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VOLATILITY SPILLOVER OF THE STOCK MARKET AND FOREIGN EXCHANGE: EVIDENCE FROM CEE COUNTRIES

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INTRODUCTION

0.1 Background

Contagion is associated with a structural change in the international spillover mechanism. Spillover effects from both the stock markets and foreign exchange rate movements have drawn the attention of researchers, policymakers and other economic agents since the global financial crisis of 2008. It is well known that this crisis has demonstrated market contagion being one of the major consequences of financial crises. Recent economic downturns have often comprised the contagion of stock markets and foreign exchange rates. These co-movements are a direct symptom of a pervasive uncertainty that goes beyond the boundaries of the individual market, including emerging and frontier markets in Europe (Bubák et al. 2011). As Yilmaz (2010) reveals that financial market crises have become a more frequently observed phenomenon, especially in emerging market economies. Moreover, it is believed that volatility transmissions in the CEE stock and foreign exchange markets are not only impacted by its own shock but also by other countries' financial market. Volatility spillovers are argued to be more noticeable among countries that operate in the same region because they are characterized with similar cultural and policies implementation as well as closely related in terms of trade policies (Sok-Gee et al. 2010). Additionally, Diebold and Yilmaz (2012) suggest that one way of establishing an early-warn-system is by observing spillovers to create information about upcoming crises. They further added that the investigation of spillover effects can also demonstrate the progress of the ongoing crisis and the impacts of policy interventions on economy recover. Thus, analysis of volatility transmissions should not only take into consideration spillovers from its own markets but also the spillover effects from neighboring nations. One of the primary complements of this thesis is to analyze and identify different channels of return connectedness and volatility spillovers across five financial markets in CEE countries (Hungary, the Czech Republic, Croatia, Romania and Poland) with empirical applications in the stock and foreign exchange markets in each selected CEE country (chapter II), integration of the stock markets (chapter III), and exchange rate sector (chapter IV). Hence, this thesis further contributes to spillover literature. Several previous scholars have analyzed spillover effects during the periods of economic distress. For instance, the 1987 European market crisis is studied by (see, e.g., Arshanapalli and Doukas, 1993; Koutmos and Booth, 1995; Meric. I and Meric G. 1997), some investigations study the Russian financial crisis such as (see, e.g., Patev et al. 2006; Diebold and Yilmaz, 2009), the 1997 Asian financial crisis (see, e.g., Arshanapalli et al. 1995; Jang and Sul, 2002; Karunanayake et al. 2010). More recently, (Sidek et al. 2011; Srivastava et al. 2015; Bae and Zhang, 2015; Maghyereh et al. 2015; Jin and An, 2016; Jebran et al. 2017; Bajo-Rubio et al. 2017) investigate stock market integration in the 2007 financial crisis period.

Thoroughly, spillover analysis is functional for policy implications and can be employed in divergent fields of economics and social science. It is obvious that the way of capturing and forecasting spillovers as well as its asymmetry is of great importance. Therefore, accurate examinations allow policymakers to interfere in the economy properly and reduce or overcome deleterious effects.

The main framework that this thesis builds upon is the return and asymmetric volatility spillovers approach of the multivariate Exponential Generalized Autoregressive Conditional heteroskedasticity (EGARCH) model proposed by Nelson (1991), which permits to identify which forces drive the relevant markets and which are driven by those markets. This approach allows us to estimate return and volatility spillovers without the restriction of a specific structure in terms of the contemporaneous correlation, asymmetric spillover effects. Furthermore, based by several diagnostics, Nelson (1991) and Engle and Ng (1993) find that the EGARCH model executes better than other GARCH-type models since the latter tends to underpredict volatility related to negative innovations. In a same vein, Lim and Sek (2013) show that asymmetric EGARCH models can be the better model to forecast and capture the volatility. The main advantage of the EGARCH model is that there are no parameter restrictions required to guarantee positive variance all the time (Koutmos and Booth 1995). This is significant because some of the coefficients in the conditional variance specification violate the non-negativity assumption (Hamao et al. 1990). Briefly, modelling the multivariate EGARCH model can successfully capture the price and volatility spillovers among financial markets in the selected countries. To measure the accuracy and reliability of the return and volatility spillovers, bivariate EGARCH is introduced in chapter II, multivariate EGARCH is employed in chapter III and chapter IV respectively. Thus, the second main concentration of this thesis is that the method employed is a multivariate extension of Nelson (1991) univariate EGARCH model. Modeling the return and spillover effects of the five financial CEE markets simultaneously has several advantages over the univariate approach that has been used so far. First, it removes the two-step procedure, thereby keeping away from problems of estimated regressors. Second, it enhances the efficiency and the power of the tests for cross market spillovers. Third, it is methodologically compatible with the conception that spillovers are significant demonstrations of the influence of worldwide news on any given markets. Specifically, the multivariate EGARCH model allows own market and cross market shocks to utilize an asymmetric effect on the volatility in a given market based on the test of asymmetries.

In addition, the analysis of volatility spillover in the emerging and frontier markets in CEE countries served as the subject of interest for most international portfolio managers as these markets provide further portfolio diversification and offer a higher rate of return to investors because these markets are somewhat risky as compared to the financial markets in the advanced economy (Sok-Gee et al. 2010). According to Koutmos and Booth (1995), portfolio managers can make use of information of the market they involved in transactions as well as information from other stock markets which are relevant to the movement in the domestic markets. Additionally, financial markets in the CEE countries are believed to bring opportunities for international investors since this region is well-known for its political stability. Hence, in-depth analysis of these markets concerning the volatility of its financial markets will shed some lights to portfolio managers in connection with the risk associated with investments in these markets.

Overall, the ultimate goal of this thesis is to extend previous methodologies and findings related to return and volatility spillovers in financial markets and to fill some lacunae in the literature.

0.2 Overview

This thesis includes three main topics in the field of spillovers using the multivariate EGARCH model. Put differently, this thesis is making use of a battery of econometrical models described in each chapter to capture return and volatility spillovers. The structure of the thesis is as follows

Chapter I represents the literature overview

Chapter II examines the dynamics of volatility spillover between stock and foreign exchange market: Empirical evidence from Central and Eastern European countries.

Chapter III addresses the question: Does volatility transmission between stock market returns of Central and Eastern European countries vary from normal to turbulent periods?

Chapter IV investigates volatility behavior of the foreign exchange rate and transmission among Central and Eastern European countries

Chapter I briefly reviews several articles that investigate the volatility spillovers among financial markets in the CEE countries.

Chapter II investigates the asymmetric volatility spillover effects between stock and foreign exchange markets using daily data. Obviously, the interlinkage between the two main financial markets had produced loads of papers for a long time. According to Wong (2017), the interrelatedness between stock prices and exchange rates may influence the execution of monetary policy and fiscal policy. Furthermore, a strong connectedness between them would have significant implications for economic policies and international capital budgeting decisions because negative innovations influencing one market may be quickly dispatched to another through contagious effects (Chkili and Nguyen, 2014). Kanas (2000) concludes that the huge increase in interdependency has also increased volatility spillovers between stock and foreign exchange markets. For example, Kanas (2000), Yang and Doong (2004), Aloui (2007), Valls and Chuliá (2014), Mozumder et al. (2015), Segal, Shaliastovich and Yaron (2015), Jebran and Iqbal (2016), Baruník, Kočenda and Vácha (2016) among others analysed the links between stock and foreign exchange returns.

Bivariate EGARCH model is employed to examine the volatility spillovers and co-movement between stock and foreign exchange markets of the five CEE countries. The entire investigation period is subdivided into two sub-periods:

the pre-crisis period, from 1 April 2000 to 29 August 2008; and the post-crisis period, from 1 September 2008 to 29 September 2018. The results point to bidirectional volatility spillovers between the stock and foreign exchange markets of Hungary in all periods, and of Poland in the post-crisis period, unidirectional volatility spillovers in Croatia in the pre-crisis period, and from the stock market to the exchange market in the Czech Republic during two periods. In the post-crisis period, the two financial markets show the absence of volatility spillovers in Croatia.

Chapter III focuses on the integration of the CEE stock markets using daily data that also subdivided into pre and post the global financial crisis. The main reasons why to investigate the transmission mechanism of price and volatility spillovers across Budapest, Warsaw, Prague, Bucharest and Zagreb stock markets is threefold. First, the pivotal role of emerging markets which is becoming more interesting for investors and policymakers. Second, Central and Eastern European countries have attempted to increase cooperation and trade among themselves. Third, we modeled the possible returns and asymmetric volatility spillovers among five emerging markets in which previous studies only focused on the dynamic relationship between returns and transmissions. There have been numerous investigations among stock markets in different countries to identify the transmission mechanism (Jebran et al. 2017; Huo and Ahmed, 2017; Bala and Takimoto, 2017; Ghouse and Khan, 2017; Baumohl et al. 2018; Mensi et al. 2018; Morales Zumaquero and Sosvilla Rivero, 2018; Caloia et al. 2018; Lau and Sheng, 2018; BenSaida et al. 2018; Tiwari et al. 2018; Ahmed and Huo, 2018; Naresh et al. 2018; Xuan Vinh and Ellis, 2018).

The main aim of this chapter empirically formulates and estimates the volatility spillover by a multivariate EGARCH model of the daily stock markets returns for selected countries. The model is employed to examine the first and second-moment interdependencies among the various markets. The results reveal that the volatility transmission mechanism is asymmetric, bad news in a given market increase volatility in the next market to trade considerably more than positive innovations for the whole period. However, these results exclude the Croatian stock market in the pre-crisis period and the Czech Republic stock market in the post-crisis period. We find evidence of price spillovers of the intraregional linkages among the stock price movements in the five Central and

Eastern European countries. For the second moment interactions, the results highlight certain interesting findings that the stock markets are more substantially integrated into a crisis.

Finally, chapter IV focuses on the foreign exchange rate markets in the CEE countries based on the model developed in chapter III. There is a slight difference between the model used in chapter III, we also apply the multivariate EGARCH model but the first moment of return series are used in the mean equation instead of the second moment in chapter III. This measure represents the magnitude of asymmetric shocks and the degree of bilateral interrelatedness because these markets are less volatile than stock returns. Over the past several decades, the majority of Central and Eastern countries running de jure floating exchange rate regimes have smoothly progressed. There are several substantial papers such as (Fidrmuc and Horváth, 2008; Bubak, 2009; Greenwood et al. 2016) who are interested in the analysis of foreign exchange market interdependence and detection of the return and volatility spillovers targeting at helping many market participants make the financial decisions.

This study utilizes the daily US dollar exchange rate data in an attempt to answer the question of the changing nature of volatility spillovers among foreign exchange markets in these nations. The findings indicate that the return spillovers exhibit more significant in the pre-crisis period than in the post-crisis period in the CEE countries. The foreign exchange markets become more independent in a crisis situation. Similarly, the volatility spillover between the foreign exchange markets decreases dramatically and financial markets have not been transmitted during the crisis period. The results also show that Polish and Romania exchange markets influence other markets, especially during the turmoil period. These results raise a question related to the role of market consensus versus information during the period of stress. It would be tested by future researchers using new or more enhanced models to capture the effects and predictions of volatility behavior during the extreme turbulent periods.

Based on the three above topics, we have produced three paper-based thesis namely, "Dynamics of volatility spillover between stock and foreign exchange market: empirical evidence from Eastern European countries", "Does volatility transmission between stock market returns of Central and Eastern European countries vary from normal to turbulent periods? evidence from EGARCH model?" and "Volatility Behavior of the Foreign Exchange Rate and Transmission among Central and Eastern European Countries: Evidence from EGARCH model", respectively, which are accepted for publication.

LITERATURE OVERVIEW

There are countless studies conducted in exploring integration and spillover effects across financial markets in the finance literature. Most of the researchers made their significant contribution to the existing literature by filling the gap of exploring knowledge about the volatility transmission mechanism of the dynamic linkage between the exchange rates and the stock market in the different countries. In this study, we primarily based on the previous literature in connection with the topic of volatility transmission across countries. In addition, the flow-oriented and stock-oriented models are two original models widely used by the majority of the previous investigations.

1.1 The flow-oriented model

This model based on the idea that the exchange rate is primarily determined by a country's account balance. The flow-oriented model suggests that a positive relationship between the exchange rate and stock prices. In this model, Dornbusch and Fischer (1980) assumes that changes in the foreign exchange rate can affect international competitiveness and trade balance. Therefore, they affect real income and inputs. The model posits that the causality relationship running from exchange rate to stock prices can be explained as follows: the domestic currency depreciation will make local firms more competitive by making cheaper exports in international trade. The higher exports will lead to the higher wealth of firms by appreciating the domestic firm's stock prices.

1.2 The stock-oriented model

Branson and Henderson (1985), Frankel (1983) report that the exchange rate is determined by the demand and supply of financial assets such as equities and bonds. This model is classified into monetary models and portfolio balance model. The model suggests that there is a negative relationship between stock prices and exchange rates. It means that stock prices have an impact on exchange rates. Such model reports that investors hold local and foreign assets such as domestic and foreign currencies. According to the portfolio balance model, an increase in domestic assets stock price will result in domestic currency depreciation, so investors tend to buy more domestic assets and sell foreign assets so as to have more local currency in hand for the purpose of purchasing new domestic assets. This mechanism will lead to domestic currency depreciation. The increase in wealth of investors due to increase in domestic assets price stimulate investor's portfolio decisions. Thus, higher interest will motivate foreign demand for domestic currency in order to buy new domestic assets. This will lead to currency appreciation. The monetary approach postulates the exchange rate as the price of the financial asset. Because the value of a financial asset is determined by the present value of anticipated cash flows, the exchange rate is determined by all the macroeconomic factors affecting the anticipated value

1.3 Volatility and its properties

According to Alexander (2008a), volatility depicts the annualized standard deviation of the returns on investment. To wit, volatility of an asset can be accurately defined as an annualized measure of the dispersion in a stochastic process that is applied to model log returns. Investments or equities can be of various types. Volatility, as a measure of portfolio risk, presents annualized standard deviation of portfolio returns (Alexander, 2008b). Additionally, volatility of a stock price or an exchange rate is a measure of uncertainty of future stock price or exchange rates movements and uncertainty about the returns provided by the stock or exchange rate. Therefore, volatility of a stock price or an exchange rate portrays standard deviation of the return provided by the stock or exchange rate in one year, when return is continuous compounding. As per (Hull, 2005), the volatility of a stock or an exchange rate is impacted by new information. Investors will revise their opinions about the value of a stock or an exchange rate, based on the innovation, and the price will be able to change and this will cause volatility to change as well. In an economic context which is arbitrage-free, volatility of asset prices is directly connected to the rate of information flow into the market (Ross, 1989). Nevertheless, Hull (2005) documents that volatility is also caused by trading to a great extent. A definition of spillover is established by Engle et al. (1990), markets operate effectively during a day when one market closes, another opens. As a result, information set for current market consists of yesterday’s news, and today’s news from the previously closed market. Allen et al. (2013) report that if one market volatiles resulting in a volatility of other markets or Lee (2013) says that if one market volatiles giving rise to lagged volatility in other market, these situations can be referred to as spillover effects. The terms of volatility spillover and volatility transmission are used interchangeably in the literature (Abbas et al. 2013).

Tsay (2005) reports some essential properties of the volatility of asset returns because it has many financial applications and it has a significant determinant for options trading. Volatility modelling could calculate the value at risk of financial position which is used for risk management and enable asset allocation under a mean-variance framework. Volatility has several characteristics that are commonly found in asset returns, which play a prominent role in the development of the volatility model.

- Volatility has a property of clustering, meaning that in a certain period volatility can be very low, and in other periods it can be quite high. Volatility is observed in clusters that a large shock in one direction tends to be followed by another large shock in the same or opposite direction. Whether volatility is going to occur or not depends on the types of input data, and it is more common to appear with the daily data than the weekly or monthly data (Alexander 2008a).
- Volatility develops continuously, which means that volatility jumps are rare
- Volatility does not converge to infinity. It alternates in some ranges which implies that volatility is often stationary.
- Property of volatility is the leverage effect. This assumes that volatility reacts differently when there is a substantial price increase, rather than it does when there is a significant drop in asset price.

Alexander (2008a) documents that the assumption of return series is independent and identically distributed for the study period when modelling volatility, which implies that volatility is constant. Also, in discrete time this assumption is a feature of the equally weighted moving average estimates.

1.4 Volatility spillovers

Financial integration exists when the price movements of national stock indices or exchange rates are found to exhibit a long-run casual relationship. Therefore, the interdependence among the stock market exists where local share markets will respond similarly to common shock. The market is supposed to be inefficient when there are causal linkages among stock or exchange markets in the same region (Sok and Gee et al. 2010).

The theoretical literature on crises, contagion, and volatility spillover effects is extensive (Engle et al. 2012). From an econometric point of view, various of methodologies was adopted according to the particular interest of correlation across markets. Engle et al. (1990) employ GARCH models where either market activity in one country is present as a predetermined variable in the conditional variance of another country or the full conditional covariances are estimated. Volatility spillover is often captured in the different sorts of the GARCH-type models.

The concept of volatility spillover of asset returns can be drawn from the seminal work of (Engle et al. 1990). The authors showed the theoretical foundations for own and cross-type spillovers. The heat-wave hypothesis representing own-spillover reveals that present volatility of a market is a function of past volatility of the same market. On the other hand, the meteor-shower hypothesis representing cross-spillover illustrates that the present volatility of a market is a function of both past volatility of the same market and past volatility from other markets. It is widely noted that the meteor-shower definition of spillover encompasses both own and cross aspects.

In the empirical study, it has been proven that there is mixed evidence of own and cross phenomenon, it means that financial indices depict heat wave and meteor shower types of spillover. When markets are integrated, individually, they can get affected by the news and events emanating from each other’s socio-political, economic, legal, environmental, trade, commerce, and market innovation scenarios. It is obvious that markets integrated displays cross-market spillover in more pronounced manner. However, it has also been empirically found that markets that are not fully integrated show cross-market spillover mostly during a financial crisis, a phenomenon which is generally termed as financial contagion.

Foster and Nelson (1994) contribute a significant characteristic regarding volatility spillover to literature, that is the salient property of asymmetric. Volatility transmission also exhibits asymmetry with regards to the kind of news. Bad news seems to have a severe effect on spillover as compared to good news. This asymmetric property of spillover is a prime contributor to the cause of financial contagion.

Two main reasons for studying volatility spillover are: First, it relates to the notion of market efficiency, the own aspect of spillover is a direct result of the level of efficiency in the market. The higher level of spillover indicates the lower level of efficiency. Second, volatility transmission gives information towards the level of market integration, the cross aspect of spillover measures the extent to which markets are integrated. Higher the interdependence among markets, higher will be the cross-market spillover and greater would be chance of contagions occurring in the event of a financial crisis.

It is clear in the context of the literature, the volatility spillover can be divided into three fundamental points: first, a bidirectional volatility spillover among financial markets; second, a unidirectional flow of volatility from one market to another market and vice versa; third, non-persistence of the volatility spillover among them.

1.5 Volatility spillover in the CEE markets

The growing role of emerging financial markets in a real-world economy enhances the international investor to invest in new emerging markets with two main purposes of higher returns and risk diversification. According to Habiba et al. (2019), the degree of integration among various financial markets brings about the potential benefits from international portfolio diversification, meaning that there is no gain from portfolio diversification if the capital markets of various nations are totally integrated. Therefore, volatility transmissions among financial markets are indispensable for global investors because the dynamic linkages of financial prices affect the optimal strategy of investment and diversification.

Furthermore, volatility in a variable over a period of time leads to unpredictability, uncertainty and risk, which impacts investor's wealth and rises the bid ask spread that signifies the significant role of risk management.
A large part of the literature on the recent financial market integration has discussed volatility spillovers focusing on stock indices and currency prices. Table 1 represents a brief summary of the existing empirical analysis. GARCH-type family approaches have been employed to depict how innovations propagate, whether some connectedness among different markets exist, and how they change, if at all, during a crisis.

1.6 The EGARCH model

The finance literature is rich on the topic of interconnectedness among different financial markets. The aim of this research is to examine the return relationships and asymmetric volatility transmissions among financial markets of emerging countries in the CEE context. We employ the exponential generalized autoregressive conditional heteroskedasticity (EGARCH) model to capture the return linkages and asymmetric volatility spillovers across the CEE markets. The EGARCH model has an idiosyncratic property, which is able to explore the leverage effect of volatility – leverage effect (negative returns create more variations than positive returns) that makes model asymmetric. EGARCH model allows the variations to respond freely as the time series fall because of the negative innovations than with corresponding rises owing to the positive innovations.

ARCH (AutoRegressive Conditional Heteroscedasticity) models were gently introduced by Engle (1982), GARCH (Genenrealised AutoRegressive Conditional Heteroscedasticity) by Bollerslev (1986) and EGARCH (Exponential Genenrealised AutoRegressive Conditional Heteroscedasticity) by Nelson (1991). These models are extensively employed in various fields of econometrics, especially in financial time series analysis. Nelson (1991) proposed the exponential GARCH model in an attempt to capture the asymmetric impact of innovations on volatility, based on which many empirical studies have appeared (see, for example, Koutmos and Booth 1995; Yang and Doong 2004; Mishra et al. 2007; Bhar and Nikolova, 2009; Sok et al. 2010;

Okicic 2014; Jebran et al. 2017; Elyasiani and Mansur, 2017 etc…). Koutmos and Booth (1995) pointed out a multivariate extension of Nelson (1991) univariate EGARCH model to facilitate a simultaneous investigation of the asymmetric impact of good news and bad news on the volatility spillover across markets. In this study, bivariate and multivariate EGARCH models were applied through three primary research questions as mentioned earlier. The specifications of the EGARCH model should be illustrated in each separately part of this thesis or in APENDIX.

The significance of EGARCH model

The model captures asymmetric responses of the time varying variance to shocks and, at the same time, ensures that the variance is always positive. It was developed by Nelson (1991) with the following specification:

$$\ln(\sigma_t^2) = \alpha_0 + \sum_{j=1}^{p} \beta_j \ln(\sigma_{t-j}^2) + \sum_{i=1}^{q} \left\{ \alpha_i \left(\left| \frac{\varepsilon_{t-i}}{\sigma_{t-i}} \right| - \sqrt{\frac{2}{\pi}} \right) - \gamma_i \frac{\varepsilon_{t-i}}{\sigma_{t-i}} \right\}$$

where γ is the asymmetric response parameter or leverage parameter. The sign of γ is expected to be positive in most empirical cases so that a negative shock increases future volatility or uncertainty while a positive shock eases the effect on future uncertainty. This is in contrast to the standard GARCH model where shocks of the same magnitude, positive or negative, have the same impact on future volatility. In macroeconomic analysis, financial markets and corporate finance, a negative shock usually implies bad news, leading to a more uncertain future. Consequently, for example, shareholders would require a higher expected return to compensate for bearing increased risk in their investment. A statistical asymmetry is, under various circumstances, also a reflection of the real-world asymmetry, arising from the nature, process or organization of economic and business activity, the change in financial leverage is asymmetric to shocks to the share price of a firm.

The procedure for measuring volatility spillover of this study is implemented in the following stages. An initial step we provide descriptive statistics for stock and exchange rate returns to summarize the statistical characteristics of our sample. We then carry out the stationary test including ADF and PP test on each of the concerned variables. Next step, identifying and estimating an autoregressive and moving average (ARMA) model for the mean equation, using the residuals of the mean equation to test for ARCH effect (the significant value of chi-square depicts ARCH effect in the underlying variable). EGARCH model shall be employed on data in which ARCH effect exists. After making sure that there exists ARCH effect, we have specified and estimated the volatility spillover among stock market or foreign exchange rate market or between them. Finally, residual diagnostics have been performed (Tsay, 2005).

Table 1 Summary of the empirical literature

Author	Variables	Period	Markets Included	Method	Results
Shield (1997)	Stock market indices	1991-1995 (daily)	HU, PO	Tobit GARCH	No asymmetry exists
Scheicher (2001)	Stock market indices	1995-1997 (daily)	HU, PO, CZ	MGARCH	Interaction in returns both regional and global shocks, but news to innovations to volatility have a primarily regional character
Murinde and Poshakwale (2001)	Stock market indices	1994-2000 (daily)	CR, CZ, HU, PO,	GARCH models ARIMA, BDSL	Explanation by symmetric and asymmetric
Grambovas (2003)	Stock market indices, Exchange rates,	1994-2000 (weekly)	CZ, HU, GR	Cointegration, Granger Causality	Interconnection between exchange rates and stock prices
Kobor and Szekely (2004)	Exchange rates	2001–2003 (daily)	PO, HU, CZ	Markov regime-switching	Cross-correlations and volatility differ
Syllignakis and Kouretas (2006)	Stock market indices	1995-2005 (weekly)	PO, HU, CZ, RO	Granger Causality DCC, Markov SWARCH-L	Stock markets are partially integrated
Kocenda and Valachy (2006)	Exchange rates, Interest rates	1993-2005 (daily)	PO, HU, CZ.	TARCH	Volatility is greater under a floating exchange rate regime than under a fixed regime
Vizek and Dadic (2006).	Stock market indices	1997-2005 (daily)	PO, HU, CZ, CR	Johansen cointegration	The forces driving financial integration are quite powerful, more substantial movement
Fidrmuc and Horvath (2008)	Exchange rates	1999-2006 (daily)	CZ, HU, PO, RO	GARCH TARCH	Significant asymmetric effects of the volatility of exchange rates in new EU members states
Bubak (2009)	Exchange rates	2002-2008 (daily)	CZ, HU, PO	model-free nonparametric measures of ex-post volatility	Daily returns on the EUR/CZK, EUR/HUF and EUR/PLN exchange rates are normally distributed and independent over time

Author	Variables	Period	Markets Included	Method	Results
Harrison et al. (2010)	Stock market indices	1994-2006 (daily)	CZ, RO, HU, PO	Panel data	Stationarity for the returns of these indices and identified some common characteristics of these markets taken as a whole
Syllignakis and Kouretas (2011)	Stock market indices	1997–2009 (weekly)	PO, HU, CZ	DCC MGARCH	Increasing in conditional correlations between the US and the German stock returns and the CEE stock returns
Tudor (2011)	Stock market indices	2006-2009 (daily)	CZ, HU, PO, RO	Granger Causality VAR	Relationships among CEE stock markets are time varying
Barbic and Jurkic (2011)	Stock market indices, macroeconomic variables	1998-2010 (monthly)	PO, HU, CZ, CR	Granger Causality VECM	Established long run relationship between stock market indices and macroeconomic variables
Kizys and Pierdzioch (2011).	Stock market indices	1995-2008 (monthly)	CZ, HU, PO	Cointegration State-Space VECM	International long-run linkages varied over time
Gjika and Horvath (2013)	Stock market indices	2001-2011 (daily)	CZ, HU, PO	MGARCH DCC	The correlations among stock markets in Central Europe and between Central Europe vis–à–vis the euro area is strong
Kumar and Kamaiah (2014)	Exchange rates	1994 – 2013 (monthly)	CR, CZ, HU, PO, RO	EGARCH, Lyapunov	Foreign exchange markets exhibit deterministic chaotic behavior
Okicic 2015	Stock market indices	2005-2013 (daily)	CR, CZ, HU, PO, RO	ARIMA and GARCH	The existence of a leverage effect in the selected stock markets
Melik Kamisli et al. (2015)	Stock market indices	2008-2015 (weekly)	CR, CZ, HU, PO, RO	CCC DCC MGARCH	Cross-market correlations are constant

Author	Variables	Period	Markets Included	Method	Results
Hsing (2016)	Exchange rates, Interest rates, Real GDP	2000-2014 (quarterly)	HU	EGARCH	The HUF/USD exchange rate has a long-term equilibrium relationship with these time series variables.
Petrica and Stancu (2017)	Exchange rates	1999-2016 (daily)	RO	EGARCH, TARCH PARCH	The best model to estimate daily returns of EUR/RON exchange rate is EGARCH (2,1)
Giannellis and Papadopoulos (2011)	Exchange rates, Interest rates, Industrial production indices, National share prices indices	1991-2007 (monthly)	PO, HU, CZ	VAR CCC GARCH-BEKK	Volatility in Hungarian and Polish forex markets can be influenced by the monetary side of the economy Forex markets in France, Italy and Spain had been influenced, during the pre-EMU era, by monetary and real shocks

We report only the Central and Eastern European markets relevant for our analysis: Hu (Hungary), PO (Poland), RO (Romania), CR (Croatia), CZ (The Czech Republic). Other markets may have been considered in the corresponding studies but are not mentioned here.

1.7 Data

The data set consists of daily closing stock and exchange rate prices for five Eastern European countries, the choice of the sample period was primarily governed by the availability of data. We took daily data covering the period from 1st April 2000 to 29th September 2017. The entire investigation period is subdivided into two sub-periods: Pre-crisis period: 1st April 2000 to 29th August 2008. Post-crisis period: 1st September 2008 to 29th September 2017. The whole period in present study divides into pre and post financial crisis period on the basis of certain justifications. The reason for collecting daily data is to capture more the precise information content of changes in stock prices and exchange rates than doing with weekly or monthly data (Jebran and Iqbal, 2016), and better able to capture the dynamics between variables (Agrawal et al. 2010). The sample five European countries include Hungary, Poland, Czech Republic, Romania and Croatia and their stock indexes are: Budapest Stock Exchange BUX, Warsaw Stock Exchange WIG, Prague Stock Exchange PX, Bucharest Stock Exchange BET and Zagreb Stock Exchange respectively. The national currencies of these countries are Hungarian Forint HUF, Polish Zloty PLN, Czech Koruna CZK, Romanian Leu RON and Croatian Kuna HRK respectively. The exchange rate series are from the European countries are stated in US dollars per local currency (note that value of the dollar). The data for our empirical investigation is obtained from Bloomberg, accounted by the Department of Finance, Corvinus University of Budapest.

