillovers were also observed for the Germany–Poland, Germany–the Czech Republic, Germany–Hungary, Spain–Poland, Spain–the Czech Republic, and Spain–Hungary pairs. The highest positive values for the Spain–Poland, Spain–the Czech Republic, and Spain–Hungary pairs were recorded for the period of the euro-area sovereign debt crisis. After October 2009, the debt problems of the peripheral euro-area countries had a negative impact on their financial markets (the Spanish stock market, among others). Therefore, the level of uncertainty on the Spanish stock market was high. This uncertainty was transmitted to the CEECs because the euro-area economies are among the largest trading partners of Poland, the Czech Republic, and Hungary. As a result, the euro-area sovereign debt crisis led to an increase of uncertainty on stock markets in Central and Eastern European countries. The highest value of the net pairwise volatility spillover in the fourth phase was observed for the Spain–Hungary pair. This may have been due to the significant internal problems of Hungary between 2011 and 2012. The stock markets in other countries did not react to shocks generated in the Budapest stock exchange. Therefore, the volatility spillover from Spain to Hungary was very intense, while the spillover in the opposite direction was negligible. This result may have also been due to the very low share of the country factor in the variation of rates of return for Hungary [1]. As a result, the Hungarian stock market receives a lot of volatility from mature stock markets and gives them very little volatility. In line with expectations, net pairwise volatility spillovers between developed and CEE-3 stock markets decreased significantly after the announcement of the OMT program. A decrease in the sensitivity of stock markets to external volatility in the CEE-3 countries after 2012 is in line with the H2 hypothesis and the findings of other studies covering this period [7,30].

An analysis of the net pairwise volatility spillovers indicated that the Czech Republic received volatility and Hungary transmitted it. However, the absolute values of net pairwise volatility spillovers were rather low. The high level of correlations between shocks and the low absolute values of net spillovers tells us that none of the three analyzed countries dominates in providing shocks to other economies. In the group of the CEE-3 countries, volatility was transmitted between all countries and in all directions.

Table 6 presents the results of the estimation of the parameters of the factor model that explains performance of the rates of return on WIG, BUX and PX. These results may be treated as a robustness check. It turns out that the rate of return on WIG, BUX and PX strongly depends on the rate of return on stock markets in the richest and most crisis-affected countries. However, the role of the US and German stock markets turned out to be more important than the role of the Spanish stock exchange. The obtained results confirm findings from the research presented above.

Table 6. Results of the estimation of the parameters of the factor model.

	Poland	The Czech Republic	Hungary
Germany	0.30 ***	0.23 ***	0.24 ***
the United States	0.23 ***	0.26 ***	0.32 ***
Spain	0.21 ***	0.20 ***	0.21 ***

*, **, and *** denote significance at the 0.1, 0.05, and 0.01 levels of significance, respectively.

5. Conclusions

In the empirical investigation, the volatility spillovers between CEE-3 stock markets and mature markets were studied. Five phases of the financial markets' performance were distinguished. The evidence suggests that the highest intensity of volatility transmission was observed during the period of financial turmoil, as well as during the US subprime crisis. During the euro-area sovereign debt crisis, the reactions of investors were more differentiated, since the first wave of the crisis provided information about which classes of assets were riskier or safer. The presence of the home bias phenomenon, justified by hedging home risk, barriers to foreign investment, information asymmetries, and behavioral factors, may explain a significant decrease in volatility spillovers after the announcement of the OMT program.

High levels of correlations between shocks generated in the CEE-3 countries during unstable periods indicates that herding behaviors occurred in the Visegrad countries in the phase of financial turmoil, in the phase of the US sub-prime crisis, and during the euro-area sovereign debt crisis. This means that in the turbulent period, a negative shock in one country was treated as a disturbance in the whole region. Thus, stock markets in the CEE-3 countries did not differ from the currency markets, which were also characterized by very strong interlinkages in turbulent periods [48,50].

