Charles University in Prague

Faculty of Social Sciences

Institute of Economic Studies

MASTER THESIS

Return and volatility spillovers across financial markets in Central Europe

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Declaration of Authorship

The author hereby declares that he compiled this thesis independently, using only the listed resources and literature, and the thesis has not been used to obtain a different or the same degree.

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Prague, May 14, 2015

Signature

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Abstract

This diploma thesis is devoted to the linkages among stock, bond and foreign exchange markets in the Czech Republic, Austria, Germany and Poland during the period from the beginning of the year 2007 to the end of the year 2014. In order to complexly describe the interconnections among the markets, we utilized two kinds of spillover indices (from the generalized and structural VAR model), dynamic correlation coefficients obtained from the multivariate GARCH model and contemporaneous coefficients from the structural VAR model that was identified through heteroskedasticity in structural shocks. These methods enabled us to describe the linkages among the markets from different angles, to capture their time evolution and to obtain a notion about the transmission mechanism among these markets in Central Europe. The results, inter alia, indicate an intensifying interconnection among the markets during crisis periods, lowering impact of stock markets, increasing influence of bonds and a dominant role of German bonds and Austrian stocks. At the same time, we were able to capture the influence of the European sovereign debt crisis on the spillovers and on the intensity of linkages among the markets. We showed that the intensity of linkages among bond markets relented, probably as a result of higher emphasis on the country-specific development. The obtained results and their extensions can potentially underlie more detailed research.

JEL Classification	G15, C58, F37
Keywords	return and volatility spillovers, spillover index, the multivariate GARCH model, the generalized VAR model, financial markets

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Abstrakt

Tato diplomová práce se věnuje vztahům mezi akciovými, dluhopisovými a měnovými trhy v České republice, Německu, Polsku a Rakousku v období 2007-2014. Za účelem komplexně popsat propojení mezi trhy jsme využili dva druhy spillover indexů (na základě generalizovaného a strukturálního VAR modelu), dynamické korelační koeficienty odhadnuté pomocí vícerozměrného GARCH modelu a koeficienty strukturálního VAR modelu identifikovaného prostřednictvím heteroskedasticity ve struktuálních šocích. Tyto metody nám umožnily popsat vztahy mezi trhy z různých pohledů, zachytit jejich časový vývoj a získat tak představu o transmisním mechanismu mezi těmito trhy ve střední Evropě. Výsledky, mimo jiné, naznačují zesilující propojení mezi trhy v době finančních krizí, klesající vliv akcií ve prospěch dluhopisů a dominantní postavení rakouského akciového trhu a německého dluhopisového trhu. Zároveň jsme dokázali zachytit vliv evropské dluhopisové krize na výši přelivů a na intenzitu propojení mezi trhy. Ukazuje se, že dochází k rozvolnění vztahů mezi dluhopisovými trhy, které může být připsáno např. většímu důrazu na vývoj v jednotlivých zemích. Získané výsledky a jejich případné rozšíření se mohou stát základem pro detailnější výzkum.

Klasifikace JEL	G15, C58, F37
Klíčová slova	přelivy výnosů a volatility, spillover indexy, vícerozměrný GARCH model, generalizovaný VAR model, finanční trhy

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Acronyms

AUS Austria

CZE the Czech Republic

DCC Dynamic Conditional Correlation GARCH models

GARCH Generalized Autoregressive Conditional Heteroskedasticity model

GER Germany

GVAR Generalized Vector Autoregressive model

MGARCH Multivariate Generalized Autoregressive Conditional Heteroskedasticity model

OLS Ordinary Least Squares

POL Poland

SVAR Structural Vector Autoregressive model

VAR Vector Autoregressive model

Master Thesis Proposal

Author	Jaroslav Ketzer
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Proposed topic	Return and volatility spillovers across financial markets in Central Europe

Motivation There is no large assemblage of literature that deals with international spillovers, both within and across asset classes, despite the fact that the results of the few exceptions, for example of Ehrmann, Fratzscher, & Rigobon (2011), underline the importance of these spillovers. Understanding these linkages requires comprehensive and complete modelling of all transmission channels. It should be the aim of this thesis.

There are several appropriate tools for detecting and measuring interdependency. As a consequence of that, this thesis will apply some of these methods and describe the dynamic behaviour of the spillovers by using these methods. Total and mainly directional spillover indices, proposed by Diebold & Yilmaz (2012) as an improvement over Diebold & Yilmaz (2009)'s total spillover index, appear to be one of the most promising methods for this task. An alternative solution to shortages of the Diebold & Yilmaz (2009)'s spillover index is a method of estimation of total and directional spillover indices that was used in Wang, Liu, & Lu (2012). This approach relies on a structural VAR model in which identification of structural coefficients is carried out through heteroskedasticity modelled by a MGARCH model. Fortunately, intermediate results of this methodology (the estimation of MGARCH and structural VAR models) present additional approaches to spillovers. Interpretation of these results could complement the spillover indices and contribute to the complexity of conclusions of this thesis. (For details about the methods, see Methodology.)

The main contribution of this thesis should be a notion of how the markets are interconnected and how these interconnections have been changing over time. Spillovers between two particular markets (stock, bond, foreign exchange, money) within a country, as well as between two same markets of different countries, are of special interest. The methods mentioned above should be able to answer to these questions.

Understanding and measuring the interactions among markets is of great relevance to financial market participants in many different areas. The knowledge of spillovers, conditional variances and covariances can be utilised e.g. for forming of a portfolio, for pricing of derivatives or other assets and in risk management.

At the same time, volatility patterns during financial crises usually display certain similarities. Thus, monitoring the volatility patterns and the volatility spillovers could provide "early warning systems for emerging crises, and track the progress of extant crisis" (Diebold & Yilmaz 2012).

Hypotheses

1. The return and volatility spillovers between two parts of national financial markets (e.g. between the stock and bond markets or between the stock and foreign exchange markets) can be different across countries, i.e. interactions between, for instance, the Czech stock market and the Czech bond market can noticeably differ from interactions between the same markets in Germany.

2. There are important international spillovers among individual markets in Central Europe.

3. The spillovers evolve over time. During the financial crisis, the intensity of spillovers is growing.

Methodology Diebold and Yilmaz (2009) introduced a simple measure of independence of asset returns and volatilities that is based on forecast error variance decompositions from vector autoregressions (VARs). Unfortunately, their approach relies on the Cholesky-factor identification of VARs, and thus the results are usually dependent on ordering of variables. As a result of that, several improvements have arisen. Diebold and Yilmaz (2012) proposed a method of measuring the directional spillovers in a generalized VAR framework in which results are invariant to ordering of variables.

In this thesis, I intend to engage Diebold and Yilmaz (2012)'s and Wang, Liu and Lu (2012)'s improvements of spillover indices and to utilize these methods to capture directional spillovers of returns and volatility estimated by range-based estimators. Moreover, the spillover variation over time will be assessed. In the case of Diebold-Yilmaz (2012)'s approach, the dynamics of spillover indices will be captured by using rolling window method.

Wang, Liu and Lu (2012) applied another approach that determines unique total and directional spillover indices that are invariant to ordering of variables. Additionally, the dynamic spillover indices can be obtained through the structural GARCH model and it is not necessary to use the rolling window method.

Their approach relies on heteroskedasticity for the purpose of identifying the structural VAR model following the methodology, known as the identification through heteroskedasticity, proposed in Rigobon (2003). Rigobon (2003) showed that the estimates are consistent regardless of how the heteroskedasticity is modelled. It could be modelled by a multivariate generalised autoregressive conditional heteroskedasticity (MGARCH) model (used e.g. in Rigobon and Sack (2003) and in Andersen, Bollerslev, Diebold, Vega (2007)) or by a regime-switching model (used e.g. in Ehrmann, Fratzscher and Rigobon (2011)). In this thesis, I would like to apply the first approach and model the heteroskedasticity most likely by the commonly used Dynamic Conditional Correlation GARCH (DCC-GARCH) model of Engel (2002).

Fortunately, the estimation of the MGARCH represents another way of inspecting return and volatility spillovers. In this way, for instance, Worthwington and Higgs (2004) analysed return and volatility spillovers among Asian equity markets. At the same time, the estimated structural coefficients of the structural VAR model were utilized for examining spillovers e.g. in Ehrmann, Fratzscher and Rigobon (2011). These two alternative approaches should complement the spillover indices and contribute to the complexity of conclusions reached in this thesis.

Unfortunately, the high-frequency data is not accessible for us, and the data availability should allow us to conduct only an analysis of the daily data for several countries in Central Europe (probably for the Czech Republic, Poland, Austria and Germany). I want to focus on stock, bonds, money markets and exchange rates. According to my plan, the abovementioned methods should be applied for all pairs of selected countries. The spillovers and interactions derived by the methods will be then compared and appropriately summarized in order to confirm the hypotheses and to answer to other questions that could arise.

Expected contribution In my opinion, the contribution of this master thesis will be probably twofold. Firstly and mainly, I think that literature concerning the (international) spillovers in such a comprehensive way is quite rare if not completely missing, especially in Central Europe. Secondly, the application of this set of methods (two approaches to spillover indices, the MGARCH model and the structural VAR model) has never been used in one study before, at least according to my superficial knowledge.

Hopefully, this thesis will be able to complexly and robustly describe interactions among financial markets in Central Europe. More specifically, this thesis should describe the transmission mechanism among stock, bond, money and foreign exchange markets not only within one particular country, but also among these markets of several selected countries.

Expected outline

1. Introduction
2. Literature Review - Description of approaches to the quantification of the spillovers.
3. Methods
    (a) Vector Autoregressive Model, Variance Decomposition
    (b) Various Approaches to Spillover Indices (especially, Diebold-Yilmaz (2012)'s and Wang, Liu and Lu (2012)'s methods)
    (c) Identification Through Heteroskedasticity
    (d) DCC-GARCH model
4. Data Description and Preliminary Tests
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iv. Spillovers described by the structural VAR model

(b) Comparison of the approaches to spillovers

(c) Conclusions about the interactions among markets and among countries

6. Conclusion

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Chapter 1

Introduction

In this thesis, we focus on the stock, bond and foreign exchange markets of several countries in Central Europe (the Czech Republic, Poland, Austria and Germany). The main contribution of this thesis should be a notion of how the markets are interconnected and how these interconnections have been changing over time. Return and volatility spillovers between two particular markets (stock, bond, or foreign exchange markets) within a country, as well as between different countries are of special interest. We apply a wide range of methods (two approaches to spillover indices, the MGARCH model and the structural VAR model) that should help us to achieve this task.

The analysis of domestic and international spillovers and linkages in such a comprehensive way can contribute to the existing literature and broaden the notion about the transmission mechanism among stock, bond, and foreign exchange markets not only within one particular country, but also among these markets of several selected countries. The literature is usually devoted either to different markets within one country, or to one market across several countries. This thesis combines both approaches. Similar studies are quite rare, and in Central Europe practically missing. We believe this thesis will help to mitigate this gap.

The main goal of this thesis is to appropriately summarize the discovered spillovers in order to confirm or refute following hypotheses:

1. The return and volatility spillovers between two parts of national financial markets (e.g. between the stock and bond markets or between the stock and foreign exchange markets) can differ across countries, i.e. interactions between, for instance, the Czech stock market and the Czech bond market can noticeably differ from interactions between the same markets in Germany.

2. There are important international spillovers among individual markets in Central Europe.

3. The spillovers evolve over time. During the financial crisis, the intensity of spillovers is growing.

Understanding and measuring the interactions among markets is of great relevance to financial market participants in many different areas. The knowledge of spillovers, conditional variances and covariances can be utilised e.g. for forming a portfolio, hedging, pricing derivatives or other assets, in risk management or in preparation of regulatory policy of financial markets (Stoica & Diaconasu 2013a). At the same time, volatility patterns during financial crises usually display certain similarities. Thus, monitoring the volatility patterns and the volatility spillovers could provide "early warning systems for emerging crises, and track the progress of extant crisis" (Diebold & Yilmaz 2012).

Our results indicate quite considerable spillovers across all markets that even intensified during the crisis periods. The most influential markets appear to be the German bond market (especially during the years 2011 and 2012) and the Austrian equity market. In addition, there is a noticeable trend suggesting a weakening impact of stocks and an increasing influence of bonds. The dynamic evolution of correlation coefficients discovered lower linear dependence between the bond markets during the European sovereign debt crisis that could be interpreted as a sign of higher emphasis on the country-specific development. Despite the weaker linear dependence, the contribution of the German bonds to the other markets remarkably grew during the tensest period of the debt crisis.

This diploma thesis is organized as follows: In Chapter 2, we provide a brief overview of conclusions of existing literature. Chapter 3 describes the construction of the data set used in this thesis and presents the basic characteristics of the time series. In Chapter 4, the applied methods are introduced and their basic properties are discussed. The methods are then utilized for investigation of return and volatility spillovers across financial markets in Central Europe, and the achieved results are presented in Chapter 5. We first present the results separately for each method, and then a section is dedicated to a comparison and interpretation of the results. Although this approach may seem lengthy, we believe it will contribute to better lucidity. Finally, Chapter 6 summarizes the main results, and discusses possible implications and areas for future research.

Chapter 2

Literature Review

Literature concerning the return and volatility spillovers is quite wide, and therefore, this chapter is devoted to an overview of the empirical results and conclusions. This chapter is not structured with respect to used methods, but with respect to concerned markets. A compendious overview of the most commonly applied methods is provided e.g. in Wang, Liu, & Lu (2012).

We aim to create a support that should help us to evaluate the results reached in this thesis. The results presented in Chapter 5 will be interpreted with regard to this chapter, and therefore this chapter is organized in such a way that should facilitate it as much as possible. That is the reason why we array empirical conclusions according to the markets in question. At the same time, we pick mainly studies with results that are somehow related to the outcomes of this thesis.

2.1 General findings

An unarguable conclusion reached by many studies is that linkages among financial markets have been evolving over time, miscellaneous changes may occur, as well as a continuous evolution is present. Factors contributing to the changing interconnections could be: increasing mobility of capital coming from globalization, increasing policy coordination, abolition of capital and foreign exchange controls, technological improvements in communication, electronic trading, the rise of hedge funds and multinational companies or organizations, etc. (Diebold & Yilmaz 2012; Stoica & Diaconasu 2013a).

Naturally, we start with studies that are very similar in content to this thesis. Ehrmann, Fratzscher, & Rigobon (2011) analyse the character of spillovers both within asset classes and across financial markets. They have reached several interesting general results relevant to our interest. They examined the financial transmission among money, bond, equity and foreign exchange markets within and between the USA and the Euro area. One of their main findings is that the asset prices react strongest to other domestic asset price shocks, but, at the same time, they found evidence of significant international spillovers. As could be expected, the strongest international spillovers take place across the same markets. These spillovers are mostly positive. For instance, "a positive shock to domestic stock prices lead to a rise in foreign equity markets because firms and demand are linked internationally" (Ehrmann, Fratzscher, & Rigobon 2011).

Simultaneously, they identified the international cross-market spillovers as very important. They illustrate this conclusion by both the significance of the point estimates of coefficients and the change of the within-market coefficients when comparing the results of the structural and reduced-form models. This conclusion also highlighted that "the direct transmission channels within asset classes are often magnified substantially through indirect spillovers through other asset prices" (Ehrmann, Fratzscher, & Rigobon 2011).

Similarly, Andersen, Bollerslev, Diebold, & Vega (2007) attributed the positive coefficients indicating cross-country linkages that were not explained by US macroeconomic news to world-wide fundamental news, cross-market hedging or other non-fundamental contagion effects. At the same time, they describe stronger correlation during recessions.

An intensification of the volatility spillovers during the financial crisis which began in 2007 is documented by Diebold & Yilmaz (2012). Based on the spillover indices (introduced in Chapter 4), they emphasize spillovers from the stock markets to other markets that are particularly important during this period. On the other hand, volatility spillovers from the bond market seem to be usually lower than spillovers from the other markets. Finally, the volatility shocks in the FX market tend to be generally spilled over to the stock (and commodity) markets.

The same methodology was used by Louzis (2013) which examined spillovers among the stock, bond, money and foreign exchange markets of the euro area from 2000 to 2012. His results indicate that most of the return and volatility spillovers is transmitted by the stock markets, even during the sovereign debt crisis. He also revealed that the level of return spillovers was quite high (ranging mostly between 60 % and 80 %) and sharply increased during the financial crisis. His results suggest the Lehman Brothers collapse boosted the level of spillovers more than the European sovereign debt crisis. Louzis (2013) distinguished between bonds of periphery and investment grade countries, and it enabled him to identify a flight-to-quality from periphery to investment grade bonds from late 2010 to 2011. While the periphery bonds are detected to be receivers of return spillovers, they usually operate as a source of the volatility shocks for the other markets.

2.2 Stocks

There is a large body of literature studying interconnections among Central European stock markets. We will mention at least several studies that are relevant to this thesis.

First of all, we will mention the thesis written by Dovhunová (2014) which provide an almost exhaustive overview of literature concerning spillovers and linkages among stock markets in Central Europe. She analysed volatility spillovers across CEE stock markets. She applied the volatility spillover indices proposed by Baruník, Kočenda, & Vácha (2013) on the high-frequency data from the period from 2008 to 2010. Her results revealed the Czech stock market as the main transmitter of volatility shocks to the other markets. In accordance with literature, she assigned this result to the indirect influence of some other non-included country.

Gjika & Horváth (2012) examined comovements in Central Europe during the period from 2001 to 2011 by using asymmetric DCC model. They found strong correlations among stock markets that increases over time and especially after the EU entry and during financial crisis. Quite high correlation coefficients between the stock markets in Central Europe (particularly the Czech Republic and Poland) and Western Europe in the period 2006-2011 are reported also by Horváth & Petrovski (2012).

At the same time, Aslanidis & Savva (2010)'s results show that the correlation between the Czech and Polish stock markets and those of the eurozone has increased from 2001 to 2007. A similar conclusion was reached by Syllignakis & Kouretas (2011) that examined time-varying conditional correlations of stock markets in Central Europe during the period 1997-2009. They confirmed an increase in conditional correlations between US and the German stock returns and the CEE stock returns, especially during the financial crisis.

An opposite conclusion was obtained by Baruník & Vácha (2003) that applied wavelet analysis to high frequency financial market data from several countries in Central Europe in the period of 2008-2009. Their results revealed that "the interconnection between all the stock markets changes significantly over time and varies across frequencies" (Baruník & Vácha 2003). The strongest interdependencies were discovered between the Czech and Polish stock markets. At the same time, quite low correlations between CEE markets and the DAX index were obtained suggesting that the CEE markets are still only tightly linked to the German stock market. Concerning the financial crisis in 2008, they showed the connection between German and Czech markets decreased during this crisis.

Very low correlations between CEE markets and Western European stock markets in higher frequencies was also documented, for instance, by Égert & Kočenda (2007).

The impact of the Austrian stock market on the other equity markets in Central Europe was examined by Stoica & Diaconasu (2013a). Their tests of Granger causality revealed that the impact of the Austrian markets on the Polish and Czech stocks increased during the period 2008-2010. At the same time, an influence in the opposite direction was documented and primarily ascribed to stimulus coming from a leading market. A high influence is confirmed also by Stoica & Diaconasu (2013a) which found that US and Austrian markets exercise a higher impact on the stock markets in Central Europe than than continental leaders (Great Britain, Germany and France).

2.3 Bonds

Due to the euro area debt crisis, a focus on sovereign debt markets has increased in recent years. The crisis triggered a divergence in bond yields, and many papers have started to examine the widening yield spreads. For instance, Conefrey & Cronin (2013) apply the spillover indices to assess spillovers among bonds of ten euro area member states over the period 1999 to 2012. They interpret their results as supporting the view that "the euro area sovereign bond crisis has moved from being driven initially by broadly-based systemic concerns to a later focus on country-specific developments" (Conefrey & Cronin 2013). They welcome this development because the greater focus on country-specific issues can help avoid financial contagion. They found evidence that the pre-crisis spillover patterns were reestablished (net spillovers from the core to the periphery).

Additionally, Moloney, Killeen, & Gilvarry (2014) examined fragmentation in euro area sovereign bond markets by using moving average correlation and a bivariate DCC-GARCH model. Their results suggest that the correlation estimates for core countries (Austria among them) substantially declined only in late 2011 and recovered in late 2012. In contrast, the fragmentation of the peripheral countries last during the entire period.

Finally, an exhaustive analysis of linkages among EU sovereign bond markets was carried out by Claeys & Vasicek (2012). Among other things, they confirmed the importance of spillovers among bond yields. In relation to this thesis, their results indicate very strong mutual linkages in Central Europe (Czech, Polish and Hungarian bonds).

2.4 Foreign exchange markets

Ehrmann, Fratzscher, & Rigobon (2011) concluded that depreciation of the US dollar usually results in an increase of bond yields. They explain this reaction through the grow of inflation expectations. They also identified a different reaction of the stock markets on changes of exchange rates. While the European stock markets rise after an appreciation of EUR to USD, the US equity markets do not react. This inconsistency was explained by higher openness of the European market in comparison with the American market.

Andersen, Bollerslev, Diebold, & Vega (2007) examined the interactions among stocks, bonds and exchange rates in the USA and the UK. They obtained results suggesting that negative bond returns and positive stock returns generally lead to appreciation of the domestic currency.

2.5 Cross-market interconnections

Andersen, Bollerslev, Diebold, & Vega (2007) identified positive stock-bond correlations during expansions that were noticeably lower than negative stock-bond correlations during recessions. They ascribed this pattern to the fact that during expansions the discount effect dominates while during recessions the more important channel is the cash-flow effect. They demonstrate, inter alia, a drop of correlations between German stocks and bonds to negative values after the year 2000. Similar conclusion was highlighted by Summer, Johnson, & Soenen (2009) that the stock-bond correlations were generally positive and high, but the correlation coefficients usually decline during stock market downturns.[1] We need to keep in mind that these studies computed the changes of bond prices,

[1] The correlations of prices were negative during downturns, correlations of returns were only weaker during recessions and later phases of the expansions.

while we utilize the changes of bond yields. The change of correlation[2] from positive to negative after the year 2000 was demonstrated also by Christiansen (2004) for European bonds.

Similarly, Aslanidis & Christiansen (2011) used high frequency returns and investigated the nature of realized stock-bond correlations. The results of the paper are again consistent with positive stock-bond correlation during expansions and negative correlations during recessions when high uncertainty causes flight to safety.

Rigobon & Sack (2003) discovered strong contemporaneous interactions between American stock prices and bond yields. They show that growing stock prices usually lead to higher bond yields (through the influence on aggregate demand), and conversely, the equity prices react negatively to the bond yields (resulting from higher discount rate).[3] At the same time, they examined the correlations between the assets. They explain the changes in correlations as resulting from changes of the relative volatilities of the underlying shocks.[4]

[2] Correlations between stock returns and changes of bond prices.

[3] Consistent with results of Andersen, Bollerslev, Diebold, & Vega (2007).

[4] For instance, the correlation between equity prices and Treasury yields that became positive probably resulted from an increase in volatility of stock market shocks.

Chapter 3

Data and Preliminary Analysis

In this chapter, we describe the data that is used for the analysis in the following chapters. Section 3.1 specifies sources of the data and explains how the data is adjusted and transformed. Section 3.2 presents a basic description of the data. In particular, summary statistics, correlations, results of stationary tests and tests for heteroskedasticity are discussed.

3.1 Construction of Dataset

The goal of this thesis is to complexly and robustly describe interactions among financial markets in Central Europe. More specifically, we aim to describe the transmission mechanism among stock, bond and foreign exchange markets. We have decided to examine the markets of four European countries (Austria, the Czech Republic, Germany and Poland). This section defines the way of obtaining and adjusting the dataset that will be used for the analysis in this thesis.