The limitation of the current dissertation is that the exchange rate US dollar is used as a case study. In reality, the CEE nations are the periphery of the eurozone, the substantial exchange rate is against the euro and not the US dollar. The common trends of CEE currency exchange rates against the dollar come from the USD/Euro exchange rate. A part of the CEE currency return would be euro return. Therefore, further interesting research would be to examine whether these results hold for the case of the exchange rate Euro. However, the thesis focuses on the volatility spillover among financial markets in CEE countries, so there is a slight difference between the local currencies against Euro and USD.

1.8 Market characteristics

Stock market

The CEE countries lag behind the rest of member states in the European region by a large margin in terms of financial depth. On average, the ratio of domestic credit to the private sector as a percentage of GDP in the CEE new member states stood at slightly more than 30 percent in 2003, compared to the EU-15 average of around 120 percent. We were able to observe an improvement in the degree of financial intermediation over the past decade. Strong economic growth, structural reforms in the financial sector and progress in the privatization of banks benefited this process in most countries. In addition, bond and equity markets continue to be relatively small in the member states in CEE, both in absolute terms and in relation to GDP.

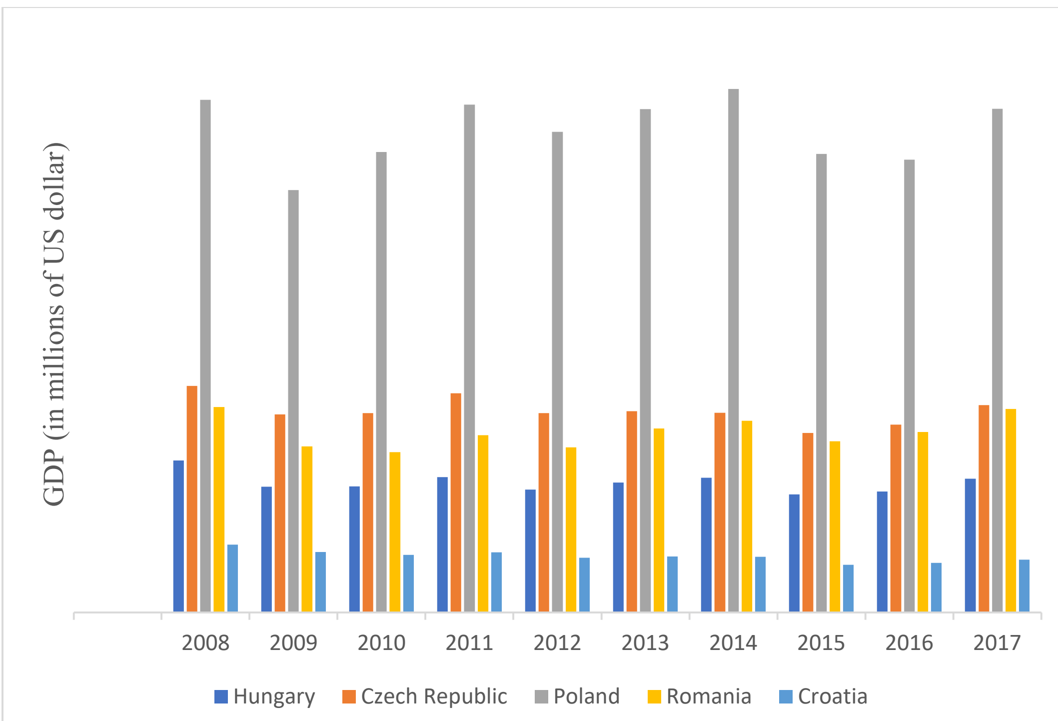


Figure 1 GDP, billion currency units
Source: World Development Indicators

The equities exchanges of Central and Eastern Europe are relatively small emerging and frontier markets. The largest market among them, the Zagreb Stock Exchange, is comparable in size and market turnover to the smallest Budapest stock exchange.

The worldwide market downturn since 2000 has influenced CEE exchange in terms of market capitalization and trading volume as it has all other exchanges in the world. The effects, however, are felt much more by CEE exchanges and raises the question of whether these exchanges can be important to CEE economies and particularly in terms of corporate finance in these countries. To assess the current stage of development of CEE securities markets in stocks and exchange markets, we look at these markets from various perspectives and compare them with other West European markets.

Figure 1 gives an overview of the important characteristics of CEE stock markets between 2008 and 2017. The graph shows that CEE stock exchanges are still relatively small. All CEE stock exchanges not only show low market capitalization but also are relatively important to the economy. This can be seen from the relation of market capitalization to GDP. In general, the selected stock markets have a capitalization of only lowest 7 percent (Romania) and largest 42 percent (Croatian) relative to GDP. This means that only a small fraction of the total value of CEE companies is traded at the stock exchanges. There is now a large gap between these still-developing stock markets and the CEE stock markets.

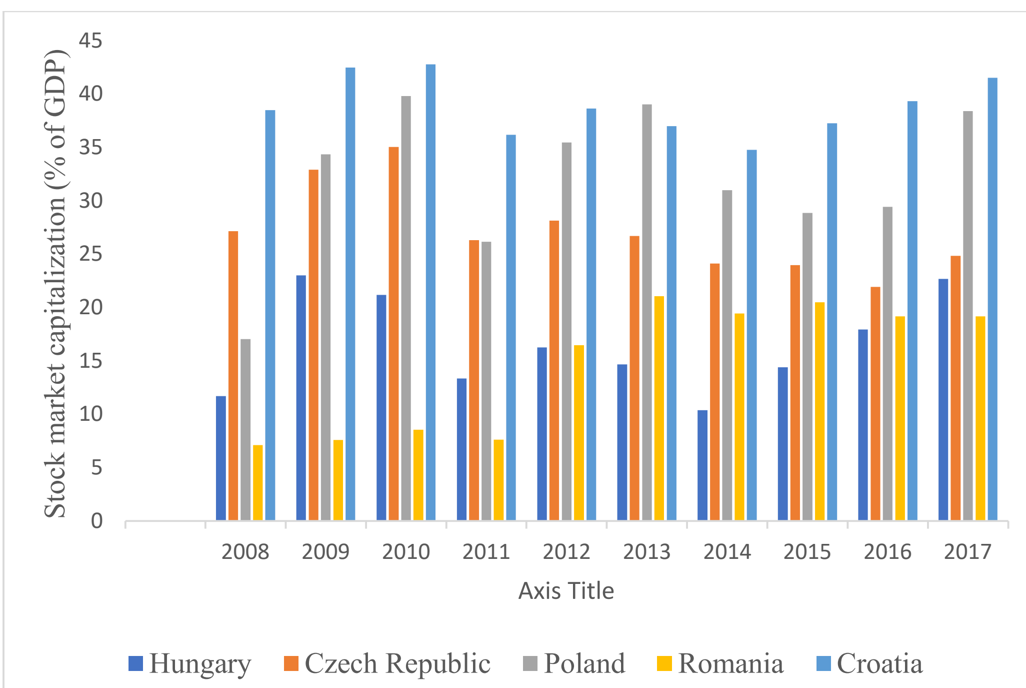


Figure 2 Stock market capitalization as percent of GDP in CEE countries

Source: World Development Indicators

Another significant characteristic of stock market is liquidity, which is often measured as the ratio of market turnover to market capitalization (Figure 2). This ratio indicates how often the total value of stocks is turned over on average during a year. A high ratio reveals that the market is relatively liquid. This is particularly important with respect to the usually large orders of institutional investors. The five CEE stock markets have slightly low turnover ratios.

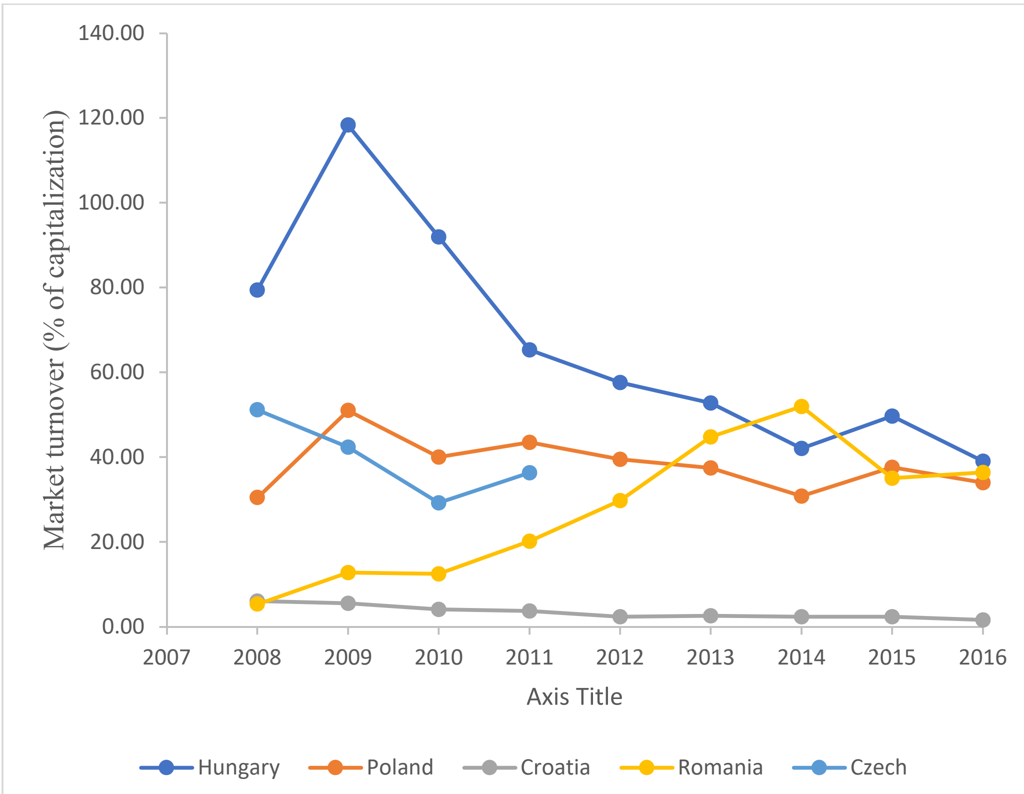


Figure 3 Stock market turnover ratio
Source: World Development Indicators

Foreign exchange market

The evolution of exchange rates currently illustrates a significant source of concern from both a micro and a macroeconomic perspective. The exchange rate is one of the most synthetic prices in an economy and it is also the expression of a general equilibrium among the market for real goods and services, the currency market and capital market, which has the apparent potential of effecting the general economic equilibrium in any economy. The behaviour of the exchange rate is influenced, at its turn, by the degree of economic growth, the changes in the general level of prices, the industry structure of the economy, the country's level of international competitiveness and its degree of trade and financial openness, the political stability and government's ability to deal with internal crises which would occur. This diversity of determinants that impact directly or indirectly the exchange rate raises the issue of the easiness of managing such a complex and dynamic macroeconomic variable.

Over the past several decades, the number of countries running de jure floating exchange rate regimes has steadily grown. In some influential papers show that there is a discrepancy between de jure and de facto, and countries appear to actively restrict fluctuations in the external value of their national monies.

The diversity in the exchange rate regime choices also reflects different stabilization strategies and the availability of alternative monetary policy frameworks. Achieving price stability still remains the main stabilization task. The exchange rate regimes of the former communist countries in the region are quite diverse, ranging from stabilized arrangement to free floating. This diversity can be explained by the structural diversity of these countries, on one hand, and by the need felt by these countries to better control inflation and exchange rates at the same time. In general, there are some substantial differences for some countries and some years. We observed the volatility of exchange rates and stock indices of these countries currencies against the US dollar over the same time span. (see Figure 4)

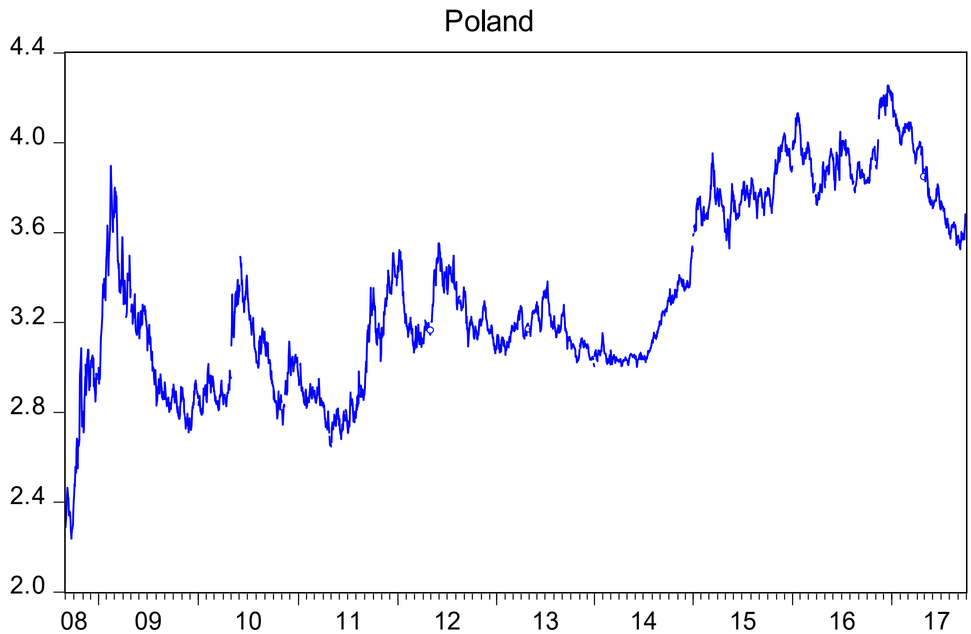
Table 2 Exchange rate regimes in 5 CEE countries, 2008-2014

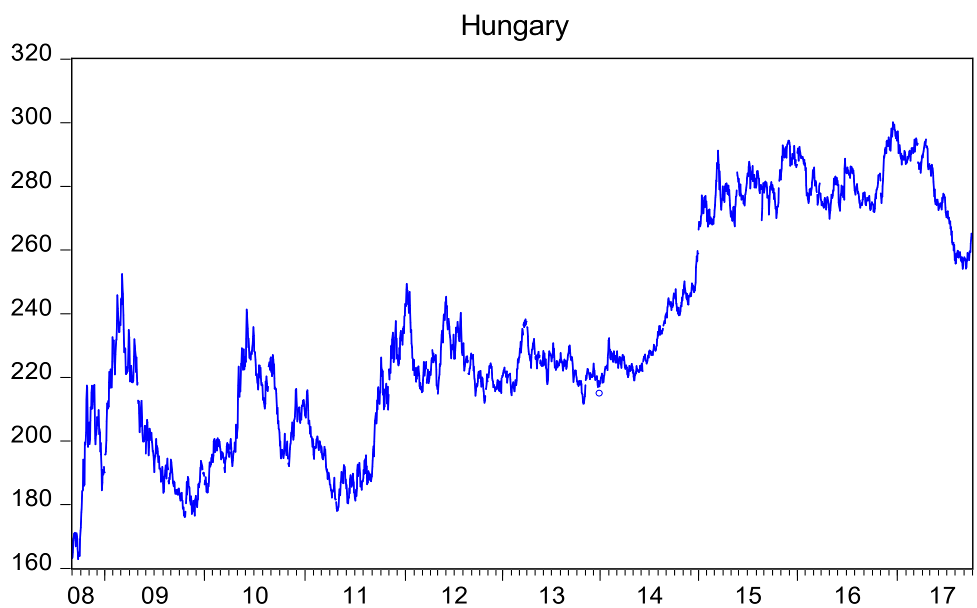
	2008	2009	2010	2011	2012	2013	2014
Croatia	8	4	6	6	6	6	6
Czech Republic	10	10	10	10	10	8	4
Hungary	9	9	9	9	9	9	9
Poland	10	10	10	10	10	10	10
Romania	9	9	9	9	9	9	9

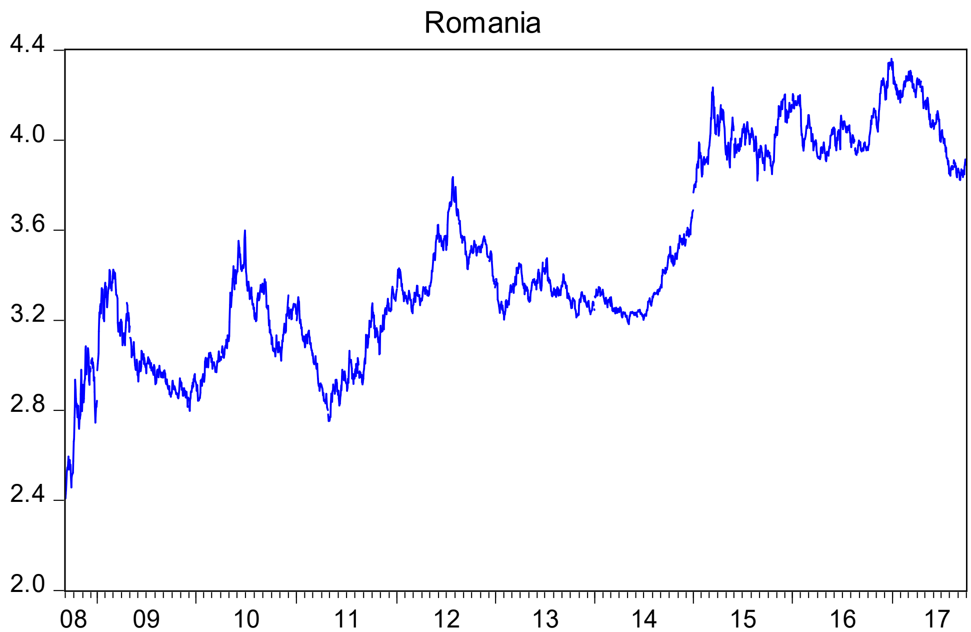
Notes: 4= Stabilized arrangement; 6=Craw-like arrangement; 7=Managed floating with no pre-determined path for the exchange rate; 8=Other managed arrangement; 9=Floating; 10=Free floating

Source: IMF's Annual report on exchange arrangement and exchange restrictions

(a) Daily foreign exchange prices






Romania
4.4
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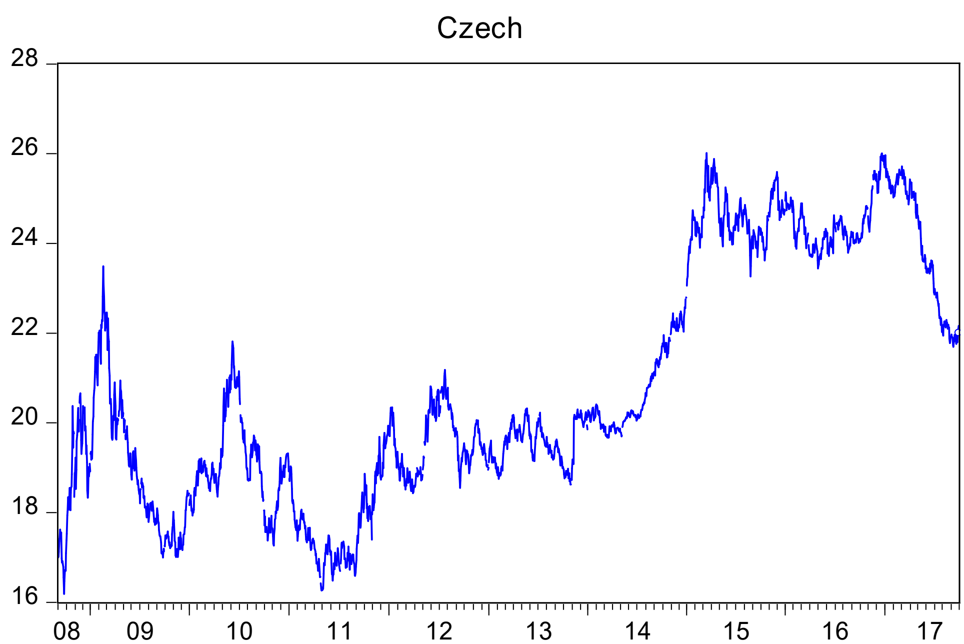
Czech
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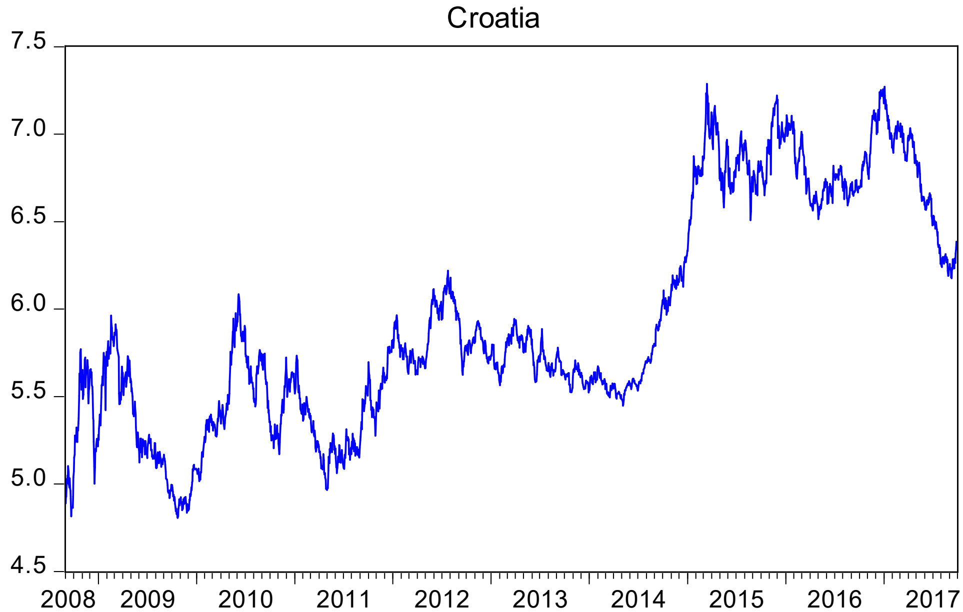
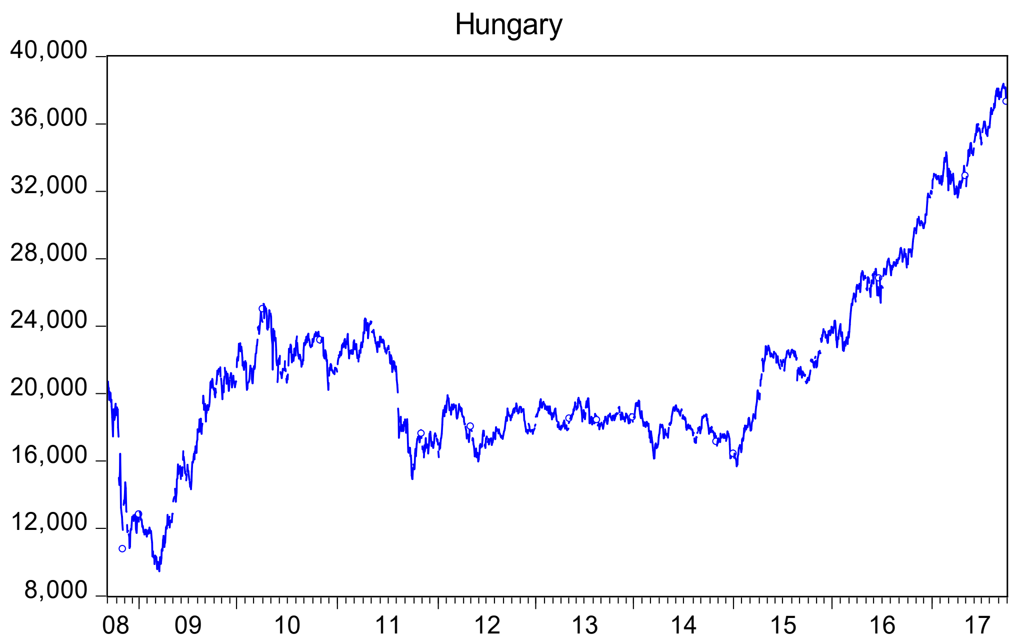
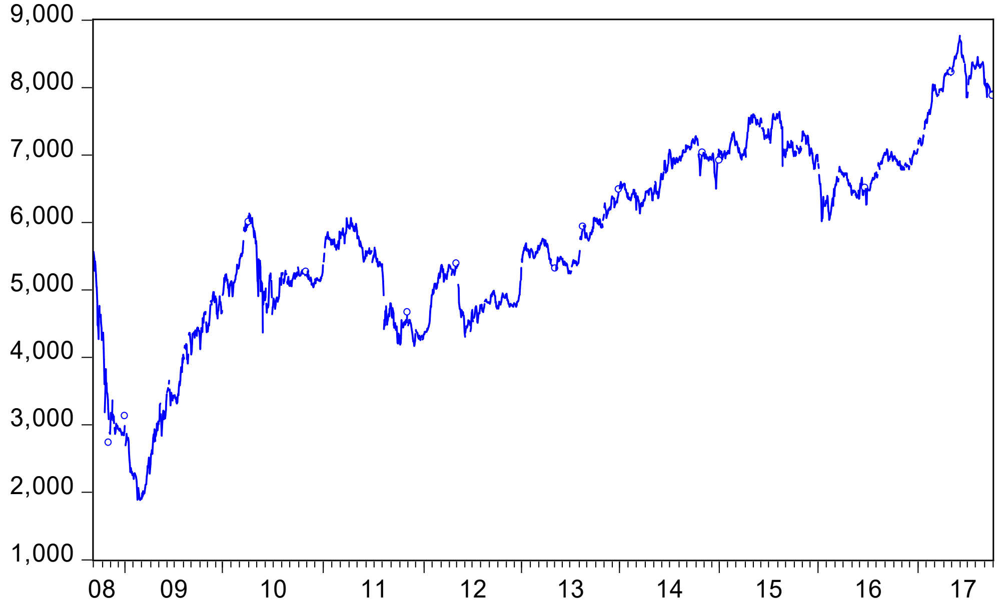


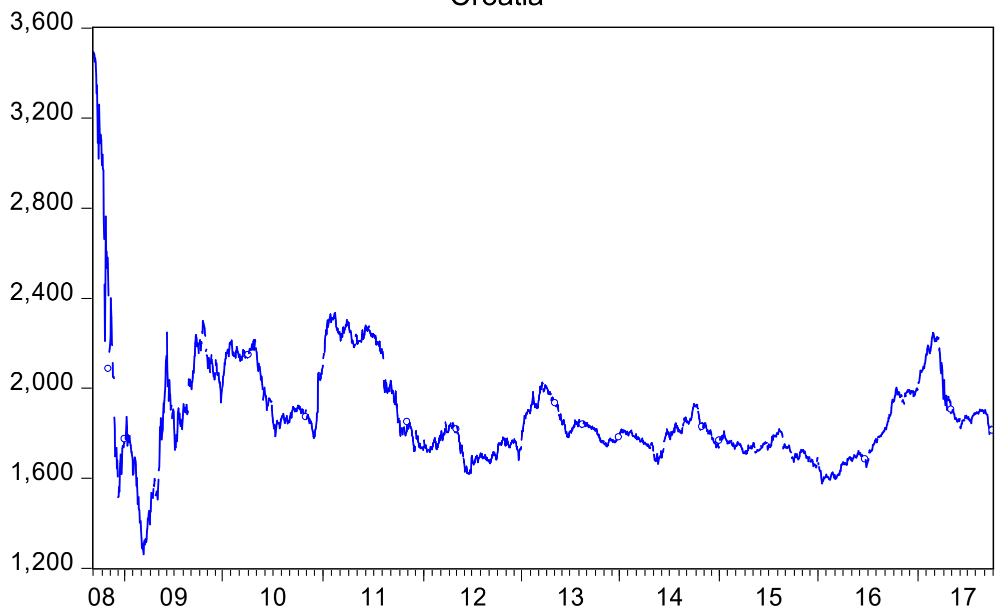
(b) Daily stock prices



Romania



Croatia



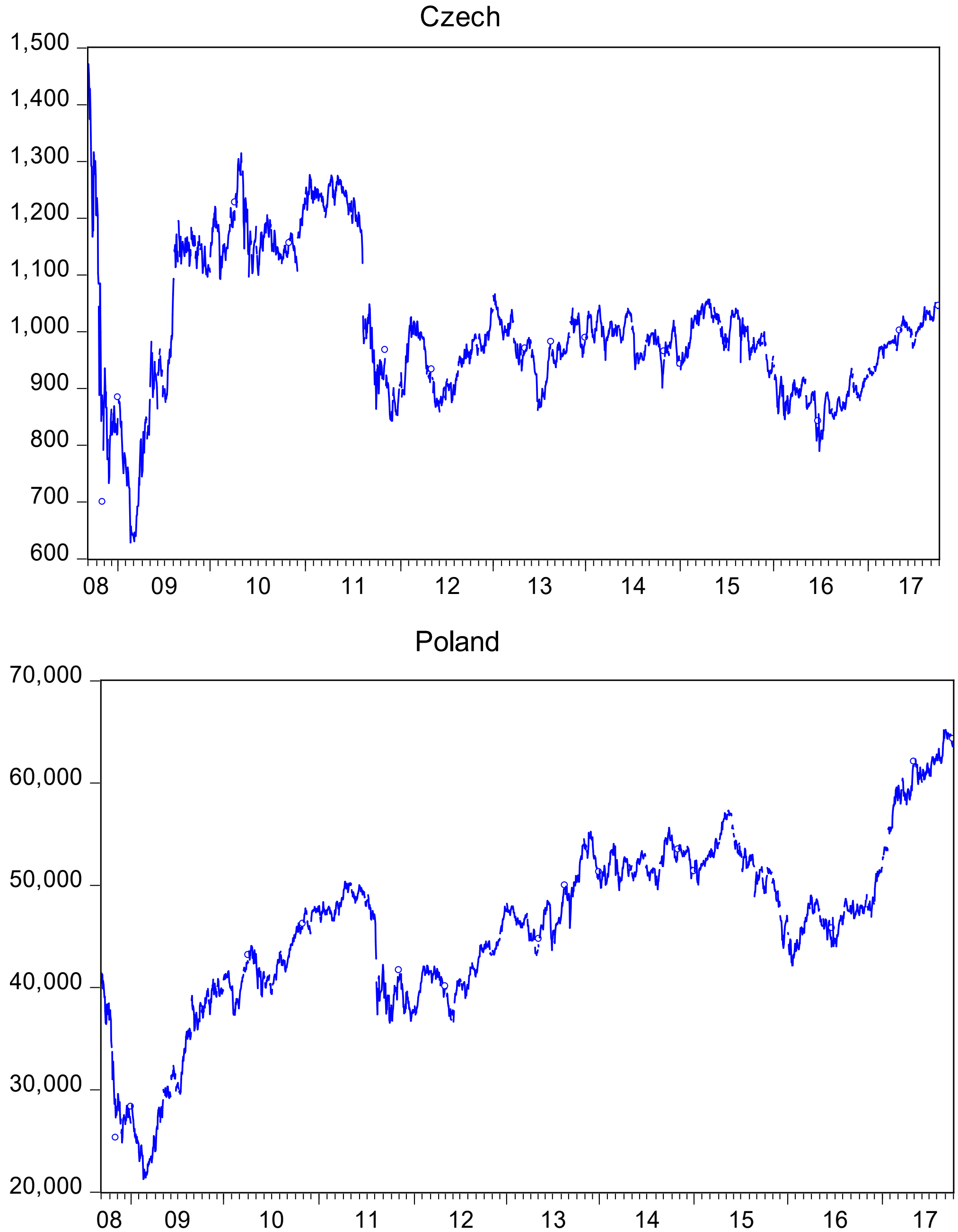


Figure 4 Foreign exchange and stock prices, 2008-2017

THE DYNAMICS OF VOLATILITY SPILLOVER BETWEEN STOCK AND FOREIGN EXCHANGE MARKETS: EMPIRICAL EVIDENCE FROM CENTRAL AND EAST EUROPEAN COUNTRIES[1]

We use an Exponential Generalised Autoregressive Conditional Heteroskedasticity (EGARCH) model to investigate the asymmetric volatility spillover effects between the stock markets and foreign exchange markets in Hungary, Poland, the Czech Republic, Romania and Croatia for the periods before and after the financial crisis. The study covers the entire period from 1 April 2000 to 29 September 2017. The results reveal bidirectional volatility spillover between the stock and foreign exchange markets of Hungary in all periods, and of Poland in the post-crisis period, unidirectional volatility spillover in Croatia in the pre-crisis period, and from the stock market to the exchange market in the Czech Republic during two periods. In the post-crisis period, the two financial markets show the absence of volatility spillover in Croatia. Furthermore, empirical results from our analysis provide valuable insights to investors, multinational companies and economic policymakers regarding financial decision-making.