An analysis of net pairwise volatility spillovers between markets showed that the stock markets of Poland, the Czech Republic, and Hungary are volatility takers. They received a great deal of volatility from the American, German, and Spanish stock markets, and they transmitted little volatility to other markets. The intensity of taking shocks from mature stock markets differed across phases. In the phase of financial turmoil and in the phase of the US sub-prime crisis, very intensive volatility transmission from the US was recorded. The German stock market also proved to be an important giver of volatility to the stock markets of the CEE-3 countries. The phenomenon of volatility spillover from Spain turned out to be much weaker than the spillover from Germany and the US. The high level of correlations between the shocks generated in the CEE-3 countries, as well as the low absolute values of net spillovers, tells us that none of the three analyzed countries have dominated in providing shocks to other economies. In the group that encompasses Poland, the Czech Republic, and Hungary, volatility was transmitted between all markets and in all directions.

The results provide recommendations for policymakers of the CEE-3 countries. Firstly, since Poland, the Czech Republic, and Hungary are volatility takers and receive a great deal of volatility from mature stock markets, policymakers should monitor the level of uncertainty in mature stock markets in order to identify a risk of an increase in volatility in the domestic market. In particular, the monitoring process should be intense during the turmoil phases. Moreover, policymakers should be cautious in the case of negative shocks in one country of the CEE-3 group. Such a shock may lead to adverse conditions in other countries of this region.

The results could also provide recommendations for investors. High correlation levels indicate that benefits from portfolio diversification are limited. This concerns turbulent periods in particular. However, the evidence suggests that in recent years, diversification opportunities have been much better due to lower correlations among shocks. Portfolio analyses that encompass the assets of the countries of Central and Eastern Europe should take problem of volatility spillovers into account the. Since Poland, the Czech Republic, and Hungary are volatility takers, investors should take into account not only the implied volatility for the Warsaw, Budapest, and Prague stock markets but also volatility spillover measures and the volatility of mature markets.

The most important limitation of the paper is that it is based on the analysis of only three stock markets in Central and Eastern Europe. Future research will be devoted to the analysis of co-movements for larger group of countries in Central and Eastern Europe.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