The data has been obtained from two sources. The evolution of the Czech and Austrian stock market indices (PX and ATX index, respectively) was obtained on the website at www.stocktrading.cz. The rest of the applied time series was found in the database at stooq.com. The sample covers the period from the beginning of the year 2007 to the end of the year 2014.

As we have already mentioned, we are interested in the evolution of four stock markets. We assume that the performance of the stocks in a particular country is represented by its general stock index, therefore we may use the following indices: the Austrian Traded Index (ATX), the Czech PX Index (PX), the German DAX Index and the Polish WIG30.

The evolution of the bond markets is presumed to be typified by the countries' 10-year bond yields.

Finally, the foreign exchange market is described by the exchange rate between the currencies of two particular analysed countries. The pairs of countries are thus represented by the following exchange rates: CZK/EUR, PLN/EUR and PLN/CZK. If Austria and Germany are the analysed countries, the exchange rate for the U.S. dollar against Euro (USD/EUR) is used.

In order to have enough observations, we apply the data with daily frequency. Obviously, several problems arise. Firstly, most of the markets are open only on weekdays and consequently we have dataset with irregular frequency. Secondly, we may miss some values at some markets due to country specific holidays and other days during which the markets are closed. This is the reason why we need to adjust the dataset before starting the analysis. We have adjusted the dataset by removing the values observed on days when at least one market was closed. This step significantly reduced the number of observations to 1928.

Additionally, the daily data may contain too much noise, and the application of the daily data is usually linked to the so called day-of-the-week effect (Roca 1999). We believe these features of the daily data will not cause any considerable issues, and the results of our analysis will be influenced only insignificantly.

The adjusted dataset may be used to produce the time series of returns and volatilities. We use the logarithmic returns for all markets, that means we compute the differences of logarithms of observed values. We follow the procedure of estimation that was applied in Diebold & Yilmaz (2012), and thus the daily variance is estimated by an estimator derived by Parkinson (1980). The estimator defined in Equation 3.1 uses the highest value P_{it}^{max} and the lowest value P_{it}^{min} in market i on day t.

$$\widehat{\sigma}_{it}^2 = 0.3607\big[\ln(P_{it}^{max}) - \ln(P_{it}^{min})\big]^2 \tag{3.1}$$

The annualized daily percent standard deviation σ_{it}^{an} in market i is then given by the following expression

$$\widehat{\sigma}_{it}^{an} = 100\sqrt{241 \cdot \widehat{\sigma}_{it}^2} \tag{3.2}$$

where the number 241 represents an approximation of the number of trading days in any given year.[1]

[1]The number of trading days is approximated by an average number of common working days in the analysed countries.

3.2 Data Description

In the previous section, the construction of the time series in our dataset was described. In this section, we investigate basic properties of the time series. We present the most frequently used summary statistics, the results of the augmented Dickey-Fuller test (ADF) and tests of heteroskedasticity together with basic correlation analysis.

The evolution of the stock, bond and foreign exchange markets is depicted in Figures 3.1, 3.2 and 3.3. As may be seen in Figure 3.1, the stock markets in all countries have very similar development. In 2007 and 2008, the stock markets were declining. The decline strengthened in September 2008 when the Lehman Brothers declared bankruptcy. In the beginning of 2009, a slight growing trend started and had lasted until the end of 2011. After that, only German stock market have continued to grow. The remaining stock markets have stagnated around the values from the end of 2011.

Figure 3.2 describes the development of the 10-year bond yields of the analysed countries. A noticeable decreasing trend may be observed. Another insight may be taken into account. If we accept the concept of the financial theory that higher risk should be connected with higher yields, Figure 3.2 provide us, among other things, a comparison of riskiness of the countries. German, generally considered as the least risky country, had the lowest yields of 10-year bonds among the countries. Poland, on the other hand, appeared to be the most risky country because it had the highest yields during the whole period.

Finally, quite diverse development of the exchange rates may be found in Figure 3.3. Three periods deserve to be mentioned. First, the start of the financial crisis in 2008 is connected with rapid changes. During the period foregoing the fall of Lehman Brothers, the American dollar appreciated with respect to the Euro. After that, the depreciation of the Czech crown and Polish Zloty with respect to the Euro and depreciation of the Polish Zloty with respect to the Czech crown followed. The second period of abrupt changes occurred in 2011. Third, the foreign exchange intervention of the Czech national bank resulted in depreciation of the Czech crown with respect to the Polish Zloty and the Euro.

The plots[2] of returns and volatilities confirm that the most active were stock, bond and foreign exchange markets around the fall of Lehman Brothers in September 2008. The second period of higher volatilities was in August

[2]The plots are enclosed to this thesis.

Figure 3.1: **Evolution of the stock markets**

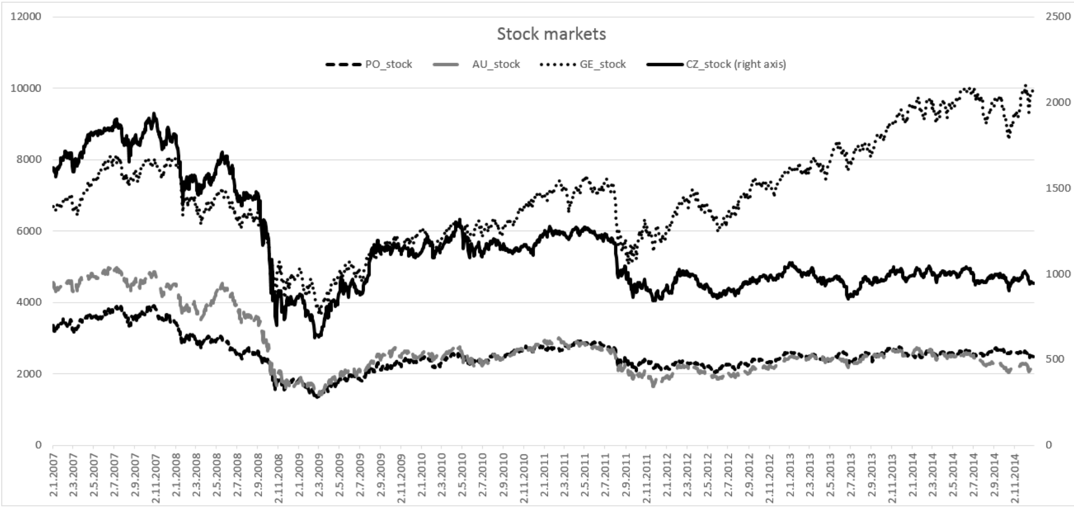
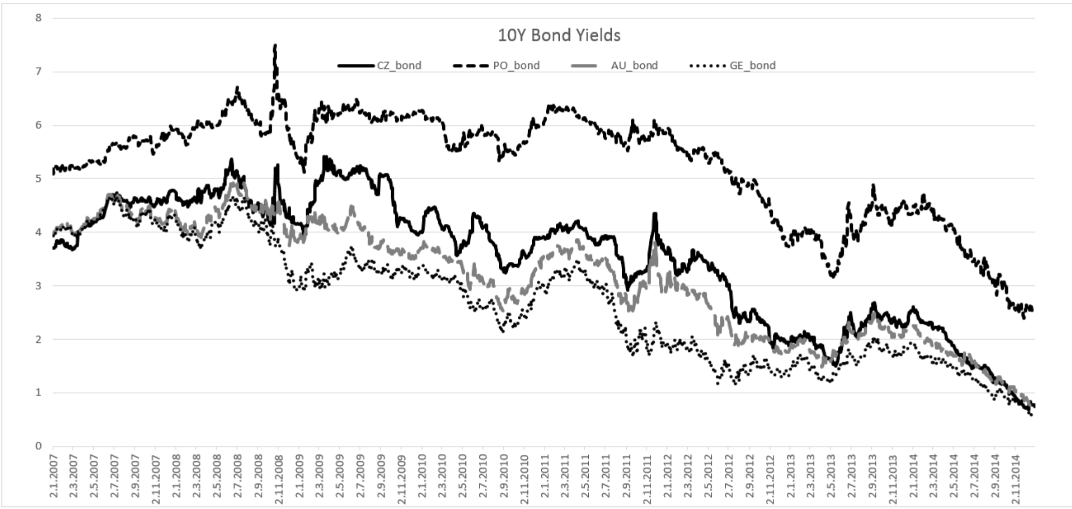


Figure 3.2: **Evolution of the bond yields**



2011. While the higher volatilities on the stock markets alleviated before the end of the year 2011, on the bond market, the volatilities had remained for the rest of the analysed period.

Table 3.1 provides descriptive statistics. The sample mean, standard deviation, median, maximum and minimum, skewness and kurtosis are presented for each return series for the period from the beginning of the year 2007 to the end of the year 2014. The same statistics for the initial time series and for volatilities for the same time period and plots of all time series may be find in the enclosed file.

Figure 3.3: **Evolution of the exchange rates**

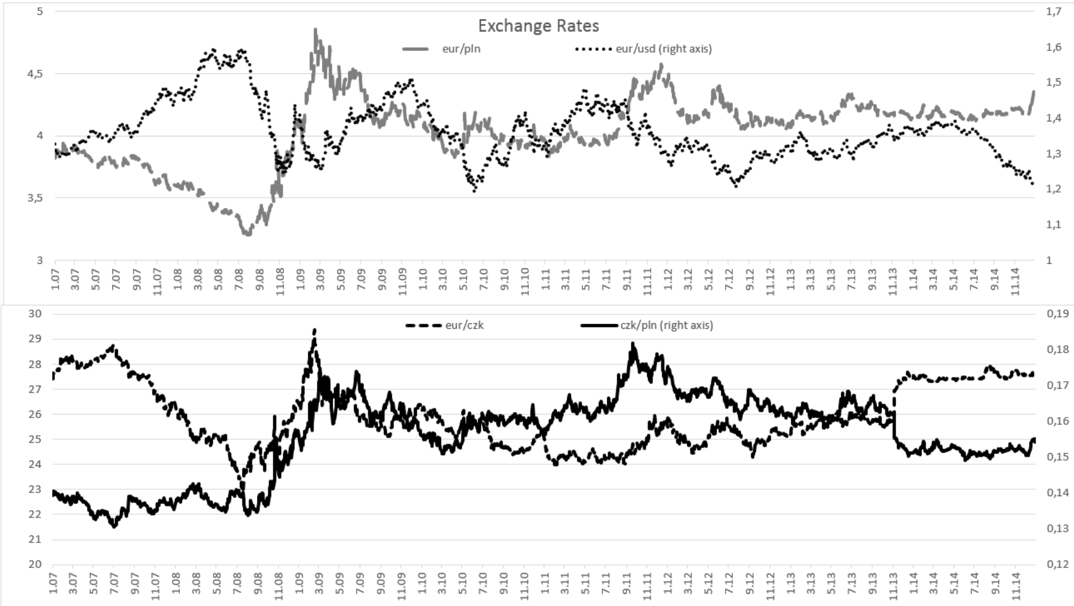


Table 3.1: **Summary statistics of returns**

	Mean	**Std**	**Median**	**Max**	**Min**	**Skewness**	**Kurtosis**
czbond	-0,000835	0,017206	-0,000494	0,180382	-0,115960	1,041477	16,459559
czstock	-0,000278	0,016468	0,000085	0,123641	-0,161855	-0,537888	17,160771
pobond	-0,000371	0,011836	-0,000166	0,098343	-0,089726	0,567433	13,580129
postock	-0,000154	0,016218	0,000264	0,108961	-0,084428	-0,145382	7,306275
aubond	-0,000890	0,017197	-0,000838	0,090471	-0,075724	0,158842	5,934369
austock	-0,000388	0,018322	0,000401	0,120210	-0,102526	-0,228151	8,219359
gebond	-0,001030	0,023207	-0,000574	0,148898	-0,129520	0,045382	6,613844
gestock	0,000199	0,015244	0,000877	0,107975	-0,083963	0,009077	9,397127
pln/czk	0,000053	0,005855	0,000000	0,056852	-0,040715	0,221996	11,419933
czk/eur	0,000005	0,004888	-0,000109	0,044461	-0,034295	0,503958	12,844324
pln/eur	0,000061	0,006990	-0,000205	0,047750	-0,051007	0,265603	11,081772
usd/eur	-0,000046	0,006747	0,000180	0,038572	-0,034540	-0,011598	5,808025

(Computed in Matlab)

Most of the mean returns are negative and very close to zero. The standard deviations of returns and summary statistics of volatilities indicate that the stock and bond markets in the researched countries are more volatile than their exchange rates.

The distribution of returns does not appear to be normal. All time series of returns have skewness which is usually different from zero, and the kurtosis that exceeds three in all cases. Excess kurtosis (leptokurtosis) is a typical feature of returns of financial markets, and its presence is supported also by our results.

In Table 3.2, the results of the augmented Dickey-Fuller test (ADF test) for

Table 3.2: **Results of ADF tests**

	levels			returns					
czbond	-1.0739	0.3237	-2.757	-45.9817	***	-46.0833	***	-46.3103	***
czstock	-1.1952	-1.7899	-2.0069	-33.0148	***	-33.0202	***	-33.0167	***
pobond	-0.9214	0.0280	-2.0497	-41.5229	***	-41.5489	***	-41.6583	***
postock	-0.8872	-1.9761	-1.8342	-43.2057	***	-43.1983	***	-43.1964	***
aubond	-1.3600	-0.0607	-3.3264	-40.1361	***	-40.2252	***	-40.3352	***
austock	-1.5182	-1.8310	-1.6996	-41.2164	***	-41.2232	***	-41.2237	***
gebond	-1.5856	-0.3751	-3.1462	-44.5413	***	-44.6193	***	-44.6766	***
gestock	0.5779	-0.7884	-1.7483	-43.7672	***	-43.7632	***	-43.7683	***
pln/czk	0.2130	-2.0087	-1.8939	-43.7668	***	-43.7590	***	-43.7614	***
czk/eur	-0.0532	-2.1161	-2.0916	-45.4925	***	-45.4807	***	-45.4947	***
pln/eur	0.2222	-2.1551	-2.6498	-45.4078	***	-45.3995	***	-45.3879	***
usd/eur	-0.4064	-2.1806	-2.7787	-45.3822	***	-45.3721	***	-45.3778	***

	volatility					
czbond	-2.3142	**	-4.4809	***	-6.7508	***
czstock	-2.9314	***	-5.9236	***	-6.3760	***
pobond	-2.7716	***	-6.0163	***	-7.2370	***
postock	-2.6074	***	-5.8341	***	-7.1150	***
aubond	-1.3084		-4.3773	***	-5.9595	***
austock	-2.4642	**	-4.9840	***	-5.3669	***
gebond	-1.3239		-4.0138	***	-5.1951	***
gestock	-2.6302	***	-5.5164	***	-5.7503	***
pln/czk	-1.7718	*	-4.2698	***	-4.4920	***
czk/eur	-2.0073	**	-3.9887	***	-4.4721	***
pln/eur	-2.1184	**	-4.2531	***	-4.4146	***
usd/eur	-1.6008		-4.2822	***	-4.5467	***

Notes: ***, **, and * denote levels of significance (1%, 5%, and 10%, respectively). The columns contain the test statistics for following specifications: no constant, constant, constant and trend (Estimated in Matlab)

a unit root in a univariate time series are presented. The construction of the ADF test is described e.g. in Cheung & Lai (1995). The number of lags is determined according to the Schwarz information criterion (SIC) with the maximum number of 10. The tests are performed for all three basic specifications (no constant, constant, constant and trend).[3] The results indicate that the time series of returns are all stationary because we reject the null hypothesis of a unit root at 1% level of significance in all cases. The same conclusion probably applies to the time series of volatilities despite the non-rejection or rejection only at higher level of significance for some time series in the case of the specification without constant.

The presence of heteroskedasticity in data is very important because we will, as shown in Section 4.3, use it for identification of the structural VAR model. Hence, we perform tests that should verify whether the heteroskedasticity is

[3]The test statistics in Table 3.2 are listed exactly in this order.

Table 3.3: **Tests of heteroskedasticity**

	$\mathbf{Q_{LB}}$		**ARCH-LM**		**GARCH**		**ARCH**	
czbond	175.1254	***	123.5748	***	0.9515	***	0.0485	***
czstock	1128.5631	***	482.6956	***	0.8306	***	0.1453	***
pobond	405.6578	***	266.0492	***	0.8627	***	0.1325	***
postock	349.3003	***	250.6413	***	0.9246	***	0.0709	***
aubond	220.8375	***	138.4991	***	0.926	***	0.0729	***
austock	950.4455	***	436.1065	***	0.901	***	0.084	***
gebond	320.1321	***	193.3689	***	0.9345	***	0.0655	***
gestock	493.377	***	287.8707	***	0.8867	***	0.0972	***
pln/czk	256.4636	***	211.5408	***	0.8921	***	0.0751	***
czk/eur	349.1483	***	198.6841	***	0.9136	***	0.0864	***
pln/eur	701.962	***	357.149	***	0.906	***	0.0926	***
usd/eur	371.3114	***	230.7373	***	0.9527	***	0.043	***

Notes: ***, **, and * denote levels of significance (1%, 5%, and 10%, respectively.
(Estimated in Matlab)

present. The first test is the Ljung-Box test with 5 lags, described in Ljung & Box (1978), applied to the squared returns. The null hypothesis assumes the squared returns are independent. As we see in Table 3.3 (the statistic Q_{LB}), we reject the null hypothesis in all cases. The same conclusion is attained by the ARCH-LM test with 5 lags, proposed by Engle (1982). The null hypothesis that the autoregressive conditional heteroskedasticity is not present is again rejected for all time series.

At the same time, parameters of an univariate GARCH(1,1) in form (3.3) are estimated

$$E(x_t)^2 = \alpha_0 + \alpha_1 x_{t-1}^2 + \beta_1 E(x_{t-1})^2 \tag{3.3}$$

where $E(x_t)^2$ is the conditional variance and x_t^2 are the squared returns. The parameters α_1 and β_1 are presented in Table 3.3 as ARCH and GARCH, respectively. At least one parameter is significant at 1% level for all time series. It is a good sign, and therefore we may deduce that there is some kind of hetereskedasticity in the data and that we will be able to take advantage of it during the identification of the structural VAR model.

A primary notion about interconnections between markets may be obtained through correlation analysis. Correlation coefficients between returns of two particular financial markets are presented in Table 3.4. As the correlation coefficients suggest, the strongest connection is between national stock markets. In particular, the highest correlation coefficient 0.8104 is between the German and Austrian stock market, followed by the correlation coefficients between the Czech and Austrian (0.7485), Czech and Polish (0.6744), Polish and German (0.6743), Polish and Austrian (0.6543), and German and Czech (0.6543) stock markets.

At the same time, the high correlation between the German and Austrian bond markets (0.708) should be pointed out.

It is obvious from Table 3.5, based on the fact that almost a half of the correlation coefficient is higher than 0.5, the volatilities of financial markets are far more interconnected than the returns. It is also important to mention that all correlations are positive.[4] It implies there is a quite strong positive relationship and that the high or low volatilities at any given time are usually a common feature of all markets. The highest correlation coefficient 0.8516 is between the exchange rates PLN/CZK and PLN/EUR. Similarly to the returns, there are also high correlation coefficients between stock markets, especially between the Austrian and Czech (0.762), and German and Austrian (0.7916) stock markets.

The results of the correlation analysis indicate that there is a certain linkage among financial markets and their volatilities. The correlation analysis performed in this chapter characterizes these relations only shallowly and by one number for the whole period. The following chapters will be dedicated to a deeper investigation of dynamic relationships among the financial markets in Central Europe.

[4] The exceptions are quiet low and probably not significant.

Table 3.4: **Correlations of returns**

	czbond	czstock	pobond	postock	aubond	austock	gebond	gestock	pln/czk	czk/eur	pln/eur	usd/eur
czbond	1	-0,0169	0,2519	-0,0355	0,2456	-0,0017	0,2194	0,0276	0,0576	-0,0317	0,0262	0,0336
czstock	-0,0169	1	-0,1929	**0,6744**	0,1601	**0,7485**	0,2812	**0,6338**	-0,2796	-0,1128	-0,3597	0,2452
pobond	0,2519	-0,1929	1	-0,2427	0,2287	-0,2185	0,1173	-0,2117	0,2565	0,1498	0,1554	-0,1006
postock	-0,0355	**0,6744**	-0,2427	1	0,2067	**0,6543**	0,3148	**0,6743**	-0,2806	-0,2278	-0,2565	0,2778
aubond	0,2456	0,1601	0,2287	0,2067	1	0,2169	**0,7080**	0,2911	-0,0512	-0,0443	-0,0166	0,1188
austock	-0,0017	**0,7485**	-0,2185	**0,6543**	0,2169	1	0,3772	**0,8104**	-0,2862	-0,2621	-0,2791	0,2974
gebond	0,2194	0,2812	0,1173	0,3148	**0,7080**	0,3772	1	0,4344	-0,1200	-0,1594	-0,0828	0,2212
gestock	0,0276	**0,6338**	-0,2117	**0,6743**	0,2911	**0,8104**	0,4344	1	-0,2879	-0,2897	-0,2164	0,3136
pln/czk	0,0576	-0,2796	0,2565	-0,2806	-0,0512	-0,2862	-0,1200	-0,2879	1	-0,1863	0,2217	-0,1483
czk/eur	-0,0317	-0,1128	0,1498	-0,2278	-0,0443	-0,2621	-0,1594	-0,2897	-0,1863	1	0,0185	-0,2394
pln/eur	0,0262	-0,3597	0,1554	-0,2565	-0,0166	-0,2791	-0,0828	-0,2164	0,2217	0,0185	1	-0,0872
usd/eur	0,0336	0,2452	-0,1006	0,2778	0,1188	0,2974	0,2212	0,3136	-0,1483	-0,2394	-0,0872	1

Table 3.5: **Correlations of volatilities**

	czbond	czstock	pobond	postock	aubond	austock	gebond	gestock	pln/czk	czk/eur	pln/eur	usd/eur
czbond	1	0,0330	0,4403	-0,0390	0,4829	-0,0035	0,4191	0,0307	-0,0283	-0,0598	-0,0451	-0,0726
czstock	0,0330	1	0,1779	**0,6841**	0,1321	**0,7619**	0,1114	**0,6433**	0,5416	0,5018	0,5307	0,4399
pobond	0,4403	0,1779	1	0,1241	0,3954	0,1288	0,2983	0,1254	0,1151	0,0427	0,1218	0,0201
postock	-0,0390	**0,6841**	0,1241	1	0,1042	**0,6662**	0,0977	**0,7063**	0,5427	0,5156	0,5475	0,4323
aubond	0,4829	0,1321	0,3954	0,1042	1	0,1471	**0,7585**	0,2560	0,1210	0,0744	0,1268	0,1332
austock	-0,0035	**0,7619**	0,1288	**0,6662**	0,1471	1	0,1926	**0,7916**	0,5678	0,5433	0,5759	0,5172
gebond	0,4191	0,1114	0,2983	0,0977	**0,7585**	0,1926	1	0,3046	0,1360	0,0896	0,1539	0,2230
gestock	0,0307	**0,6433**	0,1254	**0,7063**	0,2560	**0,7916**	0,3046	1	0,5641	0,5428	0,5728	0,5295
pln/czk	-0,0283	0,5416	0,1151	0,5427	0,1210	0,5678	0,1360	0,5641	1	**0,7570**	**0,8516**	0,5836
czk/eur	-0,0598	0,5018	0,0427	0,5156	0,0744	0,5433	0,0896	0,5428	**0,7570**	1	**0,6975**	0,5732
pln/eur	-0,0451	0,5307	0,1218	0,5475	0,1268	0,5759	0,1539	0,5728	**0,8516**	**0,6975**	1	**0,6034**
usd/eur	-0,0726	0,4399	0,0201	0,4323	0,1332	0,5172	0,2230	0,5295	0,5836	0,5732	**0,6034**	1

Notes: Bold values denote correlation coefficients that are higher than 0.6.
(Computed in Matlab)

Chapter 4

Methods

This chapter introduces a theoretical framework of methods that are suitable for estimating and measuring the return and volatility spillovers.