JEL: C15; F31; G15

Keywords: volatility spillover, Central and East European countries, ARCH, GARCH, EGARCH, exchange rate, stock market

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[1] Hung, N.T (2019). Dynamics of volatility spillover between stock and foreign exchange market: empirical evidence from Central and Eastern European Countries. *ECONOMY AND FINANCE: ENGLISH-LANGUAGE EDITION OF GAZDASÁG ÉS PÉNZÜGY*, *6*(3), 244-265.

2.1 Introduction

The interlinkage between stock and foreign exchange markets has attracted the attention of academic researchers and practitioners alike for a long time and offers meaningful insight into both markets. It is widely acknowledged that rapid growth in international financial markets has become substantially more integrated in recent years. The drastic increasing trend in financial assets has been followed by increasingly high demand and supply of foreign currencies. The interdependency has been generated by both the high demand for currencies and equity flows, leading to some degree of interdependency in both securities and currencies. According to Kanas (2000), the huge increase in interdependency has also increased volatility spillovers between stock and foreign exchange markets. Positive and significant spillovers of volatility transmission may increase the non-systematic residual international portfolio risk faced by global investors, which might reduce the gains from international portfolio diversification. In reality, volatility analysis helps us to understand the information mechanism in both financial markets, including price and volatility spillovers across markets, shock propagation across foreign exchange and stock markets, and hedging strategy problems (Aloui, 2007).

Recently, there has been a lot of interest in the financial press in the relationship between returns on the stock and foreign exchange markets because of the financial roles both variables play in prominent portfolio decisions and economic development. Theory suggests two broad channels which link returns in stock and foreign exchange markets. The first approach, known as flow-oriented models of exchange rates (Dornbusch and Fischer, 1980), posits that there exists a positive linkage between exchange rates and stock prices, specifically centred on the current account and trade balance. The second approach, known as stock-oriented models of exchange rates (Frankel, 1983), suggests that the exchange rate is determined by the demand and supply of financial assets such as equities and bonds. More recently, information about volatility spillovers between the two financial markets has been studied by many researchers from different countries. However, this paper distinguishes itself from previous studies on the following grounds. While a great many studies exist in developed and emerging markets, for developing markets such as Hungary, Poland, the Czech Republic, Romania and Croatia, there have been only two investigations – by Morales (2008), and Fedorova and Saleem (2010) – regarding volatility spillover effects between stock and foreign exchange markets. Morales (2008) undertook her study on pre- and post-Euro periods in Hungary, Poland, the Czech Republic and Slovakia, while Fedorova and Saleem (2010) focused on questions of volatility spillover effects in Poland, Hungary, Russia, and the Czech Republic. However, in this research, we studied the Hungarian, Polish, Czech, Romanian and Croatian financial markets during the subprime financial crisis period, and the methodology adopted is not the same as that of our purposed study.

In this paper, we employ the EGARCH model to address some critical research questions: first, the persistence and asymmetric effects in the conditional volatility of daily returns on stock and exchange indices in Central and East European countries in the pre and post-crisis periods; and second, whether there is a relationship between the two financial markets in these countries. In addition, comparisons between different countries and various time periods were performed. The next section provides a review of the relevant literature. Section 3 discusses the EGARCH model. Section 4 presents and discusses the estimation results of the EGARCH model. Section 5 summarizes the study and concludes with some implications.

2.2 Review of the literature

There is a rich body of empirical literature with regard to investigation of the volatility transmission mechanism in the dynamic linkage between exchange rates and the stock market. We must mention the theoretical framework of Diebold and Yilmaz (2009, 2012, 2014), whose generalized VAR model has shed light on the connectedness of stock returns as well as the volatility index. Nevertheless, the asymmetric aspect has not been mentioned in these studies. In our research, we applied the popular GARCH family of econometric models to capture the information mechanism of volatility spillovers.

Many of these studies are based on the Generalized ARCH (GARCH) framework in examining volatility spillovers between two financial markets in different countries. It is clear that in the context of the literature, volatility spillovers can be divided into three key points first, a bidirectional volatility spillover between two markets; second, a unidirectional flow of volatility from stock market to exchange market and vice versa; and third, non-persistence of volatility spillovers between two financial markets.

The first study analyzing volatility spillovers was conducted by Kanas (2000), who used daily data for the period from 1 January 1986 to 28 February 1998, and investigated six industrialised countries – namely the U.S., U.K., Japan, Germany, France and Canada – by employing the bivariate EGARCH model for conditional variances. He found evidence of spillovers from stock returns to exchange rate returns for all countries except Germany, and the non-persistence of spillovers from exchange to stock markets.

Yang and Doong (2004) applied the bivariate EGARCH model on weekly data from 1 May 1979 to 1 January 1999 to examine the nature of the mean and volatility spillover between stock and foreign exchange markets for the G7 countries. Their empirical evidence supports the existence of the asymmetric volatility spillover effect from the stock market to the foreign exchange market in France, Italy, Japan and the U.S.

Aloui (2007) explored the nature of the mean, volatility and causality transmission mechanism between stock and foreign exchange markets in the U.S. and some major European markets (France, Germany, Belgium, Spain and Italy). The dataset consisted of daily closing exchange rates and stock indexes for these countries. The asymmetric volatility transmission was illustrated using the EGARCH model. He found the asymmetric and long-range persistence volatility spillover effect and evidence of causality in mean and variance in the two markets for both pre- and post-Euro periods. Additionally, the author confirmed that stock returns had a more significant effect on the foreign exchange rate for the two sub-samples.

Volatility spillovers between stock returns and foreign exchange rates in four Central and East European countries (Hungary, the Czech Republic, Poland and Slovakia) were studied by Morales (2008). The author applied daily data for the period 1999–2006, divided into the two sub-periods of pre-Euro and post-Euro. The analyses were carried out using the EGARCH model, which apparently confirmed the non-existence of significant volatility spillover from stock to foreign exchange markets in these countries. However, the overall finding was that the lack of significant spillovers from exchange rates to stock returns and volatility in both markets tended to decrease after the countries joined the European Union.

Fedorova and Saleem (2010) investigated the dynamic volatility spillover between stock and currency markets in the emerging Central and East European markets of Poland, Hungary, Russia and the Czech Republic, by estimating a bivariate GARCH-BEKK model using weekly returns. The findings showed strong evidence of direct linkage between equity markets and currency markets in terms of both returns and volatility. Unidirectional volatility spillovers from currency to stock markets were highlighted in all countries except the Czech Republic in this research.

Valls and Chuliá (2014) used a multivariate asymmetric GARCH model to examine volatility spillovers between stock and currency markets in Asian economies, consisting of 2,893 observations of daily indices in the period 2003–2014. Their results presented evidence of bidirectional volatility spillovers between both markets, independently of the individual country's level of development.

Mozumder et al. (2015) examined volatility spillovers between stock prices and exchange rates in three developed and three emerging countries, including Ireland, the Netherlands, Spain, Brazil, South Africa and Turkey, across the recent pre-crisis, crisis and post-crisis periods, using weekly data and employing a bivariate EGARCH model. The study concluded that there were asymmetric volatility spillover effects between both markets in both developed and emerging economies during the financial crisis. Namely, their findings indicated that there was a unidirectional volatility spillover effect running from stock returns to exchange rate returns in developed countries. Volatility spillovers between the two markets ran in the opposite direction in the emerging countries, but there was a bidirectional volatility spillover between both financial markets in Brazil. At the same time, Segal, Shaliastovich and Yaron (2015) suggested empirical methodologies for studying good and bad aggregate uncertainty in terms of defining bad and good uncertainty as the variance portion of an aggregate variable. The findings proposed that good certainty is associated with subsequent positive growth of aggregate measures of consumption, while bad uncertainty is followed by a decline in this growth rate. Additionally, based on the theoretical framework, the results showed that asset prices rise with good uncertainty, while declining with bad uncertainty. This means that their research question stated that macroeconomic uncertainty increases or decreases aggregate growth and asset prices was addressed.

The dynamics of volatility spillover between stock markets and foreign exchange markets in Asian countries (China, Hong Kong, India, Japan, Pakistan and Sri Lanka) were empirically investigated by Jebran and Iqbal (2016) using the EGARCH model. This study considered daily data from 4 January 1999 to 1 January 2014. Their research pointed out bidirectional asymmetric volatility spillover between the stock and foreign exchange markets in Pakistan, China, Hong Kong and Sri Lanka. For India, the findings showed unidirectional transmission of volatility from stock to exchange markets. Nevertheless, the analysis also confirmed no evidence of volatility spillover in both markets in the case of Japan. At the same time, Baruník, Kočenda and Vácha (2016) utilized data covering most liquid U.S. stocks in seven sectors to examine how to quantify asymmetries in volatility spillovers that emerge because of bad and good volatility. The authors illustrated that the asymmetric connectedness of stocks at the disaggregate level, as well as spillovers of good and bad volatility, were transmitted at various magnitudes. Also, their findings revealed that the overall intra-market connectedness of U.S stocks increased substantially during the recent financial crisis.

It is clear from the above review of the relevant literature that results are mixed with respect to volatility spillover effects in various periods, as well as in different countries. This study aims to contribute to the existing literature by filling the gap in knowledge about the volatility transmission mechanism in the dynamic linkage between exchange rates and the stock market in the selected countries, by adopting an empirical approach based on a multivariate EGARCH model. Also, based on the EGARCH model, the relationship between stock and exchange rate movements has been estimated, while questions in previous research have centred only on the first movements of the joint stock and exchange rate distributions. Another contribution of our study in the long term is the consideration of daily data for the pre-crisis period of nine years and the post-crisis period of 10 years, because daily data capture more information than weekly and monthly data, and thereby ascertain the extent to which the recent financial crisis affected the link in question. Furthermore, empirical results from our analysis are of great interest to investors, multinational companies and economic policymakers regarding financial decision-making.

2.3 Methodology

2.3.1 Data

The data set consists of daily closing stock and exchange rate prices for five Central and East European countries, covering the period from 1 April 2000 to 29 September 2017. The entire investigation period is subdivided into two sub-periods: the pre-crisis period, from 1 April 2000 to 29 August 2008; and the post-crisis period, from 1 September 2008 to 29 September 2017.

The whole period in the present study divides into pre and post-financial crisis periods on the basis of certain justifications. The reason for collecting daily data is to capture more precisely the information content of changes in stock prices and exchange rates than can be achieved with weekly or monthly data (Jebran and Iqbal, 2016), and to better capture the dynamics between variables (Agrawal et al. 2010). The sample five European countries are Hungary, Poland, the Czech Republic, Romania and Croatia, and their stock indexes are: Budapest Stock Exchange BUX; Warsaw Stock Exchange WIG; Prague Stock Exchange PX; Bucharest Stock Exchange BET; and Zagreb Stock Exchange. The national currencies of these countries are the Hungarian forint (HUF), Polish złoty (PLN), Czech koruna (CZK), Romanian leu (RON), and Croatian kuna (HRK), respectively.

The exchange rate series from the European countries are stated in U.S. dollars per local currency (note value of the dollar). Because stock markets operate for five trading days from Monday to Friday and foreign exchange markets operate for six trading days (excluding weekends and holidays), this research makes a common data series by adjusting the dates of both the stock and exchange rate indices.

The data for our empirical investigation is obtained from Bloomberg, accounted by the Department of Finance, Corvinus University of Budapest. The daily return data series are calculated as $R_{i,t} = 100 \times \ln(P_{i,t}/P_{i,t-1})$, where $P_{i,t}$ is the price level of market i (i = 1 for the stock market and i = 2 for the foreign exchange rate) at time t. The plots of stock prices and exchange rate series for five countries in the sample illustrate the volatility that occurs in bursts. The raw series are plotted in Figure 5, where stock markets and foreign exchange rate markets in five countries fluctuate in the pre- and post-crisis periods.

Table 3 Descriptive statistics of daily returns of stock indices

Countries	Hungary	Poland	Czech	Romania	Croatia
Panel A. Pre-crisis period					
Mean (%)	0.04	0.03	0.05	0.11	0.07
SD (%)	1.39	1.30	1.26	1.78	1.39
Skewness	-0.0883	-0.2559	-0.1862	-0.1390	0.5367
Kurtosis	4.3107	5.1726	5.4575	21.9218	16.726
Jarque-Bera	157.88**	449.76**	559.39**	313.320**	16342.68**
PP test	-44.47*	-44.92*	-44.96*	-43.33*	-44.93*
ADF test	-44.49*	-44.79*	-44.96*	-43.36*	-44.92*
N	2166	2166	2173	2099	2069
Panel B. Post-crisis period					
Mean (%)	0.02	0.02	-0.01	0.01	-0.02
SD (%)	1.62	1.22	1.4927	1.52	1.18
Skewness	-0.1033	-0.5254	-0.6210	-0.7250	0.0734
Kurtosis	11.4429	7.9297	20.3306	15.5740	27.2175
Jarque-Bera	6746.18**	2407.276	28642.34**	15240**	55425.20
PP test	-45.07*	-34.53*	-39.97*	-44.89*	-44.53*
ADF test	-35.42*	-42.73*	-44.53*	-44.93*	-25.32*
N	2270	2274	2277	2283	2268

Notes: SD represents standard deviation. N: Observations

Critical values at 1%, 5% and 10% are -3.43, -2.86 and -2.56, respectively. PP is Phillips-Perron test. ADF is Augmented Dickey-Fuller test. * denotes the level of significance at 5%, ** indicates $p < 1\%$

Source*:* calculations of the author

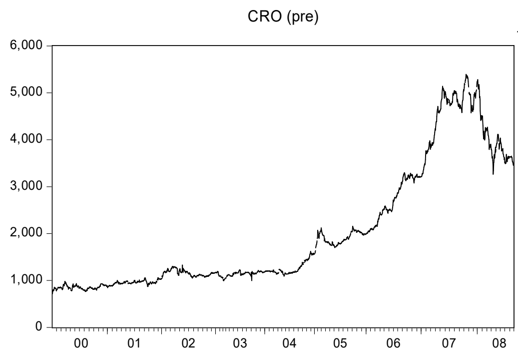
Table 4 Descriptive statistics of daily returns of exchange indices

Countries	Hungary	Poland	Czech	Romania	Croatia
Panel A. Pre-crisis period					
Mean (%)	-0.0196	-0.026	-0.033	0.0129	-0.02
SD (%)	0.78	0.6937	0.7049	0.6516	0.69
Skewness	0.4141	0.2921	0.0008	0.9338	-0.0863
Kurtosis	6.1554	5.3131	4.2452	20.066	5.0085
Jarque-Bera	960.48**	513.65**	140.39**	25778.4**	350.36*
PP test	-46.89*	-43.80*	-47.20*	-48.94*	-50.02*
ADF test	-46.89*	-43.80*	-47.19*	-48.80*	-49.99*
N	2166	2166	2173	2099	2069
Panel B. Post-crisis period					
Mean (%)	0.02	0.02	0.01	0.02	0.01
SD (%)	1.0559	1.04	0.85	0.77	0.69
Skewness	0.1971	0.2039	-0.1349	0.2228	-0.0347
Kurtosis	6.0054	6.6307	8.3099	6.6083	5.6903
Jarque-Bera	869.04**	1264.76**	2681.99**	1257.42**	684.43**
PP test	-47.65*	-47.85*	-48.39*	-45.12*	-47.68*
ADF test	-47.61*	-47.71*	-48.38*	-34.59*	-47.68*
N	2270	2274	2277	2283	2268

Note: SD represents standard deviation. N: Observations

Critical values at 1%, 5% and 10% are -3.43, -2.86 and -2.56, respectively. PP is Phillips-Perron test. ADF is Augmented Dickey-Fuller test. ** denotes the level of significance at 5%, * indicates $p < 1\%$.

Source: calculations of the author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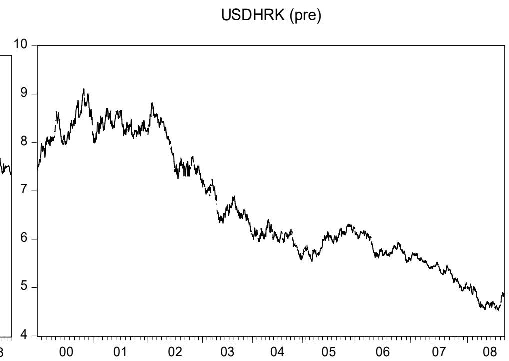
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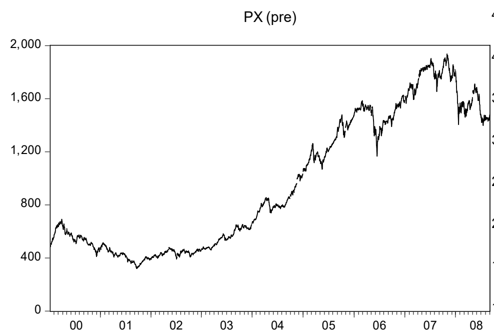
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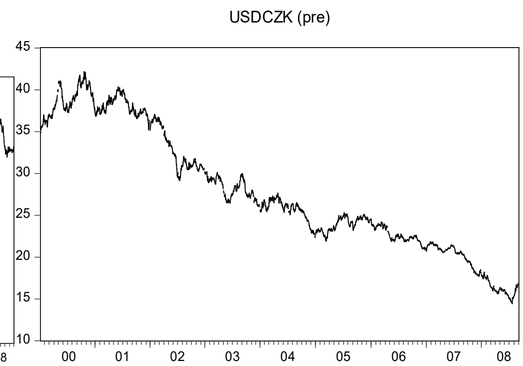
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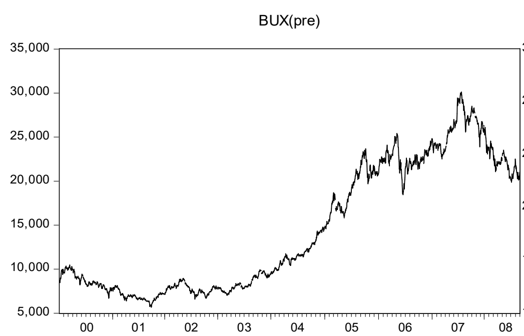
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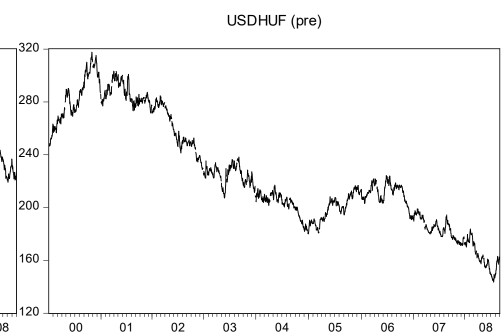
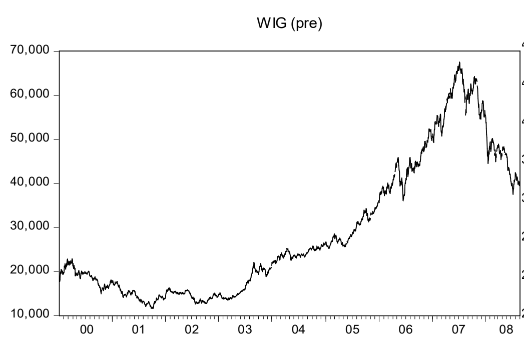

USDHUF (pre)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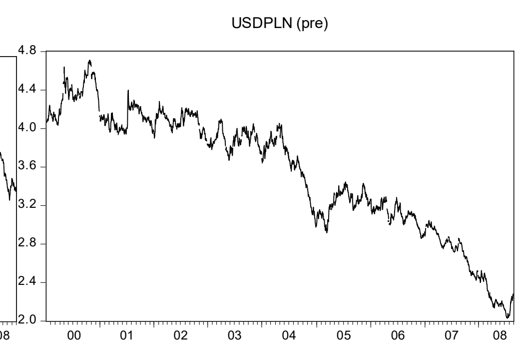
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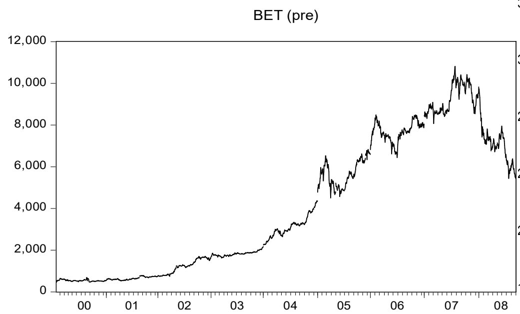
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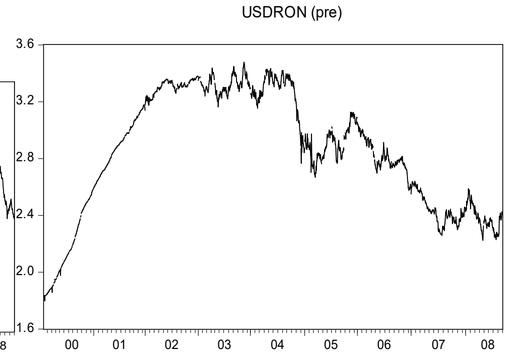
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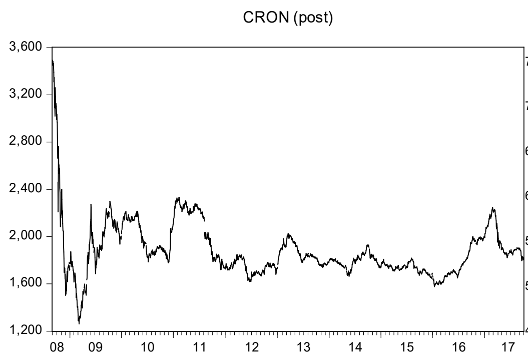
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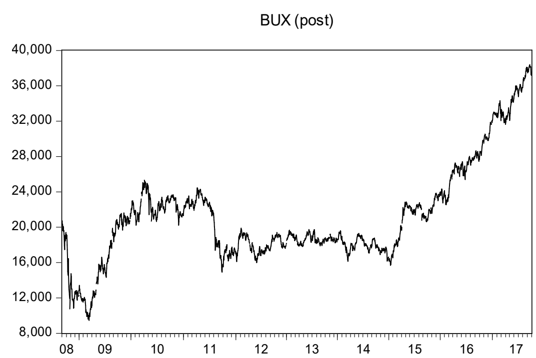
USDHRK (post)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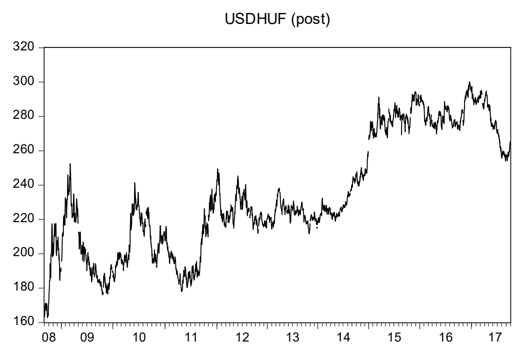
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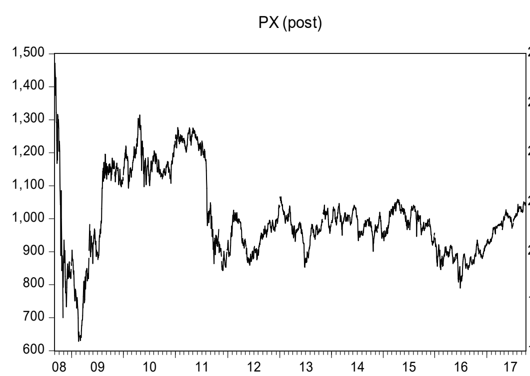
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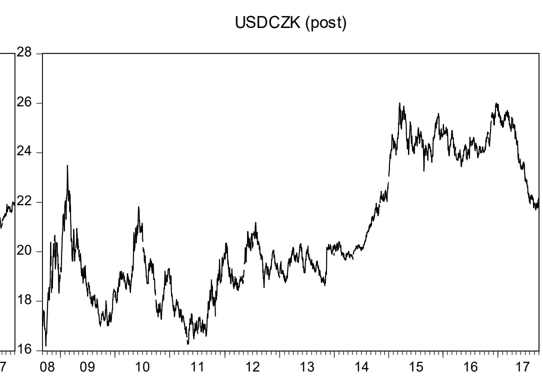
USDCZK (post)

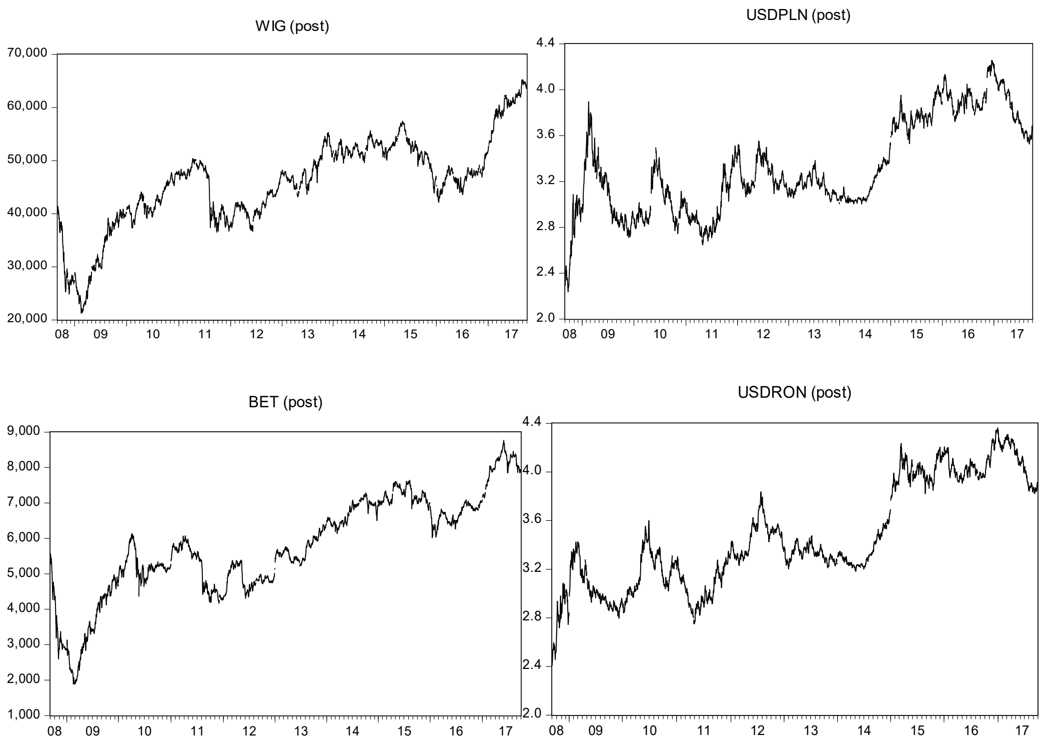

Figure 5 Plots of the indices for the sample pre- and post-crisis periods
Source: calculations of the author

2.3.2 Model Specification

Unit root test

The stationary of the series is considered by commonly checking through Phillips-Perron (PP, 1988) and Dickey-Fuller (ADF, 1979) methods to ensure that the results of the analysis are not spurious. These tests have been implemented to confirm that the data were stationary at level.

