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Essays on Volatility and Contagion in Financial Markets

Kersti Harkmann

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Essays on Volatility and Contagion in Financial Markets

KERSTI HARKMANN

TALLINN UNIVERSITY OF TECHNOLOGY
School of Business and Governance
Department of Economics and Finance
This dissertation was accepted for the defence of the degree on 21 January 2021

Supervisor: Professor Karsten Staehr, Ph.D.
Department of Economics and Finance
Tallinn University of Technology
Tallinn, Estonia

Opponents: Anita Suurlaht, Ph.D.
Assistant Professor in Banking and Finance
UCD Michael Smurfit Graduate Business School
University College Dublin
Dublin, Ireland

Christopher Hartwell, Ph.D.
Professor and Head of the International Management Institute
ZHAW School of Management and Law
Zürich University of Applied Sciences
Zürich, Switzerland

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted elsewhere for a doctoral or equivalent academic degree.

Kersti Harkmann

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KERSTI HARKMANN

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List of Publications

The list of the author's publications, on the basis of which the thesis has been prepared:

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II Harkmann, Kersti (2020). Integration of the Baltic stock markets with developed European markets. *International Journal of Finance and Economics,* forthcoming, DOI: https://doi.org/10.1002/ijfe.2165. (ETIS 1.1.)

III Filipozzi, Fabio; Harkmann, Kersti (2020). Optimal currency hedge and the carry trade. *Review of Accounting and Finance*, vol. 19, no. 3, pp. 411–427. DOI: http://dx.doi.org/10.1108/RAF-10-2018-0219. (ETIS 1.1)

Author’s Contribution to the Publications

I The author of the thesis is the sole author of the article.

II The author of the thesis is the sole author of the article.

III The author of the thesis was mainly responsible for the literature review and the empirical investigation. The author of the thesis co-wrote the article and acted as the corresponding author in the submission and publishing processes.

Introduction

Ever since the modern portfolio first became popular, one of the guiding principles of financial theory has been that investors who want to be on the safe side should keep their portfolios diversified. The integration of financial markets has been accompanied by an increase in financial openness internationally and a growing number of investors investing abroad in search of the benefits of diversification.

The Global Financial Crisis (GFC) that followed the bankruptcy of Lehman Brothers in September 2008 served as a wake-up call for both academics and practitioners and drew attention to the extreme comovements in financial markets. The crisis spread across borders and caused unexpected comovements in the markets, which challenged efforts at diversification. More generally, recent decades have seen increasing globalisation and financial integration, which in turn may have accelerated the spillover of shocks across markets and countries.

It is evident that capital markets have continued to develop and become much more interconnected, and they move quickly in reaction to news and to changes in the world, but it is still a challenge to predict periods of extreme volatility and comovements. Market crashes can be short-lived, as illustrated by events after the earthquake in Japan in March 2011, but they can also be followed by deep economic recessions like the Great Depression in the 1930s. Figure 1 shows key stock market indices from the USA, Germany and Sweden from 1994 to 2020. The figure provides a first-hand illustration of the substantial volatility and covariation of these stock market indices.

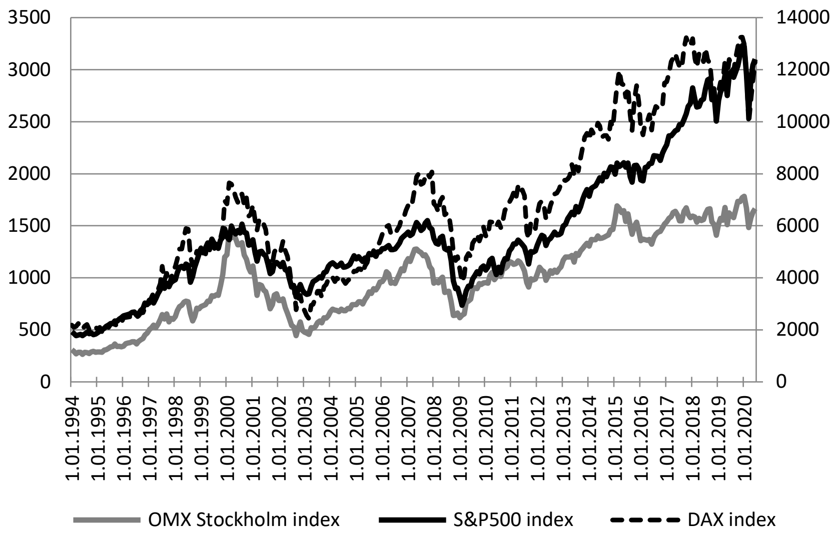

Figure 1. *S&P 500 index, DAX index and OMX Stockholm index*
Source: World equity indices, Bloomberg

Note. Figure 1 depicts the S&P 500 index from the USA and the Swedish stock market index OMX Stockholm on the left vertical axis and the German stock market index DAX on the right vertical axis.

Laeven & Valencia (2018) report that between 1970 and 2017 there were altogether 151 systemic banking crisis events around the world, meaning there were around three major banking crises each year. On top of these, Laeven & Valencia (2018) also identify 236 currency crises, and 74 sovereign debt crises. Many of these events started from unexpected shocks that affected financial markets seriously and caused extreme volatility and comovements for extended periods of time.

More recently, the Global Financial Crisis and the European Debt Crisis that started in late 2009 have received a lot of attention because of their contagious nature. The outbreak of the Covid-19 pandemic means that there is once again much attention on the topic of the extreme volatility and cross-market contagion in financial markets.

The Global Financial Crisis that evolved after the bankruptcy of the Lehman Brothers and the subsequent European Debt Crisis led to extensive financial market fluctuations, and these developments have been the main sources of motivation for this thesis. The GFC caused extreme volatilities and comovements to occur simultaneously in financial markets and raised the question of whether these comovements were temporary or longer-lasting, perhaps because financial markets were becoming more highly integrated.

The thesis studies the volatility, contagion, and incidental comovements in financial markets from two dimensions: how the comovements can be measured in the short and long-term perspectives, and how an investor should deal with these comovements. Understanding the comovements in financial markets and how to measure them might help both participants in financial markets and decision makers to take suitable steps to tackle financial shocks. As the beginning of the 21st century has shown, unexpected shocks appear repeatedly and create endless research questions.

The existing literature on comovements in financial markets has mainly concentrated on the relationships between financial indices in developed, large and liquid markets (Forbes & Rigobon, 2002; Chiang et al., 2007; Asongu, 2012; Mobarek et al., 2016; Panda & Nanda, 2017). The literature on comovements in financial markets is less extensive for emerging market economies and smaller developed economies, and this also applies to the literature on spillovers and contagion in the CEE region.

The vast part of the literature on correlation and cointegration analysis has been centred on the larger financial markets in the CEE region, principally those in Poland, Hungary and Czechia.[1] The literature on the comovements between the Baltics and developed financial markets is quite limited with a few notable exemptions (Maneschiöld, 2006; Syllignakis & Kouretas, 2011; Olbrys & Majewska, 2014; Boţoc & Anton, 2020). The first two publications in this thesis help address the gap in the literature about short and long-term comovements by putting a special focus on the Baltic financial markets. It should be noted that the past has shown that under certain circumstances even relatively small financial markets can cause volatility and contagion.

Another area connected to the time-varying nature of comovements and cross-correlations between financial markets that has not received enough attention in the literature is the question of how to preserve wealth in portfolio management and how the optimal hedging level is linked to the returns of underlying assets in the form of bond yields. Some aspects of hedging currency exposure have been addressed, but there is no comprehensive assessment of different hedging strategies and their

[1] See for instance Gilmore & McManus (2002), Voronkova (2004), Égert & Kočenda (2007), Syriopoulos (2007), Gilmore et al. (2008), Horváth & Petrovski (2013), Gjika & Horváth (2013), and Hung (2019).

relationship to currency carry trades. The existing literature suggests that the hedging strategy depends on the composition of the portfolio, and the correlations and covariance between different asset classes, and also on changes in the covariance structure (Haefliger et al. 2002; Ackermann et al. 2016; de Boer et al. 2019). However, the link between the hedging strategy and currency carry trades has received little attention. The third publication in this thesis adds to the literature by helping to disentangle the question of how the optimal hedging strategies rely on the comovements of underlying assets and how the optimal hedge levels are linked with carry trades.

Three approaches and methods are used in the thesis. First, it studies the effects of shocks and the comovements in financial markets by taking a close look at the correlations between selected stock markets. The thesis presents evidence that in times of crisis, the dynamic conditional correlations might increase, and this can be attributed to increased financial integration but also captures the moments of contagion. Second, the thesis studies the long-term relationships between stock markets using cointegration analysis. Third, it studies how investors could respond to volatility and covariations in the currency markets to hedge the currency risk of their bond investments by computing and assessing different hedging strategies. The thesis improves the understanding of the challenges that stem from volatility, comovements and contagion in financial markets.

The thesis consists of three articles, of which one has been published and two are forthcoming. The articles focus on financial markets and their intrinsic patterns of volatility and cross-market contagion. The first two articles use stock market data from selected countries, while the third one considers currency and bond markets.

The rest of the thesis is organised as follows. Section 1 discusses the characteristics of volatility, comovements and contagion and how they can be measured. It further discusses how the dynamics of comovements and covariations feed into portfolio theory. This is followed by an overview of the three publications of the thesis. Section 2 contains the final comments summarising the contributions of the articles and presenting possible avenues for future research. Appendices I-III contain the three publications of the thesis.

1 Volatility and contagion

Shocks in financial markets create periods of volatility when prices swing wildly and rapidly between very high and low levels. These periods can often be quite short but they can also translate into financial crises or prolonged periods of instability. It has been observed that if volatility increases in one market, similar comovements may coincide and occur even in countries that are not closely linked to the country where the crisis that caused the volatility originated (Karolyi & Stulz, 1996; Serwa & Bohl, 2005; Corsetti et al., 2005; Lee et al., 2007; Chiang et al., 2007). Such movements and the simultaneous occurrence of instabilities are often manifestations of contagion.

In a broad perspective, contagion is often used as a synonym for spillovers of shocks or disturbances from one financial market to another. However, the term contagion has been used and preferred in the literature since the 2000s because of the need to differentiate between comovements that occur in response to fundamental causes like common shocks and tight links between countries, and comovements that occur in response to changes in investor sentiment. Masson (1998) helps to elucidate the differences between comovements caused by fundamentals and those caused by spillovers. Masson (1998) argues that simultaneous comovements can be explained by monsoonal effects, spillovers and pure contagion. A monsoonal effect, or global shock, occurs when the world is hit by a common shock that causes volatility everywhere and markets react simultaneously in a similar way. Indeed it has been shown that global shocks, such as those from changes in the US economy, are the main drivers of comovements in stock markets (Gomes & Taamouti, 2016; Chen, 2018).

One of the earliest works to show that price changes and volatility in the markets cannot always be explained by changes in the underlying economic fundamentals was a study by Robert Shiller (1981, 2014). He found that a large part of the volatility of stock prices could not be attributed to changes in fundamentals or news about fundamentals but was instead connected to an unobservable fear of uncertainty among investors (Shiller, 1981). Market sentiment has also been the focus of the works of Joseph E. Stiglitz, who advocates the view that financial markets fail to function perfectly because of information asymmetries (Löfgren et al., 2002). This school of thought has been developed further by Benhabib et al. (2016) for example, who show how information frictions can cause sentiment-driven changes in markets that can in turn cause volatility to rise, resulting in a financial crisis. Nițoi & Pochea (2020) show that the beliefs of investors can move the markets in the direction of those beliefs and this may increase the correlations between markets; negative sentiments are especially important in intensifying comovements.

When there are spillovers and interdependence, shocks in one market cause comovements in other markets and spread across borders because the markets are closely connected through financial and trade links. This also means that the more financially integrated markets are, the more likely spillovers and comovements are (Chen, 2018). Where there is less integration, the financial markets are driven by country-specific factors to a larger extent.

In cases of pure contagion as described by Masson (1998), simultaneous comovements and crises are caused by events elsewhere but cannot be explained by global shocks, fundamentals or close links between the countries. The emergence of simultaneous extreme comovements can be explained by changes in market sentiment. These shifts are caused by surprising bad news, which can be called wake-up calls as in

Van Rijckeghem & Weder (2003) and Mobarek et al. (2016), and which may result in herding behaviour. This means that under certain conditions some highly unlikely events can intensify and cause extreme volatility and comovements (Devereux & Yu, 2020).