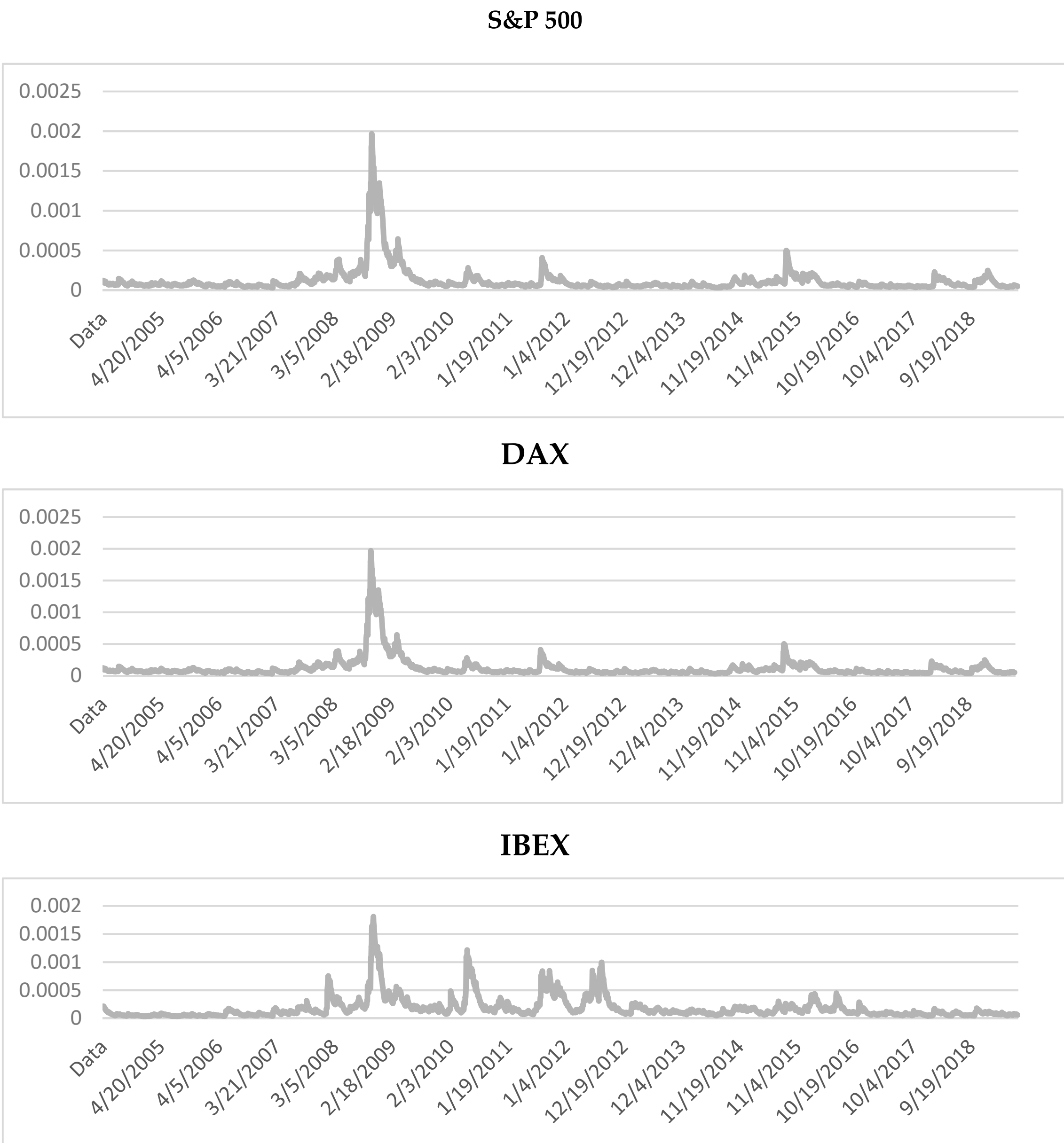


Figure A1. Time-varying volatility of shocks for developed countries.