EGARCH model

The empirical study for examining whether the volatility of stock returns affects and is affected by the volatility of exchange rate returns is intended to be captured by employing the Exponential Generalized Autoregressive Conditional Heteroskedasticity (EGARCH) model developed by Nelson (1991). The EGARCH specification is applied to test whether the volatility spillover effects are asymmetric. The simple GARCH model enforces a symmetric effect of volatility (positive shocks) and is not able to capture asymmetric shocks (negative shocks) because of the conditional variance being a function of lagged residuals and not their signs. There is no such restriction in the EGARCH model on the parameters, and the EGARCH model is able to capture both symmetric and asymmetric shocks. Therefore, numerous empirical studies are based on the EGARCH framework to specify volatility spillovers between different financial assets in different countries. For instance, except for the aforementioned scholars (Mishra et al. 2007; Choi et al. 2010; Qayyum and Kemal, 2006; Okpara and Odionye, 2012; Beer and Hebein, 2011). In this study, we applied the EGARCH (1,1) model to examine the transmission mechanism of volatility separately for each selected country.

EGARCH model for volatility spillover from foreign exchange market to stock market

$$R_t = \alpha_0 + \alpha_1 R_{t-1} + \alpha_2 R_{t-1(ER)} + \varepsilon_t \tag{2.1}$$

$$h_{t(SP)} = \beta_0 + \beta_1 h_{t-1} + \beta_2 \left| \frac{\varepsilon_t - 1}{\sqrt{h_{t-1}}} \right| + \phi \frac{\varepsilon_t - 1}{\sqrt{h_{t-1}}} + \delta_{(resid(ER))} \tag{2.2}$$

The equations (2.1) and (2.2) represent the EGARCH (1,1), which is applied for examining volatility spillover from the foreign exchange market to the stock market in each country.

EGARCH model for volatility spillover from stock market to foreign exchange market

$$K_t = a_0 + a_1 K_{t-1} + a_2 K_{t-1(SP)} + \varepsilon_t \tag{2.3}$$

$$h_{t(ER)} = \gamma_0 + \gamma_1 h_{t-1} + \gamma_2 \left| \frac{\varepsilon_t - 1}{\sqrt{h_{t-1}}} \right| + \varphi \frac{\varepsilon_t - 1}{\sqrt{h_{t-1}}} + \psi_{(resid(SP))} \tag{2.4}$$

Table 5 Description of Parameters Equations (2.1)-(2.4)

Explanation	**S**	**E**
The conditional mean equation	(2.1)	(2.3)
The conditional variance equation	(2.2)	(2.4)
Return	R_t	K_t
Intercept	α_0	a_0
Measuring the effects of previous day's return on today's return	α_1	a_1
Measuring the effects of exchange rate returns on stock returns	α_2	
Measuring the effects of stock returns on exchange rate returns		a_2
Error term	ε_t	ε_t
Log of conditional variance	$h_{t(SP)}$	$h_{t(ER)}$
Volatility constant	β_0	γ_0
Function of volatility (consistency)	β_1	γ_1
Volatility reaction to change in news	β_2	γ_2
Measuring asymmetric effect of volatility	ϕ	φ
Volatility spillover	δ	ψ

Note: S is stock return, E is exchange rate

The procedure for measuring volatility spillover in this study was implemented in the following stages. As an initial step, we provided descriptive statistics for stock and exchange rate returns to summarize the statistical characteristics of our sample. We then carried out the stationary test including ADF and PP tests on each of the concerned variables. The next step was identifying and estimating an autoregressive and moving average (ARMA) model for the mean equation, using the residuals of the mean equation to test for the ARCH effect (the significant value of chi-square depicts the ARCH effect in the underlying variable). The EGARCH model is to be employed on data in which the ARCH effect exists. After making sure that there exists an ARCH effect, we specified and estimated the volatility spillover between the stock market and foreign exchange rate market. Finally, a residual diagnostics/ARCH-LM test was performed

2.4 Results

Descriptive statistics for stock and foreign exchange rates as well as the unit root are reported in Table 3 and 4 The analyses reveal that sample means of stock returns are positive and significantly different from zero for five countries, except for the Czech Republic and Croatia, in the post-crisis period. The sample variances range from 0.69% for Croatia to 1.62% for Hungary. Similarly, the Hungarian and Polish exchange markets have the highest daily average return over the study period. Skewness and kurtosis coefficients indicate that return series are far from the normal distribution, and this is formally confirmed by the Jarque-Bera test statistics. Finally, all exchange rate changes and stock return series are found to be stationary at level (e.i I(0)) at the 1% significance level according to the PP and ADF statistics. Table 6 represents the results of the purpose of ARCH effect for the underlying variables (stock prices and exchange rate) over the study periods. The ARCH effect illustrates the presence of autocorrelation and heteroskedasticity issues in data. The result shows that there is strong evidence of the existence of the ARCH effect in all concerned series. EGARCH (1,1) can be employed on data having the ARCH effect in data.

Examining the volatility spillover between stock and exchange markets by using the EGARCH (1,1) model is the final step. We have studied on each market information spillover separately for each country. First, we conducted analyses by examining volatility spillover from the foreign exchange market to the stock market, after which we continued to examine volatility spillover from the stock market to the exchange market. For selecting the appropriate lag length of each model, the basis of Akaike's information criterion has been selected.

Table 7 presents the EGARCH estimations for both the mean and conditional variance equations. The mean equation results show that changes in the exchange rate have a significant negative impact on stock returns in Hungary and Poland over the study period, and in the Czech Republic, Romania and Croatia in the post-crisis period; while insignificant, however, in the Czech Republic, Romania and Croatia in the pre-crisis period. The significant negative impact of the foreign exchange market on the stock market reveals that changes in the exchange market could reduce stock returns in these countries, decreasing the profitability and stock prices of firms. The negative effect of the exchange market would create fluctuations in the trade balance and competitiveness of the given country. As a result, it would decrease real income and economic growth (Jebran and Iqbal, 2016).

Table 6 ARCH test

Countries	Hungary	Poland	Czech	Romania	Croatia
			Stock indices		
Panel A: Pre-crisis period					
Constant	1.254^{*}	1.021^{*}	0.892^{*}	1.525^{*}	1.137^{*}
AR(1)	0.061^{*}	0.042^{**}	0.071^{*}	0.390^{*}	0.271^{*}
ARCH test	80.09^{*}	110.57^{*}	141.74^{*}	362.65^{*}	240.30^{*}
Panel B: Post-crisis period					
Constant	1.137^{*}	0.579^{*}	0.659^{*}	0.942^{*}	0.544^{*}
AR(1)	0.290^{*}	0.020	0.228^{*}	0.306^{*}	0.297^{*}
ARCH test	363.55^{*}	309.09^{*}	559.10^{*}	411.67^{*}	550.14^{*}
			Exchange rates		
Panel A: Pre-crisis period					
Constant	0.515^{*}	0.331^{*}	0.402^{*}	0.2085^{*}	0.335^{*}
AR(1)	0.097^{*}	0.137^{*}	0.012	0.567^{*}	0.108^{*}
ARCH test	25.01^{*}	72.17^{*}	21.37^{*}	576.77^{*}	59.96^{*}
Panel B: Post-crisis period					
Constant	0.498^{*}	0.408^{*}	0.291^{*}	0.256^{*}	0.276^{*}
AR(1)	0.042^{**}	0.158^{*}	0.084^{*}	0.038	0.173^{*}
ARCH test	251.82^{*}	403.89^{*}	325.83^{*}	291.60^{*}	151.88^{*}

Note: the ARCH test is the arch effect test.

* denotes the level of significance at 5%, ** indicates $p < 1\%$

Source: calculations of the author

The results of the negative impact of the foreign exchange rate market on stock returns are similar to those of Aloui (2007), Yang and Doong (2004), and Jebran and Iqbal (2016). The findings support the theoretical prediction of stock-oriented models in which it is reported that there is a negative relationship between foreign exchange rate and stock price.

In the case of the Czech Republic, Romania and Croatia, the insignificant effect of exchange rates on stock returns in the pre-crisis period may postulate the effective hedging strategies against currency risk in these countries. The results of our empirical analysis indicate that there is also an insignificant linkage between stock market changes and foreign exchange rate dynamics in all countries over the study period except Romania in the post-crisis period. The mean equation reveals that stock market fluctuations have a significant negative effect on exchange rate returns in Romania in recent years, supporting the theoretical prediction of the portfolio balance model, which posits that exchange rates respond to demand and supply on the stock market. Consequently, an increase in domestic stock prices will lead investors to sell foreign assets in the market for the purpose of purchasing domestic assets. This result is in line with a study such as that by Jebran and Iqbal (2016). Additionally, as regards other countries, the weakness or absence of impact of stock prices on exchange rates supports the theoretical prediction of a monetary approach which presumes that there is no linkage between exchange rates and stock prices. These results are consistent with Hung (2017).

Turning to the second moment interdependencies, the variance equation results indicate coefficient δ, which measures volatility spillover from exchange market to stock market and indicates whether this spillover is asymmetric, which is statistically significant for Hungary and Poland in all the periods, and for Romania and Croatia in the pre-crisis period. For the pre-crisis period, the coefficient is positive in the case of Hungary, Poland and Romania, while negative in the case of Croatia. For the post-crisis period, the coefficient is positive for Hungary and Poland. The positive coefficient illustrates that foreign exchange market volatility is increasing the volatility of the stock market; on the other hand, the negative coefficient shows that foreign exchange market volatility is decreasing the volatility of the stock market. In the case of Hungary, Poland and the Czech Republic, the findings are consistent with Morales (2008), Aloui (2007), and Valls and Chuliá (2014).

The coefficient ψ measures volatility spillover from stock prices to exchange rates. The coefficient is statistically significant for Hungary and the Czech Republic in all periods, but insignificant in the case of Poland and Romania in the pre-crisis period, and for Croatia in the post-crisis period. The coefficient is negative in all cases. This negative coefficient describes that stock market volatility is decreasing the volatility of the foreign exchange market. It is important to note that we find no volatility spillover from exchange market to stock market in the case of the Czech Republic in both periods, and in Romania and Croatia in the post-crisis period, and no volatility spillover from the stock market to the exchange market in the case of Poland and Romania in the pre-crisis period, and Croatia in the post-crisis period. These results are in line with Fedorova and Saleem (2009), but inconsistent with Morales (2008).

Briefly, the results are mixed when we compare the volatility spillover with different countries and during two periods because changes in volatility spillover between stock returns and foreign exchange markets have changed over time; in particular, they have increased in the post-crisis period, which is consistent with the notion that financial market integration increased after the crisis period. The results show that there is a bidirectional volatility spillover between the stock and foreign exchange market in Hungary in all periods, and in Poland in the post-crisis period, which represents the information inefficiency of these stock markets; meanwhile, there is unidirectional volatility spillover in Croatia in the pre-crisis period, and from the stock market to the exchange market in the Czech Republic during two periods. However, there is no volatility spillover in Croatia in the post-crisis period, which implies effective strategies against stock market and exchange rate fluctuations. The absence of volatility spillover from the exchange market to the stock market in the case of the Czech Republic (two periods), and Romania and Croatia (post-crisis period), could indicate effective hedging strategies against currency risk. Finally, the asymmetric spillovers from stock returns to exchange rates have all the positive signs and can be interpreted by stating that good news has a greater impact on volatility than unexpected bad news. On the other hand, the asymmetric spillovers from exchange rates to stock returns have all the negative signs, implying that negative shocks generate more volatility than positive shocks of the same magnitude.

In order to evaluate the robustness of the estimation results, we examined the ARCH effect on the residuals of each model to determine whether the ARCH effect still exists in the model. The null hypothesis is that there is an ARCH effect. As can be seen in Table 7, the results of the ARCH test illustrate that we find strong evidence of the absence of the ARCH effect for all series considered except for Romania, when we estimate the volatility spillover from the stock market to the foreign exchange market in the pre-crisis period. This is similar to the findings of the study by Kamisli et al. (2015) and also a limitation of this investigation. Hence, using the EGARCH model can successfully capture the price volatility interaction between stock and exchange markets.

Table 7 Volatility spillover between stock and foreign exchange markets

Countries	Hungary	Poland	Czech	Romania	Croatia
Volatility spillover from foreign exchange market to stock market					
Panel A: Pre-crisis period					
α_0	0.041	0.053**	0.074*	0.075*	0.099*
α_1	0.033	0.061*	0.049**	0.143*	0.037
α_2	-0.083**	-0.116*	-0.022	0.021	-0.014
β_0	-0.082*	-0.080*	-0.133*	-0.221*	-0.167*
β_1	0.943*	0.979*	0.939*	0.916*	0.924*
β_2	0.147*	0.112*	0.192*	0.406*	0.285*
ϕ	-0.052*	-0.028*	-0.095*	-0.033*	-0.008
δ	0.055*	0.014*	-0.0006	0.134*	-0.092*
ARCH LM(1)	0.019(0.89)	3.21(0.07)	4.48(0.03)	0.39(0.53)	2.14(0.14)
Panel B: Post-crisis period					
α_0	0.031	0.033	0.005	0.027	0.015
α_1	-0.016	0.052**	0.024	0.067*	0.055*
α_2	-0.11*	-0.102*	-0.111*	-0.049**	-0.066*
β_0	-0.110*	-0.094*	-0.159*	-0.285*	-0.156*

β_1	0.986*	0.986*	0.980*	0.957*	0.987*
β_2	0.152*	0.123*	0.209*	0.393*	0.200*
ϕ	-0.063*	-0.045*	-0.067*	-0.062*	-0.036*
δ	0.016**	0.027*	0.004	0.011	-0.001
ARCH LM(1)	0.63(0.42)	0.76(0.37)	0.61(0.43)	2.38(0.12)	0.06(0.79)
Volatility spillover from stock market to foreign exchange market					
Panel A: Pre-crisis period					
a_0	-0.017	-0.033**	-0.031**	0.078*	-0.036*
a_1	0.010	0.072*	-0.013	0.0004	-0.072*
a_2	-0.018	-0.004	-0.016	-0.002	0.0002
γ_0	-0.130*	-0.216*	-1.025**	-0.100*	-0.057*
γ_1	0.864*	0.901*	-0.367**	0.993*	0.995*
γ_2	0.080*	0.181*	0.073**	0.123*	0.069*
φ	0.078*	0.074*	0.073*	-0.038*	-0.001
ψ	-0.046*	-0.010	-0.051**	-0.004	-0.015*
ARCH LM(1)	0.48(0.48)	0.60(0.43)	0.01(0.90)	80.7(0.00)	0.02(0.86)
Panel B: Post-crisis period					
a_0	0.011	0.016	0.017	0.011	0.014
a_1	-0.026	-0.04**	-0.005	-0.008	-0.032
a_2	-0.001	-0.025	0.015	-0.023**	-0.018
γ_0	-0.046*	-0.062	-0.077*	-0.050*	-0.047
γ_1	0.996*	0.994*	0.992*	0.993*	0.996*
γ_2	0.058*	0.078*	0.091*	0.057*	0.047*
φ	0.025*	0.028*	0.019*	0.0211*	0.029*
ψ	-0.016*	-0.022*	-0.021*	-0.012*	-0.007
ARCH LM(1)	0.08(0.76)	1.25(0.26)	0.34(0.55)	0.14(0.70)	4.49(0.03)

Note: * denotes the level of significance at 5%, ** indicates $p < 1\%$. Numbers in parentheses are probability.

Source: calculations of the author

Implications for portfolio designs and hedging strategies

According to Kroner and Ng (1998), estimating the right time-varying covariance matrix is extremely important for asset pricing, portfolio selection and risk management. In order to shed light on the significance of the covariance matrix to these sorts of financial problems, we employed our results to two problems. First, we take into consideration the problem of computing the optimal fully invested portfolio holdings. This application would address the types of problems faced by portfolio managers when deriving their optimal portfolio holdings. Second, we consider the problem of estimating a dynamic risk-minimizing hedge ratio.

Portfolio weights

In order to apprehend the connotation of the covariance matrix in connection with financial decisions, we follow the applications proposed by Kroner and Ng (1998) by taking into account a portfolio that minimizes risk without lowering expected returns. The portfolio weight of holdings of two equity indices in a country is given by:

$$\omega_{12,t} = \frac{h_{22,t} - h_{12,t}}{h_{11,t} - 2h_{12,t} + h_{22,t}}$$

and

$$\omega_{12,t} = \begin{cases} 0, & if\ \omega_{12,t} < 0 \\ \omega_{12,t}, & if\ 0 \le \omega_{12,t} \le 1 \\ 1, & if\ \omega_{12,t} > 1 \end{cases}$$

Where $\omega_{12,t}$ is the portfolio weight for the stock index with respect to the foreign exchange index at time t. $h_{12,t}$ is the conditional covariance between stock and foreign exchange indices, and $h_{22,t}$ is the conditional variance of the foreign exchange index. Apparently, the weight of the foreign exchange index in the one dollar portfolio is $1 - \omega_{12,t}$.

Hedge ratios

We follow the example developed by Kroner and Sultan (1993) to estimate the risk – minimizing hedge ratios for two equities in CEE countries. In order to minimize the risk of several portfolios, a long position of one dollar taken in one sector index should be hedged by a short position of \$ β_t in second sector index in a country at time t. The β_t can be written as:

$$\beta_t = \frac{h_{12,t}}{h_{22,t}}$$

where β_t is the risk minimizing hedge ratio for two indices.

Table 7.1 Optimal portfolio weights and hedge ratios

Portfolio	Weight ($\omega_{12,t}$)	Beta (β_t)
Hungary	0.2985	0.2346
Czech	0.2730	0.0617
Poland	0.3508	0.2607
Romania	0.1731	0.1875
Croatia	0.2154	0.0751

The average values of $\omega_{12,t}$ reported in Table 7.1 are a function of the conditional variances of stock and foreign exchange sectors for each time period. For example, the average value of $\omega_{12,t}$ of a portfolio including the stock and foreign exchange sector indices in Hungary is 0.2985. This suggests that the optimal holding of the stock index in one dollar of stock/foreign exchange index portfolio for Hungary is 29 cents, compared with 71 cents for the foreign exchange index. These optimal portfolio weights indicate that investors in Hungary should own more foreign exchanges than stocks in their portfolios. The case is the same for the Czech Republic, Poland, Romania and Croatia, where the foreign exchange sector overwhelmingly dominates the stock sector, possibly because the selected countries have the highest own volatility and volatility spillovers in the stock market.

The second column of Table 7.1 documents the average values of β_t for the CEE markets. By following this hedging strategy, one dollar long in the stock index, for instance, in the Hungarian financial market should be shorted by 23 cents in the foreign exchange sector in that market. The most expensive hedge in Poland market is by hedging the stock index with short positions in the foreign exchange sector. Nevertheless, the most hedging to hedge long positions is between the stock and foreign exchange in the Czech Republic, where a one dollar long position is the former can be hedged by a 7.5% cents short position in the latter.

2.5 Conclusion

In this study, we have investigated the empirical dynamics of volatility spillover effects between stock markets and foreign exchange markets in Central and East European countries – namely Hungary, Poland, the Czech Republic, Romania and Croatia – across the pre-crisis and post-crisis periods using the EGARCH model.

Our empirical evidence shows that there is a bidirectional volatility spillover between stock and foreign exchange markets in Hungary in all periods, and in Poland in the post-crisis period. The results also reveal unidirectional volatility spillover in Croatia in the pre-crisis period, and from the stock market to the exchange market in the Czech Republic during two periods. In the post-crisis period, the two financial markets show the absence of volatility spillover in Croatia. The spillovers are asymmetric in nature in all financial markets. Volatility spillover from stock returns to exchange rates decreased after the crisis period. The volatility persistence indicates that there was volatility persistence in all series in all periods; in general, the persistence of exchange market volatility was found to be greater than stock market volatility.

Our findings have several important economic and financial implications for economic policymakers and investors. First, international portfolio managers and hedgers may be better able to understand how the two financial markets interrelate over time, which might benefit them in forecasting the behaviour of one market by capturing the other market's information. Second, the information concerning the nature of volatility transmission across stock and exchange markets in a country could be important for policymakers and decision-makers from an economic stability perspective as financial market integration through exchange rates implies financial sector integration. Third, for investors, the findings could be particularly important when they aim to compile an efficient portfolio, as they can apply these results in reducing their risk, increasing their returns, and making decisions in the selected markets.

The State Bank of these countries would take into account the impact of exchange rate, stock price fluctuations and its influence on both markets since the behaviour of the global portfolios is significantly impacted by the behaviour of the two financial markets. Further, policymakers in these countries should design a policy that helps minimise the adverse influence of volatility if they wish to stabilize the stock and foreign exchange prices and minimise the adverse effects of exchange rate and stock price volatilities on investment decision. By doing so, the stability in the two financial markets is significant to promise foreign direct and portfolio investments, which exert a positive influence on economic growth and promote macroeconomic stability of these nations.

DOES VOLATILITY TRANSMISSION BETWEEN STOCK MARKET RETURNS OF CENTRAL AND EASTERN EUROPEAN COUNTRIES VARY FROM NORMAL TO TURBULENT PERIODS?[2]

This study investigates the transmission mechanism of price and volatility spillovers across Budapest, Warsaw, Prague, Bucharest and Zagreb stock markets in the pre and post 2007 financial crisis period under the framework of the multivariate EGARCH model. By using daily closing prices, the results highlight certain interesting key findings. We found evidence of price spillovers of the intraregional linkages among the stock price movements in the five countries. The results of our analysis show the existence of bidirectional volatility spillovers between stock markets of the Czech Republic and Croatia in the pre-crisis period, and between Hungary and Romania in the post-crisis period. Also, there are significant volatility spillovers from Croatia to Poland and from Poland to the Czech Republic during two periods. The volatility is found to respond asymmetrically to innovations in other markets. The findings also indicate that the stock markets are more substantially integrated into crisis, as well as the persistence of volatility spillovers between the stock markets increases, and the financial stock markets become more integrated after crisis period. Finally, the integration of these markets has significant implications for policymakers and investors.

Keywords**:** Volatility spillover, 2007 financial crisis, market integration, Central and Eastern Europe.

JEL classification indices: C15, C51, G15

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[2] Hung, N.T. (2019). Does volatility transmission between stock market returns of central and eastern European countries vary from normal to turbulent periods? evidence from EGARCH model. Acta Oeconomica.

3.1 Introduction

Analyses of stock market volatility spillovers dated back to (Engle et al. 1990; Nelson, 1991), who created much attention in the literature related to financial markets. The concept of volatility spillover of asset returns can be drawn from the seminal work of (Engle et al. 1990). The heat-wave hypothesis and the meteor-shower hypothesis have been introduced as the theoretical foundations for own and cross-type spillovers. The heat-wave hypothesis representing own-spillover illustrates that the current volatility of a market is a function of past volatility of the same market. On the other hand, the meteor-shower hypothesis representing cross-spillover reveals that the current volatility of a market is a function of both past volatility of the same market and past volatility from other markets. There have been many studies based on the GARCH-type framework to examine volatility spillovers among financial markets in different countries. The key study of (Nelson, 1991) contributed a significant characteristic regarding volatility spillover to literature, which is the salient property of asymmetric. Volatility transmission also exhibits asymmetry with regards to the kind of news. Bad news seems to have a severe effect on spillover as compared to good news. This asymmetric property of spillover is a prime contributor to the cause of financial contagion. It is clear that in the context of the literature, the volatility spillover can be divided into three fundamental points: first, a bidirectional volatility spillover among stock markets; second, a unidirectional flow of volatility from a stock market to another stock market and vice versa; third, non-persistence of the volatility spillover among them (Hung, 2018).

It is strongly believed that regional economic integration across the world is a consequence of increasing regionalization of economic activities and liberalization of financial markets. This is also the result of the increased globalization of financial markets, the interdependence of major financial markets around the world, international investment processes and market contagion effects. In addition, the international volatility spillover effect of markets has important implications for domestic economies and for international diversification. Systematical understanding of short-run interdependence in return and volatility spillovers and the nature of the markets provide valuable information on diversification and hedging strategies**.** The important topic of investigation of transmission of stock market information and the behaviour of emerging markets among Central and Eastern European countries in particular, global equity markets in general, has attracted great attention from academic researchers and industry professionals because the openness of financial markets contributes to economic development. Scholars and policymakers are attempting to understand the changing pattern of integration behaviour of developed markets with emerging markets and its performance in the post-crisis period. It is obvious that emerging nations have experienced several crises during the last three decades, namely stock market crash in 1987, the Asian currency crisis in July 1997, the Mexican currency crisis in 1994 and the subprime crisis of 2007-2008. The term "turbulent" episodes, with some key features, are large negative asset returns, and high volatility and their effects have swiftly proliferated to other emerging economies (Melik Kamisli et al. 2015). An investigation of volatility spillover effects between equity markets could provide straightforward insight for foreign investors who seek for diversification opportunities abroad. This is because price, volatility and interlinkages of stock markets imply that the volatility of markets tend to move together, and the potential gains from international diversification will be reduced. Interestingly, developing markets in emerging economies with a relatively high and stable growth rate in Central and Eastern European countries such as Hungary, Poland, the Czech Republic, Romania and Croatia in recent years is especially remarkable, and they are usually good choices for market participants looking to diversify their portfolios internationally (see Figure 6). It is the case because these stock markets are achieved substantial level of development, the same in size and institutional characteristics. Therefore, taking into account the empirical research of volatility spillovers and intraregional linkages has become necessary from the particular perspective of portfolio diversification and hedging strategies.

The purpose of this study is to analyze the changes in the co-movement of return and volatility spillovers among the stock markets of the countries which have undergone the crisis directly in the neighbouring Central and Eastern European countries using the Exponential Generalized Autoregressive Conditional Heteroskedasticity EGARCH framework. More specifically, we selected five stock markets, namely Budapest Stock Exchange BUX, Warsaw Stock Exchange WIG, Prague Stock Exchange PX, Bucharest Stock Exchange BET and Zagreb Stock Exchange CRON as neighbouring countries. The period of study is then divided into two sub-periods of the pre-crisis and post-crisis period. It is clear that the crisis seems to have the common impact on these countries as a whole. Rapid economic growth has been accompanied by a sharp increase in the size of the stock market; therefore, we consider whether or not the integration of financial markets in the post-crisis period takes place. As Jebran et al. (2017) explained that the long-lasting effect of the subprime crisis of 2007-2008 was probably due to increasing stock market integration in emerging markets of Asia.

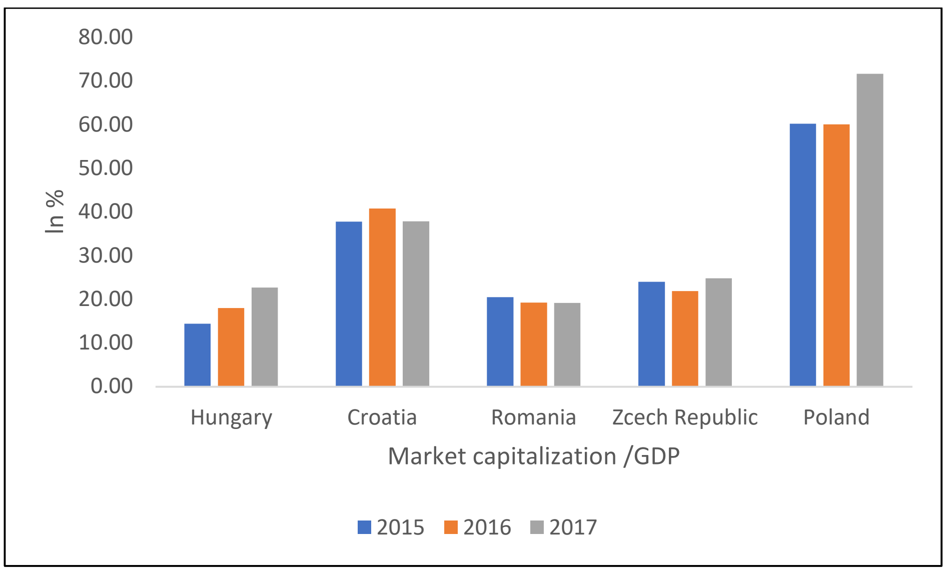


Figure 6 Significance of selected equity markets

Source: Web pages of equity exchanges and Bloomberg

Although there are numerous literatures on equity market integration internationally, this paper contributes to the existing literature of the ongoing debate about stock interaction in several ways. Firstly, we consider five markets including important markets of Central and Eastern Europe, and the pivotal role of emerging markets which is becoming more interesting for investors and policymakers since throughout analysis of the movement of information across emerging markets will provide useful information for investors, which might help international portfolio diversification. Secondly, Central and Eastern European countries have attempted to increase cooperation and trade among themselves in order to examine integrations among the stock markets, taking account of pre and post financial crisis which is prominent. Thirdly, we modeled the possible returns and asymmetric volatility spillovers among five emerging markets in which previous studies only focused on the dynamic relationship between returns and transmissions. Hence, this present study would be somewhat different from previous studies.

Based on the results and findings of this study it can be concluded that there is new evidence on price and volatility spillovers across the five developing stock markets for the periods before and after 2007-2008 financial crisis. The process of integration of the Central and Eastern European countries is relatively remarkable in the post-crisis period, and it is expected to continue to progress further given the initiatives undertaken by the countries' policymakers.

The rest of the paper is organized as follows. Section 2 describes a brief review of previous research on the studies of return and volatility spillovers across markets. Methodology and data employed for under study are explained in Section 3. Section 4 discusses the results on volatility spillover. The final section includes conclusions and recommendations.