The very nature of financial markets means that changes in stock market indices and returns are inevitable, as is the occurrence of periods when the markets exhibit covariation. A global factor may provoke strong reactions and temporarily cause high levels of comovement, like after the earthquake in Japan in 2011 as shown in Asongu (2012), while in the absence of a single major surprise, financial markets change, co-vary and diverge from each other for many reasons, including country-specific ones, but still follow similar trends. Some moments of comovements are temporary while others remain persistent, like the Global Financial Crisis that started in 2008 and is notable for the record levels of extreme volatility seen around the globe for a prolonged period (Idier, 2011). The time dimension of these comovements is of the utmost importance, as investigating long-term and short-term comovements in financial markets helps to reveal the specific nature of volatility, comovements and contagion. This thesis describes comovements in financial markets by explicitly distinguishing between long-term interdependence and short-term contagion.

Short-term comovements and extreme cases of comovement are often associated with contagion. These comovements are often studied using some form of correlation analysis (Forbes & Rigobon, 2002; Gjika & Horváth, 2013; Nițoi & Pochea, 2020). It is believed by some that high levels of correlation between financial markets are a sign of integration, as discussed for example by Dellas & Hess (2005) and Donadelli & Paradiso (2014). No less importantly, high levels of correlation could also be indications of short-term comovements and spillovers, and under certain conditions could also be evidence of pure contagion. In fact, correlations between markets increasing significantly and beyond their normal levels during periods of high volatility may be taken as evidence of pure contagion. Such episodes of contagion that are not justified by fundamentals can be short term in nature, as discussed above.

Cointegration analysis helps in studying the comovements of financial markets from another perspective. It helps to determine whether there is some kind of long term equilibrium relationship between financial markets. Cointegration analysis allows financial markets to drift apart in the short term but if there is cointegration between them, it will show that they adjust back to their joint equilibrium path sooner or later and that in the long term a shock in one market will lead to corrections in the other one as well. In other words, cointegration between markets means that the markets are integrated and shocks will always spill over to other markets over time.

Correlation and cointegration analyses investigate the short-term and long-term dynamics of the comovements in financial markets and may therefore be seen to complement each other. The third perspective of the thesis connects the implications of comovements and covariances in financial markets with portfolio theory. Modern portfolio theory is built on the finding that the uncorrelated returns of asset markets can be used in a portfolio to provide protection against risk. Investors can gain from international diversification if the returns from global financial markets are not correlated. Starting from the 1970s, many studies have found gains from cross-country diversification because the risk levels of a portfolio can be minimised considerably if assets with low or negative correlations are incorporated into a portfolio (Solnik, 1974; Meric & Meric, 1989; Cosset & Suret, 1995; Driessen & Laeven, 2007; Flavin & Panopoulou, 2009).

However, the extensive research on the integration of financial markets has shown that financial markets have become more interconnected over time, and long-term relationships have strengthened (Longin & Solnik, 1995; Baumöhl & Lyócsa, 2014; Panda & Nanda, 2017). The resulting increases in correlations and covariances have implications for international portfolio management as they make international diversification less effective. Furthermore, comovements are not only important inside the one asset class of stock markets, as the comovements between various asset classes must also be borne in mind. This becomes especially important when there is foreign currency exposure, as there is in an international portfolio.

Correlation analyses and cointegration techniques are employed in this thesis to study volatility, contagion and comovements in financial markets. Another perspective is added to this as the peculiarities of comovements, covariations and correlations are also studied by using regression analysis to bring together comovements and portfolio theory.

Publication I studies the correlations between selected stock markets. High levels of correlation may first be a sign that financial markets are highly integrated, but they may under certain conditions indicate pure contagion, as discussed earlier. Either way, the correlations between markets illustrate the short-term relationships between them, while cointegration between markets shows long-term and more persistent relationships.

The cointegration method is used in Publication II to study the comovements and the long-term relationships that the Baltic stock markets have with selected stock markets that are more advanced. While the correlation analysis gives a picture of rapid reactions and may be seen as illustrating contagion, the cointegration analysis sheds light on the fundamental links and on interdependence.

Publication III approaches the presence of volatility and comovements from another perspective as it investigates how the peculiarities of volatility and comovements can be addressed in the context of portfolio theory, given that the standard mean-variance portfolio theory of Markowitz (1952) is built on the notion that the optimal portfolio allocation depends on the structure of the correlations of the underlying assets.

Next, subsections 1.1, 1.2 and 1.3 provide overviews of the three publications of the thesis.

1.1 Overview of Publication I

Publication I, *Stock Market Contagion from Western Europe to Central and Eastern Europe during the Crisis Years 2008-2012*, explores the short-term comovements between selected stock markets in Europe. More specifically, the coefficients of dynamic conditional correlation (DCC) between the STOXX 50 Index, which is used as a proxy for the euro area stock markets, and selected stock indices from Central and Eastern Europe are computed for a period when financial markets in Europe were being influenced by the Global Financial Crisis and the European Debt Crisis.

The publication uses daily data from the Euro STOXX 50 Index and daily stock market indices for Bulgaria, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland and Romania. All these stock market indices rose strongly starting from the early 2000s until 2007, when they all dropped sharply. Furthermore, even though the stock markets recovered somewhat after hitting their lowest levels in 2008, the European Debt Crisis and the accompanying uncertainties kept their rises modest.

The methodology is built on Engle's (2002) dynamic conditional correlation (DCC) approach, which adjusts the correlations between variables for changes in volatility by fitting generalised autoregressive conditional heteroscedasticity (GARCH) models individually onto the indices used. This approach helps first to account for the volatility bias and second, in studying how the dynamic correlations change over the time.

Following the approach in Engle (2002), the dynamic conditional correlation coefficients between the returns of the daily stock market indices are computed for the selected CEE indices and the STOXX 50 Index. The results indicate that even though the estimated DCCs increased on average over the period following the Lehman Brothers' bankruptcy, there are no noticeable permanent shifts towards higher and stable levels of correlation. This could be proof of slow but gradual integration between the markets, with contagion effects appearing from Lehman Brothers and the European Debt Crisis. From the portfolio theory perspective, this could mean that most of the benefits of diversification disappear over the long run.

The correlations between the Euro STOXX 50 and Bulgaria and Latvia are particularly low, and are even at some points negative. Czechia, Hungary and Poland show higher levels of correlation with the Euro STOXX 50, which may not be surprising given the characteristics of these CEE countries. While Bulgaria and Romania only entered the European Union in 2007, Czechia, Poland and Hungary have been members since 2004, and the stock markets of these three countries are relatively large and liquid next to smaller markets such as those in the Baltic States.

The highest levels of dynamic correlations are found for all the CEE countries in the period between 2008 and 2012; the peaks in correlations seem to coincide with the episode of the Lehman bankruptcy and around the sovereign debt crisis. The dynamic correlations soared sharply about one month after Lehman Brothers filed for bankruptcy in September 2008. The average of the dynamic correlations increased to the highest level in the sample shortly after Greece sought financial support in April 2010. These increases in correlations are noticeable and add further evidence for the presence of contagion in these stock markets between 2008 and 2012. As these jumps in the dynamic correlations have been brief and volatile it can be concluded that these higher levels represent contagion rather long-term stable integration between the markets.

Publication I helps to shed light on the contagion from stock markets in Western Europe to markets in Central and Eastern Europe over the sample period studied. It does not however provide an answer for the channels or features of such contagion, as both monsoonal effects, spillovers and pure contagion may be present. As discussed earlier, the correlation analysis helps in studying the short-term relationships between the markets but it does not manage to disentangle the integrated markets from the others without further study.

The paper was presented at the 5th international conference *Economic Challenges in Enlarged Europe* in 2013 in Tallinn, Estonia. Earlier versions were presented at the doctoral summer school in 2013 and at various doctoral seminars at Tallinn University of Technology. The paper was accepted for publication in the journal Eastern European Economics in 2014.

1.2 Overview of Publication II

Publication II, *Integration of the Baltic stock markets with developed European markets*, explores the degree of integration between the financial markets in the Baltic States and Western European and US markets using cointegration analysis based on Johansen (1988, 1991).

The publication focuses on the stock markets in the Baltic States and examines whether they have long-term relationships with the Euro STOXX 50 index, the Finnish OMX Helsinki index, the Swedish stock market index, and the S&P 500 stock market index in the US. The weekly returns of the stock market indices are used and the sample covers the period from December 2005 to December 2015.

The cointegration approach facilitates the measurement of financial integration between the markets in the longer term, and of which shocks are transmitted across borders to the Baltic region. As discussed earlier, correlations between asset returns do not provide much information on possible longer-term relationships between markets, but if the stock markets are cointegrated, they follow the same path and only deviate temporarily from their long-run relationship.

The results of Publication II are interesting. First, despite the preparatory work that the Baltic States did to join the single currency union and the accession itself, there is no evidence of long-term relationships between the Baltic stock markets and the euro area markets proxied by the Euro STOXX 50 and the Finnish index. This result shows that even though the Baltic States were already members of the European Union and were moving towards accession to the euro area and then became members of it, as Estonia did in January 2011, their stock markets were not really integrated with the Western markets during the period considered. Likewise, the study found no evidence of integration between the Baltic stock markets and the markets captured by the S&P 500 index.

The most striking result of the study is that all of the Baltic indices exhibit a long-term relationship with the Swedish index. The analysis using vector error correction models (VECM) shows firstly that the Baltic States are exposed to changes coming from Sweden, and secondly that shocks in the Swedish market pass through to the Baltic markets and cause adjustments in them. This means for instance that negative shocks that originate from the Swedish financial market and affect the Swedish stock market index may be transmitted to the markets in the Baltic States.

These long-term relationships are also studied from another angle to shine further light on the cointegration between the stock markets under review. Cointegration analyses using rolling windows over consecutive sub-samples also provide evidence of long-run equilibrium relationships between the Baltic and Swedish markets.

The paper was presented at the doctoral summer school in 2015 and in doctoral seminars at Tallinn University of Technology. The paper was accepted for publication in the journal International Journal of Finance and Economics in July 2020.

1.3 Overview of Publication III

Publication III, *Optimal currency hedge and the carry trade*, takes as its starting point the volatility and comovements of financial markets and investigates the consequences of these from the perspective of portfolio management. It explores how the risk-minimising investor can tackle with the problem of volatility by using hedging to preserve the value of a portfolio of global government bonds that is exposed to foreign currency fluctuations and the covariations between all the components of the portfolio. Publication III compares the efficiency of different hedging strategies.

One of the main contributions of Publication III is its use of a portfolio of multiple foreign bonds to mimic the portfolio of an official institution. Other assumptions that are closer to reality mean that a weekly hedging horizon is used instead of a daily approach, a restriction on the short-selling of currencies is explored, and forward contracts are applied instead of futures.

The weekly data are taken for the period from January 2000 to January 2018. Because there are foreign bonds in the portfolio, the foreign currencies used are the US dollar, the Japanese Yen, the UK pound sterling, the Australian dollar, the Canadian dollar, the Norwegian krone and the Swiss franc.

The analysis is conducted using simple regression methods to find the optimal hedge ratios. This somewhat basic approach is complemented by using the dynamic conditional correlation method of Engle (2002) to find the time-varying hedge ratios. This innovation helps first in finding the optimal time-varying hedge ratios that account for the changes in the covariations and volatilities of the returns, and this then also helps to disentangle the relationship between the optimal hedging strategy and the carry trades.

The results are straightforward and show that it is not optimal for a risk-averse investor to leave their foreign exposure unhedged, as hedging reduces the volatility of the bond portfolios considerably. Furthermore, investors can achieve a better risk-adjusted return by fine-tuning their currency exposure using optimal hedge ratios. Comparing different portfolios built either on hedge ratios found by simple regression of on time-varying hedge ratios does not give a final answer as to whether one strategy performs better than the other, but it can be concluded that both strategies achieve the objective of minimising the variance of a foreign portfolio. What the analysis shows is that the optimal portfolio contains carry trades, meaning there is an inverse relationship between the optimal hedge ratios and the levels of interest rates.

The results are robust to various changes. The conclusions are the same for monthly data and in different market conditions, as the sample was split for the periods before and after the Lehman Brothers default.

Before being published in the Review of Accounting and Finance, an earlier version of the paper was issued under the title *Currency Hedge – Walking on the Edge?* in the Working Papers of Eesti Pank (5/2014). It was presented at the 6th International Conference *Economic Challenges in Enlarged Europe* in 2014, Tallinn, Estonia. The paper was accepted for publication in the journal Review of Accounting and Finance in August 2020.