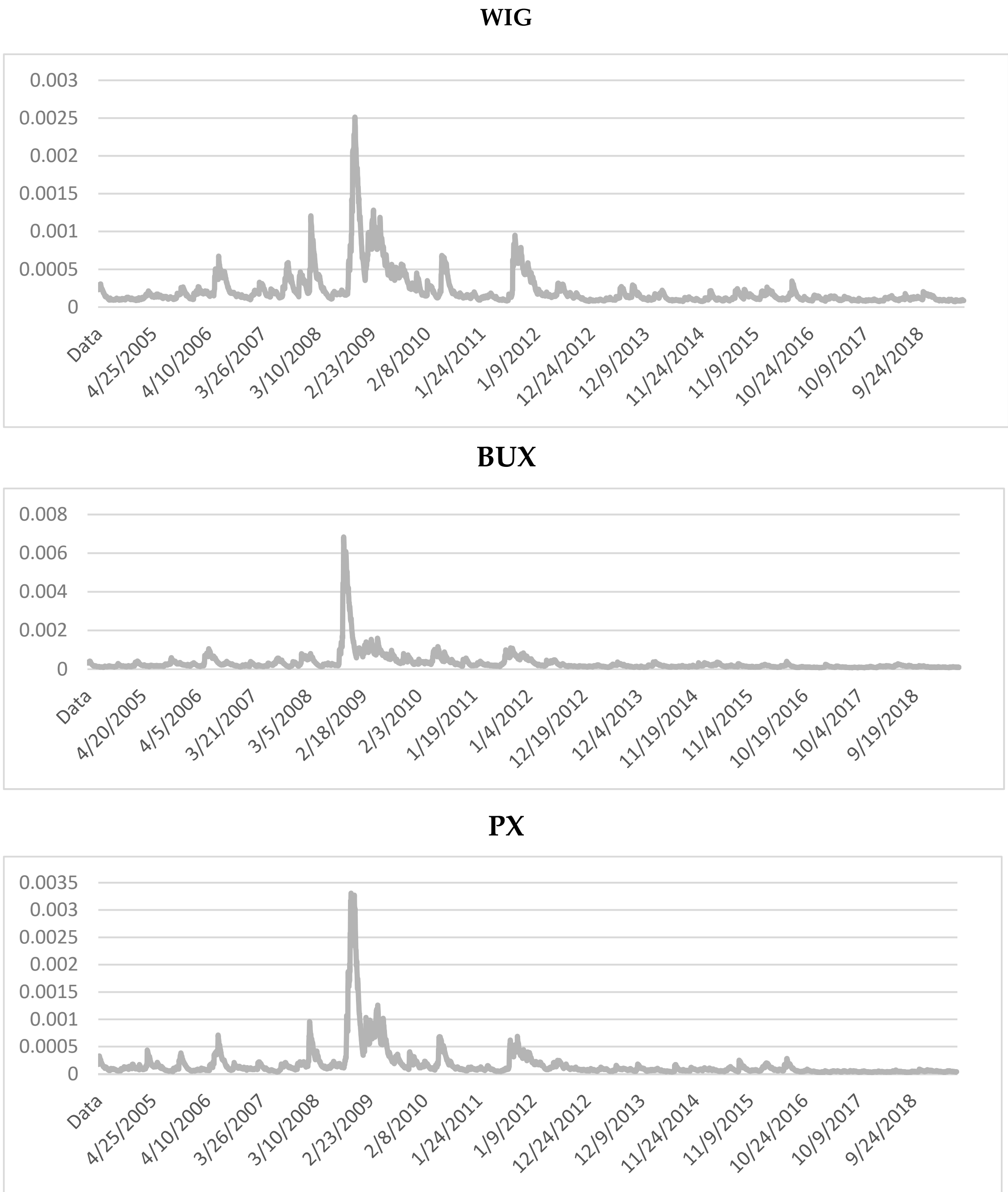


Figure A2. Time-varying volatility of shocks for the CEE-3 (Central and Eastern European: the Czech Republic, Hungary and Poland) countries.