3.2 Literature review

Interdependence among international markets has attracted great attention from academic researchers and practitioners. It has been investigated in two primary contexts: interdependence in returns and interdependence in volatility. This interdependence exists in stock markets in the region which will respond similarly to common shocks. In finance literature, numerous studies have been interested in exploring the financial integration and volatility spillover effect among the stock markets. Also, some of the scholars have mentioned the so-called market liberalisation, the market crisis on volatility spillover of the dimension of information across borders. Most of the studies have concentrated on the interdependence of developed markets such as the US, Japanese and major European markets (Ko and Lee, 1991; Koutmos and Booth, 1995; Maghyereh et al. 2015). Some of the researchers have also paid their attention to studying the developed Asian and emerging markets (Jang and Sul, 2002). The earlier studies illustrated slight integration and spillover effect between the stock markets (Ko and Lee, 1991; Panton et al. 1976; Kim et al. 2015; Bhar and Nikolova, 2009). However, most recent investigations indicated strong interdependence between them because of the development of advanced technology and financial deregulations of financial markets (Johsi, 2011; Okicic, 2015; Alotaibi and Mishra, 2015; Jebran et al. 2017; Huo and Ahmed, 2017; Ghouse and Khan, 2017; Bala and Takimoto, 2017; Jebran et al. 2017; Baumohl et al. 2018; Mensi et al. 2018; Morales Zumaquero and Sosvilla Rivero, 2018; Caloia et al. 2018; Lau and Sheng, 2018; BenSaida et al. 2018; Tiwari et al. 2018; Ahmed and Huo, 2018; Naresh et al. 2018; Xuan Vinh and Ellis, 2018).

More recently, there have been several interesting investigations under the GARCH-type framework, for instance, Alotaibi and Mishra (2015) examined the effects of return spillovers from regional (Saudi Arabia) and global (US) markets to GCC stock markets (Bahrain, Oman, Kuwait, Qatar, United Arab Emirates). Their findings reported that there existed the significant return spillover effects from Saudi Arabia and US to GCC markets, and trade, turnover, and institutional quality had significant influences on regional volatility spillovers from Saudi Arabia to GCC markets. Bala and Takimoto (2017) highlighted the lower correlations among emerging markets and these coefficients had the dramatical increase during financial crises. They also detected evidence of volatility spillovers and observed that own-volatility spillovers were higher than cross-volatility spillovers for emerging markets. Ghouse and Khan (2017) studied dynamic linkages and spillover effect between Pakistani and leading foreign stock markets, and the authors documented the mixed co-movements between leading stock markets and Pakistani stock market, also bidirectional spillover effect between DFMGI (Dubai Financial Market General Index) and KSE100 (Karachi stock market). Huo and Ahmed (2017) conducted a study of the influence of the recently introduced Shanghai-Hong Kong stock connect. Their results revealed that the new stock connect contributed to the increasing importance of the Chinese mainland stock market and economic activities. Lau and Sheng (2018) found out evidence of the inter-regional spillover effect in daytime returns and Shanghai stock market was the least integrated of all nine markets selected by considering the inter-and intra-regional spillover effects across international stock markets in London, Paris, Frankfurt, Toronto, New York, Tokyo, Shanghai, Hong Kong, and Mumbai. Baumohl, E. et al. (2018) analyzed 40 developed, emerging and frontier stock markets during periods 2006-2014, and documented that volatility spillovers decreased when temporal effects with regard to the US equity markets. These markets were characterized by greater temporal proximity. Ahmed and Huo (2018) shown substantial evidence of bidirectional feedback relationships between Chinese and most of the African stock market prices and at least a unidirectional flow of spillover effect from China to most of the African stock markets. Xuan Vinh and Ellis (2018) illustrated the statistically significant correlation, return spillover and volatility linkage between Vietnamese stock market with other advanced stock markets of the US, Hong Kong and Japan.

The volatility transmission mechanism using GARCH-type models across various markets is also researched by different articles including those by (Nath Mukherjee and Mishra 2010; Singh et al. 2010; Sok et al. 2010; Lahrech and Sylwester, 2011; Natarajan et al. 2014; Dedi and Yavas, 2016; Gamba et al. 2017; etc..). Nath Mukherjee and Mishra (2010) studied stock market integration and volatility spillover between India and its major Asian counterparts and found that contemporaneous intraday return spillovers between India and its Asian counterparts were positively significant and bi-directional. The four Asian markets of Hong Kong, Korea, Singapore and Thailand were where there was a significant flow of market information to India. Singh et al. (2010) examined price and volatility spillovers across North American, European and Asian stock markets. The results indicated that a particular index was mostly affected by the indices which opened/closed before it and there was a more considerable regional influence among Asian and European stock markets. Sok et al. (2010) studied volatility spillovers among the ASEAN-5 (Malaysian, Indonesian, Siamese, Singaporean, Philippines) stock markets and between the ASEAN-5 with the United States and Japan for a period after the Asian financial crisis. The paper highlighted intraregional linkages among the stock price movements in the ASEAN-5 and volatility spillovers in the ASEAN-5 were more influenced by the stock market in the United States relative to the Japanese. Lahrech and Sylwester (2011) measured the extent of integration and co-movement in the Latin American equity markets of Argentina, Brazil, Chile and Mexico with the U.S equity market and found that there was an increase in the degree of co-movement between these countries and the US. Natarajan et al. (2014) focused on the mean-volatility spillover effects happening across markets of Australia, Brazil, the US, Germany and Hong Kong. The analysis provided the strong evidence of mean and volatility spillover across some stock exchanges. From Latin American nations, Gamba et al. (2017) reported that Brazil is a net volatility transmitter for most of the sample period, while Chile, Colombia and Mexico are net receivers. The volatility spillover is substantially higher between 2008Q3 and 2012Q2, and shock transmission from the United States to Latin America dramatically increased around the Lehman Brothers' episode. We shall only present the following recent results of the econometric modeling of the conditional mean and volatility spillovers of stock returns from the emerging and frontier stock markets and state of the art results using GARCH-type models.

In European countries context, Shield (1997) considered two emerging Eastern European markets (Hungary and Poland) to investigate stock return volatility. Tobit GARCH model was employed, and the estimation pointed out that no asymmetry exists in either emerging market. Scheicher (2001) investigated the regional and global integration of stock markets in Hungary, Poland and the Czech Republic by employing a vector autoregression with a multivariate GARCH component and found that there was an existence of limited interaction in returns both regional and global shocks, but news to innovations to volatility have a primarily regional character. At the same time, Murinde and Poshakwale (2001) studied volatility in the six emerging stock markets including Croatia, the Czech Republic, Hungary, Poland, Russia and Slovakia. Their estimations based on ARIMA, the BDSL procedure and symmetric as well as asymmetric GARCH models indicated that daily return volatility exhibits significant conditional heteroskedasticity and non–linear effects. GARCH models provided the explanation by symmetric and asymmetric, but it was not significant enough for predicting future volatility. Moreover, estimating the behaviour of stock returns in the case of stock markets from Central and Eastern Europe mainly concerned with the relationship between returns and conditional volatility was conducted by (Okicic, 2015). The findings provided parsimonious approximations of conditional mean and volatility dynamics in daily return series based on ARIMA and GARCH specifications, and the author demonstrated that there was strong evidence of the existence of a leverage effect in the selected stock markets. In these Central and Eastern European countries, based on weekly data, Melik Kamisli et al. (2015) also identified the structure of conditional correlations between stock markets returns as well as observed the volatility transmission between these countries. By using constant conditional correlations GARCH (CCC-GARCH) models over dynamic GARCH models, the results of this study have some key findings analogous to (Okicic, 2015). The findings imply that most of the conditional correlations between stock markets returns of the selected nations are constant. This means that markets do interact with each other regarding shocks and volatility. Two other studies by Dedi and Yavas (2016) and Yavas and Dedi (2016) examined linkages and volatility spillovers in equity markets using the GARCH types model. Dedi and Yavas (2016) focused on the financial markets of Germany, the United Kingdom, China, Russia and Turkey, while Dedi and Yavas (2016) conducted their research in Germany, Austria, Poland, Russia and Turkey. The two studies utilized Exchange Traded Funds (ETF) instead of the benchmark indices that were mostly used in the literature. This was because ETFs had undergone dramatic growth and become the preferred mediums of investment for hedge funds and institutional investors. Moreover, the advantage of applying the ETF data was that it allowed the mitigation of certain critical issues that emerged in traditional academics, such as the volatility of exchange rates, diversities in stock exchange trading times, bank holidays and restrictions on cross-border trading and investments. The findings of Dedi and Yavas (2016) indicated that the existence of significant co-movements of returns and evidence of volatility between them Russia and Turkey exhibited the highest volatility. Further, the lowest volatility occurred in the markets of the UK and China. Similarly, Yavas and Dedi (2016) also confirmed that there was strong evidence of volatility spillovers and the existence of significant co-movement of return among these countries; mainly, the Russian and Turkish markets were more volatile than Austria. As a matter of fact, the results of the volatility transmission and the time-varying nature of volatility provided an explanation for the implications for those investors and portfolio managers who evaluated such information and rebalanced their portfolios to finally achieve efficient portfolio diversification. In addition, there were significant implications concerning European Neighbourhood Policies (ENP), entailing that if the ENP implements different kinds of programs that continue to bear fruit, it may possibly result in greater integration of the equity markets of the EU and the border countries. Also, ENP might create increased volatility transmissions among the highly connected markets. As a result, investors desiring to diversify their portfolios might choose the market elsewhere in which do not move together. However, the limitation of using ETFs had not been around long enough to be tested for crisis situations.

Though there is a vast amount of literature on volatility spillover across markets, only a few of them have mentioned the investigation of the effect of the financial crisis on equity market integrations. The 1987 European market crisis was studied by (see, e.g., Arshanapalli and Doukas, 1993; Koutmos and Booth, 1995; Meric. I and Meric G. 1997). Some investigations studied the Russian financial crisis such as (see, e.g., Patev et al. 2006; Diebold and Yilmaz, 2009), the 1997 Asian financial crisis (see, e.g., Arshanapalli et al. 1995; Jang and Sul, 2002; Karunanayake et al. 2010). More recently, (Sidek et al. 2011; Srivastava et al. 2015; Bae and Zhang, 2015; Maghyereh et al. 2015; Jin and An, 2016; Jebran et al. 2017; Bajo-Rubio et al. 2017) investigated stock market integration in the 2007 financial crisis period. The global financial crisis 2007-2009 and its influence across financial markets have stimulated considerable interest in the analyses of stock market volatility spillovers. Most of those findings reveal that the stock markets have grown more substantially integrated into the post financial crisis period.

In general, although the state-of-the-art results from the literature review summarised above are that dynamic interactions exist between stock markets as well as market integration after the financial crisis period; there is still a need to carry out investigation into the frontier and emerging markets of Central and Eastern Europe in the recent financial crisis period.

Furthermore, the objective of this paper is to examine volatility spillovers existing across five countries in Central and Eastern Europe and to determine the direction of influence within those markets before and after the 2007 financial crisis period. Volatility spillovers of returns across markets will, thus, provide important implications for portfolio choice and risk management.

3.3 Methodology

3.3.1 The multivariate EGARCH model

A rich empirical investigation exists on the examination of the asymmetric volatility spillovers between financial markets. In this study, we adopt the model of EGARCH to analyze a financial time series to monitor volatility spillover effects. The multivariate Exponential Generalized Autoregressive Conditional Heteroskedasticity (EGARCH) model is employed so as to examine market interdependence and volatility transmission between stock markets in different countries. The simple GARCH model enforces a symmetric effect of volatility (positive shocks) and is not able to capture asymmetric shocks (negative shocks) because of the conditional variance being a function of lagged residuals and not their signs (Jebran et al. 2017; Hung, 2018). The EGARCH specification is suitable for the study of volatility spillover effects because it is able to capture the contemporaneous correlation between the stock indices under study (Jane and Ding, 2009). Additionally, the EGARCH modelling is applied to test whether the volatility spillover effects are asymmetric. Furthermore, Koutmos and Booth (1995) put forward that the model captures the asymmetric effect of negative and positive returns on the conditional variance and thus allows the news generated in one market to be evaluated in term of size and sign by the next market to trade. Therefore, numerous empirical studies based on the EGARCH framework to specify volatility spillovers between different financial markets in different countries, (Koutmos and Booth, 1995; Mishra et al. 2007; Yang and Doong, 2004; Bhar and Nikolova, 2009; Sok et al. , 2010; Okicic, 2014; Elyasiani and Mansur, 2017; Jebran et al. 2017; etc..), for instance. In this paper, we applied the EGARCH (1,1) model to examine the transmission mechanism of volatility between five financial markets in Central and Eastern Europe. The EGARCH specification Nelson (1991) may be represented as follows:

The conditional mean equation

$$R_{i,t} = \alpha_{i,0} + \sum_{j=1}^{5} \alpha_{i,j}\varepsilon_{j,t-1} + \varepsilon_{i,t}, \text{ for } i,j=\overline{1,5} \tag{3.1}$$

The conditional variance equation

$$\sigma_{i,t}^2 = \exp\left\{\beta_{i,0} + \sum_{j=1}^{5} \delta_{i,j} f_i(z_{j,t-1}) + \gamma_i \ln(\sigma_{i,t-1}^2)\right\}, \text{ for } i,j=\overline{1,5} \tag{3.2}$$

The asymmetric transmission of shock from market j to market i

$$f_j(z_{j,t-1}) = \left(|z_{j,t-1}| - E\left(|z_{j,t-1}|\right) + \phi_j z_{j,t-1}\right), \text{ for } i,j=\overline{1,5} \tag{3.3}$$

where relative asymmetry measured by the conditional covariance specification:

$$\sigma_{i,j,t} = \rho_{i,j}\sigma_{i,t}\sigma_{j,t}, \text{ for } i,j=\overline{1,5} \text{ and } \quad i \neq j \tag{3.4}$$

The function f_i generates sequences of zero mean, identically and independently distributed random variables by construction and allowing past standardized innovations to affect asymmetrically. The terms $|z_{j,t-1}| - E\left(|z_{j,t-1}|\right)$ in Equations (3.3) capture the size effect and the term $\phi_j z_{j,t-1}$ measures the sign effect. When ϕ_j is negative it will increase the volatility by more than a positive realization of equal magnitude. Similarly, if the past absolute value of z_t

is greater than its expected value, the ongoing volatility will rise. This effect is referred to as leverage effect and is pointed out by (Nelson, 1991).

We summarize each of the relevant terms in equations (3.1) - (3.4) in Table 8**.**

Table 8 Description of Parameters Equations (3.1)-(3.4)

Explanation	Parameters
The continuous compounding returns of the stock index	$R_{i,t}$
The constant	$\alpha_{i,0}$
Extend for price spillover across markets	$\alpha_{i,j}$
Stochastic error terms	$\varepsilon_{i,t}$
Allow for autocorrelation in the return due to non-synchronous trading (Hamao et al. 1990)	$\alpha_{i,j}\varepsilon_{j,t-1}$
Standardised residuals assumed to be normal distribution with zero mean and variance $\sigma^2_{i,t-1}$	$z_{i,t-1} = \frac{\varepsilon_{i,t-1}}{\sigma_{i,t-1}}$
Size effect	$\lvert z_{j,t} \rvert - E\left(\lvert z_{j,t} \rvert\right)$
Persistence of Volatility	γ_i
Volatility spillover from the respective stock market to the stock market under consideration	$\delta_{i,j}$
The constant level of volatility	$\beta_{i,0}$
Asymmetric effect of volatility	ϕ_j
Correlation coefficient of standardised residuals	$\rho_{i,j}$
The conditional covariance	$\sigma_{i,j,t}$

Note: persistence of volatility in which the unconditional variance is finite if $\gamma_j < 1$ and if $\gamma_j = 1$, then the unconditional variance does not exist and the conditional variance follows an integrated process of order one.

The term $\sum_{j=1}^{5}\delta_{i,j}f_i(z_{j,t-1})$ is defined in equation (3.2) and partial derivatives are:

$$\partial f_j(z_{j,t})/\partial z_{j,t} = 1+\phi_j, \text{ if } z_j > 0 \text{ and,}$$

$$\partial f_j(z_{j,t}) / \partial z_{j,t} = -1+\phi_j \text{, if } z_j < 0.$$

Asymmetric is demonstrated if ϕ_j is negative and statistically significant. A significant positive $\delta_{i,j}$ couples with a negative ϕ_j implies that negative innovation in market j have a higher impact on the volatility of market i than positive innovations (Koutmos and Booth, 1995). Relative asymmetry is defined as $|-1+\phi_i| / (1+\phi_i)$. This quantity is greater than, equal to, or less than 1 for negative asymmetry, symmetry and positive asymmetry respectively (Bhar and Nikolova, 2009). The conditional correlations are presupposed to be constant over time (Bollerslev, 1990). With the assumption that the conditional joint distribution of the returns of the five markets are normal and given a sample of T observations, the log-likelihood function of a multivariate EGARCH model can be expressed as (Koutmos and Booth, 1995):

$$L(\Theta) = \left(\frac{1}{2}\right)(NT)\ln(2\pi) - \left(\frac{1}{2}\right)\sum_{i=1}^{T}\left(\ln|S_t| + \varepsilon_t^{'} S_t^{-1} \varepsilon_t\right) \tag{3.5}$$

where N is the number of equations, Θ is the parameter vector to be estimated, $\varepsilon_t^{'} = (\varepsilon_{1,t}, \varepsilon_{2,t}, \varepsilon_{3,t}, \varepsilon_{4,t}, \varepsilon_{5,t})$ is the 1×5 vector of innovations at time t, S_t is the 5×5 time varying conditional variance-covariance matrix with diagonal elements are given by equation (4). The log-likelihood function is estimated using the (Berndt et al. 1974) algorithm.

The procedures of this research shall be conducted in the following four stages (Tsay, 2005): i) conducting the unit root test for relevant variables to make sure that all variables are stationary series ii) identifying and estimating an autoregressive and moving average (ARMA) model for the mean equation, using the residuals of the mean equation to test for ARCH effect iii) estimating EGARCH model for volatility spillover and iv) checking the robustness of the estimation.

3.3.2 Data

Data used in this paper consists of time series of daily stock market indexes at the close of the markets in five Central and Eastern European countries. We take daily data covering the period from 1st April 2000 to 29th September 2017, in terms of local currency in order that all indices are in domestic currency to avoid problems associated with transformation because of fluctuations in exchange rates (Gupta and Guidi, 2012). The key points of this study are to make comparisons the changes as well as to show the interrelation and volatility spillovers among five financial markets before and after 2007's financial crisis period. Therefore, the entire investigation period is subdivided into two sub-periods: pre-crisis period: 1st April 2000 to 29th August 2008, and post-crisis period: 1st September 2008 to 29th September 2017. The number of observations across the market is 4013, which is less than the total number of observations because joint modelling of five markets requires matching returns.

The reason for collecting daily data is to capture more precise information content of changes in stock prices than doing with weekly or monthly data (Jebran and Iqbal, 2016), and better able to capture the dynamics between variables (Agrawal et al. 2010). The five sample European countries include emerging markets: Hungary, Poland, Czech Republic, and frontier markets: Romania, Croatia (msci.com, 2018) and their stock indexes are Budapest Stock Exchange BUX, Warsaw Stock Exchange WIG, Prague Stock Exchange PX, Bucharest Stock Exchange BET and Zagreb Stock Exchange CRON respectively. The data for our empirical investigation is obtained from Bloomberg, accounted by the Department of Finance, Corvinus University of Budapest. The reason why we chose these markets is that the capital ones of these markets are known as frontier markets and emerging markets, so emerging and frontier capital markets have vastly different characteristics than developed capital markets (Okicic, 2014). Primary features of emerging and frontier market are that average returns are higher, correlations with developed market returns are low, returns are more predictable and volatility is higher (Bekaert and Harvey 1997). The daily return data series are calculated as $R_t = 100 \times \ln(P_t/P_{t-1})$, where P_t is the price level of the market at time t. The logarithmic stock returns are multiplied by 100 to approximate percentage changes and avoid convergence problems in estimation.

3.4 Empirical findings

3.4.1 Preliminary statistics

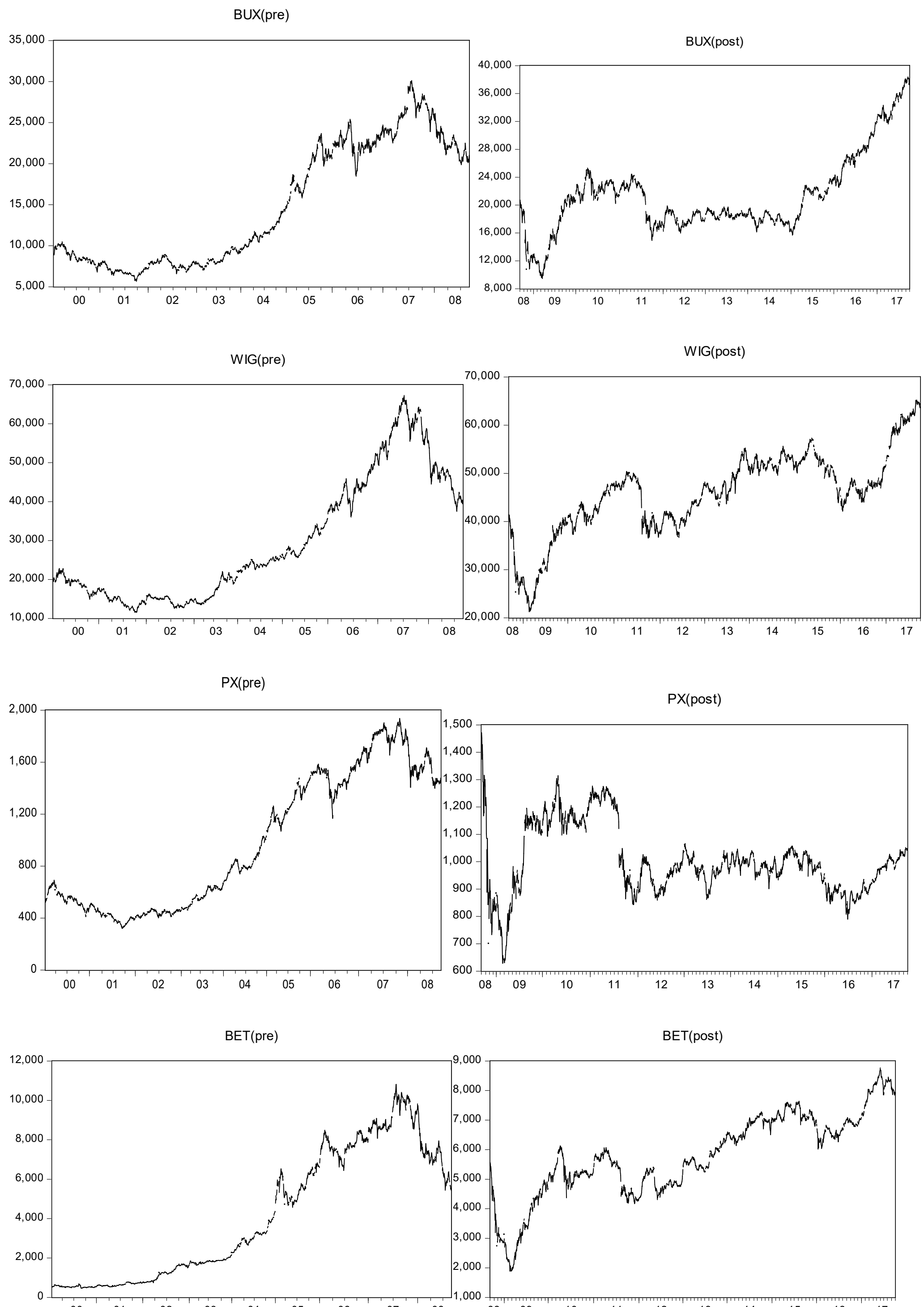
Table 9 depicts summary statistics for the daily returns of the five markets as well as statistics testing for normality, unit root and ARCH test for both sub-periods. The analyses show that sample means of stock returns are positive and significantly different from zero for five countries over the study period except for the Czech Republic and Croatia in the post-crisis period. The Romanian stock market has the highest daily average return of 0.12% in the pre-crisis period, and the figure for Hungarian market is 0.02% in the post-crisis period. On average, the stock displays a negative return -0.0159% for the Czech Republic and -0.0309% for Croatia in the post-crisis period, mostly because of the effects of recent global crises and Eurozone turmoil (Melik Kamisli et al. 2015). The unconditional volatility of stock markets is measured by standard deviations. The sample variances range from 1.36% for the Czech Republic to 1.76%. for Romania in the pre-crisis period, and 1.25% for Croatia to 1.70% in the post-crisis respectively. The measures for skewness and excess kurtosis indicate that all return series are skewed and highly leptokurtic with respect to the normal distribution. This is formally confirmed by The Jarque-Bera test statistics. In the next step, the stationarity of the data is tested. All stock returns series are found to be stationary at level (e.i I(0)) at the 1% significance level according to the PP ADF statistics for both sub-periods. Similarly, the ARCH effect illustrates the presence of autocorrelation and heteroskedasticity issues in data. The result shows that there is the strong evidence of the existence of ARCH effect in all concerned series. Hence, modelling the EGARCH model can successfully capture the price volatility interaction between financial markets.

The raw series are plotted in Figure 7 where stock market returns in five countries fluctuate. We observed that all the five stock markets follow similar movements over the study period. Nevertheless, all the concerned variables present a downward trend after the eruption of the subprime financial crisis. The downward trend reveals that the subprime financial crisis affected the financial performance of the indices

Table 9 Descriptive statistics of daily return of stock indices

Countries	Hungary	Poland	Czech	Romania	Croatia
Panel A. Pre- crisis period					
Mean	0.0450	0.0377	0.0550	0.1220	0.0778
Median	0.0208	0.0326	0.1013	0.1155	0.0645
Maximum	9.4805	6.6392	8.0836	14.576	14.978
Minimum	-6.8735	-8.4678	-7.8757	-9.7428	-9.0232
Std. Dev	1.4857	1.3834	1.3627	1.7648	1.4109
Skewness	0.1670	-0.1929	-0.2845	0.1607	0.5071
Kurtosis	5.0120	5.2244	5.9688	9.9593	15.465
Jarque-Bera	327.24*	400.96*	718.87*	3818.1*	12304*
PP test	-42.191*	-42.043*	-42.333*	-38.909*	-42.077*
ADF test	-42.195*	-41.915*	-42.324*	-38.737*	-42.054*
ARCH test	11.287*	4.221**	18.431*	94.118*	104.82*
Panel B. Post- crisis period					
Mean	0.0278	0.0218	-0.0159	0.0163	-0.0309
Median	0.0465	0.0554	0.0233	0.0504	-0.0047
Maximum	22.016	8.4639	12.364	10.564	14.778
Minimum	-14.985	-8.2888	-19.901	-14.754	-14.587
Std. Dev	1.7085	1.2903	1.5844	1.6108	1.2508
Skewness	0.3525	-0.3405	-1.2358	-1.0197	-0.6072
Kurtosis	23.391	9.5029	27.580	17.187	27.580
Jarque-Bera	36825*	3781.7*	53986*	18174*	75053*
PP test	-45.349*	-42.929*	-44.718*	-44.696*	-43.424*
ADF test	-45.340*	-33.826*	-35.777*	-44.713*	-25.497*
ARCH test	92.763*	90.151*	360.76*	300.03*	300.45*

Notes: *,** denotes significance at the 1% and 5% level. All returns are expressed in percentages. ADF and PP test represents the augmented Dickey and Fuller test and Phillips Perron test of stationarity respectively. ARCH test is employed to test the presence of ARCH effect in the data sets.
Source: calculations of the authors



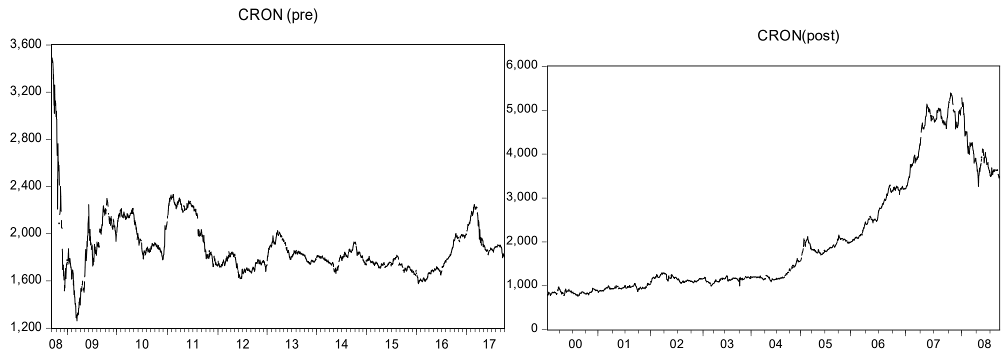


Figure 7 Plots of the stock indices for the sample pre-and post-crisis periods

Source: Own research

Table 10 Unconditional Correlation Coefficients in both periods

	Hungary	Poland	Czech	Romania	Croatia
Hungary	1.000	0.602 (0.507)	0.612 (0.237)	0.188 (0.117)	0.418 (0.175)
Poland		1.000	0.690 (0.248)	0.170 (0.136)	0.472 (0.209)
Czech			1.000	0.190 (0.120)	0.567 (0.119)
Romania				1.000	0.173 (0.128)
Croatia					1.000

Note: Numbers in parentheses are correlation coefficient in the pre-crisis period.
Source: calculations of the authors

We present the sample correlations for all markets in Table 10. The highest correlation we can find is between Poland and the Czech Republic (0.690), followed by the correlation between Hungary and the Czech Republic (0.602) in the post-crisis period. On the other hand, the figure representing the correlation between Poland and the Czech Republic is (0.248) in the pre-crisis period. In general, the correlation coefficients among financial markets have an upward trend after the eruption of the subprime financial crisis.