2 Final Comments

This thesis is based on three publications and investigates issues stemming from volatility and contagion in financial markets. Contagion, alternatively known as spillovers or extreme comovements in financial markets, was widely discussed after the crises that hit the world in 1997-1998. It received even more attention after the bankruptcy of Lehman Brothers in 2008 and the eruption of the Global Financial Crisis. The outbreak of Covid-19 in December 2019 has once again led to extreme volatility in financial markets, and it is clear that issues of contagion are as topical as ever, since comovements in financial markets are omnipresent.

This thesis studies the comovements in financial markets from two angles. It first discusses how to measure the extent of comovements, and second it addresses the question of how portfolio management can deal with the consequences of cross-country comovements and covariations.

Publications I and II complement each other by emphasising the differences between the short and long-term dynamics of the comovements. The results from the first publication show that the dynamic conditional correlations (DCCs) are not constant over time and depend on the volatility of the underlying market. The results also show that the DCCs for the markets studied have increased gradually, though this growth is not stable as there are moments of high levels of correlation that do not last for long. The results from Publication II indicate that there is a cointegrating relationship between the stock markets in the Baltic States and Sweden but no long-term relationships between the Baltic States and the euro area or the USA. When these results are compared, it becomes clear that the comovements do not necessarily mean the financial markets are integrated. The shocks to financial markets that cause volatility may escalate the short-term ties as the sentiment of investors changes and the comovements increase and lead to higher correlations. The results indicate that during periods of high stress, there may be temporary extreme comovements, which are often referred to as contagion.

However, even if the correlations increase, this does not necessarily mean that they will then remain at the elevated levels. During stable times, the extreme correlations decrease and become cleaned of the temporary volatility, so in the long term, the comovements of the financial markets should not be based on temporary market sentiments but should arise as markets align with those that they are cointegrated with.

The results from Publications I and II show that shocks may, in the short term, tighten the short-term temporary ties and increase comovements between financial markets even in the absence of deep financial integration. Where there is strong financial integration however, measured in the form of cointegration in Publication II, the exogenous shocks are expected to be magnified as the financial integration works as a channel through which shocks are propagated. Furthermore, these long-term relationships do not appear suddenly, but rather evolve slowly and should be seen as long-term phenomena that may amplify the shocks.

Closely connected to this, though coming from another perspective, is the question of how investors should respond to volatility and comovements, and this is studied in the third publication. The optimal composition of a portfolio is governed by the correlations between underlying assets, but, as discussed in the first two publications, it is in the nature of comovements to be dynamic. Shocks that hit financial markets daily cause investors to shift their preferences and change their positions, and so cause volatility. These peculiarities are brought together in Publication III, which analyses how a risk-minimising investor could use hedging to preserve the value of their portfolio of bonds denominated in foreign currency. The results show that the overall risk level of a portfolio can be lowered considerably by hedging some part of the currency exposure.

Though each of the publications in this thesis covers different aspects that emerge from the volatility and comovements of financial markets, some limitations of the work may be noted. The DCC method of Engle (2002) describes well the short-term comovements between the developed and the CEE stock markets, and the cointegration methods of Johansen (1988, 1991) help to identify the long-term equilibrium ties between the markets. Both of these show that under certain circumstances, the shocks to financial markets may propagate and create considerable comovements. However, it was beyond the scope of the publications in this work to explore the fundamental underlying reasons, and so the studies do not consider which shocks cause these dynamics. Thus one major stream of work that can be explored further would be to study the comovements jointly in terms of the dynamic conditional correlation of financial markets and the potential drivers of the comovements, which may be macroeconomic fundamentals or the risk perception of investors. It would also be interesting to compare the drivers of short-term comovements of the integrated financial markets and markets that are not integrated in terms of cointegration.

Further to this, the size of the sample studied in Publication II was limited to the Baltic stock markets, and so expanding the cointegration analysis to, for instance, the other CEE stock markets would help in drawing wider conclusions about the short and long-term ties between the CEE markets and developed stock markets.

Closely connected to the result that the comovements and cross-correlations tend to increase during periods of high stress in financial markets, as discussed in Publication I, is the question of whether the ties also increase between different asset markets during periods of high volatility. Given that bond markets are usually perceived as safe-haven assets and there is a tendency to move investments from stock markets to bond markets when risk aversion increases among investors, further analysis could concentrate on comovements between foreign stock markets and foreign government bond markets. This line of research would support further work on the issues covered in Publication III.

A key implication that emerges from the studies in this thesis is the understanding that even though international financial integration may give better access to capital, it comes with the side effect that it acts as a channel that allows the free movement of capital and helps propagate and potentially amplify both positive and negative shocks. Given the interconnectedness of financial markets and the transmission of volatility, Publication III underlines the opportunities that hedging foreign currency exposure offers for risk-averse market participants.

Financial markets never rest, volatility is ever-present, and there are always comovements and occasionally extreme jumps and sharp declines in asset prices. The continuously changing nature of the financial markets means there will always be new issues to investigate.

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Abstract

Essays on volatility and contagion in financial markets

This thesis consists of three publications investigating volatility and comovements in financial markets.

Stock Market Contagion from Western Europe to Central and Eastern Europe during the Crisis Years 2008-2012 focuses on the short-term comovements in financial markets shown in stock market returns. The dynamic conditional correlation (DCC) method of Engle (2002) is used. The publication inspects the dynamic time-varying conditional correlations between the stock market benchmark for the euro area and stock markets in Central and Eastern Europe. The correlations between the Euro STOXX 50 Index and stock market indices for Bulgaria, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland and Romania are studied. The dynamic conditional correlation coefficients increase gradually between 2002 and 2012. The analyses also demonstrate that the DCCs increase extensively when there is high stress in the financial markets. The dynamic correlations between the indices increased noticeably during the Global Financial Crisis, and the peaks in the DCCs coincide with the major shock events of the sovereign debt crisis.

Integration of the Baltic stock markets with developed European markets examines long-term comovements using the cointegration methodology of Johansen (1988, 1991). The study assesses the extent of long-term integration of the Baltic stock markets of Estonia, Latvia and Lithuania with financial markets in Western Europe and the USA. The advanced stock markets are proxied by the Euro STOXX 50 index, the Finnish OMX Helsinki, the Swedish stock market index, and the S&P 500 index in the US. The empirical analysis over the period 2005-2015 reveals that the Baltic stock markets are integrated with the Swedish stock market, and that the transmission of shocks goes from Sweden to the Baltic States. There is no evidence of any long-term relationships between the Baltic markets and the euro area or the USA, which suggests the Baltic markets offer diversification benefits for some stock markets.

Optimal currency hedge and the carry trade investigates how the side effects of comovements and volatility in financial markets can be mitigated in portfolio management. The publication studies how a risk-minimising investor holding a portfolio of foreign currency bonds could respond to covariations of the underlying assets to preserve the value of the portfolio by hedging some of the currency exposure. The portfolio studied consists of foreign bonds and the US dollar, the Japanese Yen, the UK pound sterling, the Australian dollar, the Canadian dollar, the Norwegian krone and the Swiss franc. The performance of different hedging strategies is compared and the results show that for a risk-minimising investor, the hedging is always more beneficial than leaving the currency exposure open. The optimal hedging is superior to full hedging of the currency exposure. Moreover, it can be observed that portfolios with optimal hedges imply carry trades.

Lühikokkuvõte

Esseed volatiilsusest ja nakkuslikkusest finantsturgudel

Käesolev doktoritöö „Esseed volatiilsusest ja nakkuslikkusest finantsturgudel” põhineb kolmel publitseeritud artiklil. Finantsturgude volatiilsust ja koosliikumisi uuritakse kahest vaatenurgast: mil viisil saab finantsturgude koosliikumisi mõõta ja kuidas saab finantsturgude koosliikumiste tagajärgedega tegeleda. Kahes publikatsioonis keskendutakse valitud aktsiaturgude koosliikumiste uurimisele. Kolmas artikkel käsitleb viise, kuidas riskikartlikud investorid saavad enda võlakirjaportfelli valuutaturgude volatiilsuse eest kaitsta. Finantsturgude koosliikumisi uuritakse nii lühi- kui ka pikaajalises perspektiivis, mis aitab illustreerida aktsiaturgude integratsiooni ja nakkuslikku olemust.

Doktoritöö esimene publikatsioon „Kriisiaegne Lääne aktsiaturgude nakkuslikkus Kesk- ja Ida-Euroopa aktsiaturgudele aastatel 2008 kuni 2012“ uurib Euroopa finantsturgude lühiajalisi koosliikumisi globaalse finantskriisi ajal. Artiklis kasutatakse päevaseid aktsiaturgude andmeid ja dünaamilise konditsionaalse korrelatsiooni meetodit. Euroopa aktsiaturgude võrdlusindeksina kasutatakse publikatsioonis Euro STOXX 50 indeksit ning selle korrelatsiooni hinnatakse Balti riikide, Ungari, Poola, Tšehhi, Bulgaaria ja Rumeenia aktsiaindeksitega.

Leitud korrelatsioonikordajad tõendavad valitud aktsiaturgude koosliikumisi ja finantskriisi nakkuslikkust. Tulemused näitavad, et ajal, mil finantsturud olid finantskriisist tingituna väga volatiilsed, suurenesid ka korrelatsioonikordajad valitud indeksite vahel hüppeliselt. Suurimad keskmised korrelatsioonitasemed saavutati Lehman Brothers’i pankroti ja Euroopa võlakriisi ajal, kui Kreeka taotles finantsabi. Need järsud tõusud on ajutised ja iseloomustavadki finantsturgude lühiajalisi koosliikumisi. Teisisõnu, isegi kui finantsturgude koosliikumine lühiajaliselt suureneb, ei pruugi finantsturud olla omavahel püsivalt integreeritud. Ajutised tõusud on pigem tõendus finantskriiside nakkuslikkusest, mitte pikaajalisest stabiilsest seosest finantsturgude vahel. Vaadeldes korrelatsioone kogu uuritud perioodi vältel, on näha, et vaatamata ajutistele hüpetele suurenesid korrelatsioonid nende aastate jooksul üksnes marginaalselt.

Doktoritöö teine publikatsioon „Balti aktsiaturgude integratsioon arenenud aktsiaturgudega“ käsitleb finantsturgude pikaajalisi koosliikumisi. Artiklis kontrollitakse, kas Balti riikide aktsiaturgude ja valitud riikide aktsiaturgude vahel esineb ajavahemikus 2005-2015 kointegratsioon ehk pikaajaline stabiilne tasakaaluseos. Artiklis kasutatakse nädalase sagedusega andmeid. Arenenud aktsiaturgude võrdlusindeksitena kasutatakse Euro Stoxx 50 indeksit, OMX Helsingi aktsiaindeksit, Rootsi aktsiaindeksit ja USA S&P 500 indeksit.

Esiteks tõestab analüüs, et Rootsi ja Balti aktsiaturgude vahel esineb kointegratsioon. See oluline tulemus näitab, et isegi kui aktsiaturud liiguvad ajutiselt erisuunaliselt, taastub varem või hiljem tasakaaluline liikumine. Teiseks annab analüüs kinnitust sellest, et igasugune šokk Rootsi aktsiaturgudel kandub üle ka Balti aktsiaturgudele. Šokke ja finantskriise, mis kanduvad üle kointegratsiooni tõttu, ei saa pidada nakkuslikeks. Pigem on tegemist loomuliku levikuga, mis on tingitud turgude integratsioonist ja lähedastest seostest. Tulemused näitavad ka seda, et Balti aktsiaturgudel puudub pikaajaline tasakaalu seos teiste arenenud aktsiaturgudega. Seega pakuvad Balti riikide aktsiaturud arenenud aktsiaturgudele portfelli hajutamise võimalusi.

Doktoritöö kolmas publikatsioon „Optimaalne valuutariski maandamine ja *„carry“* tehingud*“* otsib vastust küsimusele, kuidas saaksid institutsionaalsed ja riskikartlikud investorid vähendada finantsturgude koosliikumiste mõju välisriikide võlakirjadesse investeerimisel. Moodne portfellijuhtimisteooria eeldab, et optimaalses portfellis kasutatakse omavahel instrumente, millede omavaheline korrelatsioon on negatiivne või puudub. Arvestades asjaolu, et teatud juhtudel – eriti finantskriiside ajal – finantsturgude koosliikumised suurenevad, vajavad riskikartlikud investorid meetodeid portfelli riski vähendamiseks. Artiklis kontrollitakse, kas ja millises ulatuses saab vähendada välisriikide võlakirjadest koosneva portfelli volatiilsust valuutariskide maandamise abil.