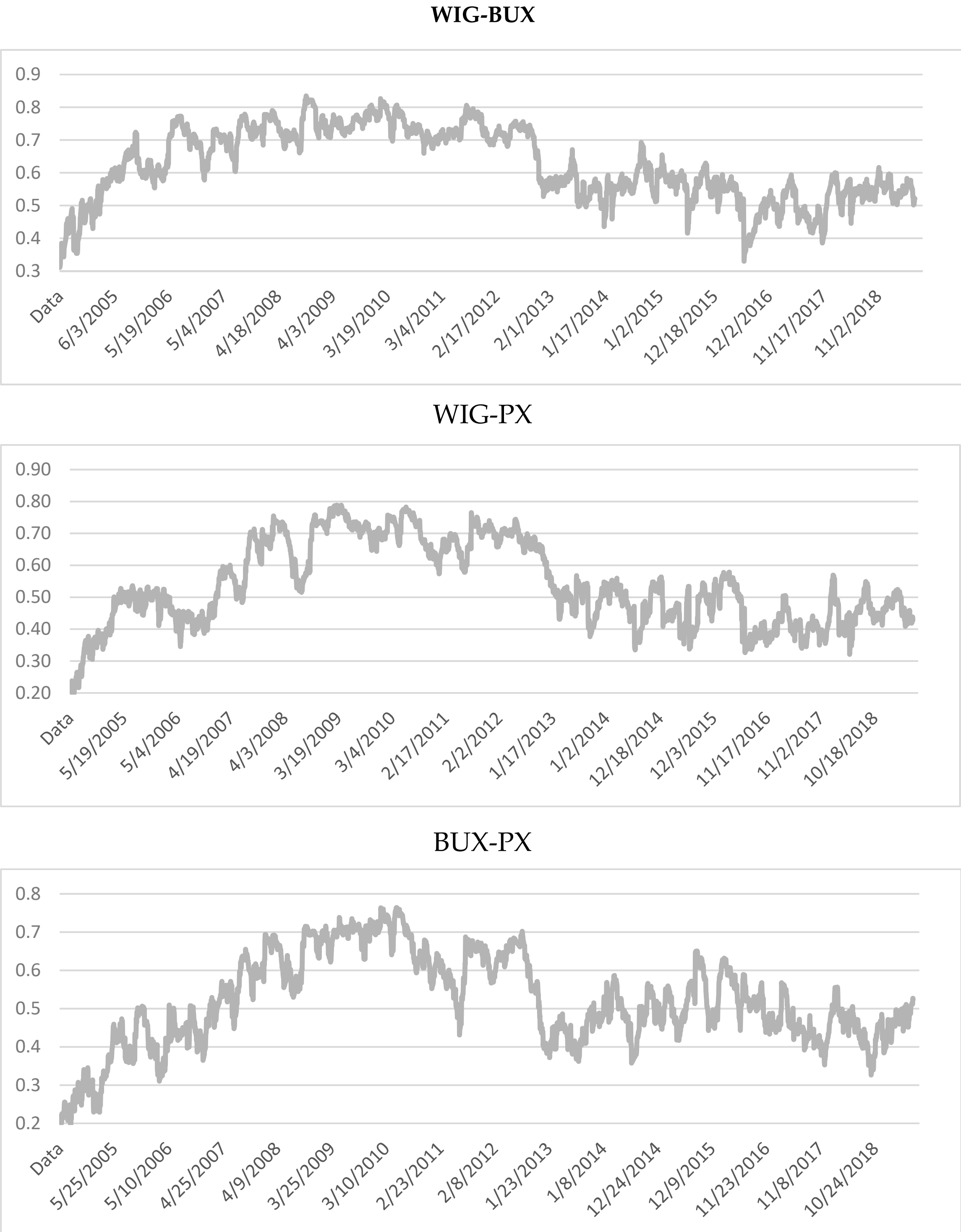


Figure A3. Conditional correlations between shocks in the group of CEE-3 countries.