3.4. 2 Price and volatility spillovers

In order to find price and volatility spillover under the EGARCH framework, estimating the system of equations (1)-(5) based on the maximum likelihood is the final step. The results of the extended EGARCH model are estimated in Table 11 (pre-crisis period) and Table 12 (post-crisis period). In terms of the mean equations for the stock returns of the five countries show that there are significant own lagged price spillovers in the stock market of Romania over the study period. On the other hand, in the case of Poland, the own lagged return spillovers were only statistically significant in the pre-crisis period, while the Czech Republic was in the post-crisis period. The analysis of the individual country in Central and Eastern Europe for mean returns found that the Hungarian stock market is influenced by the returns in the stock market from Poland in sub-periods. This phenomenon is similar to the case of Croatia affected by the stock market of Romania. These results are consistent with (Sheicher, 2001). The price movement in the Czech Republic has a positive impact on the stock market of Romania in the pre-crisis period and negative influence on the Croatian stock market in the post-crisis period respectively. Particularly, the Croatian stock market seems to be affected by the price movements of the stock markets in the Czech Republic and Romania in the post-crisis period and Hungary in the pre-crisis period, while in the post-crisis, price spillover from Romania to Poland is significant. Furthermore, the bidirectional relationship in market returns also appears between Romania and Hungary, Romania and the Czech Republic, Croatia and Hungary in the post-crisis period as indicated by Table 5. These results reveal that rapid growth in international financial stock markets has become substantially more integrated in the post-crisis period. This remarkable result is compatible with the investigation of (Jebran et al. 2017).

Turning to volatility spillover (second moment interdependencies), the estimation results of EGARCH model represent the conditional variance in each market affected by innovations coming at least from one of the other five markets in the two sub-periods. Specifically, there are significant volatility spillovers from Croatia to Poland and from Poland to the Czech Republic during two periods. In addition, the result reveals bidirectional volatility spillover between the Czech Republic and Croatia in the pre-crisis period, and between Hungary and Romania in the post-crisis period. This result is also supported by (Okicic, 2015) for the period from October 2005 to December 2013.

Similarly, it can be seen from the significant coefficient of the parameter δ_i that the volatility spillover comes from the financial markets in the post-crisis period, but having non-persistence in the pre-crisis period, for instance, Romania to Hungary, Romania to Poland, Hungary to the Czech Republic, Hungary to Romania, Croatia to Romania, Hungary to Poland, the Czech Republic to Croatia, Hungary to Croatia and Romania to Croatia. This suggests that the financial crisis has a huge influence on the association between financial stock markets, and financial integration dramatically increases in crisis situations. This result tallies with (Melik Kamisli et all. 2015). Differently, there is a strong evidence of the volatility spillover from the financial stock markets to the other stock markets in the pre-crisis period, but having the absence in the post-crisis period, namely the Czech Republic to Hungary, Romania to the Czech Republic, Croatia to the Czech Republic and Poland to Romania.

More importantly, the asymmetric parameters measured by ϕ is statistically significant in all markets except with Croatia in the pre-crisis period and the Czech Republic in the post-crisis period. We can conclude that the volatility transmission mechanism is asymmetric; this result confirms our assertion that both the size of the innovations are crucial determinants of volatility spillovers. This result supports (Bajo Rubio et al. 2017) and (Jebran et al. 2017) who found that negative shocks which have more significant impact than that of positive innovations in emerging economies.

In order to evaluate the robustness of the estimation results, we examined the ARCH effect on the standardized residuals of each model to determine whether the ARCH effect still exists in the model. The null hypothesis is that there is no ARCH effect (Tsay, 2005). The results of the ARCH-LM test illustrate that we find strong evidence that there is no ARCH effect for all series considered at 1% significance level. Therefore, modelling the EGARCH specifications can

Table 11 Volatility spillover in the pre-crisis period

Coefficients	Hungary	Poland	Czech	Romania	Croatia
α_0	0.0578^{***}	0.0676^{**}	0.0908^{*}	0.1050^{*}	0.1007^{*}
α_1	-0.0271	0.1063^{**}	0.0350	0.1891^{*}	0.0384
$\alpha_{Hungary}$		-0.0249	-0.0168	-0.0030	0.0505^{***}
α_{Poland}	0.0737^{***}		0.0341	0.0050	0.0269
α_{Czech}	0.0439	0.0095		0.0541^{***}	-0.0324
$\alpha_{Romania}$	-0.0047	-0.0217	0.0344		0.0756^{*}
$\alpha_{Croatia}$	-0.0121	0.0094	-0.0098	-0.0034	
β_0	-0.0183	-0.0572^{*}	-0.0980^{*}	-0.1768^{*}	-0.1992^{*}
γ	0.9204^{*}	0.9753^{*}	0.9360^{*}	0.9353^{*}	0.8764^{*}
β_1	-0.0979^{*}	0.0909^{*}	0.1626^{*}	0.3230^{*}	0.3549^{*}
ϕ	-0.0625^{*}	-0.0203^{***}	-0.0786^{*}	-0.0246^{**}	-0.0096
$\delta_{Hungary}$		-0.0208	0.0163	0.0026	0.0047
δ_{Poland}	0.0122		-0.0358^{**}	-0.0810^{*}	-0.0006
δ_{Czech}	-0.0284^{**}	-0.0125		0.0143	-0.0906^{*}
$\delta_{Romania}$	-0.0120	-0.0027	-0.0510^{*}		-0.0103
$\delta_{Croatia}$	0.0025	0.0023^{**}	0.0039^{*}	-0.0080	
ARCH test	0.180(0.671)	2.652(0.103)	3.146(0.076)	0.717(0.397)	0.145(0.702)

Notes: Numbers in parentheses are the probability. *, **, *** denote significance at the 1%, 5% and 10% level respectively.
Source: calculations of the authors

successfully capture the price and volatility spillovers among financial stock markets in five countries.

Briefly, there are notable differences of volatility transmission mechanism between financial stock markets in the two sub-periods. The remarkable results play a prominent role in shedding lights on how the integration between five financial stock markets varies from normal to turbulent periods. This is because the integration of stock markets was influenced by the subprime financial crisis period

Table 12 Volatility spillover in the post-crisis period

Coefficients	Hungary	Poland	Czech	Romania	Croatia
α_0	0.0339	0.0403**	0.0100	0.0290	0.0132
α_1	-0.0042	0.027	-0.0641**	0.0720*	0.0148
$\alpha_{Hungary}$		0.0131	0.0328	0.0584*	0.0255***
α_{Poland}	-0.0616***		0.0224	0.0132	0.0194
α_{Czech}	-0.0103	-0.0343		-0.0512**	-0.0244***
$\alpha_{Romania}$	0.3404*	0.3126*	0.3115*		0.1416*
$\alpha_{Croatia}$	0.0171***	-0.0081	0.0072	0.0213	
β_0	-0.1144*	-0.090*	-0.1232*	-0.2973*	-0.1392*
γ	0.9848*	0.9892*	0.9831*	0.9506*	0.9912*
β_1	0.1572*	0.1180*	0.1600*	0.4209*	0.1794*
ϕ	-0.0366*	-0.023***	0.016	-0.0303**	-0.0168**
$\delta_{Hungary}$		-0.0365*	-0.0498*	-0.0525**	-0.0592*
δ_{Poland}	-0.0039		-0.0579*	-0.0081	0.0108
δ_{Czech}	-0.0177	0.0053		0.0141	0.0572*
$\delta_{Romania}$	-0.0378*	-0.0326*	-0.0064		-0.0521*
$\delta_{Croatia}$	-0.0148	0.0141***	-0.0110	-0.0285***	
ARCH test	0.179(0.672)	0.547(0.459)	0.716(0.397)	0.372(0.541)	0.156(0.692)

Notes: Numbers in parentheses are the probability. *, **, *** denote significance at the 1%, 5% and 10% level respectively.
Source: calculations of the authors.

and the mutual relationship between the five financial stock markets became more correlated during the financial crisis period. Integration of financial markets brings unification between the markets and reduces frictions. Globalization has played significant role in increasing cross-border trade and capital flows by easing the barriers, due to which markets have integrated (Joyo and Lefen, 2019). Our findings are consistent with (Patev et al. 2006; Xuan Vinh and Ellis, 2018; Jebran et al. 2017).

Overall, we provide evidence of an increasing financial integration for most emerging stock markets. Findings report that the financial globalization process goes hand in hand with strong regionalization because countries' stock markets are mostly influenced by the innovations originating from their own area.

3.5 Conclusion

In this paper, we empirically formulate and estimate the volatility spillover by a multivariate EGARCH model of the daily stock markets returns for five emerging markets, namely Hungary, Poland, the Czech Republic, Romania and Croatia reflecting the outlook of investors in these countries. The model is employed to examine the first and second moment interdependencies among the various markets in the pre and post subprime financial crisis period. The pre-crisis period covers from 1st April 2000 to 29th August 2008 and the post-crisis period is considered from 1st September 2008 to 29th September 2017. The volatility transmission mechanism is asymmetric, bad news in a given market increase volatility in the next market to trade considerably more than positive innovations for the whole period. However, these results exclude the Croatian stock market in the pre-crisis period and the Czech Republic stock market in the post-crisis period. The results reveal that volatility spillover varies from normal to turbulent periods. We found evidence of price spillovers of the intraregional linkages among the stock price movements in the five Central and Eastern European countries. For the second moment interactions, the results highlight certain interesting findings that the stock markets were more substantially integrated into a crisis situation. In addition, the persistence of volatility spillovers among the stock markets increases and the financial stock markets become more integrated after the crisis period.

From the results above, our study has several important economic and financial implications for economic policymakers and investors. In terms of price volatility, the increase in co-movement is significant since a global market shock might create excessive fluctuation in emerging markets as they are more vulnerable to global shocks, and to lower commodity prices, they can experience a sudden acceleration of systematic risk through deteriorations in both the capital and currency crisis (Kim et al. 2015). Also, the process of globalization and financial liberalization is the primary factor to promote further international linkages (Xuan Vinh and Ellis, 2018). Therefore, investors should take into account of the price movements from the stock markets over the region in their investment strategies. Moreover, Singhal-Ghosh (2016) suggest that investors tend to diversify their investment portfolio and hedging in order to maximize returns and minimize risks. Elyasiani and Mansur (2017) also provide a valuable channel of diversification for investors at the time of market distress as well as in making optional investment decision. Regarding volatility spillover, the integrations among financial markets suggest that investors would have low diversification opportunities. The study of (Ahmed and Huo, 2018) documents that market integration will kindly provide several new opportunities to accelerate productivity and economic growth; new economic partnership will extend the region's global competitiveness in attracting investment. Investors in the five Central and Eastern European countries can also consider diversifying their investment strategies by following the integration of different financial markets. Furthermore, policymakers should consider previous market condition and integration of financial markets before implementing policy on the stock market because there are considerable impacts on the financial performance of the markets and the subprime financial crisis spillover from one market to other markets (Jebran et al. 2017).

VOLATILITY BEHAVIOR OF THE FOREIGN EXCHANGE RATE AND TRANSMISSION AMONG CENTRAL AND EASTERN EUROPEAN COUNTRIES[3]

This paper attempts to examine the changing nature of volatility spillovers among foreign exchange markets of select Central and Eastern countries, namely Hungary, the Czech Republic, Croatia, Romania and Poland in the pre and post 2007 financial crisis period. Daily data ranging from April 2000 to September 2017 is used for the purposed of analysis. In order to capture volatility transmission and its asymmetry, the multivariate EGARCH model is utilized to catch the effect of good and bad news. The key findings of the study provide useful insights into how information is transmitted and disseminated across CEE-5 foreign exchange markets. In particular, the estimation presents the precise measures of return spillovers and volatility spillovers. The analysis highlights that the foreign exchange markets become more independent after crises. Similarly, in such time, the volatility spillover between the foreign exchange markets decreases dramatically and financial markets have not been transmitted during the crisis period. Also, we find that positive shocks generate more volatility spillovers than negative shocks of the same magnitude. The asymmetric spillover effect is evident for price shocks originating from CEE-5 foreign exchange markets. Further, our findings have essential portfolio management implications for international investors and policymakers.

Keywords: Exchange rate, volatility spillover, multivariate EGARCH, Central and Eastern Europe.

[3] Hung, N. T. (2018). Volatility Behaviour of the Foreign Exchange Rate and Transmission Among Central and Eastern European Countries: Evidence from the EGARCH Model. *Global Business Review*, 0972150918811713.

4.1 Introduction

A central question of foreign exchange investors is that to what extent are currencies markets connected to one another? when they establish and manage portfolios conditional on risk-return of profiles of a basket of currencies. Foreign exchange rate volatility is the outgoing trend to enhance investors and policymakers to make the decision. According to Kanas (2001), volatility transmissions are fundamental determinants for market participants, in particular, on the foreign exchange market, it may increase the nonsystematic risk that decreases benefits from international portfolio diversification. Specifically, the financial and economic turbulence during 2007 had attracted attention in understanding the nature of information spillover among financial markets (Bubak et al. 2011). A structural change in international transmission mechanism is associated with contagion, market contagion is able to step from financial crises because of affecting the portfolio rebalancing decisions of global investors, the investment of overseas companies, the financial policy of the country, and institutional similarity to the ground zero country (Lien et al. 2018). Motivated by the impact of the 2007 financial crises, this paper studies the dynamics of price transmission and volatility spillovers to, from and among Central and Eastern European countries (CEE-5), namely the Czech Republic, Hungarian, Polish, Romanian, and Croatian currencies against the U.S dollar during the period 2000-2017. In addition, asymmetries in volatility spillovers on these foreign markets are considered seriously.

Over the past several decades, the majority of Central and Eastern countries running de jure floating exchange rate regimes has smoothly progressed. There are several substantial papers such as (Fidrmuc and Horváth, 2008; Bubak, 2009; Greenwood et al. 2016) who are interested in the analysis of foreign exchange market interdependence and detection of the return and volatility spillovers targeting at helping many market participants make the financial decisions. The vulnerability of these countries is exhibited by the nature of the behavior of their exchange rates, which appear to actively limit fluctuations. According to Carvalho Grirbeler (2010), emerging countries generally undergo from large capital flight to any bad domestic signal or systematic risk, this contrasts with developed countries where their currencies tend to be more stable. Moreover, the interconnectedness of economies leads to a contagion impact on each other as well as domestic market fusion with global market has caused the case that prices are controlled by the market, exchange rate fluctuation is one of the fundamental determinants behind unpredictability in domestic and additionally global monetary markets (Kumar et al. 2016).

Linkages between exchange rates have been studied in a considerable number of investigations (e.g., Dornbush and Fisher, 1980; Frankel, 1983), where their seminal works have been concentrated on the evaluating the degree of dependence in the foreign exchange and equity markets. Nearly, in order to give information about the volatility spillover effect among foreign exchange markets as well as their connectedness, multivariate GARCH-type models have commonly employed in the literature on volatility transmission because of allowing for modeling of variances and covariances (Carsamer, 2016).

The major contribution of this paper is the methodology and the list of nations under study. For the estimation, we adopt the multivariate EGARCH model which provides better statistical properties than the other type of GARCH specifications or Diebold-Yilmaz spillover index when dealing with the questions of the volatility of times series variables in finance. The list of countries is constructed with a focus on the currencies of CEE-5 countries. This investigation is broader than previous studies available in the current literature. In addition, our paper is first to provide a comprehensive analysis of volatility transmissions among CEE-5 countries during the subprime financial crisis. Some previous articles when carrying out the research of volatility spillover primarily ignored discussing the subprime financial crisis. Our analysis, therefore, provides a benchmark to make the comparison against the case under the 2007 financial crisis. For these reasons, our work significantly extends the frontier of the existing literature.

A competing model that Engle (1982) proposed ARCH and Bollerslev (1986) and Taylor (1986) proposed generalized ARCH, which are widely used to capture the financial market times series volatility. Afterwards, many scholars have proposed the extensions and alternative specifications on the models allows volatility to respond asymmetrically to innovations such as the Quadratic GARCH model (Engle, 1990) and applied by (Campbell and Hentschel, 1992), GARCH-M, IGARCH, EGARCH (Nelson ,1991), Threshold GARCH (Glosten et al. 1993), Asymmetric GARCH model AGARCH (Engle, 1990) and Fractionally Integrated FIGARCH (Baillie et al. 1996). However, previous studies document that the EGARCH model performs better than others to some extent. For example, based on the basis of several diagnostics, Nelson (1991) and Engle and Ng (1993) find that the EGARCH model executes better that IGARCH and the Quadratic GARCH model since the latter tends to underpredict volatility related to negative innovations. Lim and Sek (2013) compare the performance of GARCH-type models in capturing stock market volatility in Malaysia. The findings show that asymmetric EGARCH models can be the better model to forecast and capture the volatility. This result is consistent with (Pederzoli, 2006; Morales, 2008; Shields, 1997). Alberg and Yosef (2008) report that the EGARCH model using a skewed Student-t distribution is the most successful for predicting the TASE indices when they make comparisons between EGARCH and that of others (GARCH, GIR-GARCH, APARCH). Recently, Dedi and Yavas (2016) carry out the research of return and volatility spillover in equity markets in Germany, United Kingdom, China, Russia and Turkey by using various GARCH methodologies such as MARMA, GARCH, GARCH-M, EGARCH. This paper reports that EGARCH provides a better fit for these markets by comparing AIC and SIC criterion. This finding is similar to Zabiulla. (2015). The main advantage of the EGARCH model is that there are no parameter restrictions required to guarantee positive variance all the time (Koutmos and Booth 1995). This is significant because some of the coefficients in the conditional variance specification violate the non-negativity assumption (Hamao et al. 1990).

The remainder of the paper is structured as follows. In section 2, we introduce the relevant papers examining the volatility spillovers or contagion issues as well as concerned literature. In section 3, we outline the methodology and data description. Section 4 summarizes our findings and conclusions.

4.2 Review of Related Literature

The definition of volatility spillover of asset returns can be drawn from the seminal work of (Engle et al. 1990). Subsequently, there are some important investigations based on the GARCH-type framework to capture volatility spillovers among financial markets in different countries. The remarkable study of (Nelson, 1991) contributed a significant characteristic in connection with volatility spillover to literature, that is the salient property of asymmetric. Volatility transmission also exhibits asymmetry with regards to the kind of news. Bad news seems to have a severe effect on spillover as compared to good news. This asymmetric property of spillover is a prime contributor to the cause of financial contagion. It is clear that in the context of the literature of the volatility spillover can be divided into three fundamental points: first, a bidirectional volatility spillover among markets; second, a unidirectional flow of volatility from a foreign exchange market to another exchange market and vice versa; third, non-persistence of the volatility spillover among them (Hung, 2018).

The international financial system and the connection of markets have been a particular topic in financial econometrics in recent years. Also, volatility spillovers and connectedness have received much attention in the financial literature because these financial markets have a huge influence on options and hedging strategies, portfolio management, and portfolio diversification strategies (e.g., Martin Guzman et al. 2018, Barunik et al. 2017). Significant evidence of systematic volatility plays a prominent role in volatility transmission across currencies countries. A well-known implication of (Kanas, 2001) reports that positive and volatility spillovers may increase the nonsystematic risk that declines gains from international portfolio diversification. The first potential theoretical explanations for the interactions between exchange rates is the (Dornbusch and Fisher, 1980) flow-oriented model, which reports that domestic currency depreciation improves the competitiveness of local firms that results in getting bigger in their exports and future cash flows. This approach illustrates that there exists a positive linkage between exchange rates and stock prices, and specifically focusing on the current account and trade balance.

The second is known as the stock-oriented models of exchange rate determination (Frankel, 1983), which suggests that the exchange rate is determined by the demand and supply of financial assets such as equities and bonds.

The early papers in the development of the literature of volatility spillovers initiated by (Engle et al. 1990); two hypothesizes, namely: the “heat waves” and the “meteor shower”, after that (e.g., Hong, 2001; Kearney and Patton, 2000; Herwartz and Reimers, 2002) employ GARCH-type models to estimate volatility. More recently, there are the number of scholars conducted the investigation of volatility spillovers. Recent developments in the academic literature of the methodology of the volatility, besides the application of GARCH-type models, volatility spillover index was introduced by (Diebold and Yilmaz, 2009, 2012, 2014), which was based on a forecast error variance decomposition from vector autoregressions. The Diebold-Yilmaz index measures the proportion of the h-step ahead forecast error of own volatility that can be attributed to shocks emanating from other markets, meaning that we can draw the conclusion of volatility based on the value of the spillover index. Additionally, a number of volatility spillovers studies have also applied diversified forms of copula approach in currency dependence modeling, for example, (e.g., Patton, 2006; Okimoto, 2008; Aloui et al. 2013; Lien D. et al. 2018). Nevertheless, we apply the multivariate EGARCH model, which is a common technique of financial econometrics to figure out the systematical explanation of volatility transmission as well as connectedness across CEE-5 exchange markets in this paper. In the framework of this study, we briefly mention several latest previous studies in which GARCH-family model is widely used as well as its empirical demonstration on the foreign exchange market.

There have been large strands of the literature of volatility spillovers on foreign exchange markets in different countries so far. Herwartz and Reimers (2002) analyze the properties of the DEM/USD and DEM/JPY-rate with a sample period from 1975 to 1998, reveal that the underlying volatility processes exhibit serial correlation as well as evidence of high persistence in volatility, which is accurately captured by GARCH (1,1) model with leptokurtic innovations. An empirical study of asymmetric volatility of AUD, GBP, and JPY against USD modeled by (Jianxin

Wang Minxian Yang, 2009), with the application of daily GARCH-model, authors document that there is evidence of asymmetric volatility among them and the asymmetry in bilateral exchange rates is weaker than it is in trade-weighted indices. Basically, volatilities of AUD and GBP increase when they depreciate against USD, whilst JPY increases following JPY appreciation. McMillan et al. (2010) analyze the nature of return and volatility spillovers in three Euro exchange rates, such as the US dollar, Japanese yen and British pound sterling. The empirical methodology used in this investigation is the so-called realized volatility and the spillover index recently proposed by (Diebold and Yilmaz, 2009). The results highlight of contemporaneous relationships between returns on these rates and their volatility, for simply, the dollar rate dominates the other two rates in terms of both return and volatility transmission. Pankova et al. (2010) examine volatility and asymmetry of the exchange rate of the Euro/USD observed daily from June 2008 to May 2010 under GARCH (1,1) and EGARCH (1,1). They draw the conclusion that there is no asymmetry in the Euro and USD relation. Bubak et al. (2011) interest in volatility spillover of the foreign exchange markets in emerging Europe using model-free estimates of daily exchange rate volatility based on intraday data. The results find evidence of statistically significant intra-regional volatility transmission among the Central European foreign exchange markets and confirm that there is non-persistence of spillovers running from euro/dollar to the Central European foreign exchange markets. Based on a dynamic version of the Diebold-Yilmaz volatility spillover index, this study measures the overall magnitude and evolution of volatility transmission over time, and it increases in periods characterized by market uncertainty. Kamal et al. (2012) examine the performance of GARCH family models (symmetric GARCH-M, asymmetric EGARCH and TGARCH models) in forecasting the behavior of volatility of Pakistani foreign exchange market by using daily exchange rates data, ranging from 2001 to 2009. The overall results explain that the EGARCH model remains the best in exploring the volatility behavior of the data.

More recently, the majority of articles applied various kinds of models to successfully capture the volatility spillovers of foreign exchange markets across countries. For instance, Greenwood et al. (2016) used an empirical network model to study spillovers among daily returns and innovations in the option-implied risk-neutral volatility and skewness of the G10 currencies. On the other hand, at the same year, Yang et al. (2016) employ the wavelet decomposition methodology to shed light on the co-movement among foreign exchange markets using the returns of exchange rates (GBP/USD, EUR/USD, and JPY/USD). Diebold-Yilmaz volatility spillover index was used by (Barunik et al. 2017) to show how bad and good volatility propagate through the foreign exchange market using high-frequency, intra-day data of the most actively traded currencies over 2007-2015. The main results of this research are first, existing asymmetric volatility connectedness on the foreign exchange rate, second, the dominating asymmetries in spillovers are due to bad rather than good volatility, third, negative spillovers are mainly tied to the dragging sovereign debt crisis in Europe while positive spillovers are correlated with the subprime crisis. Within the GARCH framework, Kumar et al. (2016) examine the volatility and disproportionate impact on the foreign exchange markets of India and China, using daily data ranging from January 2006 to October 2015. By utilizing the EGARCH model, the results show the bidirectional volatility ad disproportionate influence among these markets. In a similar vein, Charef (2017) employs GARCH models to document the partial relationship between the evolution of exchange rates and macroeconomic variables. The monthly series of exchange market of the Tunisian dinar against three currencies of major trading partners (dollar, euro, yen) and fundamentals (trade, inflation rate, interest rate differential) covering between 2000 and 2014 is considered. Another interesting paper is by (MacDonald et al. 2018), who use a multivariate GARCH to investigate in detail the potential cross-covariance and spillover effects between the Eurozone economies and financial markets. The results reveal the important and intensive stress transmission on banking and money markets as well as the significant spillover effects from core countries.

In the Central and Eastern European context, recently, there are several prominent investigations carried out in the field of volatility spillovers of the foreign exchange markets as well as their connectedness. Hsing (2016) employs the EGARCH model and demand and supply analysis to examine the determinants of the Hungarian forint/US. Dollar exchange rate. He finds that a higher stock market index, more real GDP, a higher interest rate or a lower inflation rate in Hungary can cause the forint to appreciate. In a similar vein, Kumar and Kamaiah (2014) attempt to analyze the deterministic presence chaos in the forex markets in countries of Bulgaria, Croatia, Czech Republic, Hungary, Poland, Romania, Russia, Slovakia and Slovenia. Based on EGARCH (1,1), Lyapunov exponent values and monthly data ranging from 1994 to 2013 to explain the foreign exchange markets behavior. They find that the foreign exchange markets exhibit deterministic chaotic behavior. On the other hand, distribution and dynamics of Central-European exchange rate are investigated by (Bubak, 2009), using 5-minute intraday data in the period 2002-2008. Relying on model-free nonparametric measures of ex-post volatility, the findings demonstrate that daily returns on the EUR/CZK, EUR/HUF and EUR/PLN exchange rates are normally distributed and independent over time. In addition, Petrica and Stancu (2017) examine the change in the volatility of daily returns of EUR/RON exchange rate employing ARCH, GARCH, EGARCH, TARCH and PARCH models. They put forward that the best model to estimate daily returns of EUR/RON exchange rate is EGARCH (2,1) with asymmetric order 2 under the assumption of Student's t distributed innovation terms. More importantly, Fidrmuc and Horvath (2008) document significant asymmetric effects of the volatility of exchange rates in new EU members states including Czech Republic, Hungary, Poland, Romania and Slovakia by applying GARCH and TARCH models in the period 1999-2006. Kocenda and Valachy (2006) also study the volatility of foreign exchange markets of Poland, Hungary, Slovakia and the Czech Republic with TARCH model. Their results find that volatility is greater under a floating exchange rate regime than under a fixed regime, while Antonakakis (2012) examines price co-movements and volatility spillovers between major exchange rates before and after the introduction of the euro. He concludes that cross-market volatility transmissions are bidirectional, and the highest spillovers occur between European markets. Furthermore, Kobor and Szekely (2004) conduct the analysis of the behavior of foreign exchange volatility in four CEE countries by regime switching.

Generally, based on these aforementioned studies, it could be found that there is a little information about the volatility spillover and co-movement in the foreign exchange markets, particularly, in CEE-5 countries. Specifically, the multivariate EGARCH model is able to be applied to capture the volatility transmission in five Central and Eastern European countries might be state-of-the-art, which can be filled the gap in the existing literature. Furthermore, under study may be wonderful information channel for investors or financial analysts to look at. This paper, therefore, becomes more relevant in this context.

4.3 Research Objectives and Rationale

So far, the dynamics of asymmetric volatility connectedness concerned with the foreign exchange market has been severely limited, particularly, in CEE countries. The analysis of such interdependencies and volatility spillovers in emerging and frontier exchange markets, and their evolution over time, is thus of extreme importance impacting the decisions of central bank interventions, risk management, international trade and portfolio diversification. Furthermore, a comprehensive evaluation and comparisons of the evolution of these co-movements between pre and post-crisis period may provide straightforward insights into the transformation and the changing pace of financial integration. With advanced in financial econometrics, the current paper, the multivariate EGARCH model is applied to successfully capture the volatility spillover and their relationship in the foreign exchange markets among five Central and Eastern European economies. Our analysis proceeds in two primary parts. First, we establish a benchmark by evaluating the connectedness among currencies in the 2007 financial crisis period, from 2000 to 2017, namely, pre-crisis period: 1st April 2000 to 29th August 2008 and post-crisis period: 1st September 2008 to 29th September 2017. This finding highlights that dynamics of the foreign exchange markets exhibit more significant in the pre-crisis period than in the post-crisis period, with particularly low bilateral spillovers of prices among currencies that share a fragile relationship. Second, based on estimations of the second distribution of times series, the multivariate EGARCH model perfectly captures volatility spillovers among these exchange markets, namely the volatility spillover between the foreign exchange markets decreases dramatically and financial markets have not been transmitted during the crisis period. Our empirical work also addresses the relatively important issue by comparing the directions of volatility spillovers among CEE-5 exchange markets between pre- and post-crisis period. Finally, our study has several significant economic and financial implications for economic policymakers and international investors.

4.4 Data and Methodology

4.4.1 Methodology

Jane and Ding (2009) compared the extension of (Nelson, 1991) univariate EGARCH model to the multivariate version with the existing one given by (Koutmos and Booth 1995) favourably. Authors adequately demonstrated that the actual multivariate EGARCH model obtained was more general, and could produce more accurate inferential results, and they strongly recommended that it could be applied in future financial empirical studies. This study, therefore, employs a multivariate EGARCH model specification in order to examine market interdependence and volatility spillover between foreign exchange markets in different countries. The EGARCH model is good enough to systematically explain the leverage effects, which are usually observed in financial time series. We investigate the asymmetric volatility transmission because it is widely argued that asymmetric (negative) shocks increase more than volatility symmetric (positive) shocks of the equal magnitude. The extension of (Nelson, 1991) univariate EGARCH model to the multivariate version makes development and presentation to account for asymmetric response to a shock, which can be represented as follows: To model the short-run dynamic connectedness between exchange markets, we apply the following Vector Autoregressive model:

$$R_{i,t} = \alpha_{i,0} + \sum_{j=1}^{5} \alpha_{i,j} R_{j,t-1} + \varepsilon_{i,t}, \text{ for } i, j = \overline{1,5} \tag{4.1}$$

Equation (1) describes the returns of the five markets, whereby the conditional mean in each market is a function of own past returns and across market past returns, the coefficient $\alpha_{i,j}$ captures the lead-lag relationship between returns in different markets, for $i \neq j$. Market j leads to i if $\alpha_{i,j}$ is statistically significant. $\alpha_{i,0}$ is the constant.