Küsimust uuritakse euroala investori perspektiivist, kasutades seitsme riigi võlakirjadest koosnevat portfelli ja nädalase sagedusega andmeid. Kasutades klassikalist regressioonanalüüsi ja DCC-GARCH-mudelit, leitakse võlakirjaportfellidele optimaalsed valuutariski maandamise tasemed. Omavahel võrreldakse maandamata, täielikult maandatud ja optimaalselt maandatud valuutariskidega portfelle. Artiklis näidatakse, et valuutariski maandamisel väheneb välisriikide võlakirjade portfelli volatiilsus märkimisväärselt. Parim riski ja tulususe suhe saavutatakse valuutariski optimaalse maandamise korral. Lisaks näitavad tulemused, et optimaalselt maandatud portfelli puhul on optimaalsed valuutariski maandamise tasemed ja võlakirjade intressitasemed omavahel negatiivselt seotud - mida kõrgem on tulusus, seda madalam on optimaalne valuutariski maandamise tase.

Doktoritöö artiklid kajastavad kolme uurimisvaldkonda finantsturgude volatiilsuse ja koosliikumiste nakkuslikkuse olemusest ning saadud tulemused annavad väärtusliku panuse teaduskirjandusse. Kuna finantsturgude olemuseks on pidevalt muutuda ja reageerida nii oodatud kui ka ootamatutele uudistele, tekitavad need pidevalt uusi uurimisküsimusi. Artiklites esitatud uurimistulemused võimaldavad finantsturgude dünaamikaga seotud temaatikat veelgi põhjalikumalt uurida.

Appendix

Publication I

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KERSTI HARKMANN

Stock Market Contagion from Western Europe to Central and Eastern Europe During the Crisis Years 2008–2012

ABSTRACT: *This paper investigates possible contagion from West European stock markets to stock markets in Central and Eastern Europe. The dynamic conditional correlation (DCC) bivariate generalized autoregressive conditional heteroskedasticity (GARCH) models are used to estimate the degree of the correlations between the stock market benchmark for the eurozone and Central and Eastern Europe. The results of this paper indicate that the DCCs increased steadily between 2002 and 2012, which could be attributed to closer financial integration. During the crisis the dynamic correlations rose substantially, which suggests some contagion. Furthermore, several episodes of the sovereign debt crisis coincide with peaks in the DCCs.*

The global financial crisis started to emerge in August 2007, when the U.S. subprime mortgage market started to signal weakness, but it was not until the Lehman Brothers collapse in September 2008 that the importance of the meltdown was acknowledged. The bankruptcy of Lehman Brothers shocked financial markets, and the crisis spread to countries that did not seem to be connected with the U.S. mortgage market. This resulted in a considerable downturn in the market value of investment portfolios. The confidence loss in the market triggered a credit crunch and liquidity shortage, meaning that the crisis grew larger than had been predicted.

Kersti Harkmann is a visiting researcher in the Economics and Research Department at the Bank of Estonia and a Ph.D. candidate in financial economics at Tallinn University of Technology. The author gratefully acknowledges support from the Estonian Research Council Grants no. PUT315 and no. SF0140059s12, and Estonian Science Foundation Grant no. ETF8796. The author thanks Karsten Staehr, Fabio Filipozzi, and other conference participants for their insightful comments. The views expressed are those of the author and do not necessarily represent the official views of the Bank of Estonia.

It was even more unexpected that some West European countries proved to be highly vulnerable to the shocks when the second phase of the global financial crisis began. The European sovereign debt crisis that followed the subprime crisis moved the epicenter of these events to the eurozone and started the second phase of the financial crisis. Fears about the sustainability of government debt in Europe mounted in April 2010, when Greece asked for financial aid and Ireland and Portugal followed soon after. The fear of spillover forced European policymakers to take measures to support the fragile environment, and in 2012 Spain, one of the biggest countries in Europe, and Cyprus, one of the smallest, both requested some form of support.

Blanchard (2009) discussed the problem of the global crisis and its implications, asking why the subprime crisis in the United States had affected the global economy. His analysis showed that the size of the decline in the world stock market's capitalization was around 100 times larger than the initial estimates for the subprime losses had indicated.

This paper aims to shed light on the contagious impact of the crisis, which began in the United States and later emerged as the European debt crisis, on selected stock markets in Central and Eastern Europe. The question of contagion has attracted the attention of academic literature before, during the Asian and other crisis episodes in the mid-1990s. The recent global crisis has once again raised the problem of contagion in discussions of the benefits of financial integration and policies. The question is also of interest for portfolio management, with its focus on optimal asset allocation.

The definition of contagion used is that offered by Forbes and Rigobon, which states: "Contagion is a significant increase in the cross-market linkages after a shock to one country" (2002: 2224). As integration in the markets increases, the correlations among returns tend to increase. However, temporary increases in the correlations of financial markets during turbulent periods without any fundamental integration could often be attributed to contagion.

This study is based on Engle's (2002) dynamic conditional correlation (DCC) approach, which adjusts the correlations between variables under examination for changes in volatility by fitting generalized autoregressive conditional heteroskedasticity (GARCH) models onto the individual variables. Without any adjustment for volatility bias, a comparison of simple Pearson correlation coefficients may overestimate the existence of contagion, as was well documented by Forbes and Rigobon (2002). The analysis can easily be developed further for the study of contagion by allowing for control of whether the dynamic correlations have changed in statistically significant ways during the crisis periods from what they were in stable times.

Recent important papers on the stock markets of Central and Eastern European (CEE) countries employ empirical tests using the DCC approach in discussions of the general level of integration, the way that shocks transmit to these countries, and the effect of the U.S. subprime crisis on the CEE countries. For example, Cappiello et al. (2006) showed in their study of the period 1994–2005 that equity markets in the new member states of the European Union were little integrated with those of the eurozone before the global crisis started, but they emphasized that these countries showed increasing integration after EU accession and became more affected by the eurozone shocks.

Égert and Kocenda (2007) applied the DCC-GARCH model to intraday stock prices to examine the comovements between six European countries. Having used the data adjusted for the different trading hours, the authors concluded that for the period between June 2, 2003, and January 24, 2006, the three developed countries (France, Germany, and the United Kingdom) showed higher dynamic correlations among themselves than were seen within the emerging market group of Hungary, Poland, and the Czech Republic. The evidence also suggested that there was very low correlation (ranging between 0.01 and 0.03) between France, which was chosen as the benchmark index for the developed countries, and the emerging markets. The authors concluded that lower dynamic correlations support portfolio diversification as long as market integration does not increase significantly.

Syllignakis and Kouretas (2011) examined the dynamics of the time-varying conditional correlations in 1997–2009 and used the DCC-GARCH model on weekly stock market returns from seven Central and Eastern European countries. The high, statistically significant increases in the conditional correlation between 2007 and 2009 led the authors to conclude that emerging stock markets are exposed to negative external events and to the transmission of crises.

Gjika and Horvath (2012) used daily data from 2001 to 2011 to study the asymmetric DCCs between Central Europe and the eurozone. They found asymmetric effects in volatilities but little evidence of asymmetries in the correlations. The results also show that the Central European countries exhibit increasing conditional correlations over time. The conditional correlations and volatilities are positively related, indicating that during periods of high volatility, the benefit from diversification decreases as correlations increase.

In the study of stock market comovements between Western Europe and Central and Southeastern Europe, Horvath and Petrovski (2013) found that the Czech Republic, Hungary, and Poland were much more integrated with the West European markets represented by the STOXX index in 2006–11 than were the other countries from the region. Croatia, Macedonia, and Serbia exhibited almost zero correlation with developed European markets, although recently Croatia has begun to show a slow increase in correlations.

The literature has concluded that the growing integration of the CEE markets with international financial markets has been accompanied by naturally higher comovements, especially in those countries that joined the European Union or even the eurozone. The higher volatility during turbulent times remains relevant because the correlations might increase even after they are adjusted with the DCC-GARCH method, and this could be explained as contagion.

Therefore, the dynamics of the Central and East European stock markets continue to be of interest, as it is generally believed that access to the European

Union and to the eurozone should lead to integration with these financial markets. In other words, the movements in the eurozone stock markets should increasingly affect the CEE markets through spillover effects as integration grows. It has been widely recognized that the bankruptcy of Lehman Brothers, which can be counted as a global shock, had a severe impact on the CEE markets, but the impact of the sovereign debt crisis has not been studied extensively. This paper seeks to fill this gap by examining what the effect of the sovereign debt crisis was on the CEE stock market indices.

Data

In this paper comovements are studied through the dynamics of stock markets during the subprime crisis that started in the United States and later was manifested in Europe's sovereign debt crisis. In line with Baele et al. (2004) and Cappiello et al. (2006), stock market indices can be used to measure the integration of financial markets. Furthermore, it can be argued that stock market indices could be used as proxies among several financial market variables, as they capture changes in market conditions relatively quickly. Croux and Reusens (2013) showed that stock market indices can indeed be used as predictive variables in making forecasts of economic activity.

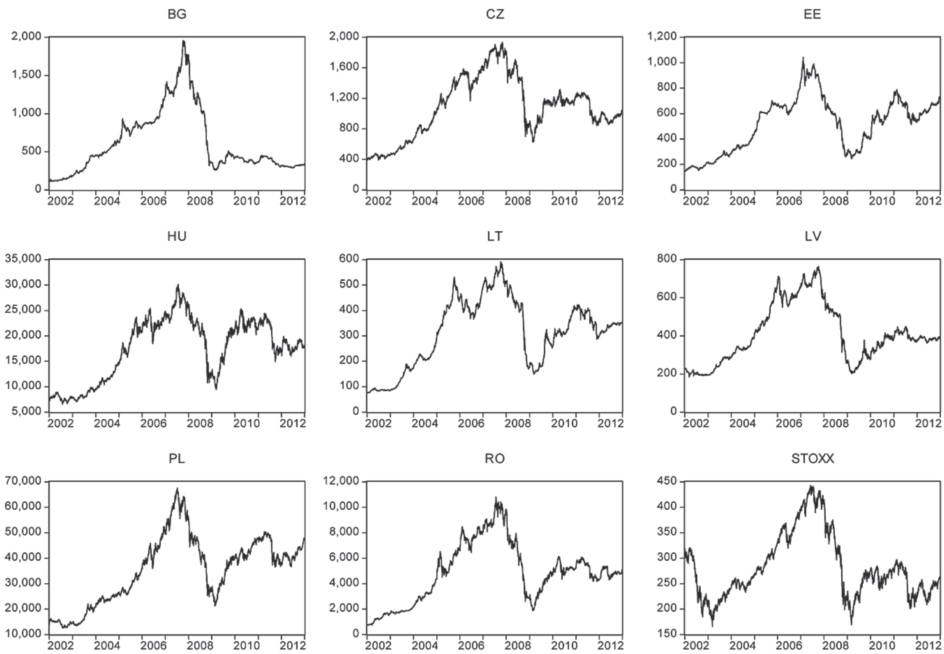
The data set includes daily observations of the Euro STOXX 50 Index and daily stock market indices for the Bulgaria (BG), Czech Republic (CZ), Estonia (EE), Hungary (HU), Latvia (LV), Lithuania (LT), Poland (PL), and Romania (RO). The correlations between the returns of the daily stock market indices are studied for these selected CEE indices and the STOXX 50 Index, which is used as a proxy for the eurozone. Movements in the levels of all these stock markets are shown in Figure 1.

All stock indices, which include both price and total return indices, are in local currencies and collected from Bloomberg. For the econometric analysis, the daily returns are calculated as follows: $r_{i,t} = (\ln(p_{i,t}) - \ln(p_{i,t-1})) \times 100$, where $p_{i,t}$ is the stock market index level in country i at time t. The data sample contains data from January 1, 2002, to December 31, 2012. Missing observations are replaced with the last available observation and the last price on the market is used.

It follows from Figure 1 that there are periods of high volatility. The returns of the stock market indices are not normally distributed and most of the series are negatively skewed in the full sample, with the exception of Latvia and Estonia. The augmented Dickey–Fuller (ADF) unit root test was used to examine the time series properties of the data. The test results, which are available upon request of the author, suggest that the stock market indices, in levels, are not stationary at the 5 percent significance level, whereas the results also indicate that the log-returns of the indices are stationary at the 5 percent level.