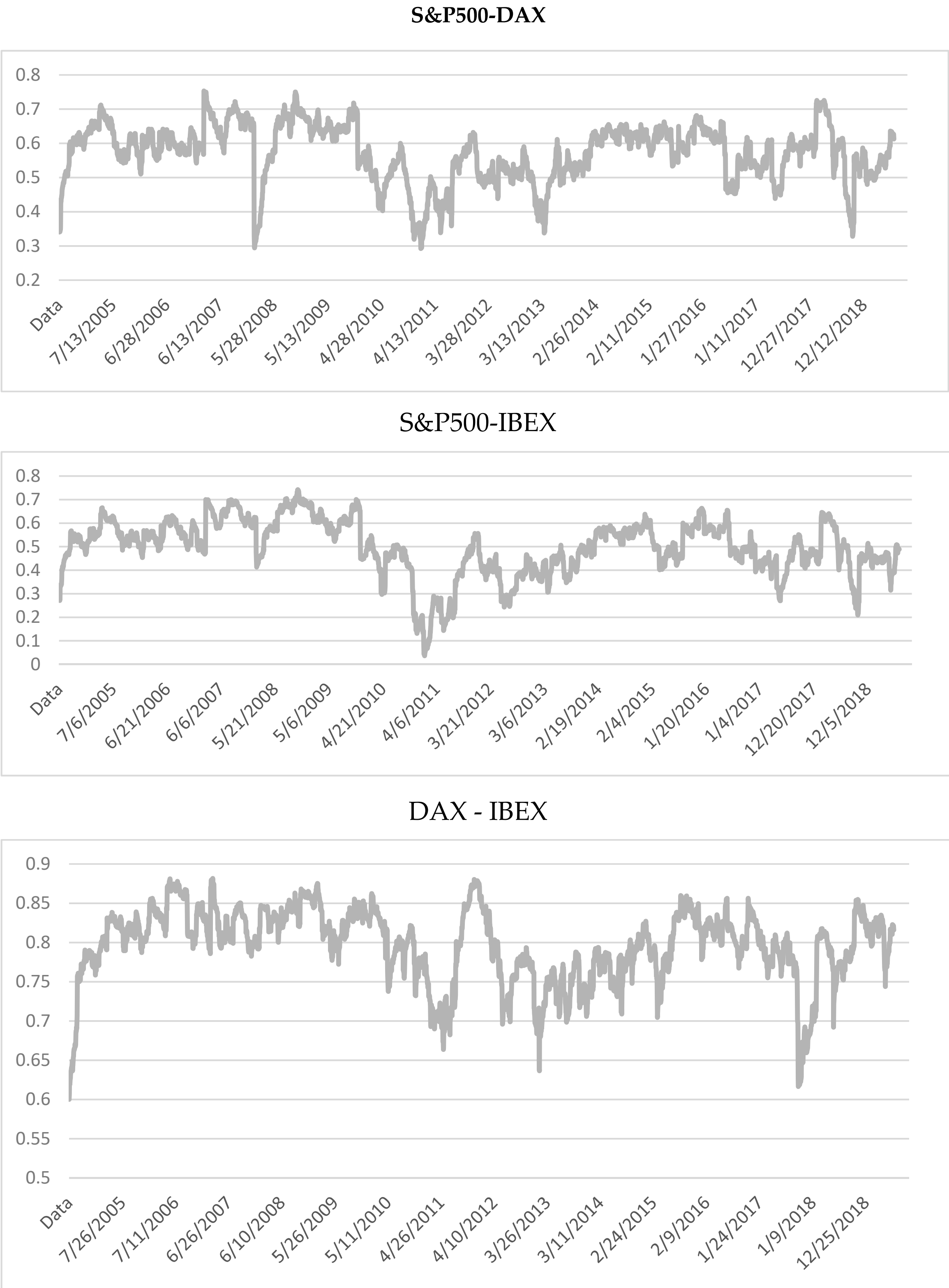
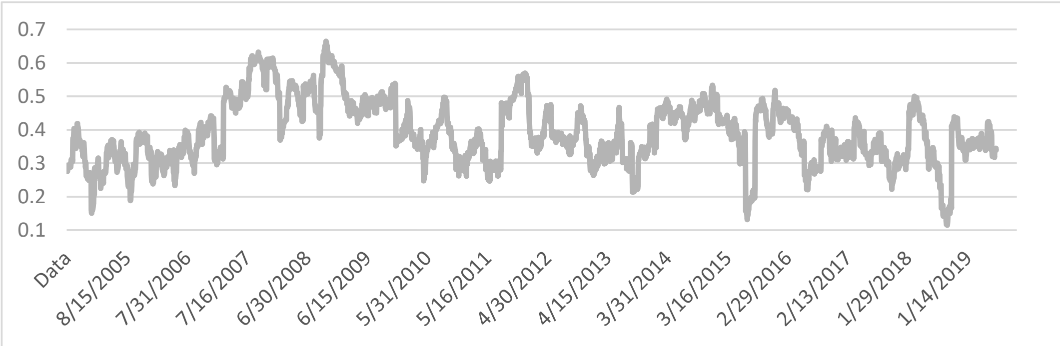
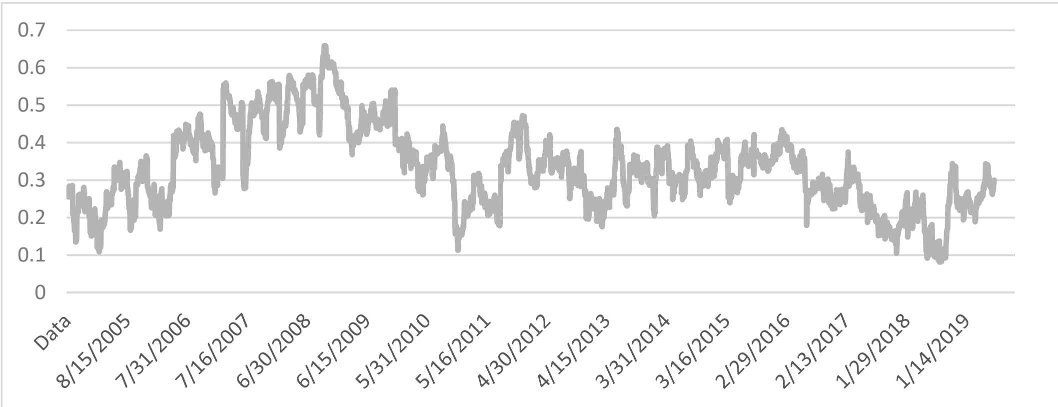