Following (e.g., Koutmos and Booth, 1995; Nelson, 1991; Kanas, 2001), we model the conditional variances according to the multivariate EGARCH model:

$$\ln\left(\sigma_{i,t}^2\right) = \beta_{i,0} + \gamma_i \ln\left(\sigma_{i,t-1}^2\right) + \sum_{j=1}^{5} \delta_{ij} f_j(z_{j,t-1}), \quad i,j = \overline{1,5} \tag{4. 2}$$

$$f_j(z_{j,t-1}) = \left[\left|z_{j,t-1}\right| - E\left(\left|z_{j,t-1}\right|\right)\right] + \phi_j z_{j,t}, \quad i,j = \overline{1,5} \tag{4.3}$$

Equation (2) describes the conditional variance in each market as a logarithm function of past standardized innovations, $z_{j,t-1} = \frac{\varepsilon_{j,t-1}}{\sigma_{j,t-1}}$, coming from both its own market and other markets. γ_i measures the persistence in volatility, Nelson (1991) puts forward that if $\gamma_i < 1$, the unconditional variance will be finite. If $\gamma_i = 1$, the conditional variance follows an integrated process of order one as the unconditional variance does not exist. $\beta_{i,0}$ is the constant level of the volatility. The conditional variance $\sigma_{ij,t}$ of $\varepsilon_{j,t}$ given Ω_{t-1} (the past information set) can be denoted as

$$\sigma_{ij,t} = \rho_{ij}\sigma_{i,t}\sigma_{j,t}, \quad i,j = \overline{1,5} \text{ and } i \neq j \tag{4.4}$$

where ρ_{ij} is the constant conditional correlation between $\varepsilon_{i,t}$ and $\varepsilon_{j,t}$ given Ω_{t-1} (Bollerslev et al. 1992).

The asymmetric influence of standardized innovations on the conditional variance is captured by partial derivatives for f_j from equation (3) as follows:

$$\frac{\partial f_j(z_{j,t})}{\partial z_{j,t}} = \begin{cases} 1+\phi_j, \text{if } z_{j,t} > 0 \\ -1+\phi_j, \text{if } z_{j,t} < 0 \end{cases} \quad \text{for } i,j = \overline{1,5} \tag{4.5}$$

$f_j(z_{j,t})$ in Equation (3) is an asymmetric function of standardized innovations. The terms $\left[\left|z_{j,t}\right|-E\left(\left|z_{j,t}\right|\right)\right]$ and $\phi_j z_{j,t}$ measures the size and sign effect respectively. If $\left[\left|z_{j,t}\right|-E\left(\left|z_{j,t}\right|\right)\right]>0$ and $\phi_j=0$, $f_j(z_{j,t})$ is positive. Additionally, if $\delta_{ij}>0$, volatility is an increasing function of the past standardized innovations. $\phi_{ij}z_{j,t}$ measures the sign effects and ϕ_j relates standardized innovations to volatility in an asymmetric manner. δ_{ij} is volatility spillover from the respective exchange market to the exchange market under consideration.

The relative importance of the asymmetry (or leverage effect) can be measured by the ratio $\left|-1+\phi_j\right|/\left(1+\phi_j\right)$, which is greater than, equal to or less than one for negative asymmetry, symmetry and positive asymmetry respectively. The total influence of spillover effects from market j to market i is captured by $\left(\phi_j+1\right)$, $i\neq j$ for a unit increment of positive innovation and $\left(-1+\phi_j\right)$, $i\neq j$ for a unit increment of negative innovation (Jane Ding, 2009).

Finally, the assumption of residuals in equation (1) is conditionally multivariate normal with mean zero and conditional covariance matrix H_t:

$$\varepsilon_t \mid \Omega_{t-1} \sim N\left(0, H_t\right) \tag{4. 6}$$

By assuming that the conditional joint distribution of the returns of the five exchange markets is normal and given a sample of T observations, the log-likelihood function of a multivariate EGARCH model can be formulated as:

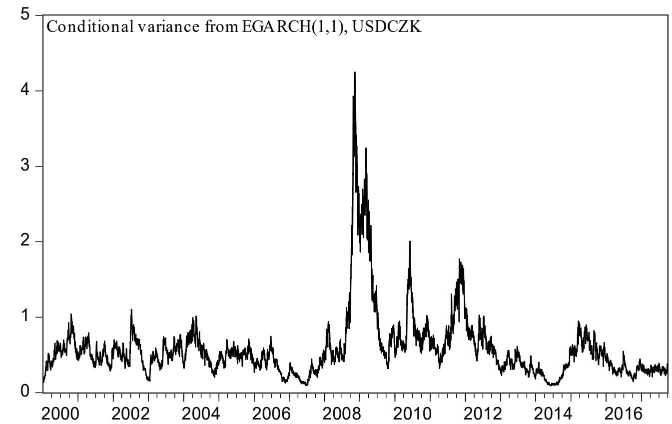
$$L\left(\Theta\right)=\left(\frac{1}{2}\right)\left(NT\right)\ln\left(2\pi\right)-\left(\frac{1}{2}\right)\sum_{i=1}^{T}\left(\ln|S_t|+\varepsilon_t' S_t^{-1}\varepsilon_t\right) \tag{4.7}$$

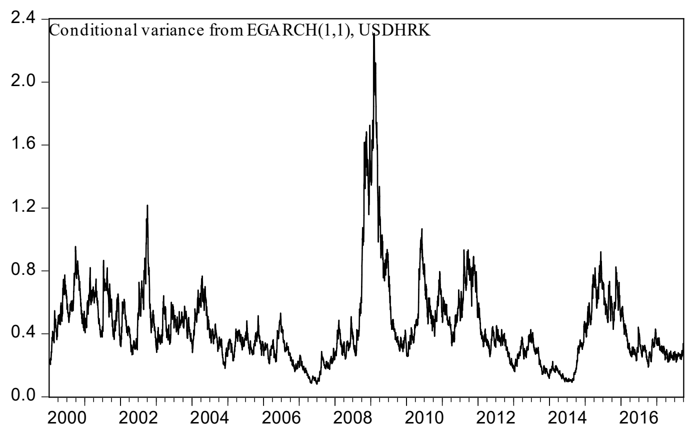
where N is the number of equations, Θ is the parameter vector to be estimated, $\varepsilon_t'=\left(\varepsilon_{1,t},\varepsilon_{2,t},\varepsilon_{3,t},\varepsilon_{4,t},\varepsilon_{5,t}\right)$ is the 1×5 vector of innovations at time t, S_t is the 5×5 time varying conditional variance-covariance matrix with diagonal elements are given by equation (2). The log-likelihood function is estimated using the (Berndt et al. 1974) algorithm.

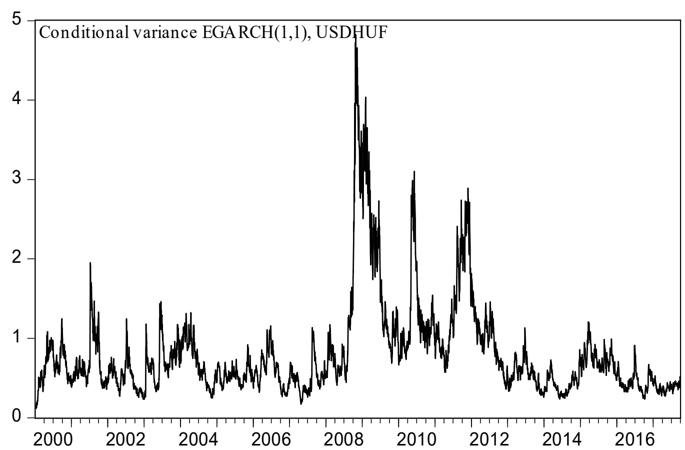
Before running the EGARCH model, the time series properties of five concerned variables are examined. If the data is stationary at levels, EGARCH model will be employed directly. The additional assumption of the EGARCH model is that there should be ARCH effect in each variable. For simplicity, the heteroskedasticity and autocorrelation problems should exist in the data. The two mandatory aforementioned properties of the data are held before estimating the parameters of the EGARCH model. The procedures of this study shall be briefly summarized in four steps (Tsay, 2005): i) conducting the unit root test for relevant variables ii) identifying and estimating an autoregressive and moving average (ARMA) model for the mean equation, using the residuals of the mean equation to test for ARCH effect and to be introduced to the variance equation as well as be used as proxy of shock emanating from one market to other market iii) estimating EGARCH model for volatility spillover and iv) the robustness of the estimation has been performed.

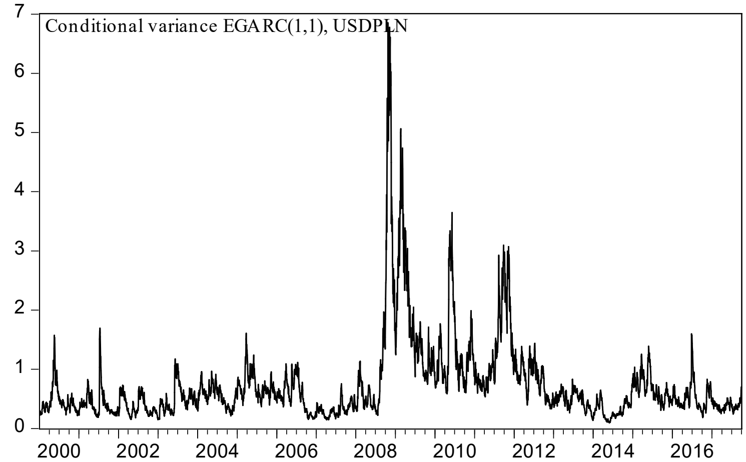
4.4.2 Data Sources

The national currencies of five Eastern and Central European countries are Hungarian Forint HUF, Polish Zloty PLN, Czech Koruna CZK, Romanian Leu RON and Croatian Kuna HRK, respectively. Our analysis is based on intraday quotes for HUF, PLN, CZK, RON and HRK against USD. Basically, the time series data used in this estimation consists of daily observations of the USD/HUF, USD/PLN, USD/CZK, USD/RON and USD/HRK exchange rates is available on the seven-day basis, ranging from 1st April 2000 to 29th September 2017 for the analytical purpose. The investigation is carried out in two stages: Pre-crisis period: 1st April 2000 to 29th August 2008 (yielding 2259 observations for each series). Post-crisis period: 1st September 2008 to 29th September 2017 (yielding 2369 observations for each series). The number of observations across the market is 4628, which is less than the total number of observations because joint modeling of five markets requires matching returns. The reason for collecting daily data is to capture more the precise information content of changes in exchange rates as well as volatility transmission between them than doing with weekly or monthly data (Jebran and Iqbal, 2016; Hung, 2018; Naik and Padhi, 2015), and better able to measure the dynamics among variables (Agrawal et al. 2010). All datasets used in this paper have been collected from Bloomberg, accounted by the Department of Finance, Corvinus University of Budapest. The daily foreign exchange series are transformed to returns, which are calculated $R_t = 100 \times \ln(P_t/P_{t-1})$, where P_t is the price level of the market at time t. The logarithmic exchange returns are multiplied by 100 to approximate percentage changes and avoid convergence problems in estimation.









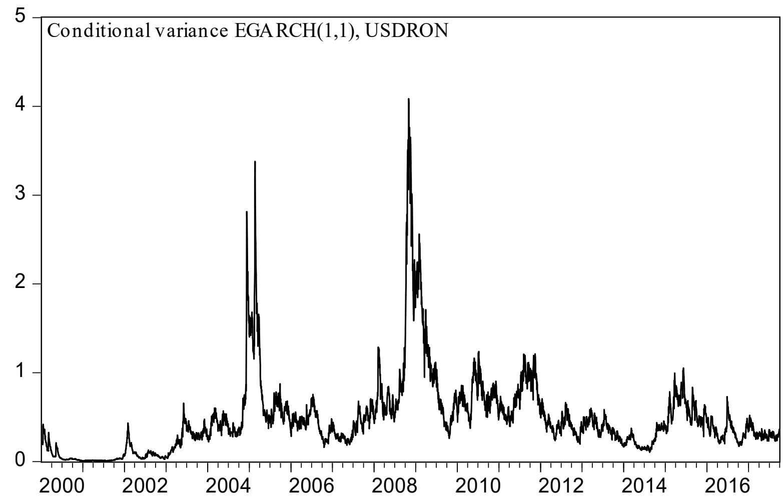


Figure 8 Conditional variances from the univariate AR(1)–EGARCH(1, 1) models for the USDCZK, USDHRK, USDHUF, USDPLN and USDRON indexes, in the whole sample period from Jan 1, 2000 to Sept 29, 2017.

Source: Authors' calculations

Figure 8 depicts the calculated volatilities for all exchange indies of the selected in the whole sample period from Jan 1, 2000 to Sept 29, 2017. It indicates a similar volatility pattern for the five exchange markets. Particularly, all five markets display relatively high volatility peaks in the global financial crisis of 2007. The results suggest that the financial crisis might be compatible with large volatility effects among these exchange markets. The global financial crisis was reflected evidently in all foreign exchange rates.

4.5 Results and Discussion

4.5.1 Summary Statistics

The descriptive statistics of the return on Czech Koruna Rate, Hungarian Forint Rate, Polish Zloty Rate, Romanian Leu Rate and Croatian Kuna Rate to US dollar are illustrated in Table 13 and Figure 9 respectively. Table 13 provides a wide range of descriptive statistics for five exchange market returns. All market return series have the small mean (less than 3 per cent in absolute value), they were negative in the pre-crisis period and positive in the post-crisis period. This reveals that exchange markets of these countries in the second stage performed better than in the first stage during the full sample period. The unconditional volatility of exchange markets in the pre-crisis period, measured by standard deviations, is lower than in the post-crisis period in selected countries. In the post-crisis period, the return volatility in Poland is highest, whereas lowest in case of Croatia. The kurtosis coefficient for all indices is positive and greater than three, the difference in skewness of all market return series is clear in sub-periods, indicating that return series are far from normal distribution, which means that they have leptokurtic distribution in nature, this is formally confirmed by The Jarque-Bera test statistics (reject the normality hypothesis for all series at one per cent significance level), this finding suggests that there was a trade-off between return and risk during the research period.

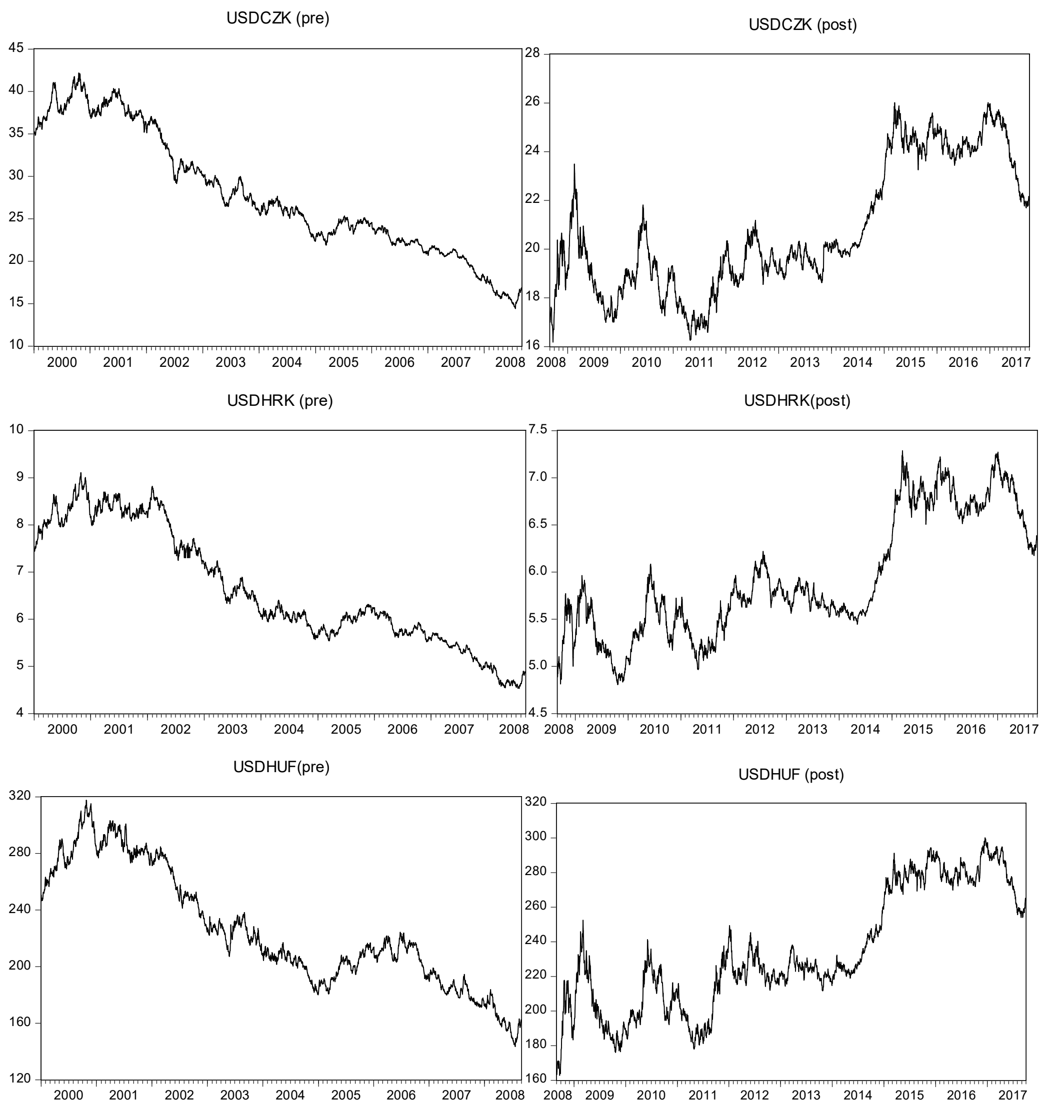
Conventional stationarity test including Augmented Dickey-Fuller (ADF) test and Philips-Perron (PP) test are actively employed to examine whether the return on daily exchange rate against US dollar is stationary series. At the 1 per cent significance level, ADF and PP test statistics are statistically significant, indicating that we reject the null hypothesis of the unit root for all return series. ARCH Lagrange multiplier (LM) test is used to examine an ARCH effect in the residuals. The results of the ARCH test shows that there is the persistence of heteroskedasticity and autocorrelation issues in data.

Table 13 Descriptive statistics of the daily return of exchange rates

	USDCZK	USDHRK	USDHUF	USDPLN	USDRON
Panel A. Pre- crisis period					
Mean	-0.0324	-0.0189	-0.0194	-0.0264	0.0126
Median	-0.0199	0.0000	-0.0291	-0.0561	0.0296
Maximum	3.1055	3.6914	5.7118	4.4332	7.5558
Minimum	-2.6907	-3.7468	-3.3316	-3.7325	-5.0778
Std. Dev	0.6910	0.6612	0.7660	0.6794	0.6311
Skewness	0.0553	-0.0982	0.4621	0.3487	0.9142
Kurtosis	4.1552	5.4339	6.2461	5.3329	20.9228
Jarque-Bera	126.779*	561.241*	1072.25*	558.056*	30550.2*
PP test	-48.246*	-50.877*	-47.719*	-44.872*	-51.242*
ADF test	-48.245*	-50.723*	-47.713*	-44.888*	-50.984*
ARCH test	24.91*	17.48*	28.32*	61.71*	600.28*
Panel B. Post- crisis period					
Mean	0.0108	0.0109	0.0197	0.0202	0.0202
Median	-0.0071	-0.0034	0.0048	0.0000	0.0000
Maximum	5.1900	3.8157	5.1655	6.8649	4.2245
Minimum	-4.6743	-3.8354	-6.5491	-5.4984	-4.7975
Std. Dev	0.8396	0.6822	1.0242	1.0348	0.7658
Skewness	0.0837	-0.0606	0.1626	0.2060	0.1576
Kurtosis	6.4679	5.7339	6.6097	6.1201	6.4208
Jarque-Bera	1189.89*	739.23*	1296.64*	977.75*	1164.90*
PP test	-48.77*	-48.73*	-48.38*	-48.28*	-46.49*
ADF test	-48.76*	48.72*	-48.37*	-48.21*	-46.54*
ARCH test	147.34*	110.65*	42.43*	164.21*	60.89*

Source*:* Authors' calculations

Notes: Exchange rates are expressed as units of currencies per unit of UD dollar. * denotes significance at the 1 per cent level at least. All returns are expressed in percentages. ADF and PP test represents the augmented Dickey and Fuller test and Phillips Perron test of stationarity respectively. ARCH test is employed to test the presence of the ARCH effect in the datasets.



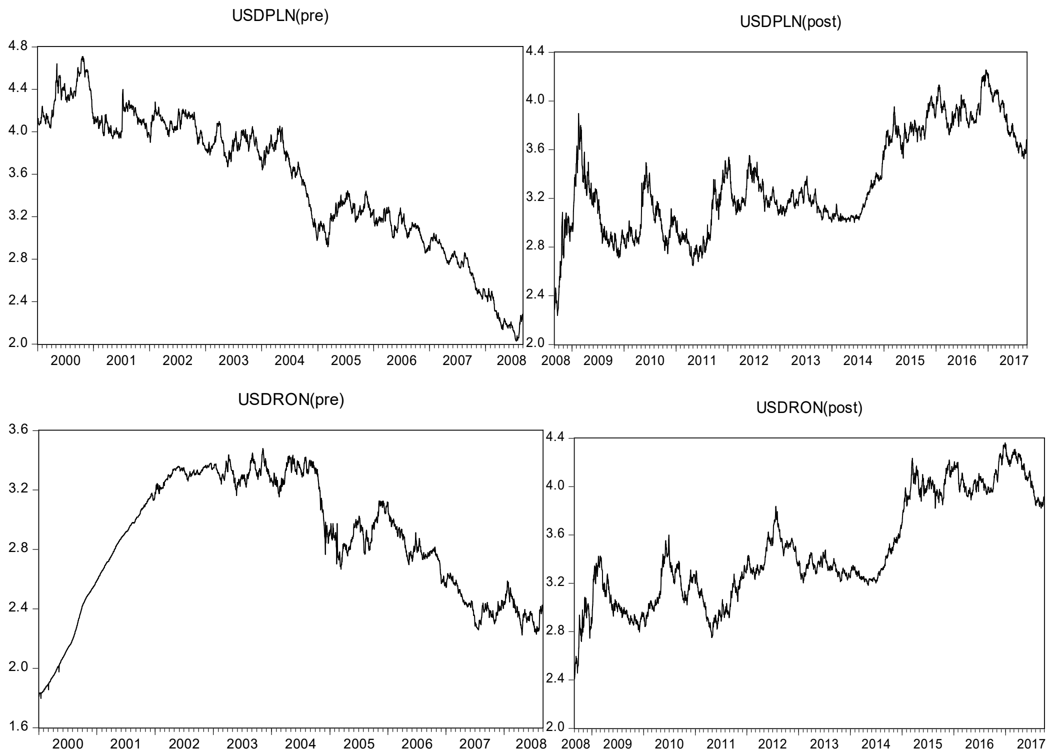
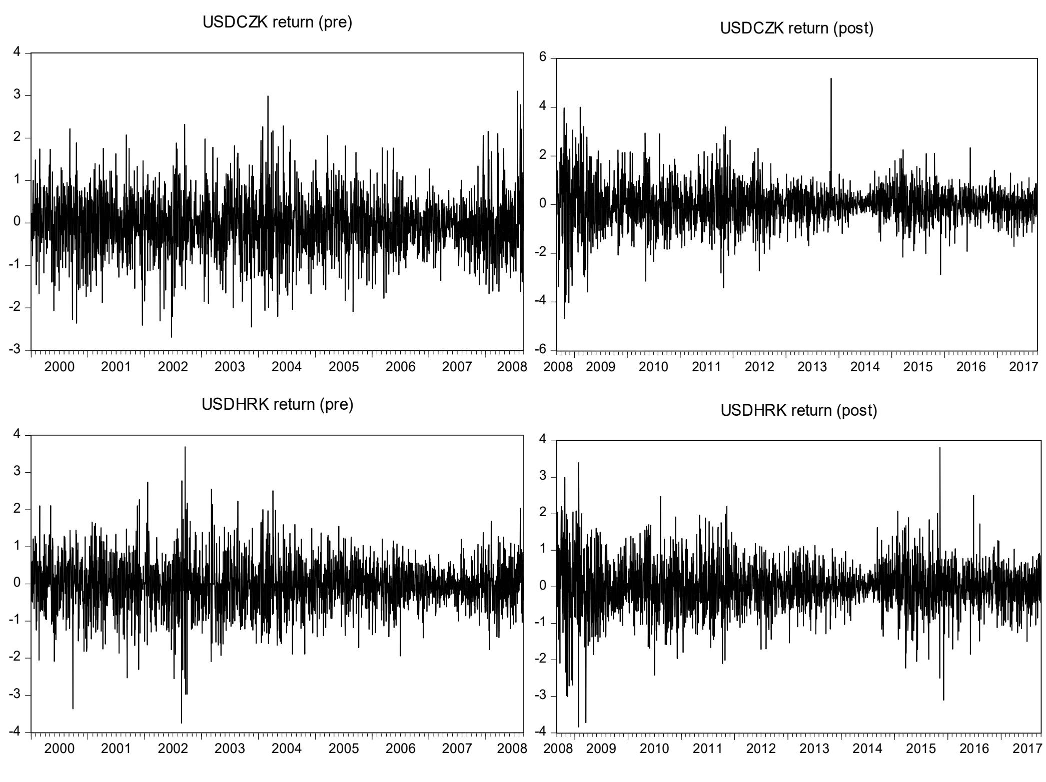


Figure 9 Plots of the exchange indices for the sample pre-and post-crisis periods.

Source: Authors' calculations



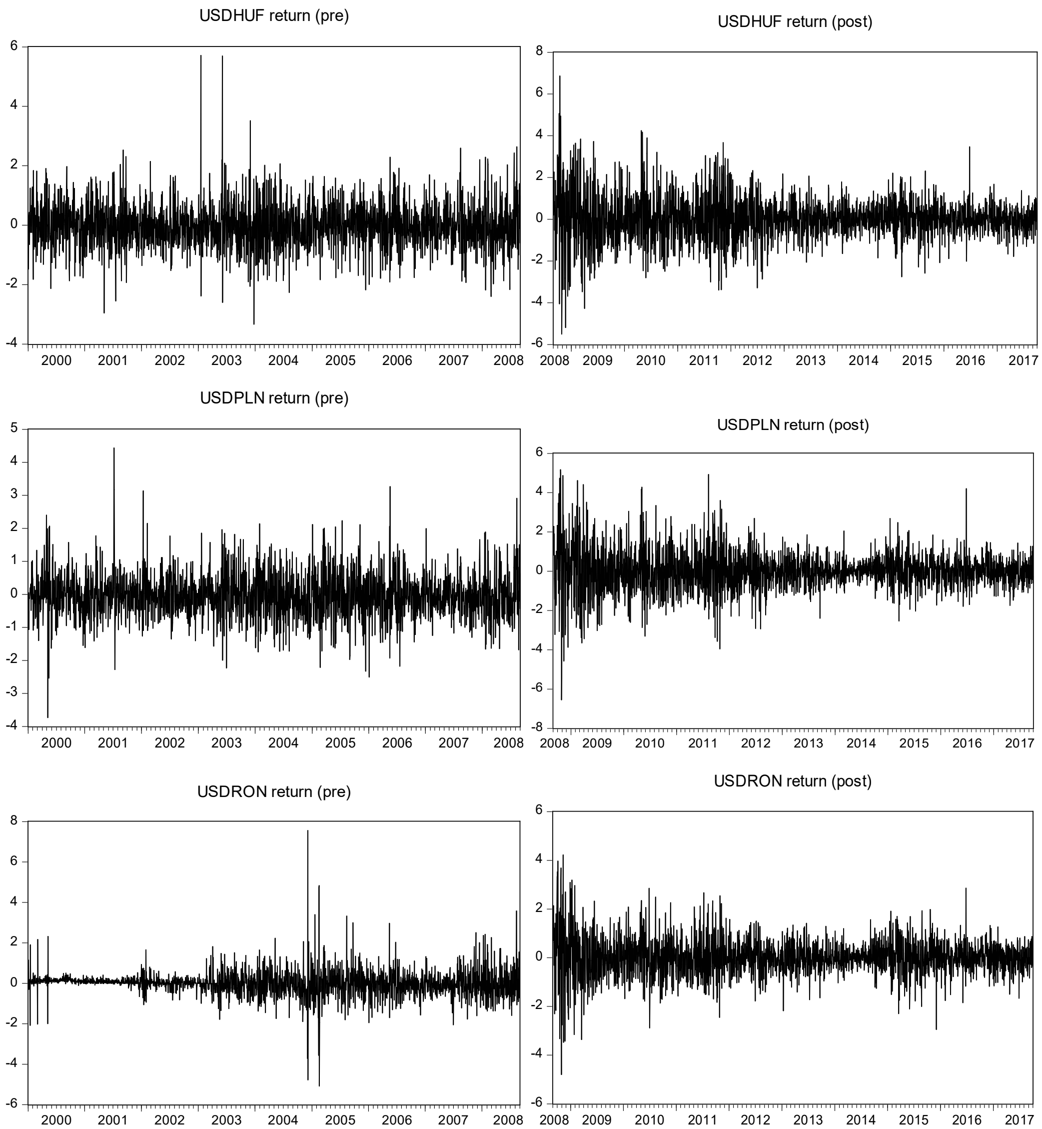


Figure 10 Plots of the exchange percentage returns for the sample pre-and post-crisis periods.