Three observations could be emphasized: (1) all stock market indices exhibited strong growth from 2002 to 2007, (2) all indices experienced a sharp decline dur-

Figure 1. **Stock Market Indices in the CEE and the Eurozone**



Source: Bloomberg.

ing 2007 through 2009, and (3) the CEE group experienced a rise after the lowest values were attained in 2008, but the growth in the indices in some countries slowed down after the European debt crisis emerged.

The dynamics are broadly similar to those of the STOXX 50 Index. Interestingly, Bulgaria has not been able to rise much above its lowest levels, while other countries such as the Czech Republic, Hungary, Latvia, Lithuania, and Romania, have recorded a dramatic increase that slowed after 2012. Some countries, notably Estonia and Poland, seemed to follow a different path.

It can be concluded that: (1) not all the markets have recovered to the levels attained prior to the Lehman bankruptcy, and (2) the beginning of the European debt crisis brought about a correction in all the countries studied. However, in some countries the second big decline was followed by a rapid rise, while in others growth has slowed to zero or has even become negative.

It is worth noting that comparison of the daily returns leads to similar conclusions. Between 2002 and 2013 the mean returns were negative in all the countries hardest hit by the sovereign debt crisis, while the other countries showed positive returns for the whole period. Since the crisis broke in 2008, only a handful of indices in Estonia, Poland, and Romania have shown positive returns.

Estimation Methodology and Results

The DCC-GARCH model proposed by Engle (2002) is used to study the dynamics of stock market indices and to find possible contagion effects when the dynamic correlations increase significantly. As shown by Forbes and Rigobon (2002), the simple unadjusted Pearson correlations tend to suffer from heteroskedasticity bias, meaning that the higher volatility during the turbulent times tends to increase the correlations simultaneously. The DCC-GARCH setup addresses this problem directly by employing standardized residuals, which are data series' residuals divided by the GARCH conditional standard deviation in correlation calculation.

Using these properties, the dynamic conditional correlations can be found, as for each time period the DCC-GARCH method continuously finds a dynamic correlation coefficient that is conditional on the past volatility, which in turn tends to vary over time as witnessed usually in the financial time series. Although the DCC-GARCH method allows for a large number of series to be estimated, in this paper the DCC-GARCH(1, 1) is used in a bivariate setting. Since the DCC-GARCH model is employed separately on each pair, the parameters are allowed to differ. It is possible to test whether comovements between the returns change significantly.

The estimation results are obtained through the following steps.[1] First, the mean equations for the return series $r_{i,t}$ for index returns i and time t are estimated by

$$r_{i,t} = \mu_{i,t} + \varepsilon_{i,t}, \tag{1}$$

where $\mu_{i,t}$ is the constant term and $\varepsilon_{i,t}$ is the residual term. Then, the conditional variance $h_{i,t}$ is estimated by univariate GARCH(1, 1) models:

$$h_{i,t} = \omega_i + \delta_i \varepsilon^2_{i,t-1} + \gamma_i h_{i,t-1}, \tag{2}$$

where ω_{i} is the constant, δ_i is the autoregressive conditional heteroskedasticity (ARCH) effect, and γ_i is the GARCH effect. A positive γ_i shows the volatility clustering and persistence. Third, the dynamic conditional correlations $p_{ij,t}$ between countries' indices i and j at time t are estimated by using the following equation:

$$\rho_{ij,t} = \frac{q_{ij,t}}{\sqrt{q_{ii,t}q_{jj,t}}} = = \frac{(1-\alpha-\beta)\overline{\rho_{ij}} + \alpha\varepsilon_{i,t-1}\varepsilon_{j,t-1+}\beta q_{ij,t-1}}{[(1-\alpha-\beta)\overline{\rho_{ii}} + \alpha\varepsilon^2_{i,t-1} + \beta q_{ii,t-1}]^{1/2} \mid (1-\alpha-\beta)\overline{\rho_{jj}} + \alpha\varepsilon^2_{j,t-1} + \beta q_{jj,t-1}]^{1/2}} \tag{3}$$

where $\varepsilon_{i,t} = \varepsilon_{i,t}/(h_{i,t})^{1/2}$ is the standardized residual term, and $\overline{\rho_{ij}}$ is the unconditional correlation of $\varepsilon_{i,t}$ and $\varepsilon_{j,t}$.

The parameters α and β show, respectively, the volatility and the persistence of the shocks: $\alpha \geq 0$ and $\beta \geq 0$ and $\alpha + \beta < 1$. More specifically, α is the measure showing the immediate and temporary impact of the volatility on the DCCs and β shows the persistence of the DCCs. The model can be estimated using maximum likelihood.

The study is designed so that the comovements between eurozone countries and the CEE markets are examined using the STOXX 50 Index as a proxy for the eurozone.

To use the DCC-GARCH(1,1) model, the models in Equations (1), (2), and (3) are estimated, so first the mean equations for mean daily returns are estimated and then the GARCH(1,1) are fitted onto each series. The dynamic conditional correlations can be found for each time period *t*. To allow better understanding, the estimated parameters for each pair are shown below in Table 1. All the values used to determine statistical significance are shown below the coefficient values. The constant term μ from the mean equations and the parameters from the variance equations are statistically significant, which justifies the use of the DCC-GARCH setup. The parameter β represents the persistence of the DCC process, so that the higher the value, the longer the effect lasts. It can be seen that the DCCs are dominated by this parameter. The restrictions that are set on α and β are also satisfied. The DCC model parameters are statistically significant in most cases.

Figure 2 presents the dynamic correlations for each country against STOXX. It can be seen from the DCCs between STOXX and other countries that the CEE countries selected for the group do not exhibit identical patterns. First, the Czech Republic, Hungary, and Poland, which have the biggest economies and the most developed financial markets, show evidence of continuously higher dynamic correlations. These results are consistent with Cappiello et al.'s (2006) finding that the three largest CEE countries exhibited the highest levels of integration with the eurozone before the crises. Poland exhibits the highest levels, ranging between 0.59 and 0.80, with an average DCC over the whole sample of 0.57, while the average dynamic correlation in Bulgaria and Latvia has mainly been below 0.2 (0.11 and 0.13, respectively). Other bigger markets such as the Czech Republic and Hungary also have higher correlations, with mean values of 0.53 and 0.55, respectively. It is also worth pointing out that the increase in the correlations in Bulgaria and Romania is very clear after 2007, when the two countries joined the European Union.

Across the sample studied, all returns show some kind of increase in the DCCs after the Lehman bankruptcy, and there are some jumps in the correlations. There has been a slight increase in the correlations between the STOXX and the markets of the Czech Republic, Hungary, and Poland, while the countries showing the lowest correlations have exhibited more growth in the correlations. Countries with smaller stock markets seem to have shown relatively lower volatility in the DCCs.

There are sharp increases in both sets of correlations with the STOXX 50 Index, but these periods are rather short. Sharp declines can also be witnessed, but these too are rather temporary in nature. In the correlations with STOXX, it is the markets with higher liquidity that tend to show higher volatility.

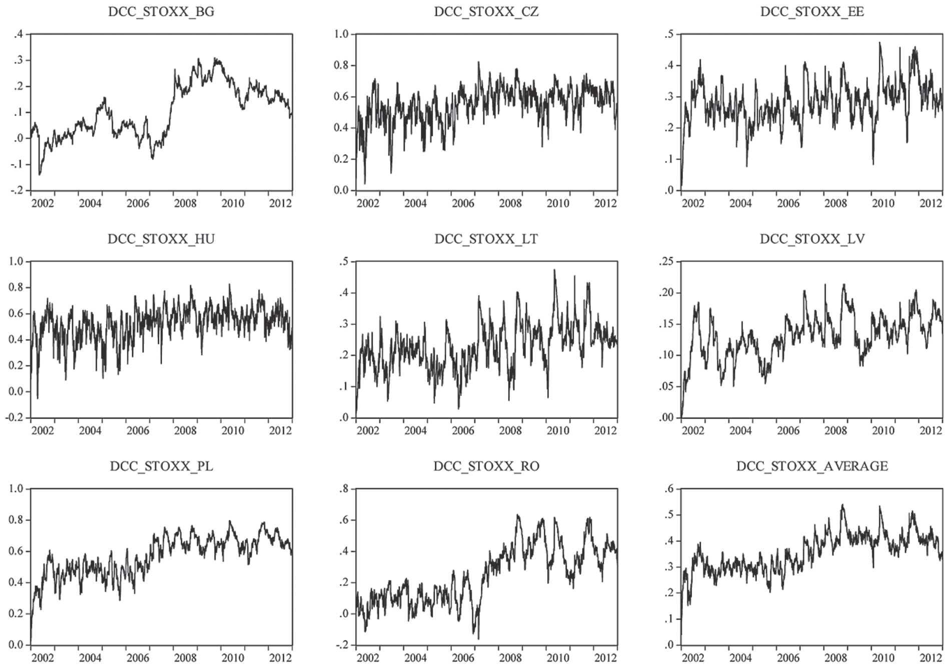
As can be concluded from the discussion above, it is difficult to disentangle country-specific shocks and the effects of the sovereign debt crisis on the DCCs. In order to capture the effects of the eurozone debt crisis on the CEE countries as

Table 1. **Estimated Parameters of Mean, Variance, and Correlation Models Against Euro STOXX 50**

	Mean Equation (1)	Variance Equation (2)			DCC Equation (3)	
Country	μ	δ	γ	ω	α	β
Czech Republic	0.1010	0.1198	0.8536	0.0510	0.0451	0.9071
	(5.33)	(10.72)	(67.08)	(5.79)	(5.82)	(59.66)
Estonia	0.0613	0.1494	0.8563	0.0187	0.0158	0.9563
	(3.95)	(9.40)	(62.33)	(4.02)	(2.83)	(69.64)
Latvia	0.0765	0.1517	0.8182	0.0566	0.0048	0.9808
	(4.39)	(7.82)	(36.80)	(5.06)	(1.34)	(107.54)
Lithuania	0.1153	0.1425	0.8392	0.0391	0.0168	0.9518
	(7.10)	(9.14)	(46.62)	(4.33)	(2.98)	(64.80)
Hungary	0.0915	0.0863	0.8877	0.0600	0.0553	0.8856
	(3.91)	(8.82)	(72.34)	(5.17)	(6.37)	(54.30)
Poland	0.0985	0.0590	0.9324	0.0148	0.0218	0.9696
	(5.31)	(10.18)	(141.06)	(3.86)	(5.23)	(163.54)
Romania	0.1272	0.1818	0.7801	0.1377	0.0224	0.9710
	(5.47)	(7.98)	(28.75)	(5.34)	(4.45)	(135.65)
Bulgaria	0.0423	0.2104	0.7484	0.0973	0.0063	0.9912
	(2.29)	(8.74)	(26.22)	(5.52)	(2.75)	(391.42)

Notes: All estimations are done for the bivariate cases; the mean equation includes only the constant and the variance is modeled by the GARCH(1,1) model.

Figure 2. **The Estimated Dynamic Conditional Correlation Coefficients** (against STOXX)



a group, the average of dynamic correlations is found (shown as the lower right plot in Figure 2).

Three different periods can be identified. First, the period between 2002 and early 2006 was relatively stable, with average correlations of less than 0.35. From 2006 the group average increased, with an upward trend that could be attributed to the increase in integration and may have been partly caused by the accession to the EU of the CEE countries.[2] The highest levels of dynamic correlations occur in the period 2008–12. Interestingly, the peaks in the correlations coincide with different crisis episodes, both within the period around the Lehman bankruptcy and around the sovereign debt crisis.

Lehman Brothers filed for bankruptcy on September 15, 2008, but the dynamic correlations peaked approximately one month afterward. The sovereign debt crisis escalated in the eurozone on April 23, 2010, when Greece sought financial support. Shortly afterward, the average of the dynamic correlations increased to the highest level seen during the period studied. Some eurozone member countries followed Greece and sought financial aid, and new policy measures were taken to support market activity. The summer of 2011 was turbulent, and this can also be seen in the average of the dynamic correlations for the CEE, as the average increased close to the levels seen after the Lehman bankruptcy.