In this thesis, we apply two approaches to the spillover indices. The first approach, proposed by Diebold & Yilmaz (2012), is based on the generalized Vector Autoregressive model (VAR); the second approach, applied e.g. in Wang, Liu, & Lu (2012), relies on heteroskedasticity for the purpose of identification of the structural VAR model following the methodology known as the identification through heteroskedasticity, proposed in Rigobon (2003).

Most of the relevant methods are discussed in this chapter. First of all, a brief introduction to VAR models is offered in Section 4.1. In Section 4.2, various approaches to spillover indices are discussed, and Diebold & Yilmaz (2012)'s and Wang, Liu, & Lu (2012)'s approaches are presented in more details. Finally, the last section of this chapter describes methods that are applied within the Wang, Liu, & Lu (2012)'s approach. Section 4.3 summarizes the methodology known as the identification through heteroskedasticity which utilizes the heteroskedastic behaviour of structural shocks in order to identify the structural VAR model. Estimates of this model may be then used for calculation of spillover indices.

4.1 Vector Autoregressive Model

The aim of this section is to briefly introduce the vector autoregressive model that is essential for all remaining methods.

As a starting point, we consider a p^{th}-order Vector Autoregressive model (VAR) defined as

$$\mathbf{y_t} = \mathbf{c} + \sum_{\mathbf{i=1}}^{\mathbf{p}} \mathbf{A_i y_{t-i}} + \mathbf{u_t} \tag{4.1}$$

where $\mathbf{c}$ is a $m \times 1$ vector of intercept terms, $\mathbf{y_t} = (y_{1t}, y_{2t}, \ldots, y_{mt})^T$ is an $m \times 1$ vector of m endogenous variables, $\{\mathbf{A_i}, i = 1, 2, \ldots, p\}$ are $m \times m$ coefficient matrices and $\mathbf{u_t}$ is a $m \times 1$ vector of error terms that satisfies following properties: $E(u_t) = 0$, $E(u_t u_t^T) = \Sigma_u$ and $E(u_t u_s^T) = 0$ for $s \neq t$ (Lütkepohl 2005).

Additionally, we assume the so called stability condition is satisfied. We say that y_t is a stable $VAR(p)$ process if

$$det\left(I_m - \sum_{i=1}^{p} A_i z^i\right) \neq 0 \qquad \text{for } |z| \leq 1, \tag{4.2}$$

where I_m denotes a $m-$dimensional identity matrix.

Under the assumption of stability, y_t would be covariance-stationary, and the model in (4.1) can be rewritten as the moving average representation,

$$y_t = \mu + \sum_{i=0}^{\infty} \Phi_i u_{t-i}, \tag{4.3}$$

where $\mu = (I_m - \sum_{i=1}^{p} A_i z^i)^{-1} c$, and Φ_i can be obtained recursively from $\Phi_i = \sum_{s=1}^{i} \Phi_{i-s} A_s$, with $\Phi_0 = I_m$, $\Phi_i = 0$ for $i < 0$ and $A_s = 0$ for $s > p$ (Lütkepohl 2005; Pesaran & Shin 1998).

The coefficients in the moving average representation in (4.3) satisfactorily describes the dynamics of the system and will be later utilized during the construction of spillover indices.

The model in (4.1) may be seen as a reduced form of the initial Structural Vector Autoregressive model (SVAR) given by

$$\mathbf{B y_t} = \mathbf{v} + \sum_{\mathbf{i=1}}^{\mathbf{p}} \mathbf{B_i y_{t-i}} + \epsilon_\mathbf{t}, \tag{4.4}$$

where the matrix $\mathbf{B}$ is a $m \times m$ matrix of coefficients and its main diagonal coefficients are scaled to 1. B_i for $i \in \{1, \ldots, p\}$ are $m \times m$ matrices of structural coefficients, $\mathbf{v}$ is a $m-$dimensional vector of structural intercepts, and $\epsilon_\mathbf{t}$ is a $m-$dimensional vector of structural errors.

The reduced form in (4.1) was gained by premultiplying the structural VAR model with the inverse of B, and denoting $\mathbf{c} = \mathbf{B^{-1} v}$, $\mathbf{A_i} = \mathbf{B^{-1} B_i}$, and $\mathbf{u_t} = \mathbf{B^{-1}} \epsilon_\mathbf{t}$. The parameters of the reduced model in (4.1), in contrast to the structural model, may be estimated by OLS.

The coefficients of the structural VAR model are not identified without any restrictions. One of the most commonly used methods is the Cholesky decomposition that achieves the identification by restricting the matrix B to be a lower diagonal matrix. Unfortunately, the results obtained by using Cholesky decomposition are dependent on ordering of variables. Consequently, the estimated structural coefficients as well as the orthogonalized impulse responses, or the forecast error variance decompositions, applied within the Diebold & Yilmaz (2009)'s approach, are not unique.

The dependence on ordering of variables during the application of Cholesky decomposition together with the absence of any theoretical support for such a decomposition are the main reasons why new solutions have been searched. In the following sections, we will introduce two alternative approaches to the forecast error variance decomposition and to the identification of structural coefficients that will help us to investigate spillovers across financial markets.

4.2 Various Approaches to Spillover Indices

Diebold & Yilmaz (2009) introduced a simple measure of independence of asset returns and volatilities that is based on the forecast error variance decomposition from the vector autoregressive models (VARs). Unfortunately, their approach relies on the Cholesky-factor identification of the VARs, and thus the results are usually dependent on ordering of variables. As a consequence thereof, several improvements have arisen.

Diebold & Yilmaz (2012) proposed a method of measuring total and directional spillovers in a generalized VAR framework in which the results are invariant to ordering of variables. This method is described in more details in Subsection 4.2.1. Another way how to evade the problem of the dependence on ordering of variables was developed by Klößner & Wagner (2012). They developed new algorithms which enable fast calculation of the minima and maxima of the spillover indices over all renumerations.

An extension of the original spillover index was designed by Baruník, Kočenda, & Vácha (2013). The authors take advantage of the high-frequency data and the concept of realized semivariance. These two advances together with the application of the Klößner & Wagner (2012)'s algorithm enable to compute assymetric volatility spillover indices considering all possible orderings.

Finally, Wang, Liu, & Lu (2012) applied another approach that determines unique total and directional spillover indices. Their approach relies on heteroskedasticity for the purpose of identifying the structural VAR model. Furthermore, the dynamic spillover indices obtained within this approach can be obtained through the conditional covariance matrix that is driven by a multivariate GARCH (MGARCH), and it is not necessary to use the rolling window method. More details about this method are provided in Subsection 4.2.2.

4.2.1 Spillover Indices in Generalized VAR Framework

The approach introduced by Diebold & Yilmaz (2012) enables to estimate total and directional spillovers that are, in contrast to the original concept of Diebold & Yilmaz (2009), unique. The procedure is based on the generalized VAR framework of Koop, Pesaran, & Potter (1996) and Pesaran & Shin (1998) and allows to obtain the forecast error variance decomposition without orthogonalization of shocks.

In order to provide an outline of the ideas behind the spillover indices, we follow the whole derivation of the generalised forecast error variance decomposition as described in Smith & Galesi (2011).

As a starting point, we consider the moving average representation in (4.3). Then the forecast error of predicting y_{t+n} conditional on the informaton at time $t-1$ and the total forecast error covariance matrix is given by (4.5) and (4.6), respectively.

$$\xi_t(n) = \sum_{s=0}^{n} \Phi_s u_{t+n-s} \tag{4.5}$$

$$\Omega_n = \sum_{s=0}^{n} \Phi_s \Sigma_u \Phi_s' \tag{4.6}$$

We want to know a part of the forecast error variance that is explained by the information about j^{th} variable, thus, we need to find the covariance matrix of the forecast error conditional on the information at time $t-1$ and the contemporaneous and expected future shocks to the j^{th} equation $u_{j,t}, \ldots, u_{j,t+n}$. Assuming normality of the error terms, $u_t \sim N(0, \Sigma_u)$, we may express the expectation about the contemporaneous and expected future shocks conditional on the shocks to the j^{th} equation as $E(u_{t+n-s}|u_{j,t+n-s}) = (\sigma_{jj}^{-1}\Sigma_u e_j)u_{j,t+n-s}$ where e_j is a selection vector which has one as the j^{th} element and zeros otherwise. Consequently, we may easily derive the forecast error ξ_t^j and its covariance matrix Ω_n^j. These are given by

$$\xi_t^j(n) = \sum_{s=0}^{n} \Phi_s[u_{t+n-s} - (\sigma_{jj}^{-1}\Sigma_u e_j)u_{j,t+n-s}] \tag{4.7}$$

$$\Omega_n^j = \sum_{s=0}^{n} \Phi_s \Sigma_u \Phi_s' - \sigma_{jj}^{-1} \sum_{s=0}^{n} \Phi_s \Sigma_u e_j e_j' \Sigma_u \Phi_s'. \tag{4.8}$$

Using (4.6) and (4.8), we can determine the decline in the n-step ahead forecast error variance of y_t as a result of conditioning on the shocks to the j^{th} equation, that is $\Delta_{jn} = \Omega_n - \Omega_n^j$. The elements on the main diagonal of the matrix Δ_{jn} embody the change in the forecast error variance of y_t with respect to a particular variable. The change with respect to the l^{th} variable is expressed by

$$\Delta_{ljn} = e_l' \Delta_{jn} e_l = \sigma_{jj}^{-1} \sum_{s=0}^{n} (e_l' \Phi_s \Sigma_u e_j)^2 \tag{4.9}$$

Finally, the portion of the decline in the forecast error variance of the l^{th} variable caused by conditioning on the expected future shocks to the j^{th} variable is

$$\theta_{lj}(n) = \frac{\sigma_{jj}^{-1} \sum_{s=0}^{n} (e_l' \Phi_s \Sigma_u e_j)^2}{\sum_{s=0}^{n} e_l' \Phi_s \Sigma_u \Phi_s' e_l} \tag{4.10}$$

Contrary to the traditional forecast error decomposition, the shocks are not orthogonalized. Consequently, the sum of the contribution of all variables to the forecast error variance of a particular variable is not equal to 1, mathematically $\sum_{j=1}^{m} \theta_{lj}(n) \neq 1$ (Diebold & Yilmaz 2012).

Diebold & Yilmaz (2012) suggest to normalize the variance decomposition matrix $\Theta = \{\theta_{lj}\}_{\substack{l=1,\ldots,m \\ j=1,\ldots,m}}$ by the row sum as

$$\tilde{\theta}_{ij}(n) = \frac{\theta_{lj}(n)}{\sum_{j=1}^{m} \theta_{lj}(n)}. \tag{4.11}$$

The newly created matrix $\tilde{\Theta} = \{\tilde{\theta}_{lj}\}_{\substack{l=1,\ldots,m \\ j=1,\ldots,m}}$ may be applied for the construction of total and directional spillover indices. Diebold & Yilmaz (2012) propose following indices:

Total spillover index The total spillover index measures the contribution of spillovers of shocks across all variables to the total forecast error variance.

$$TS(n) = \frac{\sum_{\substack{l,j=1 \\ l \neq j}}^{m} \tilde{\theta}_{lj}(n)}{m} \cdot 100 \tag{4.12}$$

Directional spillover indices The generalized VAR framework, contrary to the Diebold & Yilmaz (2009)'s approach, enables to derive the directional spillovers. Two basic variants of the gross directional spillovers measure:

1. spillovers received by market l from all other markets j by

$$DS_l^{all}(n) = \frac{\sum_{\substack{j=1 \\ l \neq j}}^{m} \tilde{\theta}_{lj}(n)}{m} \cdot 100; \tag{4.13}$$

2. spillovers transmitted by market j to all other markets l by

$$DS_{all}^{j}(n) = \frac{\sum_{\substack{l=1 \\ l \neq j}}^{m} \tilde{\theta}_{lj}(n)}{m} \cdot 100 \tag{4.14}$$

Using (4.13) and (4.14), the net directional spillovers from market l to all other markets is possible to measure by $NDS_{all}^{l}(n) = DS_{all}^{l}(n) - DS_l^{all}(n)$.

Net pairwise spillover indices These indices are of our primary interest in this thesis. The net pairwise spillovers can be quantified by (4.15) and provide the information about the net transmission of shocks from market l to market j.

$$NPS_{lj}(n) = \left(\frac{\tilde{\theta}_{jl}(n) - \tilde{\theta}_{lj}(n)}{m} \right) \cdot 100. \tag{4.15}$$

4.2.2 Spillover Indices in Structural VAR Model

This section describes the method used by Wang, Liu, & Lu (2012). They follow the methodology known as the identification through heteroskedasticity, proposed in Wright (1928), in order to identify the structural VAR model. As Rigobon (2003) showed "if structural shocks have a known correlation (zero in this case) and if parameters are stable, then the heteroskedasticity in the structural shocks" allows us to solve the problem of identification.

Once the structural coefficients in matrix $\mathbf{B}$ from Equation 4.4 are identified, the Equation 4.1 may be rewritten into a slightly different moving average representation. The coefficients C_i for $i \in \{0, 1, 2, \cdots\}$ of this moving average representation are computed assuming $c = 0$ as a solution of the following equation

$$y_t = \left(I_m - \sum_{i=1}^{p} A_i L^i\right)^{-1} \overbrace{u_t}^{=B^{-1}\epsilon_t} = \sum_{i=0}^{\infty} C_i \epsilon_{t-i} \tag{4.16}$$

where L denotes the lag operator. As we know, $u_t = B^{-1}\epsilon_t$ and therefore we can derive that $C_0 = B^{-1}$. C_i for $i \in \{1, 2, 3, \cdots\}$ are obtained recursively.

For simplicity, only one-step-ahead forecast is considered at this moment. Then the forecast error and the forecast error variance for the structural VAR model are given by

$$\xi_t^S(1) = C_0 \epsilon_t \tag{4.17}$$

$$\Omega_1^S = E(C_0 \epsilon_t \epsilon_t' C_0') = C_0 H C_O' = B^{-1}(B^{-1})' \tag{4.18}$$

since we assume that $H = E(\epsilon\epsilon') = I_m$. Thanks to the given properties of error terms in the reduced VAR model, we may similarly derive forecast error and the forecast error variance even for more-step-ahead forecasts.

Analogically to Subsection 4.2.1, we construct total and directional spillover indices for the structural VAR model as suggested by Wang, Liu, & Lu (2012). The total spillover index captures a fraction of the forecast error variance that comes from shocks to other variables, mathematically expressed as

$$TS^S(1) = \frac{\sum_{\substack{l,j=1 \\ l \neq j}}^{m} c_{lj}^2}{\sum_{l,j=1}^{m} c_{lj}^2} \cdot 100 \tag{4.19}$$

where c_{lj} is an element from the l^{th} row and j^{th} column of the matrix C_0.

In the same way, the directional and pairwise spillovers are computed. It is important to point out that original Wang, Liu, & Lu (2012)'s indices represent a slightly different fraction in comparison to the previous case. In order to ensure better comparability of the applied methods, we moderately modified the directional spillovers. The directional spillover indices for the structural VAR model which measure spillovers received by market l from all other markets and spillovers transmitted by market j to all other markets are given by Equation 4.20 and Equation 4.21, respectively.

$$SDS_l^{all}(1) = \frac{\sum_{\substack{j=1 \\ l \neq j}}^{m} c_{lj}^2}{\sum_{l,j=1}^{m} c_{lj}^2} \cdot 100 \tag{4.20}$$

$$SDS_{all}^{j}(1) = \frac{\sum_{\substack{l=1 \\ l \neq j}}^{m} c_{lj}^2}{\sum_{l,j=1}^{m} c_{lj}^2} \cdot 100 \tag{4.21}$$

The gross pairwise spillover index showing a portion of the forecast error variance received by a market j coming from another particular market l is given in Equation 4.22.

$$SPS_j^l(1) = \frac{c_{jl}^2}{\sum_{l,j=1}^{m} c_{lj}^2} \cdot 100 \tag{4.22}$$

Probably the main advantage of the approach proposed by Wang, Liu, & Lu (2012) is the ability to obtain dynamic spillover indices without using rolling samples. They exploit the conditional variance described by the MGARCH and should be able to achieve more precise values of the dynamic spillover indices than by using rolling samples in the case of Diebold & Yilmaz (2012)'s approach. This statement is supported by the fact that "the values obtained from the rolling samples are still based on the average level of the rolling windows" (Wang *et al.* 2012).

In order to derive the dynamic spillover indices, we first adjust the Equation 4.18 and, instead of the unconditional covariance matrix H, we plug in the conditional covariance matrix H_t that is based on the estimation of the MGARCH model. The covariance matrix of the structural disturbances is defined as

$$H_t = \begin{pmatrix} h_{1,t} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & h_{m,t} \end{pmatrix}. \tag{4.23}$$

Thus, the 1-step-ahead forecast error variance given by (4.18) can be rewritten as

$$\Omega_1^{DS} = E(C_0 \epsilon_t \epsilon_t' C_0') = C_0 H_t C_O' = B^{-1} H_t (B^{-1})'. \tag{4.24}$$

Now, the matrix Ω_1^{DS} can be utilized for determination of the dynamic spillover indices exactly in the same way as above. The only difference is that we use $c_{ij}^2 h_{j,t}$ instead of c_{ij}^2. For instance, the dynamic total dynamic spillover index can be then formulated as

$$DTS^S(1) = \frac{\sum_{\substack{l,j=1 \\ l \neq j}}^{m} c_{lj}^2 h_{j,t}}{\sum_{l,j=1}^{m} c_{lj}^2 h_{j,t}} \cdot 100 \tag{4.25}$$

The expressions (4.20), (4.21) and (4.22) can be adjusted analogically. At the same time, spillover indices based on more-step-ahead forecast error variance may be derived if we take into account the time-varying covariance matrix.

Still, the identification of the matrix B and the estimation of the conditional variance is not achieved. The way how to accomplish these two tasks will be described in the last section of this chapter.

4.3 Identification Through Heteroskedasticity

The problem of identification of contemporaneous coefficients in the structural VAR model is usually solved by implementing additional restrictions or by considering some modelling assumptions. One way how to overcome this problem has been introduced during recent years for example in Rigobon (2003), Rigobon & Sack (2003), and Sentana & Fiorentini (2001).

As we have already described in Section 4.1, the relationship between the structural innovations $\epsilon_\mathbf{t}$ and the innovations from the reduced VAR model $\mathbf{u_t}$ is given by

$$\epsilon_\mathbf{t} = \mathbf{B}\mathbf{u_t} \tag{4.26}$$

where the matrix $\mathbf{B}$ represents the contemporaneous relationships among variables.

Following the methodology from Wang, Liu, & Lu (2012), we assume that the structural innovations exhibit conditional heteroskedasticity in the manner of GARCH models. The behaviour of the structural innovations may be described by

$$\epsilon_\mathbf{i,t} = \sqrt{\mathbf{h_{i,t}}}\xi_\mathbf{i,t} \qquad \forall i \in (1, ..., n) \tag{4.27}$$

where $\mathbf{h_{i,t}}$ represents the conditional variance of the structural shock of i-th series at time t and ξ is a normally distributed multivariate random variable with zero mean and unitary variance, i.e. $\xi \sim N(0, 1)$.

The evolution of the conditional variances depends on their lagged values and the magnitudes of the most recent structural shocks, mathematically expressed in Equation 4.28 where φ is a k-dimensional vector of constant components of the variances and Γ and Λ are $(k \times k)$-diagonal matrices of coefficients that govern the dynamics of the variances. Γ contains so called GARCH parameters that determine the dependence of the conditional variances on their own lagged values. In Λ, ARCH parameters are contained that represent the reaction of the conditional variance to the lagged structural shocks.

$$\mathbf{h_t} = \varphi + \mathbf{\Gamma h_{t-1}} + \mathbf{\Lambda}\epsilon^\mathbf{2}_\mathbf{t-1} \tag{4.28}$$

Another equation, given by Equation 4.29, serves to standardize the unconditional variance of the structural shocks to 1. This assumption enables to identify the volatility of all variables.

$$\varphi = \imath - \mathbf{Diag}(\mathbf{\Gamma}) - \mathbf{Diag}(\mathbf{\Lambda}) \tag{4.29}$$

In Equation 4.29, $\imath$ is a k-dimensional vector of ones and the $Diag(.)$ operator extracts the main diagonal from a given matrix.

Applying the relationships in (4.26) - (4.29), we may perform the maximum likelihood estimation of the parameters by using the log-likelihood function given by

$$\mathbf{L}(\mathbf{u}, \mathbf{\Sigma}) = \sum_{\mathbf{t=1}}^{\mathbf{T}} -\frac{\mathbf{1}}{\mathbf{2}}\Bigg(\ln\left(\mathbf{2}\pi\right) + \ln\left(|\mathbf{\Sigma_t}|\right) + \mathbf{u_t'}\mathbf{\Sigma_t^{-1}}\mathbf{u_t}\Bigg) \tag{4.30}$$

where $\mathbf{\Sigma_t}$ is the matrix of conditional variances of the reduced shocks at time t.

Estimation of the parameters is performed in MATLAB by using scripts that are enclosed to this thesis. As Normandin & Phaneuf (2004) propose, a two-step procedure is applied. First, a reduced VAR(p) from (4.1) is fitted, and then, using the estimated residuals from the reduced VAR model, the MGARCH and structural parameters are estimated by maximizing the log-likelihood function in (4.30). A function *fmincon* was applied for the optimization of the log-likelihood function.

Finally, we have described all necessary methods which will be used for the investigation of the spillovers among stock, bond and foreign exchange markets in Central Europe. Now, we may step towards the presentation of the results obtained by applying the methods described in this chapter.

Chapter 5

Results and Discussion

Finally, we may approach to the chapter that will present the results obtained by the methods introduced in Chapter 4. As already mentioned, the goal of this thesis is to complexly and robustly describe interactions among stock, bond and foreign exchange markets in Central Europe. This task should be accomplished in this chapter.

We have decided to examine four countries: Austria, the Czech Republic, Germany and Poland. Unfortunately, the methods do not allow us to involve all variables described in Chapter 3 into the models at once because the estimation would be extremely demanding, and probably not feasible. In order to avoid this problem, we have decided to split the variables into six groups in such a way that every group contains all markets from two particular countries. Therefore, we have in each group two stock markets, two bond markets, and an exchange rate that should best represent the foreign exchange market between the two countries. For example, if we have a group for the Czech Republic and Poland, then the time series of returns (or volatilities) of the Czech PX index, the Polish WIG30 index, the Czech and Polish 10-year bond yields and the PLN/CZK exchange rate are involved. The same logic is applied for all other possible combinations of the countries. The only exception is the combination of Austria and Germany where the exchange rate for the U.S. dollar against Euro is used.

Consequently, we have six groups each having 5 variables for returns, as well as for volatilities. If we apply both methods of spillover indices (together with the intermediate results), we have a lot of results that will be systematically summarized in the following sections.