Figure A4. Conditional correlations between shocks in the group of developed countries.

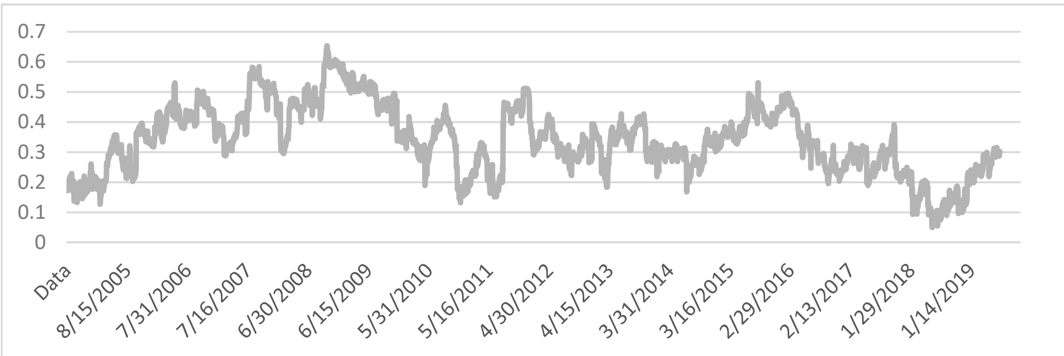
S&P500 - WIG



S&P500 - BUX



S&P500 - PX



DAX – WIG

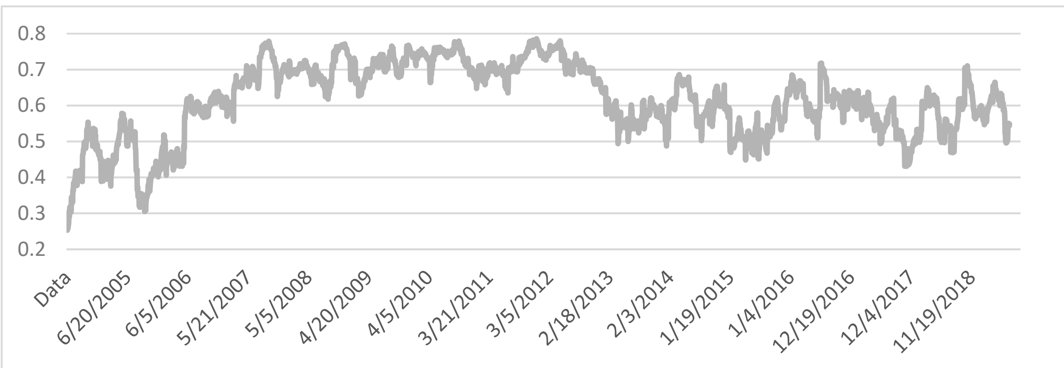