It has been tested, using multiple regression analysis, whether the increase in correlations after the various episodes of the global financial crisis was indeed statistically significant (not shown). The analysis suggested that since 2008, which is considered to be the beginning of the crisis, the increases in the correlations have been significantly bigger, and different, compared to the levels before the global financial crisis. This can essentially be attributed to contagion effects. Furthermore, the effect of the sovereign debt crisis on the dynamic correlations between the CEE group and the eurozone proxy is as strong as the effect of the bankruptcy of Lehman Brothers, if not stronger. Over the period, the correlations have nevertheless increased, while decreases in the correlations have been short-lived (the correlations fall often, but only for short periods).

These results show that the various shocks of the sovereign debt crisis have increased considerably the correlations adjusted for volatility for the group of CEE countries, which have otherwise exhibited moderate correlations with the STOXX 50 Index. These increases in the dynamic correlations have been temporary in nature and not persistent, showing that they cannot be considered to be part of a process of integration; thus it can be concluded that the episodes of the sovereign debt crisis represent contagion.

Conclusion

This paper studies the impacts of the sovereign debt crisis on selected CEE stock markets using Engle's (2002) DCC-GARCH method to calculate the DCCs. The stock markets experienced big swings in the aftermath of the bankruptcy of Lehman Brothers and during the sovereign debt crisis. The sovereign debt crisis first hit hardest in five eurozone core members— Ireland, Italy, Portugal, Greece, and Spain—and four of the five requested some kind of financial aid. To study the changes in the DCCs brought about by the escalation of the financial crisis in the eurozone, the STOXX 50 Index has been used as a proxy for the eurozone as a whole. The comovements against this proxy are calculated for Estonia, the newest eurozone member state, Latvia, and Lithuania as Exchange Rate Mechanism II members, and selected Central and South European countries, namely, Bulgaria, the Czech Republic, Hungary, Poland, and Romania.

The first results indicate that on average the DCCs between STOXX and other countries have increased steadily. The individual correlations against STOXX have not shown any significant increase during the last decade other than short, sharp jumps. Some countries, such as Bulgaria and Latvia, have exhibited particularly low correlations, while the Czech Republic, Hungary, and Poland have shown a higher degree of dynamic correlation. These results suggest that the European sovereign debt crisis has tended to increase correlation. However, these results should be studied further to take account of the effect of illiquidity in some CEE markets, different trading hours, and excess liquidity in the financial markets in general. From the portfolio theory perspective, the results show that all countries show higher correlations with the eurozone index over time. This argues for a decrease in the benefit to financial portfolios of allocating investments to these countries for reasons of diversification.

This analysis can be extended in various directions. For more precise analysis of the effects of the crisis on other European countries, the estimations could be done individually against each core eurozone member separately. Removing the lasting effects of the U.S. crisis would also allow even clearer results to be achieved. Comparing the dynamic correlations during stable periods against the turbulent times could make it possible to study whether any of the former periods have been contagious. Last but not least, different windows should be included, as it seems that for some countries the fall in the stock markets started long before Lehman Brothers filed for bankruptcy.

Notes

1. For more detail, see Engle (2002).
2. Except for Bulgaria and Romania, which joined later in 2007.

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RESEARCH ARTICLE

WILEY

Integration of the Baltic stock markets with developed European markets

Kersti Harkmann

Department of Finance and Economics, Tallinn University of Technology, Tallinn, Estonia

Correspondence
Kersti Harkmann, Department of Finance and Economics, Tallinn University of Technology, Akadeemia tee 3, 12,618, Tallinn, Estonia.
Email: kharkmann@gmail.com

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Abstract

This paper examines the extent of integration of the Baltic stock markets with the financial markets in Western Europe. The long-run relationships between the stock markets of the Baltic States and selected developed stock markets are studied by means of cointegration analysis on the weekly returns. For the Baltic stock markets and key indices from the European markets, the empirical results over period 2005–2015 provide clear evidence that the Baltic stock markets are integrated with the Swedish stock market, and that this cointegrating relationship implies transmission of shocks from Sweden to the Baltic States. The cointegration analysis is also conducted for rolling windows over consequent sub-samples, which only verifies the robustness of the integration between the stock markets of the Baltic States and Sweden. Given that there is no support for the long-term relationships between the Baltic market and euro area, it may be that Baltic markets offer diversification benefits for the euro area indices.

KEYWORDS

Baltic States, cointegration, emerging stock markets, equity markets, integration

1 | INTRODUCTION

This paper presents an analysis of the extent of integration between the stock markets of the Baltic States (Estonia, Latvia and Lithuania) and the stock markets of the developed economies in Europe. The Baltic States became members of the European Union (EU) in 2004 and soon after announced their commitment to adopting the euro as their currency. By 2015, all three countries had joined the euro area. The global integration of financial markets in recent decades, not to mention the EU accession and adoption of the common currency, should argue in favour of the integration of the Baltic States with the more developed markets in the West, especially those in the euro area.

The literature on the integration of financial markets comprises two main streams. The short-run dynamics and the co-movements are often studied by analysis of the volatility and the correlation structure of the asset returns (Gjika & Horvath, 2012; Horvath & Petrovski, 2013; Syllignakis & Kouretas, 2011). This literature offers an insight into the benefits of diversification in the short term using time-varying volatility models. It is widely agreed that the ties as proxied by high correlations and low volatilities have strengthened within the euro area over the past decade and especially prior to the global financial crisis. However, high correlations between asset returns do not provide much information in the longer-run relationships between markets.

Cointegration analysis focuses on the long-run relationships between the asset markets. If the stock markets are cointegrated, these markets will follow the same path and only see temporary divergence from their long-run relationship. As the financial markets develop, we would expect higher integration with external markets due to the growing linkages between countries' economic activities but this might in reality decrease the potential for benefits from diversification. Deeper integration might also have drawbacks as external shocks could be transmitted more easily across borders and could cause contagion. The global financial crisis affected the European economies strongly from 2008 and this raises the question of whether the crisis affected the integration of financial markets and if so, how far. The Baltic States, which have joined the EU and have all finalized their accession to the euro area, might have been prone to these spillovers due to the integration as discussed in Harrison and Moore (2009).

Even though the issues of the integration of the financial markets have been analysed extensively, very few studies focus on the Baltic States (Nikkinen, Piljak, & Äijö, 2012; Syllignakis & Kouretas, 2011). However, the Baltic States have not only gone through a major transition after the collapse of the Soviet Union but all three have joined the Eurosystem and accepted the common currency. It has been noted that the Baltic States have succeeded in achieving rapid income convergence with Western Europe even though their income levels remain below those of their peers (International Monetary Fund, 2014a). As reported by Roaf, Atoyan, Joshi, and Krogulski (2014), the growth of the Baltic States as a group exceeded the performance of other emerging European country groups in 2005–2007. The growth was driven mainly by domestic credit and was supported by foreign capital and investments and the high growth rates were followed by a severe collapse. Despite the recession, the Baltic States managed to return to economic growth in 2010 and 2011, which was the highest in the EU in 2011 even though the later GDP growth levels have remained subdued (International Monetary Fund, 2014a).

Another distinct feature of the Baltic States is that the region shares stronger trade and finance connections with the Nordic countries than the other emerging countries in Central and Eastern Europe (CEE—Poland, Hungary, the Czech Republic, Estonia, Latvia and Lithuania.). The consolidated banking data of the European Central Bank (2015) shows that foreign controlled banks held on average 97% of the total assets of the banking sector in Estonia, 64% in Latvia and 86% in Lithuania in 2008–2013, with Sweden having the closest ties within the banking industry in the Baltic States.

The Baltic States are also closely linked with Sweden through trade and investments. As reported by the IMF, Sweden has an outstanding role together with the other Nordic countries as a trade partner for Estonia, but it is also an important partner for Latvia and Lithuania. Not surprisingly, Sweden also has a dominant role in the inward FDI in the Baltics (International Monetary Fund, 2014b).

The lessons learnt from the experience of the Baltic States are relevant for the other potential members of the EU and of the euro area. Furthermore, although the countries are small compared to the other EU members, the recent past shows that shocks in relatively small financial markets can create turmoil and cause contagion (Cocozza & Piselli, 2011). This only enhances the need for an understanding of how these countries have integrated with the more developed financial markets. Both entering the common currency union and being highly connected to the Nordic economies should increase the financial integration of the Baltic States with Western Europe. The question of whether these characteristics of the Baltic States have brought about actual financial integration and whether consequently the Baltic States are more open to potential contagion has not been addressed adequately though, and this paper seeks to address these issues.

This paper studies the financial integration between the Baltic stock markets and the developed stock markets using the cointegration methodology of Johansen (1988, 1991) and weekly data from December 2005 to December 2015. Alongside the standard cointegration analysis over the whole sample, the study also uses rolling windows over sub-samples, which allows the long-run relationships to be assessed in more detail.

The rest of the paper is organized as follows: Section 2 presents a short overview of the literature about the CEE countries and their cointegration with the developed stock markets. Section 3 introduces the data and the methodology. The empirical results are presented in Section 4. Finally, Section 5 discusses the main findings.

2 | LITERATURE

This section summarizes the existing literature assessing the existence of financial integration between the stock markets from CEE and developed markets. The bulk of the literature focuses on Central European countries such as Poland, Hungary and the Czech Republic and there is little work on the Baltic States. This could be explained by the fact that these CE countries have more developed stock markets in terms of, for example, liquidity and market capitalization than the Baltic States do.

Several points brought up in the literature discussed may be emphasized. The financial integration of the emerging markets with the developed financial markets has been a gradual process and has taken time. Indeed, studies covering the period before and around the EU enlargement in 2004 indicate that the CE countries were cointegrated neither with the United States nor with other main markets in Europe such as the UK, Germany or France. For example, Gilmore and McManus (2002) study cointegration between the three Central Europe markets in Hungary, Poland and the Czech Republic and the U.S. stock markets during 1995–2001. Their analysis on weekly data does not show significant cointegration of the CE stock exchanges with the US stock market. Indeed, the authors find that the low levels of correlation between CE and the United States offer some diversification benefits for investment purposes.

Egert and Kocenda (2007) use intra-day stock market data from between 2003 and 2005 to study the integration between the CE countries and Germany, the UK and France. The analysis does not reveal any long-run relationships between the studied countries. This result is supported by a later paper of Gilmore, Lucey, and McManus (2008), who also conclude that there are no long-run relationships between the three CE countries and developed EU stock markets in Germany and the UK over the period 1995–2005 for the daily data.

It is not surprising that the results for the years before the CEE countries joined the EU do not support the existence of long-run cointegrating relationships with developed European and world markets, as these countries were still transforming their economies and building up their financial systems at that time. However, the literature also seems to suggest that the accession to the EU did not bring about higher integration, at least for Poland, Hungary and the Czech Republic. This is analysed for example in Syriopoulos (2007), who studies the CE markets and Slovakia and their long-run relationships with the United States and Germany, and concludes that the CE markets indeed move close to a long-run relationship with Germany but are little integrated among themselves. The daily data cover the period between 1997 and 2003, which also covers the creation of the EMU. Nevertheless, when comparing the relationships in the pre-EMU and EMU periods, no significant difference is found between the periods.

Demian (2011) concentrates on the question of whether joining the EU has had an impact on the integration of stock markets by studying the long-run relationships between the extended group of new EU members, covering the Czech Republic, Hungary, Poland, Romania, Slovakia and also Estonia, and the developed markets of Germany, France, the UK and Italy. A single aggregate index for the developed markets is constructed from the individual indices so that the relationships can be studied. The daily data cover the period between 2001 and 2009 and the analysis uses different sub-samples to capture the potential effect of EU accession. The analysis reveals that the relationships of the new EU members with the developed markets have strengthened over time. Nevertheless, EU accession itself does not seem to have led to an increase in the degree of integration, which somewhat supports the earlier finding of Syriopoulos (2007).

Guidi and Ugur (2014) focus on Bulgaria, Croatia, Romania, Slovenia and Turkey and find that these countries are integrated with the UK and Germany although it might be argued that the evidence is not very strong. No evidence of cointegration is found between these markets and the United States. Guidi and Ugur (2014) use weekly data from 2000 to 2013 to study both the integration and the potential portfolio diversification benefits. The authors underline that the integration should be studied with standard and rolling-window cointegration analysis in order to have a full picture of the long-run relationships, as the cointegration between the countries seems to have a time-varying nature and the degree of cointegration changes over time.

Nikkinen et al. (2012) study the degree of stock market integration between the Baltic States and Western Europe, proxied by the EURO STOXX 50, index from 2004 to 2008, using Granger causality tests and VAR analysis. Their results show that during the recent financial crisis, the integration of Baltic stock markets with Western European stock markets increased. Prior to the crisis, Estonia, Latvia and Lithuania were quite independent, but the lead–lag relationships strengthened during the crisis. During the crisis period, the Euro Stoxx index helps to explain a large part of the variance in the stock market indices of the Baltic States.