Firstly, the spillover indices obtained from the generalized VAR model with 5 lags, introduced in Diebold & Yilmaz (2012), will be discussed in Section 5.1. The conclusions will be presented simultaneously for returns and volatilities. In the same way, observations from the spillover indices based on SVAR model with 5 lags for returns will be delivered in Section 5.2.[1]

At the same time, the estimation of the MGARCH model and the contemporaneous coefficients from the SVAR model will be discussed in Section 5.3. In the end, the results will be summarized in Section 5.4 where the conclusions from the individual models will be confronted, the general results should be stated and given in the context of economic events.

5.1 Spillover Indexes from Generalized VAR

Here, the spillovers described by the spillover indices from the generalized VAR framework, as designed by Diebold & Yilmaz (2012), will be discussed. The indices are based on the VAR model of order 5 and the variance decompositions of 10-working-day-ahead forecast errors.[2]

At first, we will concentrate on the full-sample estimation of the spillover indices. It should help us to obtain a preliminary notion about the regularities that hold among the financial markets in Central Europe.

Table 5.1 contains the total and directional indices for returns. The columns represent the combinations of countries where AUS is an abbreviation for Austria, CZE for the Czech Republic, POL for Poland, and GER for Germany. *Total* spillover indices, obtained by Equation 4.12, appear in the first row of the table. They sum up by one number the portion of the forecast error variance that comes from spillovers. Then the directional spillover indices *ALLtoI*, *ItoALL*, and *NetItoALL*, describing the spillovers received by market i from all other markets, spillovers transmitted by market i to all other markets, and the difference between these two measures, are presented. The remaining rows of the Table 5.1 comprise of the gross pairwise spillover indices showing a contribution of a market to another particular market.

The notation has the following logic: *bond* is a representative of the bond yields, *stock* represents the stock market, and *ER* the exchange rate market. The number 1 in the notation labels the first country in a particular combination of

[1]The estimation of the structural VAR for volatilities is not feasible probably because of the non-normal distribution of the volatilities.

[2]Present literature agree on the fact that the spillover plots are not so sensitive to the choice of the order of the VAR model or the forecast horizon (Diebold & Yilmaz 2012; 2009). This can be confirmed also by our data sample. We do not present the indices for alternative choices of these two parameters, but it can be easily estimated by using the enclosed scripts.

the countries. Logically, the number 2 stands for the second country in the combination.[3]

5.1.1 Unconditional spillovers

Finally, we may approach to the interpretation of the results in Table 5.1.

A comprehensive view on the degree of spillovers is offered by the total spillover indices in the first row. The highest number is for the combination of Austria and Germany. The value indicates that more than 45 % of the forecast error variance come from spillovers among the markets. 35 % are transmitted among the financial market in Poland and Germany, and 31.6 % in Poland and Austria. The total spillover indices for the Czech Republic in combination with the other countries move between 27 % and 29.5 %.

The directional spillovers uncover main characteristics of the relations among the markets. First of all, quite strong directional spillovers from and to stock markets are noticed by the indices. From the *NetItoALL* row, the Austrian stock market is identified as the main contributor to the other markets. In the case of bond markets, the spillovers are fairly low with the exception of the German bond yields that appear to contribute to other market very strongly.

The directional spillovers also reveal the exchange rate markets are net receivers of spillovers from the other markets.

Looking at the pairwise spillovers from the bond markets, we may discover that, on average, almost 7.4 % of the forecast error variance is transmitted from the German bond market to the Austrian bond market, and 4.6 % in the opposite direction. Such a high connection is in the case of bonds exceptional and confirms the high interconnection among markets of these two countries. At the same time, the contribution of the German bond market to the German stock market should be mentioned - the spillovers are around 3 % of the forecast error variance. Similarly, the spillovers from the Czech bond yields to Polish bonds (1.6 %) are quite interesting.

As the directional spillovers have already revealed, the foreign exchange markets are mainly receivers of spillovers. Also the pairwise indices confirm this conclusion because all indices describing the contribution to the other markets are lower than 1 % and often very close to 0.

According to the pairwise indices, the stock markets usually strongly influence each other. Between 5 % and 6 % of the forecast error variance can be

[3] Exactly the same structure of notation is in the Table 5.2. At the same time, the same notation is valid for the remaining part of this chapter.

Table 5.1: **GVAR - Unconditional spillover indices for returns**

		czepol	czeger	czeaus	polger	polaus	geraus
Total		28,14	29,48	27,29	35,01	31,58	45,46
ALLtoI	**bond1**	1,99	2,06	1,99	3,23	4,12	7,81
	stock1	7,06	7,34	8,23	8,01	7,63	11,02
	bond2	4,18	3,82	2,80	3,60	2,79	9,13
	stock2	7,01	8,68	7,28	9,12	6,69	9,18
	ER	7,89	7,58	6,99	11,05	10,34	8,32
ItoALL	**bond1**	1,86	1,24	1,74	2,80	3,53	14,01
	stock1	10,04	7,75	8,75	11,76	11,28	11,40
	bond2	4,16	7,97	2,64	7,20	2,75	6,46
	stock2	10,54	11,94	13,71	12,34	12,97	12,56
	ER	1,54	0,57	0,46	0,91	1,04	1,04
NetItoALL	**bond1**	-0,13	-0,82	-0,26	-0,43	-0,59	6,19
	stock1	2,97	0,42	0,52	3,76	3,65	0,39
	bond2	-0,02	4,15	-0,16	3,60	-0,04	-2,67
	stock2	3,53	3,26	6,43	3,22	6,28	3,38
	ER	-6,35	-7,01	-6,53	-10,14	-9,30	-7,28
bond 1 to	**bond1**	18,01	17,94	18,01	16,77	15,88	12,19
	stock1	0,06	0,08	0,08	0,57	0,58	2,58
	bond2	1,58	0,66	1,13	0,15	0,77	7,39
	stock2	0,05	0,08	0,07	0,42	0,48	2,08
	ER	0,16	0,41	0,46	1,66	1,70	1,97
stock 1 to	**bond1**	0,31	0,33	0,32	1,36	1,28	1,59
	stock1	12,94	12,66	11,77	11,99	12,37	8,98
	bond2	0,90	1,00	0,57	1,24	0,84	0,94
	stock2	5,92	5,03	6,32	5,31	5,18	6,15
	ER	2,91	1,39	1,55	3,86	3,99	2,74
bond 2 to	**bond1**	1,35	1,44	1,43	0,64	1,26	4,56
	stock1	0,48	1,71	0,42	1,81	0,59	0,87
	bond2	15,82	16,18	17,20	16,40	17,21	10,87
	stock2	0,59	3,26	0,61	3,16	0,66	0,56
	ER	1,74	1,57	0,19	1,59	0,24	0,46
stock 2 to	**bond1**	0,27	0,25	0,20	0,98	1,32	1,50
	stock1	5,98	5,41	7,61	5,27	6,09	7,17
	bond2	1,21	2,08	1,10	2,14	1,15	0,74
	stock2	12,99	11,32	12,72	10,88	13,31	10,82
	ER	3,07	4,20	4,80	3,94	4,41	3,15
ER to	**bond1**	0,06	0,04	0,05	0,25	0,26	0,17
	stock1	0,54	0,14	0,13	0,35	0,38	0,40
	bond2	0,49	0,08	0,01	0,07	0,04	0,06
	stock2	0,45	0,31	0,28	0,24	0,37	0,40
	ER	12,11	12,42	13,01	8,95	9,66	11,68

(Estimated in Matlab)

Notes: The columns represent the combinations of countries where AUS is an abbreviation for Austria, CZE for the Czech Republic, POL for Poland, and GER for Germany. Bond is a representative of the bond yields, stock represents the stock market, and ER the exchange rate market. The number 1 labels the first country in a particular combination of countries, the number 2 stands for the second country. *Total* - total spillover index, *ALLtoI*, *ItoALL* and *NetItoAll* - directional spillover indices. The remaining groups contain the gross pairwise spillover indices.

ascribed to the spillovers between stock markets. The Austrian stock market has the highest contribution to the Czech stock market (7.6 %) and to the German stock market (7.2 %). At the same time, the stock markets considerably influence the exchange rates. The spillover indices vary mostly between 3 %

and 4.8 %, but the Czech stock market is an exception. The PX index gives only 2.9 % to the CZK/PLN exchange rate and around 1.5 % to the CZK/EUR exchange rate.

As may be seen in Table 5.2, the unconditional spillover indices for volatility bear similar regularities as in the case of returns. Generally, we could say that the indices are mostly slightly lower than in the previous case, but the main pattern remains the same.

The most considerable spillovers are again within the group of Austrian and German financial markets where the total spillover index reaches 42.3 %. In the remaining groups, the level of volatility spillovers move between 25 and 28 %.

The directional spillovers confirm the Austrian stock market and German bond market as the leading contributors to the other markets, and the foreign exchange markets as the main receivers of volatility spillovers.

The conclusions obtained from the pairwise indices for volatility do not also differ from those for returns. The stock markets, especially the Austrian stock market, seem to substantially influence the other stock markets and the exchange rates (for instance, almost 7 % of the forecast error variance is transferred from the Austrian stock market to the Czech or German equity market). A stronger impact of the Czech bond market on the Polish and Austrian bonds is now revealed than in the previous case.

Even the unconditional spillovers describing "average" connections among the markets in Central Europe during the analysed period have helped us to discover several interesting findings. Now, we will concentrate on the conditional spillover indices that will enable us to explore the dynamics behind these relations.

5.1.2 Conditional spillover indices

In this part of the thesis, the interconnections among the markets will be analysed in the greatest details. While average spillover behaviour was described in the previous subsection, now we estimate the spillover indices by applying 300-day rolling samples that enable us to capture the continuous evolution of the nature of interconnections among the markets.

As shown in Subsection 5.1.1, the return and volatility spillovers do not considerably differ, therefore, we will join together the interpretation of the results in this chapter, and try to emphasize potential differences.

At first, we will look at the total spillover index. The development for all

Table 5.2: **GVAR - Unconditional spillover indices for volatility**

		czepol	czeger	czeaus	polger	polaus	geraus
Total		**26,48**	**24,93**	**27,61**	**28,20**	**25,43**	**42,30**
ALLtoI	**bond1**	1,65	1,73	2,36	2,54	3,59	6,80
	stock1	5,90	5,14	8,00	6,03	6,60	10,64
	bond2	4,62	3,09	3,76	2,48	2,61	8,65
	stock2	5,88	7,33	5,69	8,30	4,25	6,79
	ER	8,42	7,64	7,81	8,85	8,37	9,42
ItoALL	**bond1**	3,38	1,62	2,85	2,27	2,96	13,41
	stock1	9,41	7,45	7,74	8,81	6,52	8,97
	bond2	3,06	5,95	3,03	6,43	3,42	6,47
	stock2	9,09	8,58	12,94	9,00	10,73	11,47
	ER	1,54	1,33	1,05	1,68	1,80	1,98
NetItoALL	**bond1**	1,73	-0,10	0,49	-0,27	-0,63	6,60
	stock1	3,50	2,30	-0,26	2,78	-0,08	-1,67
	bond2	-1,56	2,86	-0,72	3,95	0,81	-2,18
	stock2	3,21	1,26	7,25	0,70	6,47	4,68
	ER	-6,89	-6,31	-6,76	-7,16	-6,57	-7,44
bond 1 to	**bond1**	18,35	18,27	17,64	17,46	16,41	13,20
	stock1	0,22	0,28	0,22	0,51	0,51	2,23
	bond2	2,88	1,14	2,43	0,45	1,02	7,12
	stock2	0,07	0,08	0,06	0,28	0,35	1,35
	ER	0,20	0,12	0,14	1,04	1,07	2,71
stock 1 to	**bond1**	0,14	0,21	0,18	0,65	0,64	1,05
	stock1	14,10	14,86	12,00	13,97	13,40	9,36
	bond2	0,86	0,31	0,27	0,39	0,42	0,80
	stock2	4,84	3,74	4,72	4,70	2,70	4,35
	ER	3,57	3,19	2,56	3,07	2,76	2,77
bond 2 to	**bond1**	1,41	1,25	1,91	1,27	1,92	4,68
	stock1	0,53	0,92	0,37	0,67	0,28	0,82
	bond2	15,38	16,91	16,24	17,52	17,39	11,35
	stock2	0,45	2,88	0,41	2,65	0,42	0,35
	ER	0,68	0,90	0,35	1,84	0,81	0,62
stock 2 to	**bond1**	0,08	0,26	0,26	0,44	0,84	0,72
	stock1	4,33	3,36	6,98	4,24	5,23	6,85
	bond2	0,70	1,53	0,95	1,42	0,93	0,57
	stock2	14,12	12,67	14,31	11,70	15,75	13,21
	ER	3,98	3,43	4,76	2,90	3,73	3,32
ER to	**bond1**	0,02	0,01	0,01	0,18	0,20	0,35
	stock1	0,82	0,59	0,43	0,61	0,59	0,74
	bond2	0,18	0,10	0,11	0,22	0,24	0,16
	stock2	0,52	0,63	0,50	0,68	0,78	0,74
	ER	11,58	12,36	12,19	11,15	11,63	10,58

(Estimated in Matlab)

Notes: The columns represent the combinations of countries where AUS is an abbreviation for Austria, CZE for the Czech Republic, POL for Poland, and GER for Germany. Bond is a representative of the bond yields, stock represents the stock market, and ER the exchange rate market. The number 1 labels the first country in a particular combination of countries, the number 2 stands for the second country. *Total* - total spillover index, *ALLtoI*, *ItoALL* and *NetItoAll* - directional spillover indices. The remaining groups contain the gross pairwise spillover indices.

combinations of returns, as well as volatilities is plotted in Figure 5.1. As may be seen, the indices vary over time. The return spillovers seem to be more stable than the volatility spillovers. This conclusion corresponds to the finding of Diebold & Yilmaz (2009). They claim that the return spillovers display "an gently increasing trend associated with growing financial market integration, whereas the volatility spillovers have no trend but clear burst associated with readily-identified crisis events" (Diebold & Yilmaz 2009).

The return spillover indices started by fluctuating around 40 % (in the case of Austria and Germany around 50 %), and then have been gradually declining. This pattern is considerably violated by two periods of higher values. The first period corresponds to the period following the collapse of Lehman Brothers in September 2008, the second one starts at the second half of the year 2011 that is probably connected with the debt crisis in Europe. There are also noticeable distinctions among countries. The highest reaction to the start of the financial crisis was chiefly in the Czech Republic and Poland. In the other countries, the reaction appears to be lower. The increase of the indices during the period following the end of the year 2011 was much more important. The increase was strong in all countries, but the pattern differs. While the increase in Poland was starting more slowly and the peak was not reached before the half of the year 2012, the highest values of indices in the other countries exceeding 50 % (in the case of Germany and Austria even 60 %) appeared already at the end of the year 2011, and then a gradual decrease followed.

The variation of the total volatility spillover indices is slightly higher, but the above mentioned regularities hold. In the case of some combinations of countries, especially for the Czech Republic and Poland, there is a third period at the end of the year 2013 and at the beginning of the year 2014 when the indices grew (for the combination *czepol* even by more than 10 %).

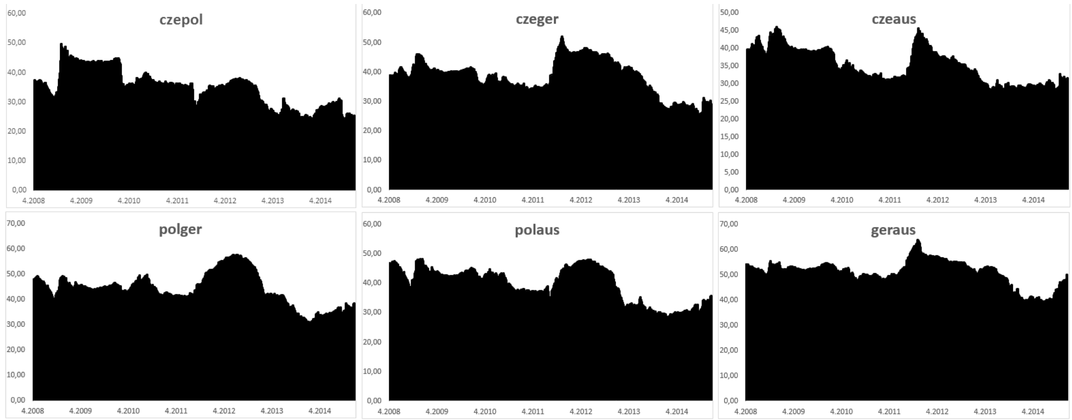
Directional spillover indices

Now, we want to look at the intensification more deeply by examining the directional spillovers. We primarily focus on the net contribution of a particular market to the other financial markets quantified by the difference between Equation 4.14 and Equation 4.13. The gross directional spillovers given by (4.14) and (4.13) may be utilized for better understanding of the underlying processes behind the changes.

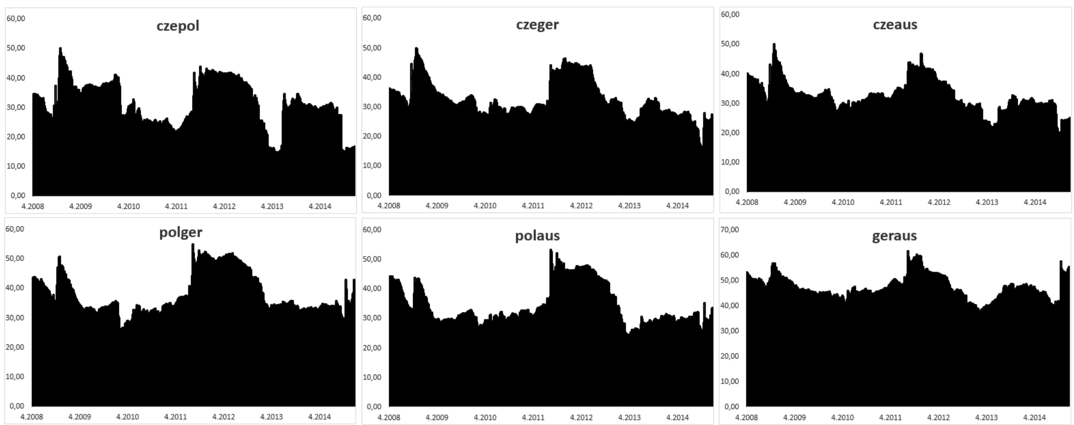
Bonds The evolution of the spillover indices describing net contribution of the bond yields to the other markets within a particular group uncovers a growing influence of the bond markets. At the same time, we have found an explanation of very low unconditional net directional indices that were caused by the

Figure 5.1: **GVAR - Evolution of the total spillover index**

(a) Returns



(b) Volatility



(Estimated in Matlab)

change of the position of the bond markets among financial markets. While all bond markets were net receivers of spillovers from the other financial markets at the beginning of the analysed period, bonds became at a certain moment net transmitters of spillovers. The time of change is different for each country.

The Czech bonds had been a receiver of spillovers till the year 2013 (especially in 2009 and 2010) when the situation changed and the bonds started to transmit around 4 % in the case of returns. In the case of volatility the spillovers exceeded even 10 %. Similar pattern is reported also by the Polish bond yields. Only the degree of return spillovers is slightly higher - the net return directional spillover index reached more than 8 % during the year 2014.

In the case of Austria, the bonds became net contributors to the other markets already in 2011 (except of the combination with Germany). The indices have been fluctuating mostly below 5 %.

Finally, the German bonds are net transmitters most of the time. Already during the year 2010, the German bond market was a net contributor of return, as well as volatility spillovers with respect to all counties. The return (volatility) spillover indices reached their peak during the first half of the year 2013 (2012), and exceeded 20 % in most of the cases.

By looking at the gross directional spillover indices, we may find that change of the character of bond markets is implied by both a declining impact of the other market on the bonds, and a growing influence of the bond markets.

Stocks Exactly the opposite development is characteristic for the stock markets. In all cases, initial high net directional spillovers were declining during the analysed period, and got very close, or even below zero at the end of the data sample. The decline was caused mainly by the lowering contribution of the stock markets to the other markets. At the same time, we may claim that the volatility spillover indices are generally lower and more volatile than the return spillover indices.

The Czech PX Index seems to influence the other markets at most during the period following the Lehman Brothers collapse when the net return directional spillover indices fluctuated around 10 %. The decline started in April 2010, and negative values occurred in the second half of the year 2011 (with respect to Poland not before the year 2013). Volatility spillovers were even during the most influential period lower, but the pattern is very similar.

The Polish stock index attained the highest values of the net directional spillovers in Summer 2008 and during the year 2010. There is an interesting drop of contribution to the other markets during the beginning of the financial crisis, but it comes from the fact that the other markets were more influential for the WIG30 index than the WIG30 index for them.

The Austrian stock market again seems to be the strongest contributor to the other markets. Within the group with the Czech and Polish markets, the net directional spillover indices of returns surpassed the 10% level during the financial crisis in 2008-2010 and during the year 2012. In 2014, the contribution got close to zero. Within the group with Germany, the spillovers are slightly weaker.

The German stock market bears a very similar pattern as the remaining stock markets. Again, a net contributor of return spillovers to other markets in the first half of the analysed period (around 5 %) changed during the year 2012 into a weak receiver of spillovers. Within the group with Austria, German equity market is a net receiver of volatility spillovers already from the year 2011.

Exchange Rates In the case of exchange rates, there is a little variation between countries and groups of countries. The foreign exchange markets operate as receivers of return and volatility spillovers throughout the whole period. The net directional spillovers from the exchange rates to the other markets fluctuate mostly between values -5 and -10. There are two periods occurring to a certain degree within all groups that should be mentioned: the year 2011 when the spillovers seem to be moderately weaker, and, on the contrary, the year 2012 during which the values fall often below -10.

Pairwise Spillover Indices

In the previous part, we focused on the directional spillover indices from and to a particular market. Now, we will look more closely at the spillovers between two concrete markets. In the first place, we will compare the relations between national stock indices and bond yields, then we will concentrate on the international interconnections, and effects of each market on the exchange rates.

Domestic spillovers between stocks and bonds Fortunately, indices between national markets for the same country do not fundamentally differ among combinations within which the country is included. Therefore, we are allowed to plot spillover indices for each country only from one chosen combination of countries.[4] The evolution of the return and volatility spillovers may be seen in Figure 5.2 where the net pairwise spillover indices describing the contribution of a particular stock market to the bond yields in the same country are displayed. Negative values thus mean that bonds contribute to stock markets and vice versa.

Generally, we may observe a decreasing trend suggesting the stock markets were gradually losing their dominance. At the end of the analysed period, bonds were net transmitters of return and volatility spillovers to stocks in all countries. In spite of this fact, there are certain distinctions in the development of the individual countries which we are going to discuss in the following paragraphs.

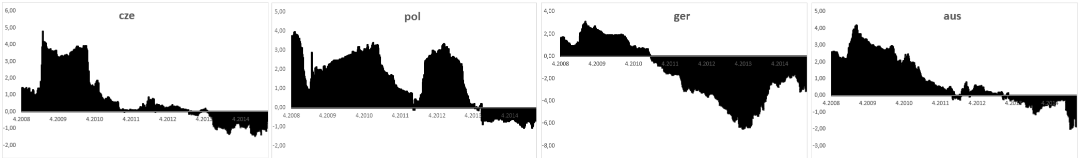
We observe quite diverse shapes, as well as magnitudes. While the return spillovers appear to be usually higher than the volatility spillovers, the periods during which the return and volatility indices for a given country are considerably positive or negative roughly correspond to each other.