Source: Authors' calculations.

Figure 9 plots the daily index values for our sample, while Figure 10 displays returns for the public Czech, Croatia, Hungary, Poland and Romania respectively. The impression is that the exchange markets are following similar movements after and before the crisis revealing the interlinkages between the five emerging economies. Volatility clustering is strongly apparent the five-time series, this characteristic indicates the presence of conditional heteroscedasticity in the variance process of the return series, and thus the use of EGARCH specifications to adequately model the volatility spillover effect between exchange market returns is compatible. As we can see from the plots, there is a downward trend across all series in the pre-crisis period. Nevertheless, all of the indices illustrate a common upward trend after the eruption of the subprime financial crisis. The exchange markets experienced an upward trend suggests that subprime financial crisis affected the exchange performance of the indices.

Table 14 Estimated cross correlation matrix of exchange market returns in both periods

	USDCZK	USDHRK	USDHUF	USDPLN	USDRON
USDCZK	1.000	0.825 (0.433)	0.823 (0.691)	0.832 (0.530)	0.818 (0.360)
USDHRK		1.000	0.759 (0.396)	0.750 (0.363)	0.840 (0.345)
USDHUF			1.000	0.858 (0.595)	0.778 (0.382)
USDPLN				1.000	0.770 (0.408)
USDRON					1.000

Source: Authors' calculations

Note: Numbers in parentheses are the correlation coefficient in the pre-crisis period.

Table 14 reports the correlation among the returns in both periods. The correlation matrix of the exchange indices highlighted that the correlations of returns range from a high of 0.858 between Hungary and Poland, to a low of 0.750 between Croatia and Poland in the post-crisis period. Similarly, in the pre-crisis period, the highest correlation coefficient belongs to Hungary and the Public Czech (0.691), whereas the lowest figure is between the Public Czech and Romania (0.360). Based on the unconditional correlations in Table 14, we can say that all the market returns are positively related to one another suggesting that all the nation exchange markets have been moving in the same direction during the sample period. In general, the correlation coefficients have a common upward trend after the eruption of the subprime financial crisis between these financial markets.

4.5.2 Volatility Estimates Using EGARCH

Table 15 Volatility spillover in the pre-crisis period

Coefficients	USDCZK	USDHRK	USDHUF	USDPLN	USDRON
α_0	0.0613^{*}	-0.0370^{*}	-0.0341^{***}	-0.0527^{*}	0.070^{*}
α_1	-0.0356	-0.1268^{*}	-0.0817^{**}	-0.0447^{*}	-0.0136
α_{USDCZK}		0.0596^{***}	0.1012^{*}	0.1000^{*}	0.0198^{***}
α_{USDHRK}	0.0494^{***}		0.0022	-0.0106	0.0051
α_{USDHUF}	-0.0141	0.0481^{***}		0.0716^{*}	-0.0056
α_{USDPLN}	0.0239	-0.038	0.0690^{***}		-0.0109
α_{USDRON}	0.0046	-0.0047	-0.0364	0.0110	
β_0	-0.0517^{*}	-0.0422^{*}	-0.1467^{*}	-0.2050^{*}	-0.0957^{*}
γ	0.9917^{*}	0.9972^{*}	0.8543^{*}	0.9104^{*}	0.9910^{*}
β_1	0.0597^{*}	0.0527^{*}	0.0822^{*}	0.1648^{*}	0.1077^{*}
ϕ	-0.0466^{*}	-0.0180	0.0527^{*}	0.0438^{**}	-0.0639^{*}
δ_{USDCZK}		-0.0203^{***}	-0.0311	-0.0143	-0.0069
δ_{USDHRK}	-0.0003		-0.0490^{***}	-0.0531^{*}	0.0563^{*}
δ_{USDHUF}	0.0416^{*}	0.0134		0.1074^{*}	0.0533^{*}
δ_{USDPLN}	0.0194^{***}	0.0325^{*}	0.1056^{*}		-0.0369^{*}
δ_{USDRON}	-0.0001	0.0036	0.0244	-0.0123	
ARCH test	0.414(0.519)	0.446(0.504)	0.660(0.416)	1.409(0.235)	71.866(0.00)

Source: Authors' calculations

Notes: Numbers in parentheses are the probability. *, **, *** denote significance at the 1 per cent, 5 per cent and 10 per cent level respectively

Tables 15 and 16 depict the results of the EGARCH model utilized for estimating the relevant parameters such as connectedness and volatility transmission between concerned variables both study periods. The results of the mean equations for the foreign exchange market's returns of the CEE-5 illustrate that there is evidence of significant own lag return spillover in foreign exchange markets of Croatia and Poland in two sub-periods, and Hungary in the pre-crisis period, this means that the

Hungarian, Croatian and Polish exchange markets are influenced by the past returns of its own. They are statistically significant at 1 per cent significance level. The notable findings show significant return transmission from Hungary, Poland and Romania to the Czech Republic in the pre-crisis period. In the post-crisis period, these coefficients are statistically significant from the Czech Republic to Romania and from Hungary to Poland. Furthermore, we find bidirectional return spillover between the Czech Republic and Croatia, Hungary and Poland in the pre-crisis period, while Hungary and Romania in the post-crisis period. Such results can confirm the strong interrelationship among foreign exchange markets in these countries, a finding in line with previous research of Bubak et al. (2011). From the available results, it can be suggested that the financial crisis caused the exchange rate price movement between financial markets. In addition, the results indicate that there is a slight decrease in financial integration in crisis situations in all analyzed countries, which indicates a presence of diversification opportunities for portfolio investors.

Turning to volatility spillovers (second moment interdependencies), the estimation results of EGARCH model show that the coefficients of volatility transmission δ_i are more statistically significant in the pre-crisis period than in the post-crisis period, which provides evidence that the conditional variance in each market is affected by innovations emanating from the other markets. We find significant volatility spillover from Croatia to the Czech Republic, the Czech Republic to Poland, Hungary to Croatia, Romania to Croatia and Hungary in the pre-crisis period, while from Croatia to Poland, Hungary to the Czech Republic, and Romania to the Czech Republic in the post-crisis period. Specifically, there is significant volatility spillover from Hungary to Poland and from Romania to Poland in the two sub-periods.

Table 16 Volatility spillover in the post-crisis period

Coefficients	USDCZK	USDHRK	USDHUF	USDPLN	USDRON
α_0	-0.0248	0.0023	0.0077	-0.0061	-0.0069
α_1	0.0363	-0.1220*	0.0365	-0.0922**	-0.0502
α_{USDCZK}		0.0978*	0.1171	0.1063***	0.0286
α_{USDHRK}	0.0524		0.0207	0.0062	-0.0087
α_{USDHUF}	0.0318	0.0431		0.0454	0.0618**
α_{USDPLN}	-0.0370	-0.0326	-.0876**		-0.0327
α_{USDRON}	-0.0989***	-0.0205	-0.1187**	-0.0862	
β_0	-0.0599*	-0.0346*	-0.0428*	-0.0650*	-0.0444*
γ	0.9926*	0.9948*	0.9954*	0.9941*	0.9936*
β_1	0.0725*	0.0372*	0.0521*	0.0786*	0.0492*
ϕ	-0.0363*	0.0147	0.0245**	0.0051	-0.0003
δ_{USDCZK}		-0.0378***	-0.0457**	-0.0606*	-0.0523*
δ_{USDHRK}	0.0026		-0.0172	-0.0123	0.0171
δ_{USDHUF}	0.0095	0.0030		0.0849*	0.0252
δ_{USDPLN}	0.0661*	0.0564*	0.0683*		0.0531*
δ_{USDRON}	0.0075	0.0063	0.0154	0.0408*	
ARCH test	0.031(0.858)	4.313(0.037)	0.211(0.645)	4.828(0.028)	1.756(0.185)

Source: Authors' calculations
Notes: Numbers in parentheses are the probability. *, **, *** denote significance at the 1per cent, 5 per cent and 10 per cent level respectively.

However, we find the absence of volatility transmission from the Czech Republic to Croatia and Romania, Croatia to Hungary, Hungary to Romania, Poland to Romania and Romania to the Czech Republic in the pre-crisis period. Similarly, having non-persistence in the post-crisis period, for instance, the Czech Republic to Croatia and Hungary and Poland, Croatia to the Czech Republic and Hungary and Romania, Hungary to Croatia and Romania, Poland to Croatia and Romania, Romania to Croatia and Hungary and Romania respectively. Such results suggest that the financial crisis has a considerable influence on the association between exchange markets, and the foreign exchange markets become less integrated into the crisis situation. Nevertheless, there is evidence of volatility transmission from exchange markets to the other markets in the pre-crisis period, but having the absence in the post-crisis period, the Czech Republic to Hungary, Croatia to the Czech Republic, Hungary to Croatia, Poland to Croatia, Romania to Croatia and Hungary. On the other hand, there are several new volatility spillovers after the financial crisis such as Hungary to the Czech Republic, Poland to the Czech Republic, Romania to the Czech Republic.

In addition, there are some bidirectional volatility spillovers occurred between Croatia and Poland, Hungary and Poland in the pre-crisis period. While we find bidirectional volatility spillover between the Czech Republic and Poland, Poland and Hungary in the post-crisis period. These findings share with (Antonakakis, 2012; Kumar et al. 2016). Briefly, the findings shed some lights on the 2007 financial crisis that how dynamics and integrations between the foreign exchange markets vary from dependence to less dependence.

More importantly, the volatility transmission mechanism is asymmetric in five markets because the asymmetric effect measured by coefficients of ϕ_i are significant for all markets during study period except the cases of Croatia, Poland and Romania in the post-crisis period. This result tallies with (Laopodis, 1998) and is not surprising, as good innovations may have a bigger shock than negative news during the turbulent period and confirm that both sizes of the news are fundamental determinants of volatility transmission mechanism.

To ensure robustness of the estimation results of our investigation, we apply the test for the existence of heteroscedasticity in the residuals is accepted in the EGARCH model (Tsay, 2005). By doing so, the ARCH effect on the standardized residuals of each model has been examined to specify whether the ARCH effect still exists in the model. Results report that there exists no problem of ARCH effect after estimation of the model for all selected time series considered at 1 per cent significance level except for the case of Romania in the pre-crisis period as indicated by Table 15 and Table 16, which nearly shows the appropriateness of the multivariate EGARCH model. Therefore, modeling the multivariate EGARCH model can successfully capture the price and volatility spillovers between financial foreign exchange markets in five countries.

A comparative analysis between pre- and post-crisis periods reveals that, with regards to return spillover, the magnitude of spillover is somewhat different between the two periods. Additionally, the term of volatility spillover, the transmission was less important after the crisis situation. Overall, the subprime financial crisis period affected the integration of exchange markets. The remarkable results indicate that the foreign exchange markets become less correlated during the financial crisis period. This is affirmed by the evidence for five countries in Central and Eastern Europe that have moved from several forms of the peg to free floating or vice versa. As already mentioned in these countries, in the former period volatility spillover can be found in terms of unidirectional, bidirectional and non-persistence flow of volatility transmission among these markets, whilst in the later no spillover can be identified.

4.6 Conclusion

In this paper, we estimate the volatility spillover effect between the USD/HUF, USD/PLN, USD/CZK, USD/RON and USD/HRK foreign exchange markets over the period 2000 through 2017 on a daily basis, namely, pre-crisis period: 1st April 2000 to 29th August 2008 and post-crisis period: 1st September 2008 to 29th September 2017. The asymmetric volatility spillover is brilliantly captured when employing the multivariate EGARCH model to delineate the volatility transmission between the times series before and after the global financial crisis. The originality of this study involves contributing to the existing literature of volatility spillover among Central and Eastern European emerging economies in the pre and post-subprime financial crisis period.

Our results highlight that the return spillovers exhibit more significant in the pre-crisis period than in the post-crisis period in the CEE-5 countries. The foreign exchange markets become more independent in a crisis situation. Similarly, the volatility spillover between the foreign exchange markets decreases dramatically and financial markets have not been transmitted during the crisis period. Results got in this work are in line with the majority of the prior studies such as (Caporale at al. 2016; Antonakakis, 2012) and contrast with the international evidence presented by (Bubak et al. 2011; Fidrmuc and Horvath, 2008) who document the existence of volatility spillovers between the Central European foreign exchange markets on an intraday basis. Also, we find that positive shocks generate more volatility spillover than negative shocks of the same magnitude, it is similar to (Barunik et al. 2017). Therefore, for example, investors can use movement in Hungarian Forint exchange rate to investigate the rest of the four foreign exchange markets movement and vice versa.

Focusing on return and volatility behavior of the foreign exchange markets, we also found that Polish and Romania exchange markets influence other markets, especially during turmoil period. This result raises a question related to the role of market consensus versus information during the period of stress. It would be tested by future researchers using new or more enhanced models to capture the effects and predictions of volatility behavior during the extreme turbulent periods.

The results provide significant implications for money managers involved in establishing dynamic portfolios and hedging strategies are effortless and diversified. The extended fluidity and transparency will be furnished by the integration of capital markets increased by a single currency in the equity and other markets, domestic and foreign, leading to a more efficient allocation of resources. (Laopodis, 1998) put forward that aside from the elimination of exchange rate risk, under the condition of the expected low levels of inflation and interest rates should boost the growth of economics, namely economic policies and different social policies would become more coordinated, result in improvements in productivity and labor mobility across nations. In addition, Carsamer (2016) reports changes in trade balance plays a critical role in volatility transmission, exchange rate co-movement and accelerating currency risk. These conveniences will make the CEE-5 currencies more attractive, such as greater volume and liquidity to contribute to the value of the firm.

On the policy implication, systematically understand the fact that volatility spillover is marginal regionally, policymakers should look at the high degree of trade openness because it does not only increase the foreign exchange movement, but also increase currency risk exposure. For central bank interventions, international trade, risk management and portfolio diversification, the volatility spillover between five foreign exchange markets may provide them benefit in predicting the behavior of one market by having the other market information. Moreover, the interest rate is still helpful for predicting exchange rates in the long term and provide a remarkable tool to hedge the risk of variation from foreign exchange market, and the local factor may have a prominent role in specifying foreign exchange markets interdependence.

Our findings also have several important implications for investors. Interest rate parity is still functional for forecasting exchange rates in the long term and provides a significant technique to hedge the risk of variation from the exchange rate. Additionally, by showing the phase patterns, we can closely monitor the snapshot of the equity price spillover channel, hence providing crucial information to implement carry trade. Furthermore, the local factor would have a prominent role in identifying the interdependence of foreign exchange markets. By doing so, it can provide relevant information to construct a portfolio and diversify risk across divergent currencies (Yang et al. 2016).

SUMMARY

The thesis was begun by highlighting the motivation of selecting this topic, then I identified the three main issues that have been implemented in the dissertation. Following this, the strands of literature in connection with volatility spillover effects among financial markets were reviewed. I shed light on the volatility spillovers among financial markets, and to answer the research questions, I would review the literature whose topics were dedicated to the stock and exchange rate markets in the CEE countries. These issues were conducted by employing the multivariate EGARCH model, which successfully captures both return spillovers and volatility transmissions among financial markets in CEE countries.

In this thesis, I adopt the multivariate EGARCH model to analyze a financial time series data to see for volatility spillover effects. This study aims at examining the issue of volatility spillovers across national stock and exchange markets in CEE region from 1 April 2000 to 29 September 2017. The entire investigation period is subdivided into two sub-periods: the pre-crisis period, from 1 April 2000 to 29 August 2008; and the post-crisis period, from 1 September 2008 to 29 September 2017. The study is primarily based on daily data that have been collected from the Bloomberg database. Based on the empirical results of investigations, the volatility transmission mechanism was confirmed. This can be systematically explained by the regional integration of the two financial markets in the CEE region.

The findings regarding the volatility spillover have been succinctly summarized as follows:

Firstly, the empirical dynamics of volatility spillover effects between stock markets and foreign exchange markets in Central and East European countries reveal that there is a bidirectional volatility spillover between stock and foreign exchange markets in Hungary in all periods, and in Poland in the post-crisis period. The results also show unidirectional volatility spillover in Croatia in the pre-crisis period, and from the stock market to the exchange market in the Czech Republic during two periods. In the post-crisis period, the two financial markets show the

absence of volatility spillover in Croatia. Specifically, the persistence of exchange market volatility was found to be higher than stock market volatility.

Secondly, based on the estimations of volatility spillovers among stock markets in CEE countries, the findings show that volatility spillover varies from normal to turbulent periods, and the stock markets are more substantially integrated. In addition, the persistence of volatility spillovers among the stock markets increases and the financial stock markets become more integrated after the crisis period.

Thirdly, the volatility spillover effect between the USD/HUF, USD/PLN, USD/CZK, USD/RON and USD/HRK foreign exchange markets over the period 2000 through 2017 on a daily basis decreases dramatically and financial markets have not been transmitted during the crisis period. More importantly, we find that positive shocks generate more volatility spillover than negative shocks of the same magnitude.

Although a comprehensive review of existing literature thoroughly discussed in detail, it should be underscored that there still exists in the exploration of interactions and volatility spillovers of the Central and Eastern European countries. Furthermore, I perceive that less attention was paid to emerging financial markets and particularly those operating in the CEE regions. Therefore, the main of this research is to provide a fresh new look into the characteristic of financial market cross-correlation dynamics and their volatility spillover effects. I suppose that the thesis is discernible from previous studies for at least three main points. First, I narrow our attention on the CEE stock and exchange markets. To the best of my knowledge, there is no previous empirical work apprehending such issues by means of second-moment analysis. Second, we use the multivariate EGARCH frameworks to extend previous studies. There is no such restriction in the EGARCH model on the parameters, and the EGARCH model is able to capture both symmetric and asymmetric shocks among the financial markets, whereas most of the previous studies examined only return linkages and transmissions. Also, it is an appropriate econometric technique for investigating the co-movement and volatility behaviour for the association between two-time series. Third, this study looks into integrations among the stock and exchange rate markets taking into consideration pre and post the global financial crisis period, which would provide valuable information on the interconnectedness in the sub-periods. Finally, the results from our study interest not only policy makers who are concerned by contagious effects and better regulations of these markets to promote economic growth, but also investors and fund managers who look for hedge their investment risks in the CEE countries.

Limitations

This study enlarges the current literature on price and volatility spillovers using the multivariate EGARCH model. However, there are several potential limitations in the design of the present investigation, including concerns about the sample and methodological limitations. The estimations of the empirical study are very positive; however, because we only look at five countries in CEE region, these findings might not translate to the financial markets of other countries in the same region. The robustness of the estimations of our research, we have used the multivariate ARCH LM test on the residuals of the model to determine whether the ARCH effect still exists in the model. As shown in parts of the results of each chapter, there exists problems of ARCH effect for some cases of all selected countries during the study period providing some indications of misspecification in each model.

Future research directions

As mentioned above, the present findings have crucial implications for the international investors, policymakers, and practitioners. In order to best inform these efforts, the future study can be extended in various ways since several questions remain unanswered. Further exciting research would be to examine these results hold for different sample size, for when each of the markets is more developed and for the whole countries in the CEE region. Our findings could be further studied by taking into consideration advanced methodologies such as wavelet transform frameworks or volatility spillover index to examine whether these results hold for the selected nations or not. At the empirical level, the results could be reinforced by the use of intra-daily data. The high-frequency data might indicate interesting empirical implications.

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APPENDIX

Multivariate EGARCH model

The multivariate time series of $\{r_t\}$ can be written as

$$r_t = \mu_t + a_t$$

where $\mu_t = E(r_t \mid \Omega_{t-1})$ is the conditional expectation of r_t given Ω_{t-1} (the past information set), and a_t is the shock of the series at time t.

The conditional covariance matrix of a_t given Ω_{t-1} is a $k \times k$ positive-definitive matrix H_t denoted by

$$H_t = Cov(a_t \mid \Omega_{t-1})$$

One way to model the heteroscedasticity for capturing asymmetric volatility patterns is to use the multivariate EGARCH model for return series $\{r_t\}$.

The Nelson's univariate EGARCH model can be extended to the multivariate EGARCH model:

$$\ln(\sigma_t^2) = \alpha_0 + \frac{I + \beta_1 B + \cdots + \beta_n B^n}{I - \alpha_1 B - \cdots - \alpha_m B^m} G(\varepsilon_{t-1})$$

$$a_t = H_t^{1/2} \varepsilon_t$$

$$a_t \mid \Omega_{t-1} \sim N_k\left(0, H_t\right), \varepsilon_t \sim N_k(0, I)$$

$$G(\varepsilon_t) = \theta\varepsilon_t + \gamma\left[\mid \varepsilon_t \mid - E(\mid \varepsilon_t \mid)\right]$$

Notes:

$\ln(\sigma_t^2)$ presents a vector of univariate $\ln(\sigma_{i,t}), i = \overline{1,k}$

α_0 is a vector of constant

α_j, β_l are $k \times k$ diagonal matrices for $j = \overline{1,m};\ l = \overline{1,n}$.

I is an identity matrix and ε_t is a vector of $\varepsilon_{i,t}, i = \overline{1,k}$

$G(\varepsilon_t)$ is a k-dimensional random sequence, which is a function of both magnitude and sign of ε_t, and θ and γ are $k \times k$ parameter matrices.

Since (m,n) = (1,0) is a general setup. We have

$$\ln(\sigma_t^2) = \alpha_0 + \frac{I}{I - \alpha_1 B} G(\varepsilon_{t-1})$$

That is $$\left(I - \alpha_1 B\right)\ln(\sigma_t^2) = \left(I - \alpha_1 B\right)\alpha_0 + IG(\varepsilon_{t-1})$$

So, $$\ln(\sigma_{i,t}^2) = \alpha_{i0}^* + \alpha_{ii}\ln(\sigma_{i,t-1}^2) + g_i(\varepsilon_{t-1})$$

where $\alpha_{i0}^* = (1 - \alpha_{ii})\alpha_{i0}, i = \overline{1,k}$

By using the summation notation, we have

$$g_i(\varepsilon_t) = \sum_{j=1}^{k} \left\{ \theta_{ij}\varepsilon_{j,t} + \gamma_{ij}\left[|\,\varepsilon_{j,t}\,| - E\left(|\,\varepsilon_{j,t}\,|\right) \right] \right\}, i, j = \overline{1,k}$$

The conditional covariance

$$\sigma_{ij,t} = \rho_{ij}\sigma_{i,t}\sigma_{j,t},\ i, j = \overline{1,k}$$

where ρ_{ij} is the constant conditional correlation between $a_{i,t}$ and $a_{j,t}$ given Ω_{t-1}.

Asymmetric effects of standardized innovations on volatility would be measured by partial derivatives for g_i :

$$\frac{\partial g_i(\varepsilon_t)}{\partial \varepsilon_{j,t}} = \begin{cases} \theta_{ij} + \gamma_{ij}, if\ \varepsilon_{j,t} > 0 \\ \theta_{ij} - \gamma_{ij}, if\ \varepsilon_{j,t} < 0 \end{cases} \quad for\ i, j = \overline{1,k}$$

Relative asymmetric would be measured by the ratio $|-\gamma_{ij}+\theta_{ij}|/\left(\gamma_{ij}+\theta_{ij}\right)$ which is greater than, equal to or less than 1 for negative asymmetry, symmetry and positive asymmetry, respectively.

Koutmos and Booth's multivariate EGARCH model

Koutmos and Booth's (1995) multivariate EGARCH model with k dimension is given by

$$\ln(\sigma_{i,t}^2)=\alpha_{i0}^*+\alpha_{ii}\ln(\sigma_{i,t-1}^2)+\sum_{j=1}^{k}\gamma_{ij}f_j\left(\varepsilon_{j,t-1}\right),\ i,j=\overline{1,k}$$

$$f_j(\varepsilon_{j,t})=\left[|\varepsilon_{j,t}|-E\left(|\varepsilon_{j,t}|\right)+\delta_j\varepsilon_{j,t}\right],\ j=\overline{1,k}$$

$$\sigma_{ij,t}=\rho_{ij}\sigma_{i,t}\sigma_{j,t},\ i,j=\overline{1,k}$$

Volatility spillovers across markets are reflected by coefficients γ_{ij} for $i\neq j$. α_{ij} captures the persistence of volatility.

The conditional covariance equation reflects the constant correlation ρ_{ij} across markets, which mainly simplifies the inference for the model. Nevertheless, a major difficulty of the constant correlation model is that the model overlooks the fact that correlation coefficients tend to change over time in real application. A way to relax the constant-correlation constraint within the GARCH framework is to specify an exact equation for the conditional correlation coefficient. This can be done by use of correlations proposed by (Tsay, 2005). First, we employ the correlation coefficient directly. Because the correlation coefficient between the returns is positive and must be in the interval [0,1]. We use the equation

$$\rho_{ij,t}=\frac{\exp(q_t)}{1+\exp(q_t)}$$

where

$$q_t = \varpi_0 + \varpi_1 \rho_{ij,t-1} + \varpi_2 \frac{a_{i,t-1} a_{j,t-1}}{\sqrt{\sigma_{ii,t-1} \sigma_{jj,t-1}}}$$

Where $\sigma_{ii,t-1}$ is the conditional variance of the shock $a_{i,t-1}$. If $\varpi_1 = \varpi_2 = 0$, then model reduces to the case of constant correlation.

To obtain parameter estimates by using the maximum likelihood method, we need the joint log-likelihood function under the distributional assumptions made previously. The log-likelihood function for the multivariate EGARCH model can be written as

$$L(\Theta) = -(\frac{1}{2})(kT)\ln(2\pi) - (\frac{1}{2}) \times \sum_{t=1}^{T} (\ln |H_t| + \varepsilon_t^{'} H_t^{-1} \varepsilon_t)$$

where k is the number of dimensions, T is the number of observations, Θ is the parameter vector to be estimated. The log-likelihood function is highly non-linear and therefore a numerical maximization technique is required. The BHHH algorithm (Berndt et al. 1974) can be used to obtain the solutions.

The BHHH algorithm – Convergence Theory

Assume K(x) is twice continuously differentiable and is defined over a compact upper contour set.

Consider the sequence $x^{(1)}, x^{(2)}, \ldots$, where

$$x^{(i+1)} = x^{(i)} + \lambda^{(i)} d^{(i)}$$
$$d^{(i)} = Q^{(i)} g^{(i)}$$

and $Q^{(i)}$ and $\lambda^{(i)}$ satisfies the previous criterion. Then $\lim_{i \to \infty} g^{(i)} = 0$.

Not every critical point of K(x) is a local maximum. If the iterative process opts a value of x where K(x) has a local minimum or a saddle point, the iterative process will stall, as g = 0 at such points. Since the process moves intentionally toward a critical point only if it is a local maximum, stalling elsewhere is only a very remote possibility. The safeguard against this possibility is accurately the same as against convergence to a local maximum that is not a global maximum: select some initial values of x. If they do not all lead to convergence to the same point, investigate the actual shape of the function with care until the global maximum is located.

Testing for ARCH effect

Let $a_t = r_t - \mu_t$ be the residuals of the mean equation. The squared series a_t^2 is then used to check for conditional heteroscedasticity, which is also known as the ARCH effects. Two tests are available. The first test is to apply the usual Ljung-Box statistics Q(m) to the $\{a_t^2\}$ series; see McLeod and Li (1983). The null hypothesis is that the first m lags of ACF the a_t^2 series are zero. The second test for conditional heteroscedasticity is the Lagrange multiplier test of Engle (1982). This test equivalent to the usual F statistic for testing $\alpha_t = 0$ in the linear regression.

$$a_t^2 = \alpha_0 + \alpha_1 a_{t-1}^2 + \cdots + \alpha_m a_{t-m}^2 + e_t,\ t = \overline{m+1, T}$$

Where e_t denotes the error term, m is a prespecified positive integer, and T is the same size. Specifically, the null hypothesis is H$_0$: $\alpha_1 = \cdots = \alpha_m = 0$. Let $SSR_0 = \sum_{t=m+1}^{T} (a_t^2 - \overline{w})^2$, where $\overline{w} = (1/T)\sum_{t=1}^{T} a_t^2$ is the sample mean of a_t^2, and $SSR_t = \sum_{t=m+1}^{T} \hat{e}_t^2$, where $\hat{e}_t^2$ is the least squares residual of the prior linear regression.

Then we have:

$$F = \frac{(SSR_0 - SSR_1)/m}{SSR_1/(T-2m-1)}$$

which is asymptotically distributed as a chi-squared distribution with m degrees of freedom under the null hypothesis. The decision rule is to reject the null hypothesis if $F > \chi_m^2(\alpha)$, where $\chi_m^2(\alpha)$ is the upper $100(1-\alpha)$ th percentile of $\chi_m^2(\alpha)$ or the p-value of F is less than α .

Multivariate EGARCH estimations:

This study followed the following step wise procedure for measuring the volatility spillover according to the papers of Jebran and Iqbal (2016), Jebran et al. (2017a), Jebran et al. (2017b), Bal et al. (2018), Kumar et al. (2016) … using Eviews.

We compute the return of time series, ARCH effect has been tested because EGARCH model can be applied on data in which ARCH effect exists means Auto Regressive Conditional Heteroskedasticity.

We have examined cross market volatility spillover between market *i* to market *j* in two ways.

- We have generated volatility residual series from a specific EGARCH model for each variable separately
- The generated volatility residuals of the financial market data sets were introduced to the variance equation of the EGARCH model and were used as proxy of shock emanating from one market to other market

RATS software provided the sample code of Koutmos and Booth's paper at: https://estima.com/forum/viewtopic.php?f=8 &t=1614

OWN PUBLICATIONS

1. Conference papers

Hung, N.T. (2017). An empirical analysis of Euro Hungarian Forint exchange rate volatility using GARCH. Challenges in National and International Economic Policies. University of Szeged, Doctoral School in Economics, Szeged, pp. 57–67

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2. Journals

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