Of more importance for the aim of this paper is the study by Harrison and Moore (2009), who examine the co-movements in the stock markets between the emerging economies of Bulgaria, Czechia, Estonia, Hungary, Poland, Latvia, Lithuania, Romania, Slovakia and Slovenia in CEE, and the developed markets of Germany and the UK in Western Europe over the period 1994–2006. The authors use rolling cointegration tests among other approaches to investigate the relationships between stock markets. They find no evidence of cointegration with developed markets for the sample period between 1997 and 2000. However, the results for the sample from 2001 to 2005 demonstrate the existence of cointegration and thus the linkages between stock markets in the CEE and in the developed markets of Western Europe, and the cointegration relationship appears to be stronger for the UK as there seems to be a break in the relationship between the CEE markets and the German stock market index DAX from the beginning of 2006 onwards.

3 | DATA AND METHODOLOGY

3.1 | Data

The data used in this paper consist of weekly Baltic stock market indices for Estonia (EE), Latvia (LV) and

Lithuania (LT) together with benchmarks for selected indices of developed Western economies. The period studied starts on December 30, 2005, by which point the Baltic States had joined the EU, and ends on December 25, 2015, resulting in 522 weekly observations. The benchmark indices used are the Euro Stoxx 50 index

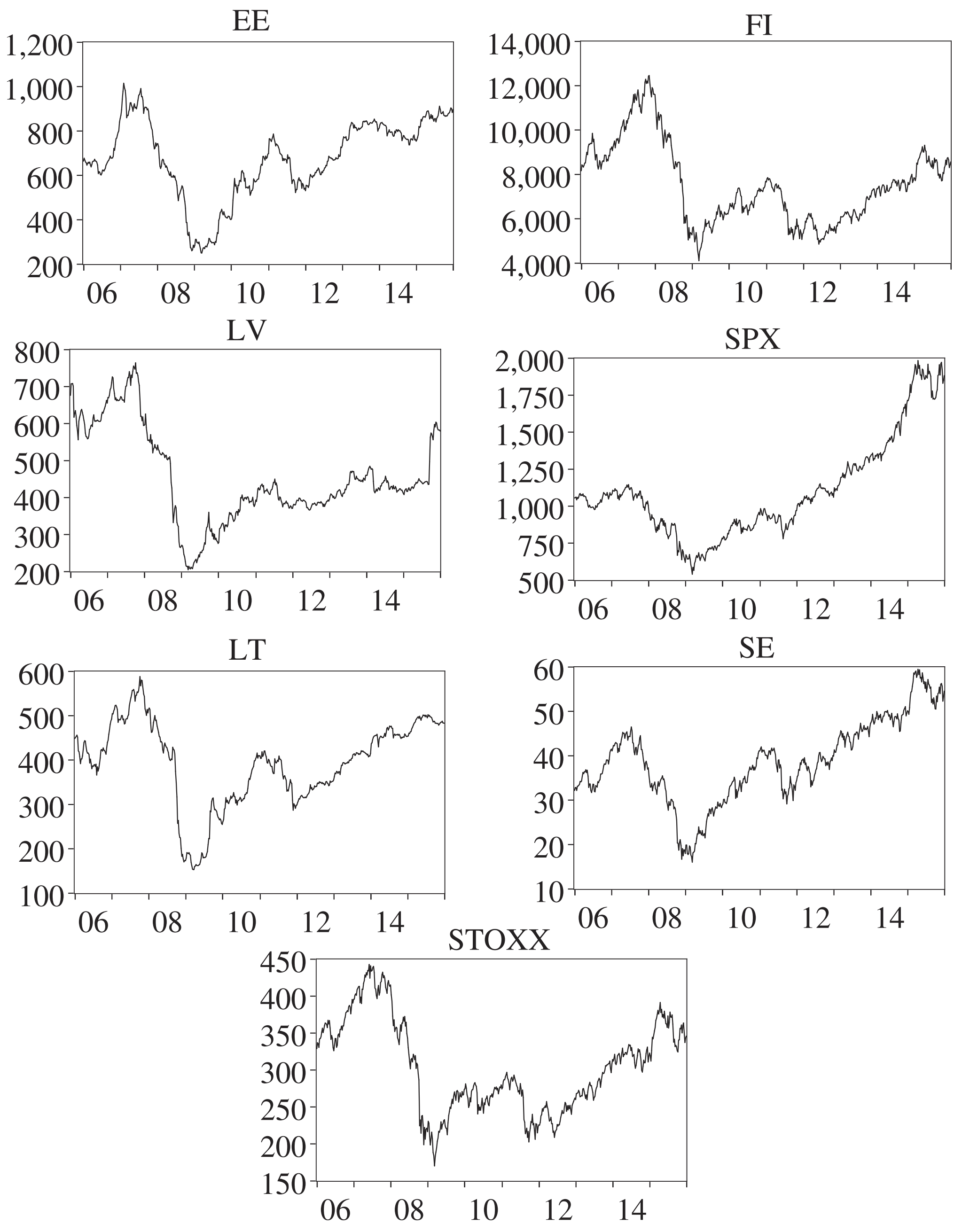

FIGURE 1 Weekly stock market indices. Log levels of indices; December 30, 2005, to December 25, 2015. Source: Bloomberg (2015). Author's calculations

(STOXX), OMX Helsinki (FI), and the Swedish stock market index (SE). Also the U.S.-based S&P500 (SPX) index has been studied for comparison. Closing prices are used and missing observations are replaced with the last available observation. All data are from Bloomberg (2015). All the stock market indices are denominated in euros and natural logarithms are used.

The dynamics of the stock markets in the sample are shown in Figure 1. The stock markets share similar trends in their dynamics in the period before the financial crisis broke out in 2008. The Baltic States experienced rapid economic growth prior to the global financial crisis and this was also manifested in the stock markets. The Baltic States, which had joined the EU in 2004, were catching up fast, but the collapse of these markets after the outbreak of the global financial crisis was more severe than the crashes in the developed markets. After the financial crisis, the development paths vary. The escalation of the sovereign debt crisis weighed more on the European markets than it did on the United States, and this is especially clear for the years after 2010–2011. The individual developments show that stock markets in Estonia, Lithuania and Sweden have recovered from the impact of the debt crisis and have shown strong growth though not all markets have returned to their peak levels by the end of 2015, as illustrated in Figure 1.

Table 1 presents the main descriptive statistics for the weekly returns of the stock market indices over the whole time sample. All markets except those of Latvia and the euro area have positive average weekly returns.

Table 2 presents correlations of weekly returns, which also illustrate the potential relationships of the stock markets. Over the whole data, Estonia shows the highest correlations with Lithuania and Sweden which in turn is highly correlated with the U.S. S&P index.

Somewhat surprising is the low levels of correlations between the euro area benchmark index and the Baltic indices. The correlations over the sample for Lithuania are highest against Latvia and Estonia. The strongest correlation for Latvia is with the Lithuanian index.

3.2 | Unit root tests

The prerequisite for using cointegration analysis is that all the variables must be integrated of order one, meaning the levels of the variables should be non-stationary but the differences stationary. This is examined using unit root tests. Table 3 reports the results from Augmented Dickey-Fuller tests (ADF) used to test the stationarity of the data. The results indicate that the log

TABLE 1 Weekly returns

	Mean	Median	Maximum	Minimum	*SD*	Obs.
EE	0.0001	0.0001	0.0274	−0.0254	0.0048	522
FI	0.0000	0.0002	0.0122	−0.0203	0.0036	522
LT	0.0000	0.0002	0.0459	−0.0361	0.0050	522
LV	−0.0000	0.0001	0.0220	−0.0241	0.0046	522
SPX	0.0002	0.0003	0.0156	−0.0263	0.0038	522
STOXX	0.0000	0.0007	0.0210	−0.0434	0.0055	522
SE	0.0003	0.0009	0.0475	−0.0696	0.0104	522

Note: Source: Bloomberg (2015). Author's calculations.
Note: Log differences of indices; December 30, 2005, to December 25, 2015.

TABLE 2 Correlations of weekly series

	EE	FI	LT	LV	SPX	STOXX
FI	0.5850					
LT	0.9315	0.7628				
LV	0.7447	0.8347	0.8544			
SPX	0.7971	0.3586	0.7123	0.4403		
STOXX	0.6923	0.9633	0.8245	0.8521	0.5254	
SE	0.9228	0.4489	0.8262	0.5277	0.9154	0.5901

Note: Source: Bloomberg (2015). Author's calculations.
Note: Log levels of indices; December 30, 2005, to December 25, 2015.

levels of the stock market series are not stationary but the log differences of the series are stationary.

3.3 | Methodology

The empirical analysis in this paper uses the standard cointegration methodology of Johansen (1988, 1991). First, unit root tests are applied to verify that the cointegration approach is appropriate. Then the existence of long-run relationships is studied using cointegration analysis over the last 10 years. As there have been several shocks during the last decade, the sub-samples of shorter periods are also assessed to account for possible structural breaks in the data. To do this, rolling windows are used. This method makes it possible to assess whether the long-run relationships change; there may be periods when some markets are cointegrated and periods when this is not the case and the stock market dynamics are random and driven only by shocks.

In the standard cointegration methodology, if the time series are cointegrated, the basic model, the vector error correction model (VECM), can be written as:

$$\Delta Y_t = \prod Y_{t-k} + \sum\nolimits_{i=1}^{k-1} \Gamma_i \Delta Y_{t-i} + \varepsilon_t, \tag{1}$$

where Y_t is a vector including the variables, here the stock market indices in log levels in this paper. The vector Γ_i stands for the estimated parameters and ε_t is a vector of errors. The number of existing cointegrating vectors r is determined by the rank of the matrix $\prod$, which can be expressed as $\alpha\beta^{'}$. The matrix β contains the coefficients for the cointegrating vector, which explain the long-run relationship of the variables. The matrix α shows the estimated disequilibrium adjustment coefficients. The rank of the matrix $\prod$ is determined by using two test statistics from Johansen (1988, 1991), namely the trace statistic and the maximum eigenvalue statistic:

$$\lambda_{trace}(r) = -T\sum\nolimits_{i=r+1}^{p} \ln\left(1-\widehat{\lambda}_i\right), \tag{2}$$

$$\lambda_{maximum\ eigenvalue}(r|r+1) = -T\ln\left(1-\widehat{\lambda}_{r+1}\right), \tag{3}$$

with r denoting the number of cointegrating vectors, which is determined by the rank of the matrix $\prod$ via its

TABLE 3 ADF Unit root tests for weekly stock market indices

	EE	FI	LT	LV	SPX	STOXX	SE
Log levels	−1.298	−2.086	−1.839	−2.079	0.549	−1.865	−1.607
First differences	−3.771*	−4.398*	−4.155*	−4.009*	−4.237*	−4.747*	−4.365*

Note: Source: Author's calculations. December 30, 2005, to December 25, 2015.
Note: The auxiliary regression for the ADF test includes a constant. Results are robust also for the ADF procedure including a constant and a trend and for the KPSS test including a constant (results available upon request). The lag length is chosen using the modified AIC criterion. * indicates the rejection of the null hypothesis of unit root in the series at the 5% level of significance where the test critical value is −2.88 for sample size T = 250 obtained from Fuller (1976).

TABLE 4 Johansen cointegration tests results

	Baltics		Baltics-SPX		Baltics-STOXX		Baltics-SE		Baltics-FI	
	Test statistic	5% critical value	Test statistic	5% critical value	Test statistic	5% critical value	Test statistic	5% critical value	Test statistic	5% critical value
Unrestricted Cointegration rank test (trace)										
None	36.28	42.44	52.54	62.99	53.49	62.99	85.21*	62.99	58.81	62.99
At most 1	18.19	25.32	31.68	42.44	30.30	42.44	37.30	42.44	31.31	42.44
Unrestricted Cointegration rank test (maximum eigenvalue)										
None	18.09	25.54	20.86	32.46	23.20	32.46	47.91*	32.46	27.50	32.46
At most 1	12.55	18.96	14.84	25.54	17.73	25.54	18.20	25.54	17.39	25.54

Note: Source: Author's calculations.
Note: Log levels of indices; December 30, 2005, to December 25, 2015.* indicates the rejection of the null hypothesis of no cointegrating equations at the 5% level of significance; the Osterwald-Lenum (1992) critical values are reported. Model: constant and trend in the cointegrating term and constant in the VAR equation. Results presented here show the lag intervals determined by the Hannan and Quinn's information criterion: for Baltics 3, for Baltics-SPX 3, for Baltics-FI 3, for Baltics-STOXX 3, for Baltics-SE 2. The results are robust also for different model specifications.

estimated eigenvalues $\widehat{\lambda}_i$. The term T is the number of observations. The trace statistic determines whether the number of cointegrating vectors is less than or equal to r with the alternative being that there are more than r cointegrating vectors. The maximum eigenvalue statistic tests on each eigenvalue whether the number of the cointegrating vectors is equal to r against the alternative hypothesis that the number of cointegrating vectors is equal to $r+1$.