First of all, we will consider the period of high net pairwise spillover indices at the beginning of the time span. In the Czech Republic, the return spillovers

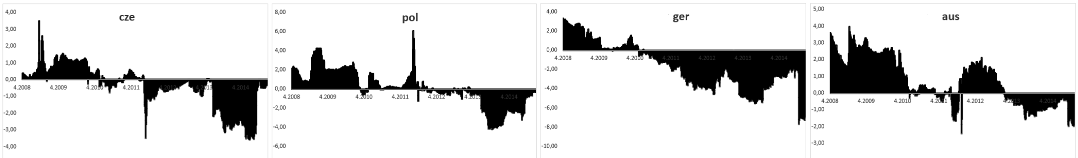
[4]Specifically, we plot the spillovers from the combination of the Czech Republic with Germany, and from the combination with the Czech Republic for the other countries.

Figure 5.2: **GVAR - Spillovers from stock markets to bonds**

(a) Returns



(b) Volatility



Notes: Evolution of the net pairwise spillover indices describing net contribution of stock markets to bond yields. Positive values mean that the stock market is a net contributor to the bond market, and vice versa.

(Estimated in Matlab)

grew after the collapse of Lehman Brothers in the autumn 2008 and had been staying at levels between 3 % and 4 % until the first half of the year 2010 when they dropped under 1 %. This increase was caused primarily by higher contribution of the stock markets to the bond yields. Volatility spillovers in the Czech Republic were during this period also moderately higher than during the remaining part of the analysed period, but they only exceptionally exceeded 1 %. Practically, the indices had been very close to zero till the second half of the year 2013 when the volatility spillovers measured by the net pairwise indices fell below -2%. In this case, the decline is explained by an increasing influence of the Czech bonds on the PX index. The decline can be observed also on the return spillover indices, but the decline is not so apparent.

During the two periods mentioned in the case of the Czech Republic, similar developments of return and volatility spillovers appeared also between the Polish stock and bond markets. Only distinction is that the grow of the indices after the start of the financial crisis in 2008 was not so sudden as in the case of the other countries, but arose gradually. Then another increase of return spillovers during the year 2012 caused by growing influence of stock markets deserves to be mentioned.

German net pairwise return (volatility) spillover indices declined from 3 % (3 %) at the beginning of the financial crisis in 2008 to -6 % (-5 %) in July 2013. After that, the indices again rose to the level around -2 %. The driving forces behind this movement are both a lowering influence of stock markets and a growing impact of bonds. A similar decline during the same period is also noticeable in Austria. In Austria, there were also noticeably higher volatility spillovers from the stock market to bonds during the year 2012.

Now, we will move from the domestic spillovers to international. First, we will examine the spillovers among the same markets (stock, or bond markets) in Central Europe. Then, we will focus on the international cross-market spillovers.

Bond yields The net pairwise return spillover indices between bond markets within all groups of countries are plotted in Figure 5.3. It should be mentioned that positive values denote periods of net spillovers from the second country's bonds to the first country's bonds, and vice versa. As may be seen, the development is quite heterogeneous, but certain similarities may be discovered.

Already the up to now discussed results denote the German bond market as the most influential bond market in Central Europe. Now, we confirm our belief, and at the same time, we are able to determine the periods during which individual countries' bond yields were predominantly influenced.

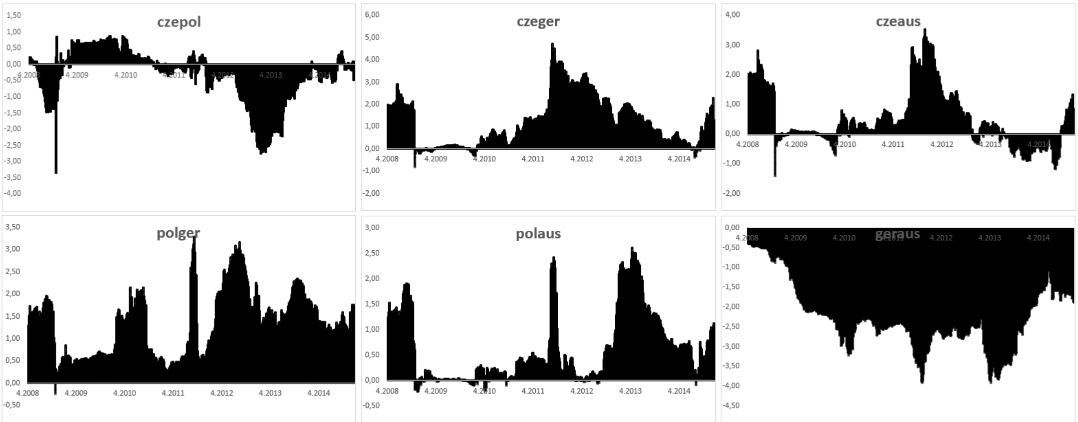
As shown in Figure 5.3, the German bonds have unambiguously an impact on the Austrian bond yields because the net pairwise spillovers are negative during the whole analysed period, chiefly from the second half of the year 2009 to the end of the year 2013 when the indices stayed below -2% with an intensification in the beginning of 2012 and in the second half of the year 2013. The gross pairwise indices fluctuating mostly above the level of 5% suggest very intensive reciprocal spillovers between the German and Austrian bonds with moderately dominating German bonds.

Concerning Poland, the interconnection between the bond markets is not so intensive. A gross impact of the Polish bond market on the German one did not arise before the second half of the year 2013. In the opposite direction, the spillovers were slightly higher, and therefore the net pairwise spillover implies that the German bond market had net influence on the Polish bond yield in 2008, in 2010, and after the year 2012.

In the case of the Czech Republic, there was a major episode of positive net spillovers from the German bond market following the second half of the year 2011 with indices exceeding 4 % in 2011, and then gradually decreasing till the end of the analyses period. The decline was caused by a decreasing impact of the German bonds in late 2012 and 2013 and growing spillovers from the Czech bonds in 2014.

Also the Austrian bond market appears to be a net transmitter of spillovers

Figure 5.3: **GVAR - Net pairwise international spillover indices between bond markets**



Notes: Evolution of the net pairwise spillover indices between bond markets. Positive values denote periods of net spillovers from the second country's bonds to the first country's bonds, and vice versa.

(Estimated in Matlab)

to the Czech and Polish bond markets. In the case of the Czech Republic, the main spillovers from Austria were detected in the second half of 2011 and in early 2012. The Polish bonds are net recipients of return spillovers in the year 2013.

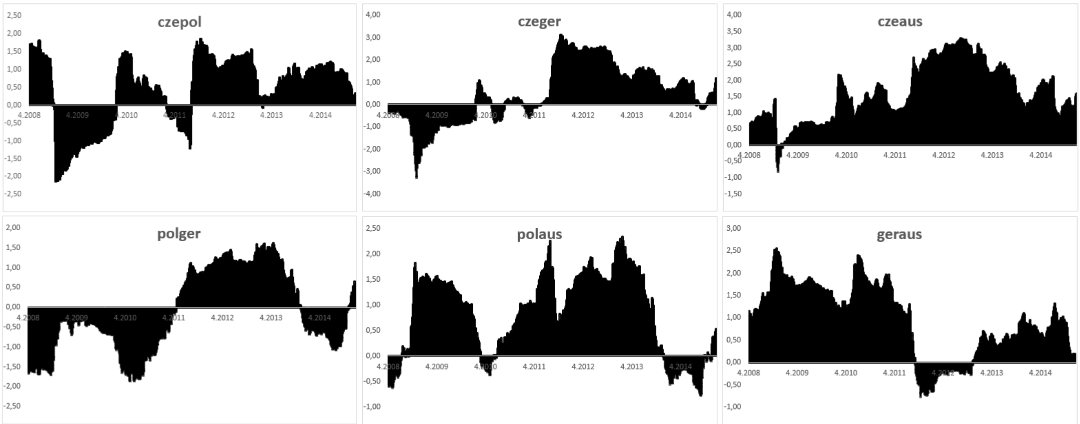
The Czech bond market had a net impact on the Polish bond market only in 2013 when the net pairwise return spillover indices reached values around -2.5 %. The Polish bonds were never source of significant net return spillovers during the analysed period.

There are also some differences between the return and volatility spillovers among the bond markets in Central Europe. Three of them are worth to mention. Firstly, the German bonds' volatility had net impact on the volatility of the Polish bonds only during the period from the year 2010 to early 2013. Secondly, the Austrian bond market influenced Polish bonds' volatility already in 2012, and in 2013, contrary to the return spillovers, there are not any considerable net spillovers in the second half of 2013. Finally, the net volatility spillovers from the Czech to Polish bonds appeared not only in the second half of 2011 and early 2012, but also in the period from 2009 to 2011.

Stock markets Now, we will move from bond to stock markets, and investigate the relationships among returns of the equity markets in Central Europe. In Figure 5.4, the evolution of the net pairwise spillover indices between the stock markets is presented. According to the preceding analysis, we have identified the

Austrian stock market as the main contributor of spillovers among the analysed countries. Here, we may affirm this conclusion.

Figure 5.4: **GVAR - Net pairwise international spillover indices between stock markets**



Notes: Evolution of the net pairwise spillover indices between stock markets. Positive values denote periods of net spillovers from the second country's stocks to the first country's stocks, and vice versa.

(Estimated in Matlab)

The net pairwise return spillover indices between stock markets are usually quite low, but the gross pairwise spillover indices fluctuating mostly between 5 % and 7 % sign substantial reciprocal influence between the markets.

Austria, as a main transmitter of spillovers among the stock markets, had net positive influence on all three remaining countries during the predominant part of the analysed period. The highest net contribution was to the Czech PX index where the net spillover indices exceeded 3 % during the year 2012. In 2008 and 2009, the net spillovers were rather low, moving mostly below 1 %. In the case of Germany, the spillovers from Austria dominated more in the first part of the analysed period till the second half of 2011. Then, the spillovers stayed close to zero. The Polish stock market received net spillovers quantified by the indices around 2 % during the whole period except of short eras in 2008, 2010 and 2014. According the indices from the generalized VAR model, Austria was never net receiver of return spillovers with indices higher than 1 %.

The German DAX index had higher net influence on the Czech and Polish stock markets during the period starting from summer 2011 to the end of 2014. Quite surprisingly the indices did not grow after the collapse of Lehman Brothers. In this periods, rather Polish and Czech markets shocks spilled over to the other markets, and, according to the indices within the group of the Czech and

Polish markets, the Czech stock market was more influential than the Polish one. In the remaining part of the analysed period, the opposite held true: Poland was mostly net transmitter of spillovers to the Czech Republic.

The development of the volatility spillovers is again very similar to the return spillovers. The net pairwise indices of volatility shocks from Austrian stock market are more biased in favour of the Austrian market. In spite of the fact, the net spillovers within the combination with Germany declined close to zero already in 2010 because of declining impact of Austrian stocks.

For the other combinations, the differences are primarily in magnitudes which are generally higher in the case of volatility spillovers.

International spillovers between bonds and stocks Now, we will focus on the international cross-market spillovers between stock and bond markets in Central Europe. The net pairwise return spillover indices from stock markets to bond markets of the other countries, plotted in Figure 5.5, will be investigated. It should be noted that the indices are surprisingly high, for instance, in comparison to international indices between markets of the same kind.

We may observe general change from an ascendancy of the stock markets to a dominance of bond markets. In the period from 2008 to 2010, the influence of the stock market preponderated within all groups. The most remarkable burst of impact happened in the second half of 2011 when the German bond yields started to considerably contribute to Czech and Polish stock markets (indices reaching as high as 4 %). Another deviation from the trend occurred in the year 2012 when the contribution of all stock markets to the Polish bond yields noticeably increased.

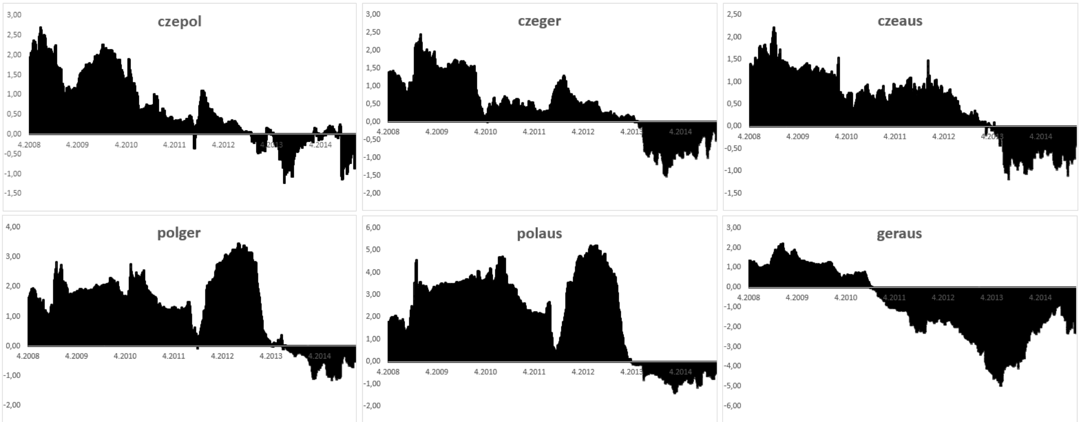
The trend described in the previous paragraph may be observed in the indices describing the net volatility spillovers between stock and bond markets. The deviation in the year 2012, however, does not come to light so boldly.

Exchange rates Firstly, we will describe the net pairwise return spillovers from the stock markets to the exchange rates. As may be seen in Figure 5.6, these spillovers are within all groups positive during a predominant part of the analysed period implying that the exchange rates are net receivers of return spillovers from the stock markets.

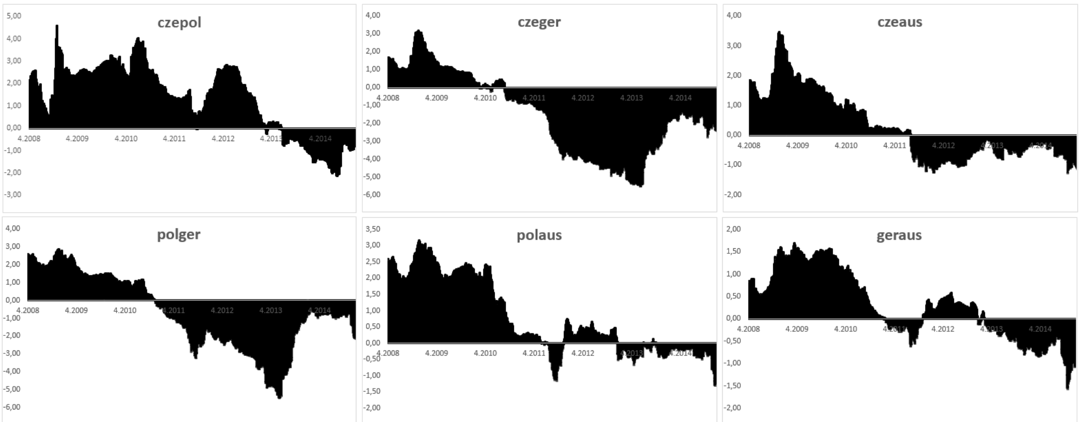
The intensity of spillovers was changing primarily due to the changing spillovers from the stock markets to the exchange rates because the spillovers in the opposite direction exceeded 1 % only very rarely.

Figure 5.5: **GVAR - Net pairwise indices of international spillovers from stock to bond markets**

(a) Stock2 to Bond1



(b) Stock1 to Bond2



Notes: Evolution of the net international pairwise spillover indices between stock and bond markets. Positive values denote periods of net spillovers corresponding to the description.

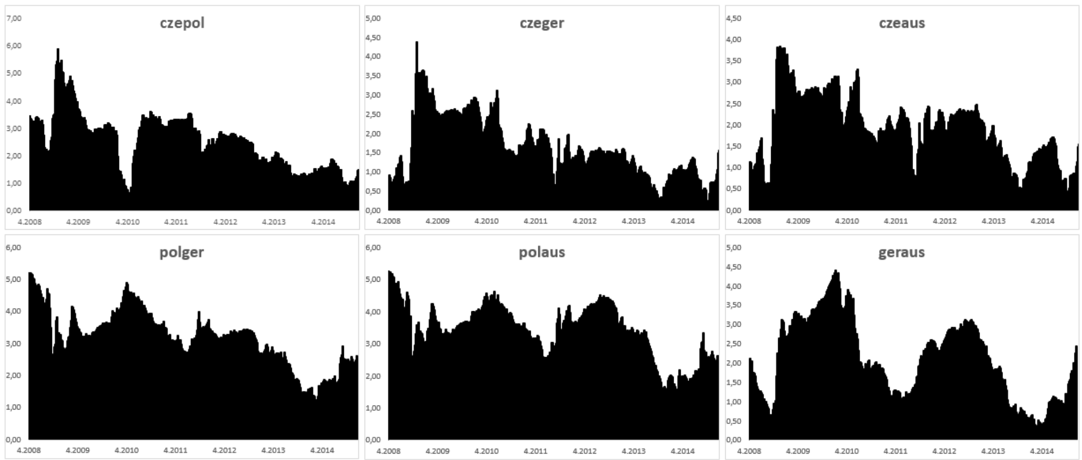
(Estimated in Matlab)

The spillover indices show that the net return spillovers from the Czech stock market to the PLN/CZK and CZK/EUR exchange rate were declining during the whole period. At the beginning of the period, the spillovers moved around 3 % with a peak during the start of the financial crisis in 2008, and gradually declined to 1 %.

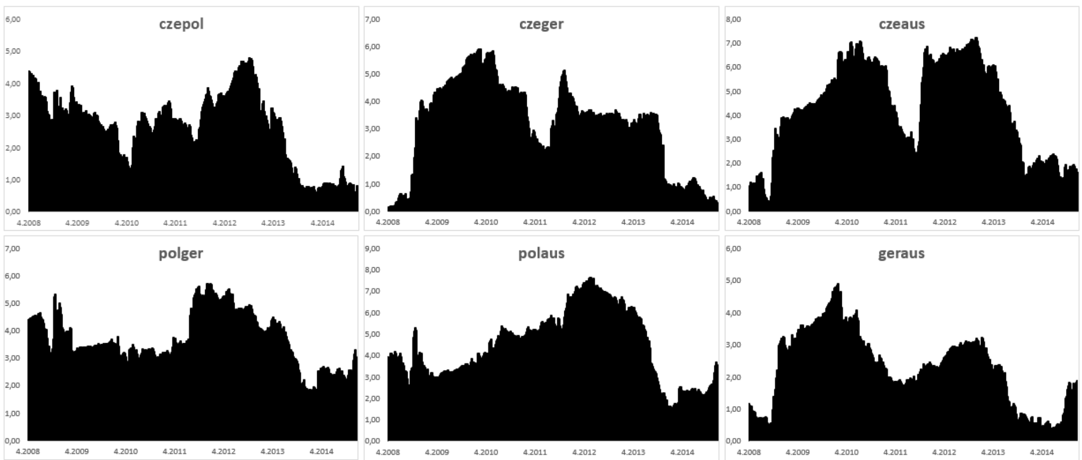
The Polish stock index gave around 5 % of the forecast error variance to the PLN/EUR in 2008. Then, a declining trend followed. This trend is violated in 2010 and 2012 when the indices are considerably higher. With respect to the PLN/CZK, the spillovers declined from 4 % in 2008 to 1 % in 2014. During the year 2012, the spillover indices deviated from the trend and the spillovers

Figure 5.6: **GVAR - Net pairwise spillover indices from stocks to exchange rates**

(a) Stock1 to exchange rate



(b) Stock2 to exchange rate



Notes: Evolution of the net international pairwise spillover indices between stocks and exchange rates. Positive values denote periods of net spillovers from the stocks to the exchange rates.

(Estimated in Matlab)

intensified.

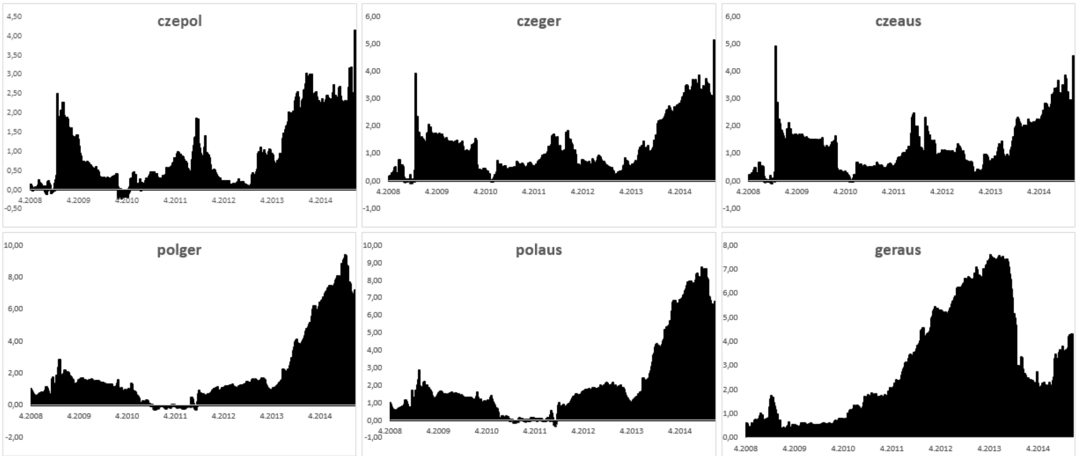
The Austrian and German stock markets had very similar relationship with the currencies. The spillovers usually fluctuated between 3 and 4 %, but they significantly declined in 2014. The net pairwise spillover indices rose in 2009-2010 and 2012 in the case of CZK/EUR. In the case of PLN/EUR, the spillovers strengthened only in 2012.

For volatility spillovers from the stock market to the exchange rates, the similar regularities as mentioned above hold. The volatility spillovers are only more volatile and the periods of deviations from the trend are usually shorter. There are no other considerable differences.

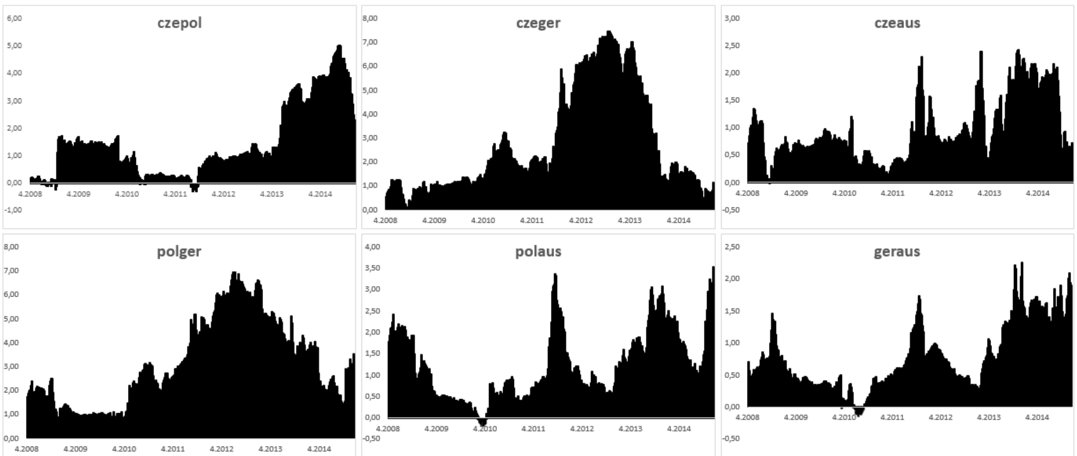
Now, we will shift to the spillovers from the bond yields to the exchange rates. The net pairwise spillovers from bond yields to the currencies stayed close to zero except of certain periods when they grew.

Figure 5.7: **GVAR - Net pairwise spillover indices from bonds to exchange rates**

(a) Bond1 to exchange rate



(b) Bond2 to exchange rate



Notes: Evolution of the net international pairwise spillover indices between bonds and exchange rates. Positive values denote periods of net spillovers from the bonds to the exchange rates.

(Estimated in Matlab)

In the case of the Czech Republic, the return spillovers intensified in 2009 and after the second half of 2013. The volatility spillovers grew also in 2012 (the return spillover did not rise so strongly). The spillovers from the Polish yields were stronger exactly during the same periods.