Figure A5. *Cont.*

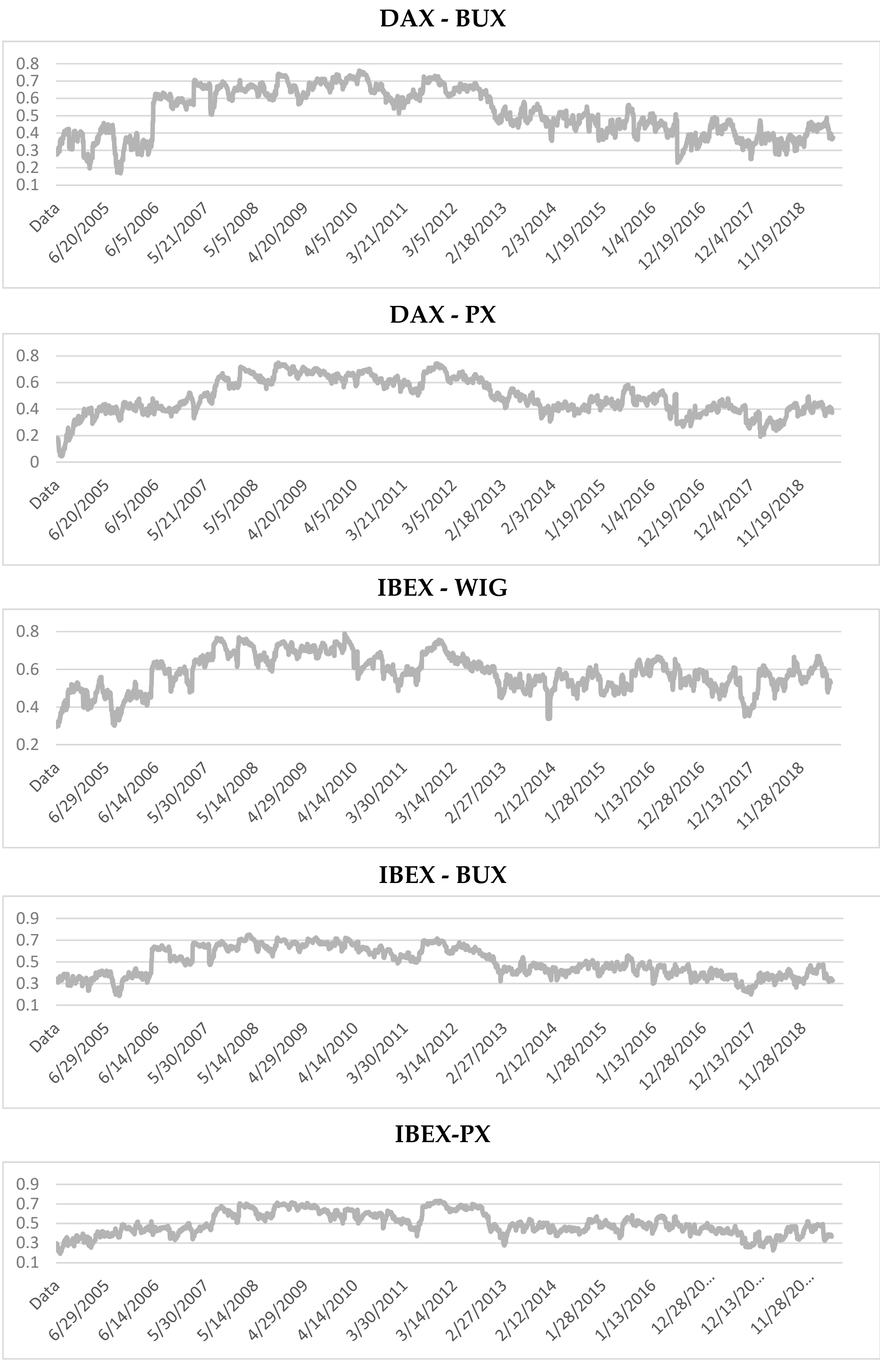


Figure A5. Conditional correlations between shocks in the group of developed countries.

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