The Austrian bond market transmits to the PLN/EUR and CZK/EUR in 2011 and 2013. The contribution of the German bonds to all exchange rates intensified during the years 2012 and 2013. The intensity of spillovers exceeded 5 % of the forecast error variance during this period. The volatility spillovers are moderately higher, but the duration of higher spillovers was shorter.

5.2 Spillover Indexes in Structural VAR

The spillover indices, obtained by the method introduced in Subsection 4.2.2, will be investigated in this section. Unfortunately, the method does not solve the issues of the Diebold & Yilmaz (2012)'s approach so seamlessly as we expected. The assumption of the constant coefficients of the SVAR approach appears to be critical. In particular, the dynamics of the spillover indices is derived only from the evolution of the conditional volatility, and the size is still based on the coefficients describing average dynamic links among the variables during the whole analysed periods. It would be desirable to let the coefficients evolve over time, but such a solution for estimation on the full-sample is not probably feasible.[5]

The obtained indices are thus derived from the average SVAR coefficients, and are not able to completely capture the dynamics of the spillovers. In spite of this fact, we have estimated these spillovers, but during the interpretation, we will concentrate only on the full sample spillover indices and the dynamic spillover indices will be utilized only for rough description of the development.

In addition, the estimation of the SVAR model produces in few cases inconsistent results. For instance, the contemporaneous coefficients between Czech and German bond yields, or German and Austrian bond yields are unusually high and with opposite signs. This signifies certain deficiencies of the estimation. Unfortunately, we have not been able to sufficiently identify and resolve this issue for the estimation based on the entire data sample with chosen mix of time series, therefore, we present the results with this inconsistency. From this reason, we marginalize these coefficients (and their implications) during interpretation, and accept only conclusions analogical to the other methods. The other estimated coefficients do not considerably indicate similar problems.

In Table 5.3, the spillover indices are presented in the same structure as for the Diebold & Yilmaz (2012)'s approach. The first row of the table contains

[5]The rolling window method or similar partition of the data sample would partly solve this issue, but we wanted to evade this solution.

Table 5.3: **SVAR - Unconditional spillover indices for returns**

		czepol	czeger	czeaus	polger	polaus	geraus
Total		20,65	34,46	24,86	14,94	23,69	31,41
ALLtoI	**bond1**	3,82	7,39	2,05	1,12	0,72	7,37
	stock1	1,84	5,78	7,35	2,01	4,80	10,82
	bond2	1,52	8,81	4,24	2,42	3,29	7,82
	stock2	7,52	6,96	5,74	5,31	6,70	4,13
	ER	5,95	5,52	5,47	4,10	8,19	1,27
ItoALL	**bond1**	1,00	6,46	3,43	1,86	3,13	4,44
	stock1	8,18	10,04	1,76	6,00	2,28	6,77
	bond2	3,77	5,51	1,53	2,30	0,77	7,32
	stock2	6,11	6,39	10,65	4,19	8,78	12,32
	ER	1,58	6,07	7,49	0,60	8,73	0,56
NetItoALL	**bond1**	-2,82	-0,93	1,38	0,74	2,41	-2,93
	stock1	6,35	4,26	-5,59	3,99	-2,52	-4,05
	bond2	2,25	-3,30	-2,71	-0,12	-2,52	-0,50
	stock2	-1,41	-0,57	4,90	-1,12	2,08	8,19
	ER	-4,38	0,54	2,01	-3,50	0,54	-0,71
bond 1 to	**bond1**	14,57	1,95	16,79	14,89	19,28	3,05
	stock1	0,11	0,22	0,12	0,14	0,18	0,04
	bond2	0,67	5,60	3,00	0,95	2,03	4,33
	stock2	0,13	0,52	0,16	0,11	0,10	0,03
	ER	0,10	0,13	0,15	0,66	0,82	0,04
stock 1 to	**bond1**	0,35	0,31	0,53	0,25	0,14	1,44
	stock1	19,85	17,46	21,15	18,95	22,03	24,26
	bond2	0,32	0,69	0,17	0,56	0,36	1,93
	stock2	6,55	4,28	0,52	4,05	0,48	2,78
	ER	0,96	4,76	0,54	1,14	1,30	0,62
bond 2 to	**bond1**	3,16	5,38	1,08	0,26	0,08	4,89
	stock1	0,19	0,04	0,12	0,43	0,16	0,99
	bond2	14,83	2,14	17,78	16,32	19,74	2,07
	stock2	0,11	0,05	0,24	1,10	0,27	1,01
	ER	0,31	0,04	0,10	0,50	0,27	0,43
stock 2 to	**bond1**	0,23	1,41	0,23	0,42	0,39	1,00
	stock1	0,96	2,00	4,89	1,15	2,38	9,64
	bond2	0,34	2,37	0,85	0,83	0,23	1,50
	stock2	15,97	27,89	10,51	19,60	8,29	23,43
	ER	4,58	0,60	4,68	1,80	5,79	0,19
ER to	**bond1**	0,08	0,29	0,21	0,19	0,12	0,04
	stock1	0,58	3,52	2,22	0,29	2,09	0,15
	bond2	0,19	0,15	0,23	0,07	0,67	0,06
	stock2	0,73	2,11	4,82	0,05	5,86	0,31
	ER	14,13	16,11	8,92	15,30	6,97	15,77

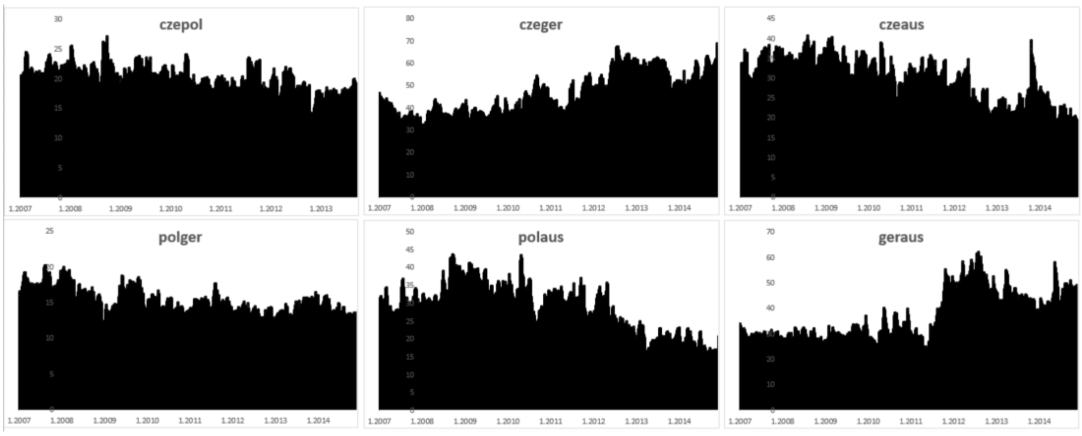
Notes: The columns represent the combinations of countries where AUS is an abbreviation for Austria, CZE for the Czech Republic, POL for Poland, and GER for Germany. Bond is a representative of the bond yields, stock represents the stock market, and ER the exchange rate market. The number 1 labels the first country in a particular combination of countries, the number 2 stands for the second country. *Total* - total spillover index, *ALLtoI*, *ItoALL* and *NetItoAll* - directional spillover indices. The remaining groups contain the gross pairwise spillover indices.

(Estimated in Matlab)

total spillover indices for all combinations of countries. Here, the highest total spillover indices are within the combination of Germany with the Czech Republic and Austria (34.46 % and 31.41 %, respectively). On the other hand, the lowest degree of spillovers shows up, if Poland is involved in the combination. In

Figure 5.8, the evolution of the total spillover indices is shown. As may be seen, the spillovers have been evolving over time. In this case, the total spillover indices do not report so common pattern for all countries as in the case of the total spillover indices obtained by GVAR model. Here, we may emphasize an intensification of the spillovers between Poland and Austria during the beginning of the financial crisis in 2008. Then, the second period of significantly higher spillovers occurred in 2012 when the spillovers within the groups with Germany remarkably grew.

Figure 5.8: **SVAR - Total spillover index**



(Estimated in Matlab)

The next three groups of indices in Table 5.3 offer the directional spillover indices as described in Equation 4.20 and Equation 4.21 (and their differences). These spillover indices mostly confirm the conclusions of the Diebold & Yilmaz (2012)'s approach. Very strong spillovers from and to stock market are again revealed. The main contributors to the other markets seem to be the Austrian stock market and the German bond market.[6]

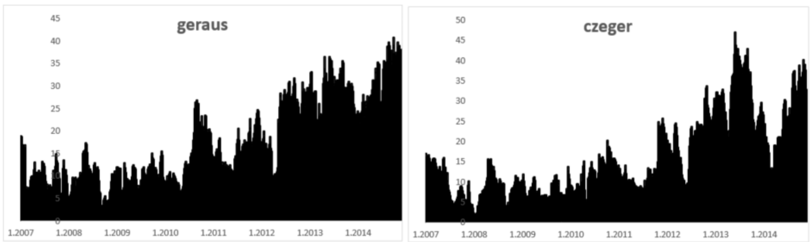
Finally, we may focus on the pairwise spillover indices based on the SVAR model. Analogically to the spillover indices from the GVAR model, the full sample indices already reveal quite interesting results. During the presentation of the results, we will restrict ourself on the full sample gross pairwise indices. We will mention also the evolution of the conditional spillover indices, however, from the reasons mentioned earlier, we are not so certain that the indices are able to capture all changes happening in the interconnections of the markets. This information is offered only as a rough supplement of the obtained information.

[6] We ignore the high contribution of the Austrian or Czech bond market, because we assume that this high values of indices follow from the improperly estimated coefficients. We believe that part of this spillover, in fact, comes from the German bond markets.

Bond yields Firstly, among the bond markets in Central Europe, the most influential market is the German one which contributes, on average, around 5 % of the forecast error variance to the Czech and Austrian bond yields. As may be seen in Figure 5.9, the spillover indices started to grow during the year 2011, and reached their peak at the end of 2013. Then the indices spillovers to the Czech market mitigated, but the high spillovers to the Austrian bonds had persisted till the end of the analysed period.

According to the full sample indices, the spillovers coming from the other bonds do not seem to be so important.[7]

Figure 5.9: **SVAR - Gross pairwise indices from German bonds to Czech and Austrian bond yields**



Notes: Evolution of the gross pairwise spillover indices between bond markets. Positive values denote periods of gross spillovers from the German stocks to the other stock markets.

(Estimated in Matlab)

Stock markets Regarding the stock markets, the gross pairwise spillover indices repeatedly confirm the Austrian market as the leading market in Central Europe. The indices indicate that the Austrian stocks give on average 4.9 % of the forecast error variance to the Czech, 2.4 % to the Polish, and more than 9.6 % to the German stock index.

The evolution of these indices is provided in Figure 5.10. A noticeable decrease implying a weakening power to influence the other equity markets is identified. The highest spillovers from the Austrian stock occurred during the year 2008 and 2009. Another elevation is noticeable during the year 2011.

Generally, quite strong interconnections among the stock markets are detected.

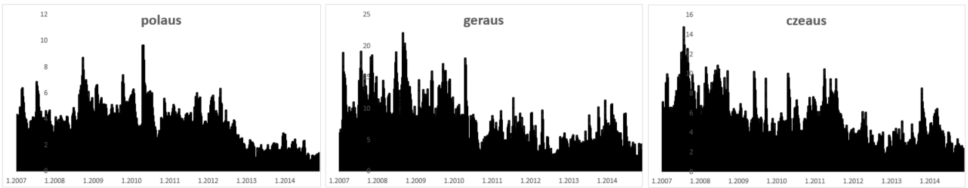
At the same time, the stock markets strongly contribute to the exchange rates. The highest contribution goes again from the Austrian index to the CZK/EUR (4.7 %) and PLN/EUR (5.8 %) exchange rates. Also, the value

[7]Except of the above mentioned imprecisenesses.

of the index describing the gross spillover of the Polish market to PLN/CZK (4.58 %) betokens a quite intensive influence.

Additionally, a surprisingly high contribution of the German stock market to the German bonds was revealed. This conclusion was reached already in the previous section, and here we obtained another confirmation of this connection between German stock and bonds.

Figure 5.10: **SVAR - Gross pairwise indices from Austrian stocks to the other indices**



Notes: Evolution of the gross pairwise spillover indices between stock markets. Positive values denote periods of gross spillovers from the Austrian stocks to the other stock markets.

(Estimated in Matlab)

Exchange rate Finally, the exchange rates appear to have an impact on the stock markets. Especially the CZK/EUR exchange rate influence the Czech and Austrian stock markets. According to the indices, shocks to this exchange rate contribute by 3.5 % (2.2 %) of the forecast error variance within the combination with German (Austrian) markets to the PX index. The Austrian market receives 4.82 %. Similar impact have the PLN/EUR exchange rate which transmits around 5.9 % to the Austrian market.

The spillovers to the bond yields are minimal.

To conclude the interpretation of the spillover indices, we may claim that, except of several deviations that could be probably explained by the imperfections of the estimation, we have obtained outcomes that are in accordance with the results from the Diebold & Yilmaz (2012)' indices.

5.3 Intermediate Results

5.3.1 Multivariate GARCH Model

In this thesis, we have allowed the structural shocks to follow the multivariate GARCH(1,1) model as described in Equation 4.28. The modelled heteroskedasticity has not only enabled to obtain the estimates of the structural coefficients, but also helped to capture the dynamic evolution of the variances of the structural shocks. Thank to that, we may obtain development of the variances and covariances of the reduced shocks by applying the Equation 4.26.

Because we have only the covariances among the reduced shocks,[8] we will focus on the linear dependence among the reduced shocks. In order to facilitate the comparison, we have, at first, calculated conditional correlation coefficients by using

$$Corr_{t,ij} = \frac{\sigma_{t,ij}}{\sqrt{\sigma_{t,ii}} \cdot \sqrt{\sigma_{t,jj}}} \tag{5.1}$$

where $\sigma_{t,ij}$ represents the covariance between i-th and j-th variable at time t. The Equation 5.1 computes an estimation of the dynamic correlation coefficients between i-th and j-th variables at time t. In the following paragraphs, we will focus on description of evolution of the correlation coefficients capturing the linear dependence between the markets.

A comparison of the correlation coefficients with the spillover indices may offer an insight into the structure of the spillover indices. The spillover indices take into account not only the covariance structure, but also the dynamic causality among the variables. In other words, the correlation coefficients describe a part of the information aggregated in the spillover indices.

Although the contemporaneous coefficients report certain imperfections, the dynamic correlation coefficients do not appear to be influenced by this fact. The assertion may be supported by a comparison with estimates of the conditional correlation coefficients of the reduced shocks produced by the DCC model that was proposed by Engle (2002). The comparison is available in an enclosed file.

Stock markets As the unconditional correlations have already revealed, the highest linear dependence is among the stock markets. The dynamic correlation coefficients between two particular markets estimated by the method described above fluctuate mostly around values of the unconditional correlations. The highest values are achieved between the German and Austrian stock indices where the correlation coefficients were above 0.8 during a predominant part of the analysed period.

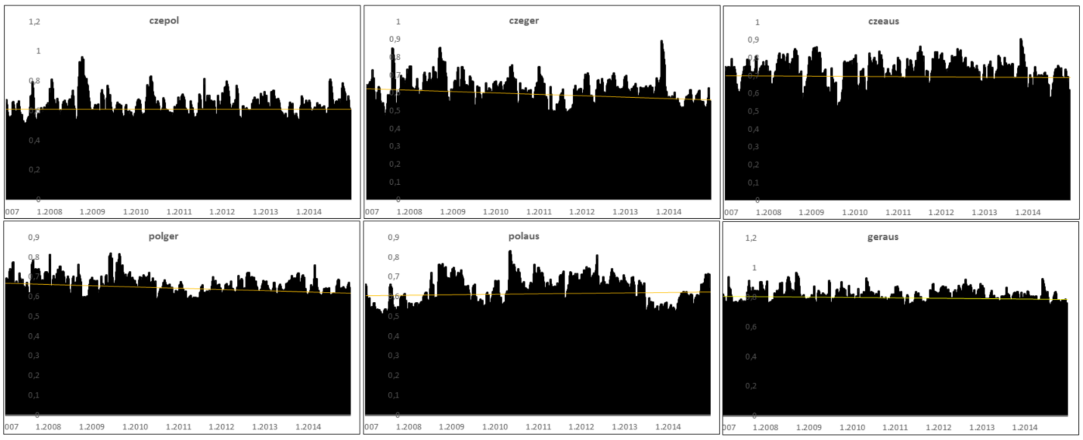
The correlation coefficients for the other combinations of the stock markets are moderately lower, but in all cases stay around 0.7. These values sign very strong linear dependence between the equity markets.

[8] We have assumed the structural shocks to be uncorrelated.

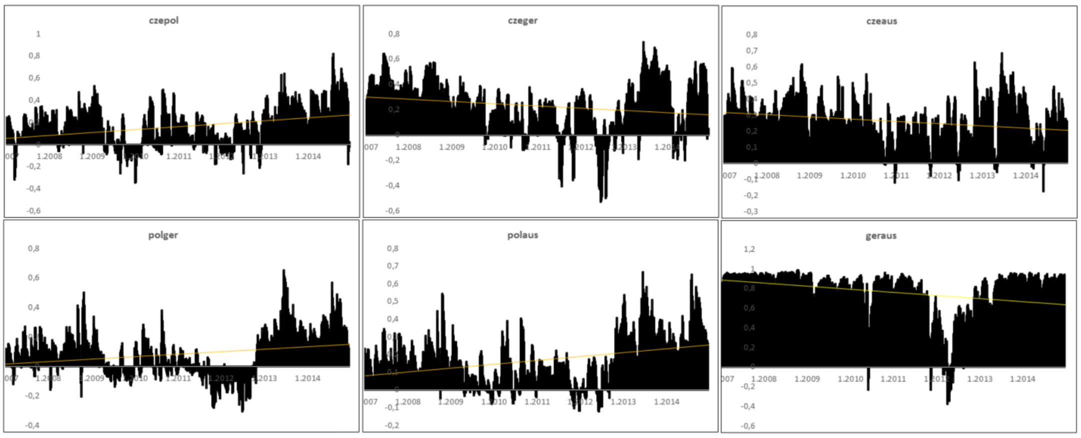
Additionally, the values remain approximately at the same levels. Relatively low variation of the correlation coefficients may be confirmed by standard deviations of the coefficients which are lower than 0.09.[9]

Figure 5.11: **Dynamic correlations between the markets of the same type**

(a) Stocks



(b) Bond yields



(Estimated in Matlab)

Bond yields The linear dependence among bond yields is not so unambiguous and stable as for stocks. Not only the standard deviations of the correlation coefficients indicate higher variation, but also the conditional correlation coefficients change remarkably (often also their sign).

The correlation coefficients between the Austrian and German bond yields have a specific development. The coefficients move mostly around 0.9 except

[9]For comparison, the standard deviations of the correlation coefficients between bond markets lie between 0.136 and 0.252.

of the year 2012 when a significant decline, even to negative values, occurred. This change of dependence can be partly connected with a cut of the rating of Austria in January 2012 (Voss 2012). A detection of such a behaviour of correlations is crucial for risk management and neglecting this drop could have serious consequences.

The other combinations of countries may be characterised by a similar development. At the beginning and at the end of the analysed period, the correlations appeared to have higher values, and during the years 2010-2012 obviously lower.

From 2007 to the end of 2009, the correlation coefficients of the Czech bond yields with German and Austrian bond yields fluctuated around 0.4. Then the coefficients declined to values around 0.2 with frequent drops to 0 and even to negative values. At the beginning of 2013, the correlations again strengthened and returned to values around 0.4. A similar development was reported also by the correlations with Polish bonds. In the first half of the period, the coefficients were slightly lower, but since the beginning of 2013, they had been also reaching values around 0.4.

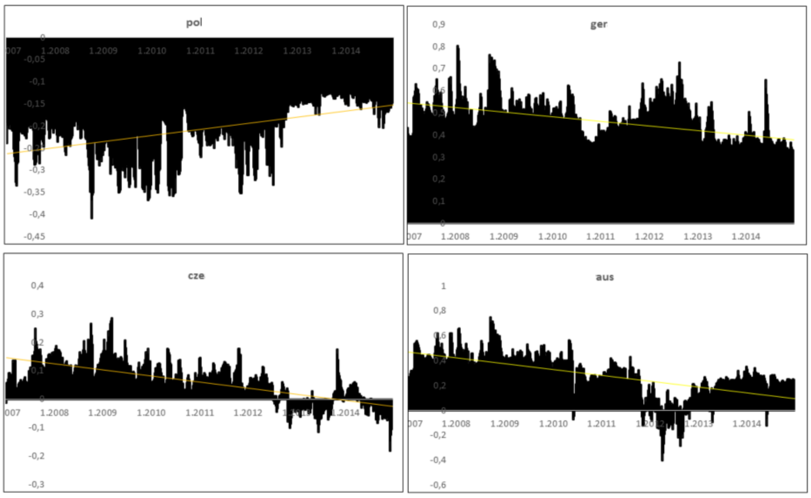
The correlation of the Polish bond yields with the German bond yields started around 0.2 and were gradually declining to -0.2 at the end of 2012. Then a sudden change happened, and the correlation coefficients returned to values above 0.2 where they had been staying till the end of 2014. The correlation with Austrian yields had a parallel development - they started around 0.25 and had been declining till the end of the year 2012 when the correlations returned to values around 0.3.

Domestic link between bonds and stocks The development of the correlation coefficient differs for each country. In the Czech Republic, the unconditional correlation lied close to zero, but the conditional started at values around 0.15, and then consecutively declined to zero or to slightly negative numbers.

In Poland, there is quite specific dependence between stock and bonds. The correlations were negative during the whole period. They started around -0.25 and gradually got to -0.2 at the end of 2014. There are two periods in 2009 and 2012 during which the correlations were even more negative and often declined below -0.3.

In the case of Austria and Germany, the correlations between stock and bonds are quite high. The evolution in both countries, however, reports a moderately declining trend (in Germany from 0.5 to 0.4, in Austria from 0.4 to 0.2). The development was corrupted by several periods: the correlations grew in Germany during the year 2012, and in Austria during the financial crisis in 2008 and 2009. On the other hand, there is a considerable drop in correlations between Austrian equity and bond markets in 2012.

Figure 5.12: **Correlation between domestic markets**



(Estimated in Matlab)

International link between bonds and stocks Even the unconditional correlations of returns have revealed quite strong international dependence between stock returns and bond yields. The dynamic correlation coefficients also confirm this conclusion, and in addition, they help us to more closely examine the evolution of the correlations.

The correlations of the Czech bond yields with the other countries' stock markets have a very similar behaviour. In the beginning, the foreign stock markets are positively correlated with Czech bond yields, but the positive dependence was gradually weakening, and in all cases changed at a certain moment into negative value of the correlation coefficients. The transition from positive to negative values occurred during the second half of 2012.

The correlations of the Polish bond yields with other stock markets do not differ remarkably from those with Polish stock markets. The correlation coefficients were negative, starting with values between -0.2 and -0.3 and gradually growing towards -0.1. In 2009 and 2012, periods of lower coefficients appeared similarly as with the domestic stock market.

The German and Austrian bonds had positive linear dependence with the foreign stock markets. Similarly, the coefficients have a declining trend. The values of coefficients fluctuate mostly between 0.2 and 0.4. Considerable deviations from an usual development occurred in 2009 when the correlation coefficients of the Austrian bond yields with the other stock markets raised, and in 2012 when the correlations between German bonds and Polish stock markets grew and the linear dependence of the Austrian bonds and German stocks relented.

Exchange rates Now, we will focus on the linear dependence of the exchange rates with stocks and bonds. At first, we will look at the relationship with stocks.

The Czech stock market has a quite stable negative correlation with PLN/CZK fluctuating around -0.3.[10] On the contrary, the correlation coefficients with CZK/EUR are very unstable. We can identify two periods (2009-2010 and 2012) when the time series of Czech stock returns and the CZK/EUR exchange rate are negatively correlated.

The Polish stock market is negatively correlated with PLN/CZK, as well as PLN/EUR. The correlation coefficients with PLN/EUR fluctuate around -0.25 and are quite stable, but the coefficients with PLN/CZK are lower and more volatile. The negative dependence signs that growing stocks in Poland are usually connected with appreciation of the Polish Zloty.

The correlations of German and Austrian stock markets with USD/EUR are positive. In 2012, the dependence slightly intensified.[11] In the case of the other currencies, the correlation is predominantly negative. Based on this fact, we may conclude that growing German or Austrian market are usually linked with appreciation of the EUR with respect to USD and depreciation with respect to the other currencies.

The correlations of bond yields with the exchange rates have very similar development as the stocks. From this reason, we will mention only the main distinctions. Generally, we may claim that the correlations are closer to zero regardless of the dependence direction.

In the case of the Austrian bond yields, we may notice that during the start of the financial crisis in 2008 and 2009, the correlations with PLN/EUR became positive contrary to the rest of the analysed period. On the other hand, the correlations with USD/EUR exceptionally dropped to negative values during the debt crisis in 2012.

Another important deviation is that the Polish bond markets have the cor-

[10] The negative linear dependence mean that the growing Czech market is usually connected with depreciation of the Czech Crown with respect to the Polish currency.

[11] The correlation of the both stock markets grew from 0.2 to around 0.4.

relations with the exchange rates positive, but the size in absolute terms and even the periods of intensifications of the dependence correspond.

At the same time, the correlation coefficients of the Czech bonds with PLN/CZK, moving mostly below, but very close to zero, started to be positive in 2012 and at the end of 2014 got above 0.2.

5.3.2 Contemporaneous Coefficients from the Structural VAR Model

The estimation of the SVAR model described in Equation 4.4 produces estimates of the coefficients capturing contemporaneous interactions among markets. Conclusions based on these coefficients will be discussed in the following subsection. While the spillover indices represent shares of the forecast error variance devoted to spillovers between particular variables, and the dynamic correlations show the linear dependence, the contemporaneous coefficients enable us to detect the direction and the intensity of contemporaneous effects between particular markets.

To facilitate the interpretation, we have firstly adjusted the coefficients in matrix B from Equation 4.4 in order to present the contemporaneous reactions. The diagonal parameters remain the same, but the off-diagonal elements in the matrix B are with opposite sign. The coefficients after such a modification are provided in Table 5.4. The coefficients may be interpreted as a percentage change in a particular variable resulting from a one percentage shock into a source variable.

There are a lot of coefficients which are statistically significant at least at 10 % level of significance (most of them even at 1 % level). Thus, we will concentrate during the interpretation only on the strongest links among variables. At the same time, we only roughly interpret the doubtful coefficients which we mentioned above.

Stock markets Also the contemporaneous coefficients indicate a very strong position of the Austrian stock markets among the analysed equity markets in Central Europe. The values of coefficients describing the effect of the Austrian stock markets on the other market lie between 0.55 and 0.66. It suggests than 1% increase of the ATX index should lead to a more than 0.5 % contemporaneous growth of the other stock markets. In the opposite direction, there are also statistically significant reactions of the Austrian stock market to the German

Table 5.4: **SVAR - Contemporaneous reactions (returns)**

		b1		s1		b2		s2		er	
czepol	**b1**	1	***	0,03		0,43	***	0,09	***	-0,07	***
	s1	-0,01		1	***	-0,01		0,09	*	-0,09	**
	b2	-0,19	***	-0,03		1	***	-0,08	***	0,08	***
	s2	-0,04	**	0,62	***	-0,03	*	1	***	0,23	***
	er	0,05	*	0,12		0,07	***	-0,53	***	1	***
czeger	**b1**	1	***	-0,11	**	1,59	***	-0,24	***	-0,04	
	s1	-0,02		1	***	0,10	***	0,04		-0,43	***
	b2	-1,49	***	-0,01		1	***	0,55	***	0,03	
	s2	-0,12	***	0,53	***	0,13	***	1	***	-0,11	***
	er	0,05	*	0,59	***	-0,15	***	-0,09		1	***
czeaus	**b1**	1	***	0,03		-0,18	***	0,15	***	-0,01	
	s1	0,01		1	***	-0,01		0,66	***	0,01	
	b2	0,42	***	0,06	*	1	***	0,15	***	0,03	
	s2	-0,07	***	0,11		0,06	**	1	***	-0,69	***
	er	0,08	**	0,13		-0,06	*	0,58	***	1	***
polger	**b1**	1	***	-0,06	**	-0,06	*	-0,07	**	0,06	***
	s1	-0,06	***	1	***	0,10	***	0,17	***	-0,10	**
	b2	0,26	***	0,10	***	1	***	0,18	***	0,00	
	s2	-0,05	**	0,43	***	0,19	***	1	***	0,06	
	er	0,03	*	0,02		-0,02		-0,17	***	1	***
polaus	**b1**	1	***	-0,04	*	-0,03		-0,12	***	0,06	***
	s1	-0,04	**	1	***	0,01		0,55	***	0,03	
	b2	0,32	***	0,13	***	1	***	0,18	***	0,06	**
	s2	-0,05	*	0,22	***	0,13	***	1	***	0,83	***
	er	0,02		-0,06		-0,01		-0,78	***	1	***
geraus	**b1**	1	***	0,49	***	-1,11	***	0,13	*	0,03	
	s1	0,12	***	1	***	-0,06	***	0,63	***	0,00	
	b2	1,19	***	-0,01	***	1	***	0,01		-0,01	
	s2	0,22	***	0,27	***	-0,15	***	1	***	0,10	***
	er	0,16	*	0,15		-0,09		-0,06		1	**

Notes: The groups represent the combinations of countries where AUS is an abbreviation for Austria, CZE for the Czech Republic, POL for Poland, and GER for Germany. B is a representative of the bond yields, s represents the stock market, and er the exchange rate market. The number 1 labels the first country in a particular combination of countries, the number 2 stands for the second country. Column description denotes the source markets that contribute to the particular market in the rows.
***, **, and * denote levels of significance (1%, 5%, and 10%, respectively)

(Estimated in Matlab)

and Polish stock price movements, but the response is much weaker (0.27 and 0.22, respectively).

The PX index seems to have approximately similar effects on the Polish (0.62) and German (0.53) equity markets as the Austrian stock index. At the same time, a slightly weaker contemporaneous reaction may be expected from the German market on the shock to the WIG30 index (the coefficient has value 0.43).

As the until now presented results indicate, the stock markets are generally very closely linked. The quite high contemporaneous coefficients may be perceived to be a confirmation of this conclusion. Simultaneously, we have repeatedly identified the Austrian stock market as a source of spillovers to the other markets.

Bond yields As we have already mentioned, we do not have confidence in the correctness of the estimates of coefficients describing the link between the bond yields. Therefore, we omit their interpretation. In spite of that, the high coefficients may be taken as a sign of strong interdependencies between the bond yields.

Link between bonds and stocks The contemporaneous coefficients reveal a significant mutual link between German stock and bond markets. The comparison of the parameters suggest that there is stronger reaction of bond yields on the movements in the German stock markets than in the opposite direction. The size of the parameters states that German bond yields grow by approximately 0.5 % if the German stock index increases by 1 %, while the stock markets respond to 1% growth of bond yields only by a 0.12% and 0.19% increase.

At the same time, quite high contemporaneous spillovers of returns from Austrian stock to Austrian bonds within the groups with the Czech and Polish markets have been discovered. The coefficients have values 0.15 and 0.18 suggesting that bonds react by almost a fifth. Additionally, the Austrian stock returns seem to be influenced also by the German bonds that conveyed on average more than 20 % of their movements.

Simultaneously, considerable international cross-market linkages has been discovered. In particular, the German bond yields and the Austrian stock market bear a significant contemporaneous impact on foreign stocks and bonds, respectively. A 1% increase of the German bond yields leads, on average, to a 0.22% growth of the Austrian stock index and 0.1% growth of the Czech and Polish stocks. On the other hand, the Austrian stock market contemporaneously contributes to the other countries' bond yields. The size of the effects lies between 0.13 % and 0.15 % as responds to a 1 % change, and their direction is positive for Czech and German, and negative for Polish bond yields.

Exchange rates The coefficients describing the contemporaneous relationship between bond yields and the particular exchange rate are often very low and only exceptionally significant. In the direction from the exchange rate to bonds, there is only one statistically significant coefficient across all groups that indicates that the Polish bond yields respond to a 1% increase of the PLN/CZK (PLN/EUR) by a 0.08% (0.06%) growth.

The contribution of bonds to the exchange rates is also very weak. We have obtained only two coefficients significant at 1% level which tell us that the CZK/EUR exchange rate usually declines when German yields grow. The second coefficient indicate that a 1% growth of Polish bonds should result in 0.07 % depreciation of Polish Zloty with respect to the Czech Crown.

The changes of the exchange rates have also an impact on the stock markets. The highest coefficients are connected with the Austrian stock index. Whereas in the case of the CZK/EUR the depreciation of the EUR supports the Austrian stock market, in the case of the PLN/EUR an increase of the ATX index results from the appreciation of the Euro. This discrepancy may be partly explained by the quite high negative correlation of the PLN/EUR with the CZK/EUR and USD/EUR exchange rates. The results thus strongly depend on the involved exchange rate.

Another two coefficients deserve to be mentioned and interpreted. The PX index responds by 0.43% increase to the 1% appreciation of the Czech Crown with respect to Euro and the Polish stock index grows by 0.23 % as the result of 1% depreciation of the Polish Zloty with respect to the Czech Crown.

In the opposite direction, from the stock markets to the exchange rates, also coefficients higher than 0.5 appear. The strongest impact is revealed for the Austrian stock market where the contemporaneous coefficients suggest that 1% growth of the stocks leads to a 0.58% appreciation of EUR to CZK and a 0.78% depreciation of EUR to PLN.[12] In addition, we have discovered a positive effect of the Czech stocks on the CZK/EUR (depreciation of CZK) and a negative impact of the Polish stock index on the PLN/CZK (appreciation of PLN). The size of the effect is by about a half.

5.4 Summary of Findings

In this final section, we try to summarize and compare the main result obtained by the individual methods.

Total spillovers The level of total spillovers among the markets was assessed by the total spillover indices which indicate that the highest degree of interconnections is present among the German and Austrian markets. We may guess that the higher dependence partially relates, for instance, to higher integra-

[12] The opposite direction is probably related to the negative correlation of the exchange rates CZK/EUR and PLN/EUR.

tion,[13] common language, and a fact that both Germany and Austria are more economically developed countries than the Czech Republic and Poland.

The development of the total spillover indices reveals an intensification during periods of growing uncertainty. Firstly, the spillovers grew after the beginning of the financial crisis in the United States of America. The crisis spread also in Europe, and the spillovers became more intensive (especially the volatility spillovers).

Another burst of spillovers is probably connected with the sovereign debt crisis that has taken place since the year 2009. Although the crisis primarily hit other members of the eurozone (Greece, Cyprus, Ireland, Spain, Portugal, Cyprus), negative consequences of the crisis had impact on all members of the eurozone. The confidence in the countries affected by the crisis (esp. Greece) even weakened during the year 2011, and the lower confidence of the investors appeared in the whole Europe. In this period, the return and volatility spillovers reached their highest values.

We can conclude the investigation of the total spillover indices by saying that we can confirm the outcomes of earlier studies.[14]. The estimates of the dynamic indices helped us to reveal an intensification of spillovers during the periods of higher uncertainty.

Stock markets Based on the results of all in this thesis applied methods, we have found evidence that there exist strong linkages among the equity markets in Central Europe. Investigation of the development of the interconnections sign tendency for gradual weakening of the linkages. Despite the decline, the spillovers usually intensify during periods of increased uncertainty. Regarding the direction of the influence, the correlation coefficients, as well as the contemporaneous coefficients confirm positive relationship between returns of the markets.[15]

The Austrian stock market was repeatedly identified as the most influential stock market which has a considerable impact on the other equity markets. Similar conclusion was obtained in e.g. Stoica & Diaconasu (2013b).

The investigation of the development of the spillovers helped us to discover that the impact is different for each country and evolves over time. While

[13]Both countries have been more than 20 years members of the European Union, the Czech Republic and Poland joined the European Union on 1^{st} May 2004.

[14]For instance, Diebold & Yilmaz (2012; 2009), Summer, Johnson, & Soenen (2009), Louzis (2013)

[15]Consistent with results and explanations of e.g. Ehrmann, Fratzscher, & Rigobon (2011) and Andersen, Bollerslev, Diebold, & Vega (2007).

the Austrian equity market was a net contributor to the German stock market predominantly in the first half of the analysed period, its net contribution to the Czech stocks strengthened mainly in the second half. The Polish stock market was influenced by the Austrian one, except of several short periods, during the whole period. Shocks in German stocks were transmitted to the Czech and Polish markets especially during the years 2012 and 2013.

Another interesting finding is that the Czech and Polish stock markets were recognized as sources of shocks during the period following the bankruptcy of Lehman Brothers. An explanation could be that these markets are more susceptible to global shocks and act as an intermediary of the global financial crisis for the German and Austrian markets. During the same period, also Dovhunová (2014) reached a similar conclusion for the Czech stock market and ascribed it to the indirect influence of some other non-included country.

Finally, the analysis of the volatility spillovers revealed the Austrian stock market is even more influential than in the case of return spillovers.

Bond yields The results of this thesis discovered several interesting findings about bond markets in Central Europe. Generally, we have found an increasing influence of the bond markets on the other financial markets that reached its peak during the year 2012.

The German bonds were labelled as the most important bonds in Central Europe. Their contribution leads primarily to the Austrian bonds. To the other countries, their net impact strengthened mainly in the period 2011-2013. During the same period, also slightly lower net spillovers from Austrian bonds to the Polish and Czech bond yields were evident. The Czech market was net contributor to the Polish bonds in 2013.

All applied methods agree on the conclusion that there are very strong interconnections between bonds of Germany and Austria. For example, the correlation coefficients reached during a major part of the analysed period values around 0.9. At the end of the year 2011, however, a sudden drop of correlations occurred. Similarly, the spillovers in both directions, identified by the gross pairwise spillover indices, significantly weakened. In late 2012, the intensity of interconnections again strengthened. Analogous development was captured by Moloney, Killeen, & Gilvarry (2014).

As an explanation for this deflection, a connection with the sovereign debt crisis could be taken into account. Just in this period, several events that could have also implications for the analysed countries happened. Firstly, a new plan to resolve the crisis was agreed by the eurozone members. One of the main points of this agreement was "asking holders of Greek debt to cut the value of their holdings by 50 %" (Voss 2012). Secondly, on October 23, 2011, Germany offered 6 billion of 10-year bonds, but the auction failed (only 3.6 billion was placed). This result showed that even the solvent economies, like Germany, can be affected by the crisis. Another event which could contribute to diffusive relations between Austrian and German markets happened in January 2012 when Standard & Poor's cut the Austrian rating from AAA to AA+ (Voss 2012).

A similar putative connection with the sovereign debt crisis may be found also in the case of the other combinations of countries. During the years 2010-2012, the conditional correlation coefficients are slightly lower than in the remaining part of the analysed period.[16] At the same time, the spillovers quantified by the gross pairwise spillover indices are, except of the influence of German and Austrian bonds, lower. This may be perceived as a signal of widening spreads, depending on confidence in the individual countries, that come to light also in Central Europe. This interpretation is in accordance with the conclusions of Conefrey & Cronin (2013). In spite of this, a growing impact of the Austrian and German bonds (members of the eurozone) during the most tense period is still indisputable.

Domestic link between bonds and stocks The investigation of the spillovers between domestic stock and bond markets also detects a lowering influence of stocks and a growing impact of bonds. At the beginning of the period, the stock market was a net contributor to the bond yields in each country, but this has changed, and at the end, the shocks spilled over rather from bond yields to the stocks.

The correlation coefficients, as well as the contemporaneous coefficients correspond to positive relation between the markets. It suggests that growing bond yields are usually connected with growing stock markets and vice versa. An exception is the connection between the markets in Poland where both the correlation and contemporaneous coefficients are negative.

If we accept the assessment of Rigobon & Sack (2003), the positive relation between stock returns and bond yields may be connected with the ascendancy

[16] Also Moloney, Killeen, & Gilvarry (2014) documented fragmentation of the peripheral countries.

of stocks. The decreasing trend of correlation coefficients is consistent with this conclusion. As the bonds become more influential, the correlation weakens.

At the same time, quite strong interconnections between stock and bond markets were identified by all methods in Germany and Austria, however, as the correlation coefficients sign, the intensity of dependence was during the analysed period decreasing. Only during the tensest period of the sovereign debt crisis, the dependence intensified, especially in Germany. On the other hand, in Austria, the connection between stock and bonds relented, probably partly because of the lowered rating of Austria.

International link between bonds and stocks The results presented in this chapter also reveal considerable international cross-market interconnections in Central Europe. Similarly, as in the previous case, we have identified an obvious shift from dominance of stocks to ascendency of bonds. The stock markets were contributors to the foreign bond markets during the years 2008-2010. On the other hand, bonds, especially the German bonds, became transmitters of net spillovers to stocks during the European debt crisis in 2011 and 2012. In addition, all stock markets were net contributors to the Polish bonds in 2012.

Regarding the direction of the dependence and causality, we have obtained quite consistent results from the investigation of the correlation coefficients and contemporaneous coefficients. In each country, the relation of the bond yields with foreign stock markets is different. In the Czech Republic, the correlation coefficients were in the beginning of the period positive, but gradually declined close to zero, to moderately negative values. At the same time, the contemporaneous coefficients describing the effect of the Czech bonds on changes in Austrian stocks are low, but positive.

Polish bonds are pretty specific. Their correlation coefficients with foreign equity markets, as well as the contemporaneous coefficient describing reaction on the changes in Austrian stock index are negative. Finally, German and Austrian bond yields are positively correlated with stock returns of the other countries.

Exchange rates Analysis of the return and volatility spillover indices identified the foreign exchange market primarily as a receiver of the shocks from the other markets. The contribution of stocks and bonds to exchange rates corresponds to the preceding conclusions because the spillovers from the equity markets preponderated in the beginning of the analysed period, and from bond markets in the second half. Spillovers from both markets intensified during the abovementioned crisis periods.

The correlation coefficients and the contemporaneous coefficients from the SVAR model detect a link between bond yields that is quite low, but the results agree on the fact that bond yields usually grow when the domestic exchange rate depreciates and vice versa. According to the structural coefficients, more likely bond yields react to the changes in the exchange rates than conversely. It would correspond to a notion that the bond yields reflect inflation expectations (Ehrmann, Fratzscher, & Rigobon 2011).

In the case of stock markets, the interconnection with the exchange rate is not so unambiguous. The correlation coefficients and the contemporaneous coefficients depend on the involved exchange rate and suggest quite diverse conclusions. It is not possible to find a pattern that would describe the connection between these markets. On the other hand, according to the conditional correlation coefficients, the direction of the dependence between two concrete markets generally stayed unchanged during the whole period.

Unarguably, we have found very intensive connections of the exchange rates with stock markets. In particular, the Austrian stock index reports very strong linkage with all exchange rates.

Chapter 6

Conclusions

This thesis is devoted to the interdependencies among the stock, bond and foreign exchange markets in the Czech Republic, Austria, Germany and Poland in the period 2007-2014.

In order to provide a complex view on the linkages among the markets, we employed two kinds of spillover indices (from the generalized and structural VAR models), dynamic correlations from the multivariate GARCH model, and contemporaneous coefficients from the structural VAR model. The results obtained by these methods describe the interconnections from different angles. The spillover indices are based on the shares of the forecast error variance ascribed to spillovers between particular markets. The dynamic correlation coefficients help us to capture dynamic evolution of the linear dependence between two particular markets, and, finally, the contemporaneous coefficients from the structural VAR model describe a reaction of a market to change in another particular market occurring in the same time period. Thank to the results, we are able to obtain a quite comprehensive picture of the interdependencies.

According to our knowledge, this set of methods has never been used in one study before. We believe this thesis offers a supplemental insight into the interdependencies among financial markets in Central Europe. Additionally, we have estimated dynamic correlation coefficients that will find application in many areas of financial theory and practice. For instance, the drop of correlations between Austrian and German bond yields demonstrate the necessity of continuous monitoring of the correlations. Neglecting this change could have serious consequences, for example, in risk management or in portfolio allocation.

At first, we shortly introduced results of the relevant literature concerning the spillovers in Central Europe, as well as in the rest of the world. Then, the applied methods were theoretically presented, and basic characteristics of the daily data were described. The main part of the thesis was dedicated to the results of the individual methods and to the summary of these results.

As the results were systematically summarized in Section 5.4, we will repeat only the main and most important conclusions. The presented results show that the spillovers evolve over time and their intensity is growing during periods of higher uncertainty (during the financial crisis, or the European sovereign debt crisis). There is an obvious trend that reveals a change of dominance that shifts from stocks to bonds. While the strongest impact of stocks on the other markets was during the beginning of the financial crisis, the bonds were main contributors especially during the sovereign debt crisis in the second half of 2011 and in 2012.

The results in Chapter 4 sign that the spillovers and linkages between two parts of national financial markets can noticeably differ across countries. One of the most remarkable differences was detected in the case of the correlation coefficients between national stock and bond markets. In this case, the correlation coefficients in Poland are, in contrast to the other countries, negative during the whole period. Several other distinctions were documented in Chapter 4

We have discovered not only a very strong international link between the same markets, but also quite intensive international cross-market relationships. Generally, the most closely related markets are between Austria and Germany. In addition, the German bond market and the Austrian stock market appear to be the most influential markets in Central Europe with a considerable impact on most of the analysed assets at least during certain periods.

The aim of this thesis was to robustly and complexly describe the interconnections among the markets in Central Europe. As it is very broad topic, we strove to achieve this task as much as possible. Unfortunately, we were not able to devote more space to certain issues. In other words, we may consider this thesis as an inspiration that can underlie further research.

In particular, we will mention the identification of the structural VAR coefficients through heteroskedasticity in structural shocks. The estimation in this thesis could be potentially improved by splitting the period into sub-periods, or by reduction of the number of included variables. The current specification, unfortunately, does not appear to be optimal. Generally, this method seems very promising and would certainly find utilization in many other areas.

At the same time, we provide only the description of the linkages (and their changes) without examining factors behind them. Recently, several studies examining these factors have been published, but the process remains still poorly understood. Additionally, we believe that some changes, e.g. the decrease of correlations between the German and Austrian bonds, would deserve to be explored in more details.

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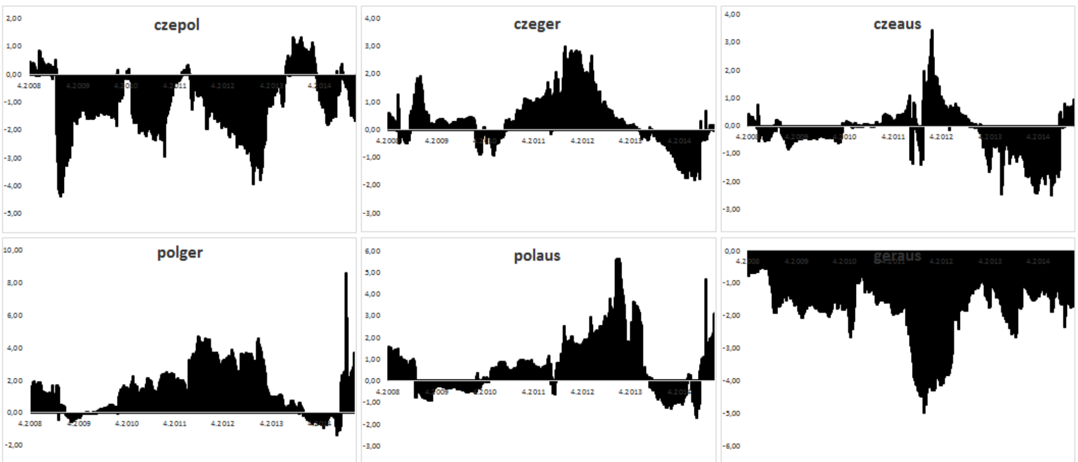
Appendix A

Additional Figures

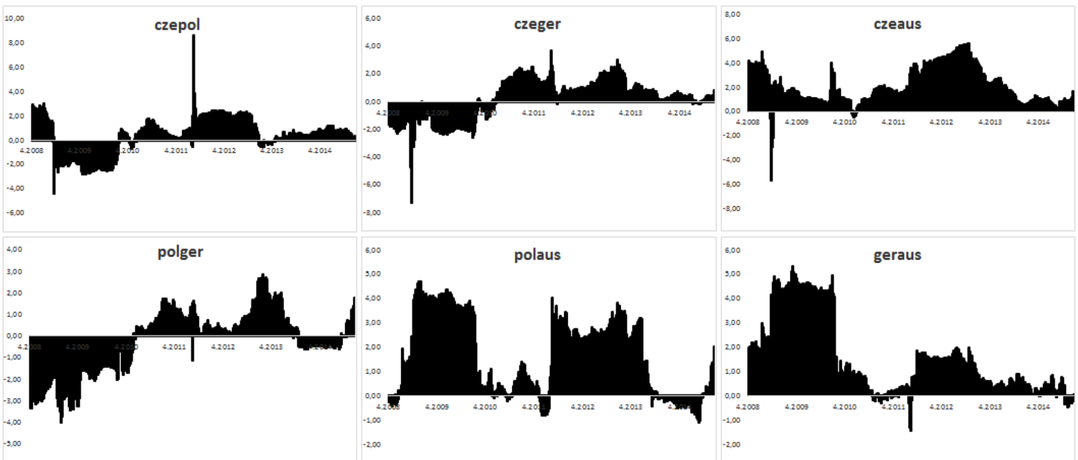
Figure A.1: **GVAR - Net pairwise international spillover indices between bond markets (volatility)**



Notes: Evolution of the net pairwise spillover indices between bond markets. Positive values denote periods of net spillovers from the second country's bonds to the first country's bonds, and vice versa.

(Estimated in Matlab)

Figure A.2: **GVAR - Net pairwise international spillover indices between stock markets (volatility)**

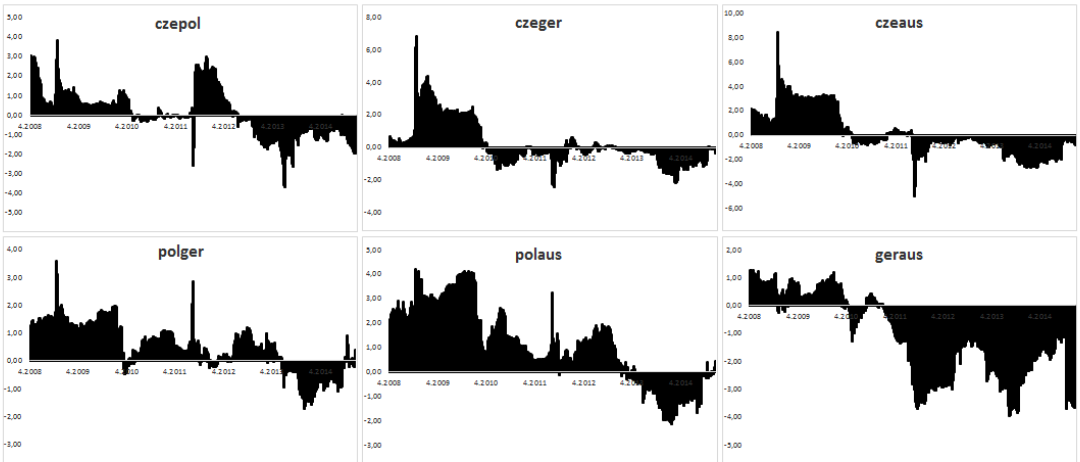


Notes: Evolution of the net pairwise spillover indices between stock markets. Positive values denote periods of net spillovers from the second country's stocks to the first country's stocks, and vice versa.

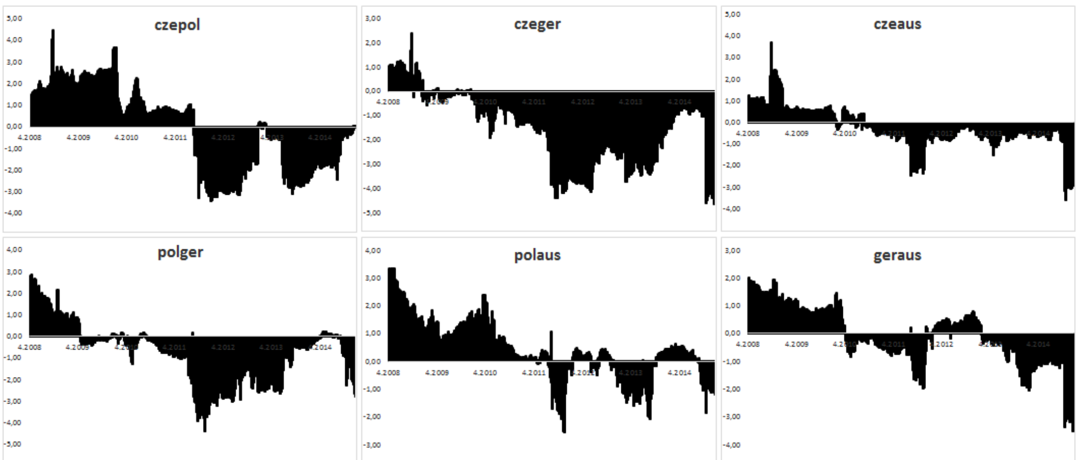
(Estimated in Matlab)

Figure A.3: **GVAR - Net pairwise indices of international spillovers from stock to bond markets (volatility)**

(a) Stock2 to Bond1



(b) Stock1 to Bond2

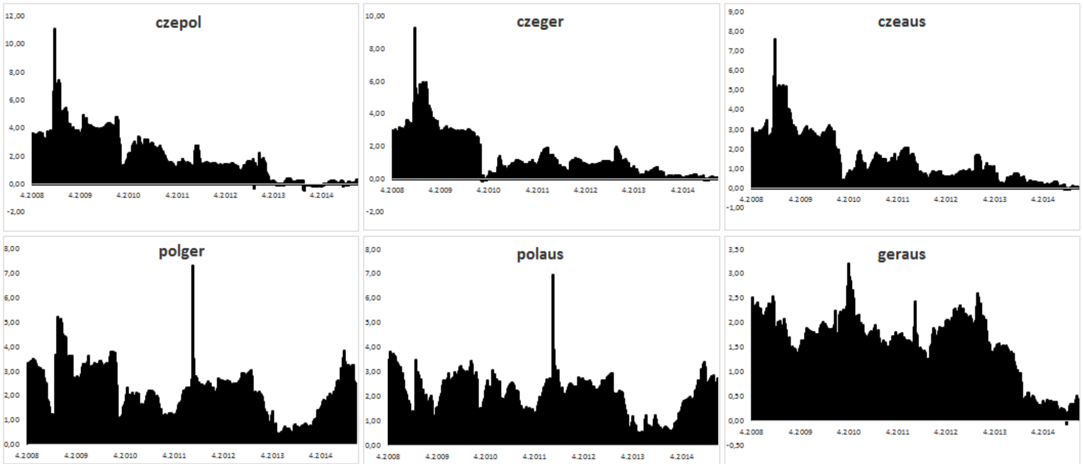


Notes: Evolution of the net international pairwise spillover indices between stock and bond markets. Positive values denote periods of net spillovers corresponding to the description.

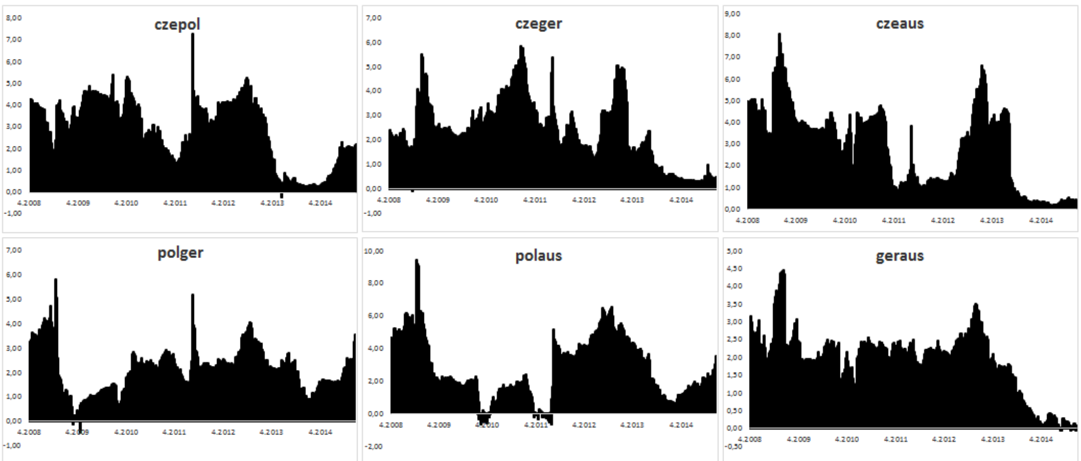
(Estimated in Matlab)

Figure A.4: **GVAR - Net pairwise spillover indices from stocks to exchange rates (volatility)**

(a) Stock1 to exchange rate



(b) Stock2 to exchange rate

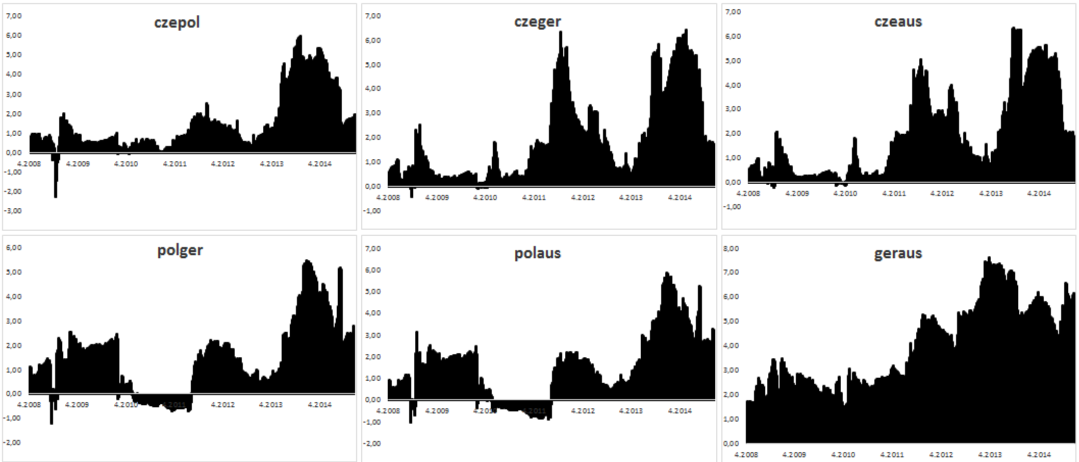


Notes: Evolution of the net international pairwise spillover indices between stocks and exchange rates. Positive values denote periods of net spillovers from the stocks to the exchange rates.

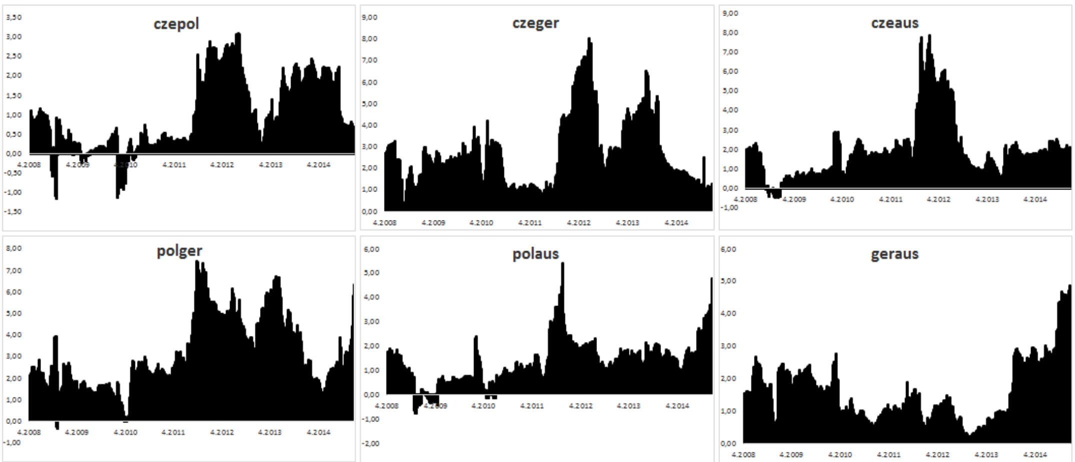
(Estimated in Matlab)

Figure A.5: **GVAR - Net pairwise spillover indices from bonds to exchange rates (volatility)**

(a) Bond1 to exchange rate



(b) Bond2 to exchange rate

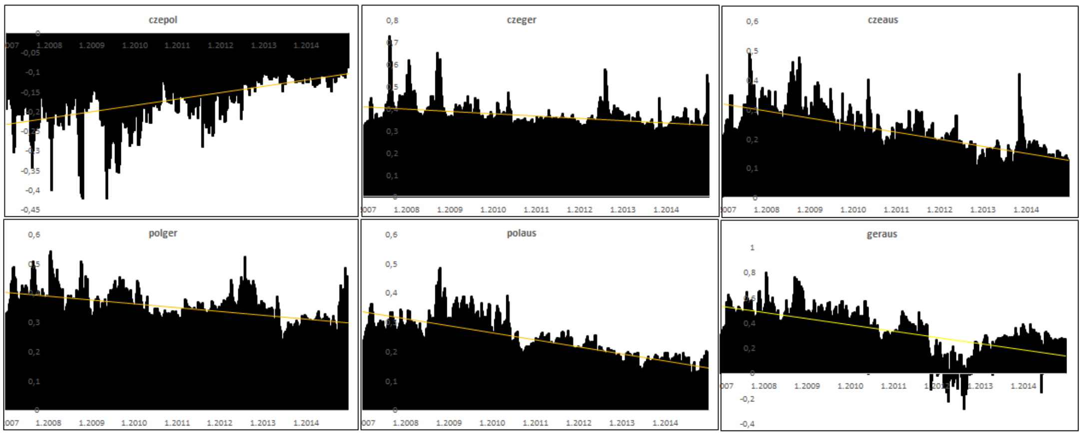


Notes: Evolution of the net international pairwise spillover indices between bonds and exchange rates. Positive values denote periods of net spillovers from the bonds to the exchange rates.

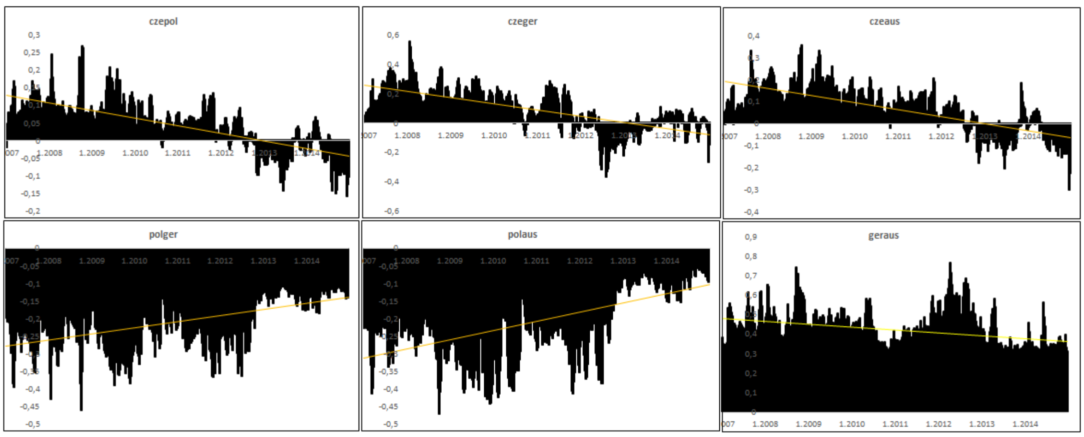
(Estimated in Matlab)

Figure A.6: **International cross-market correlations**

(a) Stock1 and Bond2



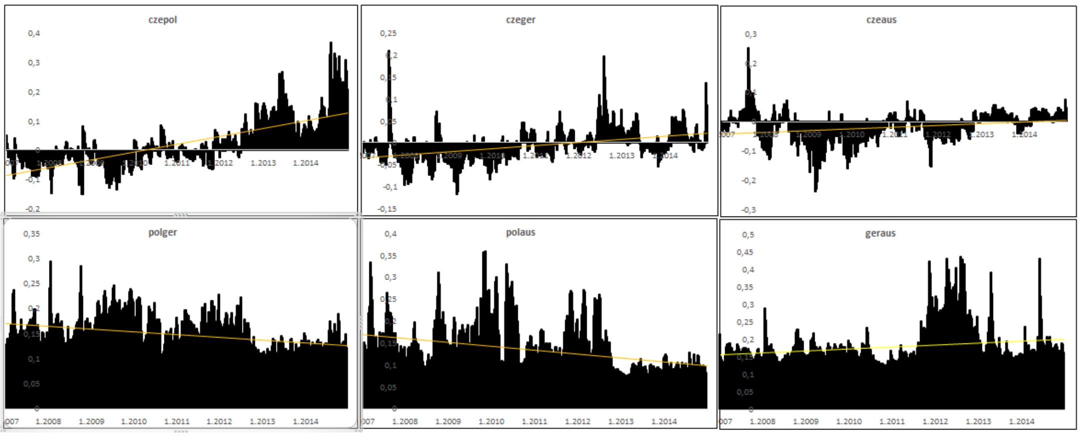
(b) Stock2 and Bond1



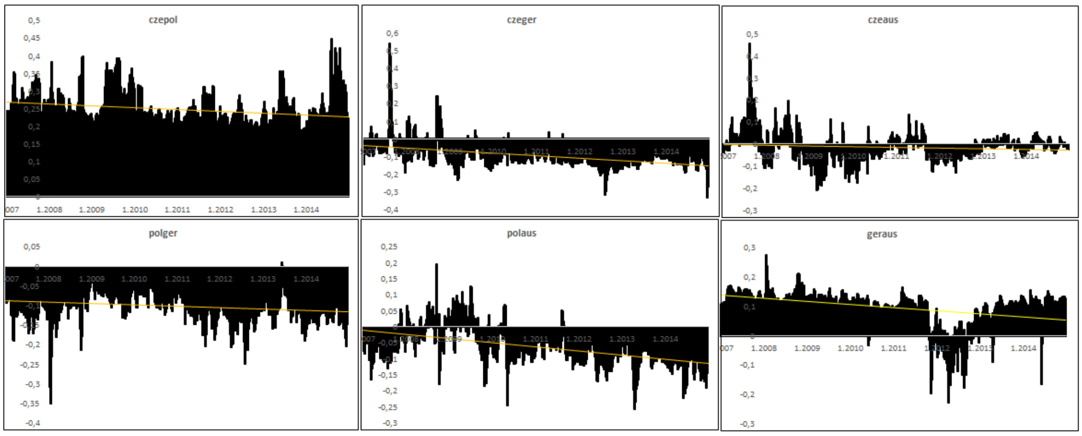
(Estimated in Matlab)

Figure A.7: **Correlations between bonds and exchange rates**

(a) Bond1 and ER



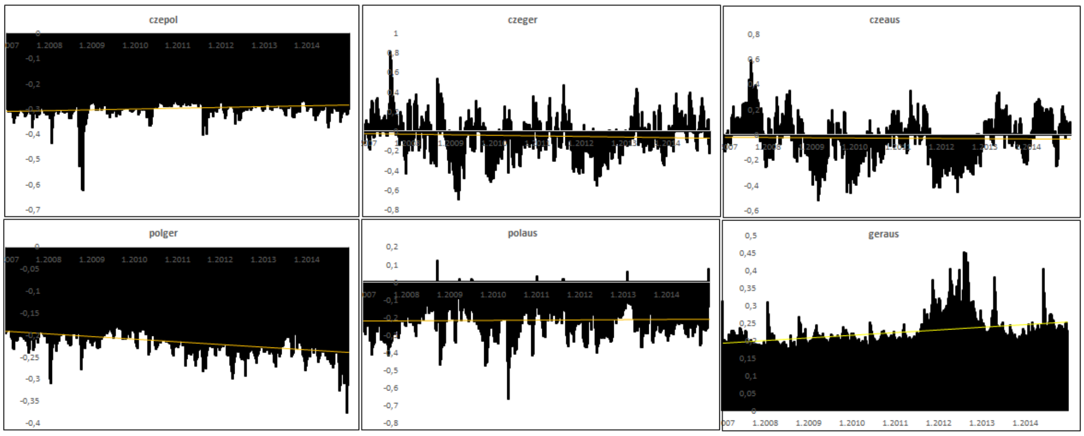
(b) Bond2 and ER



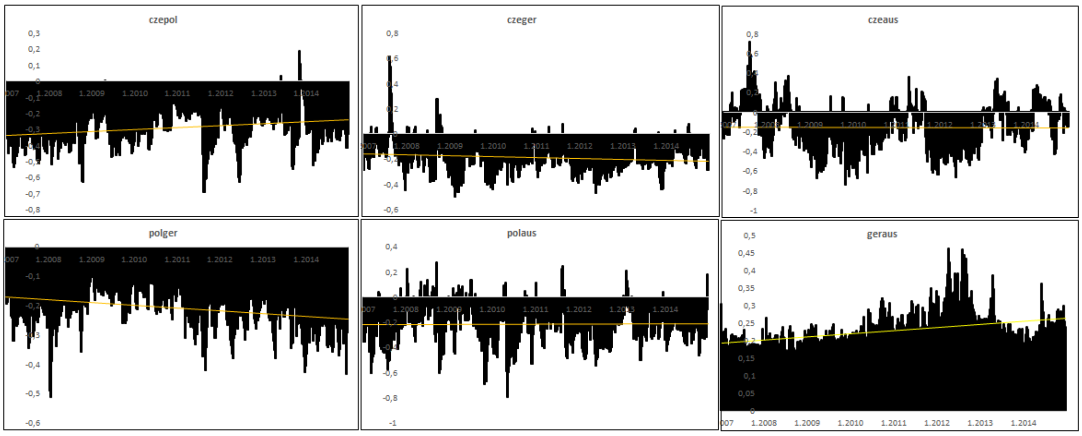
(Estimated in Matlab)

Figure A.8: **Correlations between stocks and exchange rates**

(a) Stock1 and ER



(b) Stock2 and ER



(Estimated in Matlab)

Appendix B

Content of Enclosed File

There is a file enclosed to this thesis which contains empirical data and Matlab source codes.

- Folder 1: Source codes
- Folder 2: Empirical data