The cointegration analysis over shorter subsequent windows is used to study the presence of cointegration in smaller sub-samples in order to shed light on the time-varying nature of the long-run relationships. The procedure is as follows. First, the trace statistics are calculated over the sample by moving the window over the whole sample by adding one extra observation to the end and dropping the first observation in a procedure that creates a number of trace statistics. By its nature, the rolling-window approach also helps to illustrate the influence of individual observations on cointegrating relationships between the variables considered.

4 | RESULTS

4.1 | Cointegration results—The Baltics as a group and the developed markets

First, the cointegration is studied between the Baltics as a group of all three countries and the developed stock markets one by one with the standard Johansen approach. The presence of a cointegrating vector can be interpreted as the existence of an equilibrium relationship between a Baltic stock market as a group and the developed stock market. The results are shown in Table 4.

The cointegration analysis reveals that at least one cointegrating vector can be found between Sweden and the Baltics States as a group. This result is present for both trace and maximum eigenvalue tests. However,

TABLE 5 Cointegration tests results based on information criteria

	Baltics		Baltics-SPX		Baltics-STOXX		Baltics-SE		Baltics-FI	
	SBIC	HQIC	SBIC	HQIC	SBIC	HQIC	SBIC	HQIC	SBIC	HQIC
None	−13.69*	−13.84*	−18.19*	−18.45*	−17.93*	−18.19*	−17.85*	−18.03	−17.88*	−18.14*
At most 1	−13.65	−13.83	−18.14	−18.44	−17.88	−18.18	−17.85	−18.07*	−17.83	−18.13

Note: Source: Author's calculations.
Note: Log levels of indices; December 30, 2005, to December 25, 2015.* indicates the number of cointegrating equations that minimizes either the Schwarz Bayesian information criterion (SBIC) or the Hannan and Quinn information criterion (HQIC). Model: constant and trend in the cointegrating term and constant in the VAR equation. Results presented here show the lag intervals determined by the Hannan and Quinn's information criterion: for Baltics 3, for Baltics-SPX 3, for Baltics-FI 3, for Baltics-STOXX 3, for Baltics-SE 2.

TABLE 6 Johansen cointegration test results for individual samples

	EE-SE		LT-SE		LV-SE	
	Test statistic	5% critical value	Test statistic	5% critical value	Test statistic	5% critical value
Unrestricted Cointegration rank test (trace)						
None	32.98*	25.32	47.03*	25.32	37.45*	25.32
At most 1	3.35	12.25	5.258	12.25	4.89	12.25
Unrestricted Cointegration rank test (maximum eigenvalue)						
None	29.63*	18.96	41.77*	18.96	32.56*	18.96
At most 1	3.35	12.52	5.26	12.52	4.89	12.52

Note: Source: Author's calculations.
Note: Log levels of indices; December 30, 2005, to December 25, 2015.* indicates the rejection of the null hypothesis of no cointegrating equations at the 5% level of significance; the Osterwald-Lenum (1992) critical values are reported. Model: constant and trend in the cointegrating term and constant in the VAR equation. Results presented here show the lag intervals determined by the Hannan and Quinn's information criterion: for EE 3, for LT 2, for LV 3. The results are robust also for lag lengths determined by the Schwarz's Bayesian information criterion.

there is no evidence of cointegration either for the Baltic States between themselves or between the Baltics and the other indices.

In addition, the existence is also tested using information-criteria methods to estimate the number of cointegrating equations as papers by Cheng and Phillips (2009) and Wang and Bessler (2005) suggest. The results are shown in Table 5. Both the Hannan and Quinn information criterion (HQIC) and the Schwarz Bayesian information criterion (SBIC) provide the same conclusion as the Johansen cointegration tests except for Sweden as the HQIC indicates cointegration while the SBIC does not.

These results suggest that even though the Baltic States joined the EU in 2004 and the euro area starting in 2011, they have not yet integrated fully into the financial market of the euro area, at least in terms of long-run relationships between the stock markets.

Beine and Candelon (2007) find that a higher degree of common trade could be one of the determinants increasing the co-movements between returns. The results regarding the lack of cointegration between the Baltic States and the euro stock market benchmark are in line with the literature, which suggests that neither the accession to the EU or the adoption of the euro is necessarily associated with increased integration (Demian, 2011; Syriopoulos, 2007).

There is evidence that indicates that a higher share of foreign banks' presence makes countries more prone to the transmission of shocks across borders (Popov & Udell, 2012). The dominance of the Nordic banks in the

TABLE 7 Cointegration tests results based on information criteria for individual samples

	EE-SE		LT-SE		LV-SE	
	SBIC	HQIC	SBIC	HQIC	SBIC	HQIC
None	−8.34	−8.41	−8.42	−8.47	−8.20	−8.27
At most 1	−8.35*	−8.44*	−8.45*	−8.52*	−8.21*	−8.30*

Note: Source: Author's calculations.
Note: Log levels of indices; December 30, 2005, to December 25, 2015.* indicates the number of cointegrating equations that minimizes either the Schwarz Bayesian information criterion (SBIC) or the Hannan and Quinn information criterion (HQIC). Model: constant and trend in the cointegrating term and constant in the VAR equation. Results presented here show the lag intervals determined by the Hannan and Quinn's information criterion: for EE 3, for LT 2, for LV 3. The results are robust also for lag lengths determined by the Schwarz's Bayesian information criterion.

TABLE 8 Vector error correction estimates

	EE-SE		LT-SE		LV-SE	
β_1	EE(−1)	1.000	LT(−1)	1.000	LV(−1)	1.000
β_2	SE(−1)	−1.380	SE(−1)	−1.317	SE(−1)	−1.333
		(−20.51)		(−18.13)		(−12.98)
Trend	Trend	0.001	Trend	0.001	Trend	0.002
Constant	C	−1.660	C	−1.430	C	−1.679
	D(EE)	**D(se)**	**D(LT)**	**D(se)**	**D(lv)**	**D(se)**
α	−0.072	0.004	−0.071	−0.018	−0.052	0.001
	(−4.70)	(−0.19)	(−6.35)	(−1.23)	(−5.54)	(−0.05)

Note: Source: Author's calculations.
Note: Log levels of indices; December 30, 2005, to December 25, 2015. Vector error correction estimates are found by Equation (1), where the matrix β contains the coefficients for the cointegrating vectors, which explain the long-run relationship of the variables. The matrix α shows the the speed of adjustment to the long-run equilibrium. Only the adjustment parameters of the cointegration equations are shown. T-statistics are shown in brackets. Model: constant and trend in the cointegrating term and constant in the VAR equation. Results presented here show the lag intervals determined by the Hannan and Quinn's information criterion: for EE 3, for LT 2, for LV 3. The results are robust also for lag lengths determined by the Schwarz's Bayesian information criterion.

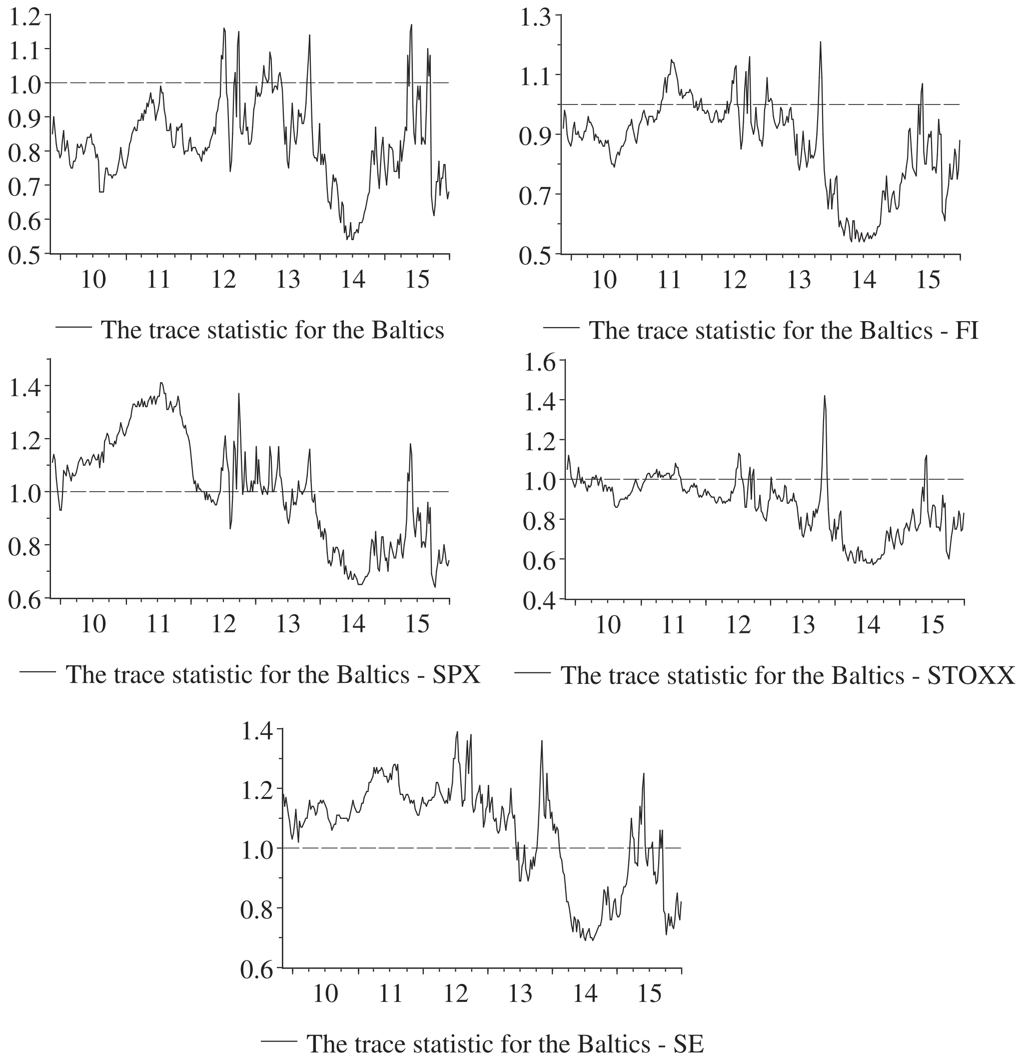

FIGURE 2 Cointegration results for rolling-window estimations for the Baltics as a group and the developed markets. Source: Author's calculations. The lines represent the trace statistics λtrace found by Equation (2), which have been calculated rolling over subsequent subsamples for the null hypothesis r = 0. The window size is 200 weeks, which is approximately 4 years. Model: constant in the cointegrating term and in the VAR equation. Results presented here show the lag intervals determined by the Hannan and Quinn's information criterion for the whole sample as shown in Table 4: for Baltics 3, for Baltics-SPX 3, for Baltics-FI 3, for Baltics-STOXX 3, for Baltics-SE 2. The trace statistics have been normalized with their 5% critical values. Values above one indicate a rejection of the null hypothesis that the number of cointegration vectors is zero and indicate the presence of a long-run relationship

Baltic banking sector might thus be another reason for the cointegration between these countries. Which of the factors is the more relevant determinant of the integration of the stock markets is a topic for further research. In any case, the relationship between the Baltic States and Sweden seems to be the strongest and is thus analysed in more detail in the next section.

4.2 | Cointegration results—The Baltic states individually and Sweden

Here the individual relationships between the Baltic markets and Sweden are studied using the standard Johansen cointegration analysis. First, the standard cointegration analysis is done for bivariate models. Then, the vector error correction estimates are analysed to study how the equilibrium is achieved and what the magnitude of the adjustment is.

The results of the bivariate cointegration tests are presented in Table 6. The results from the cointegration test for Sweden are straightforward and show that the stock markets in the Baltic States are individually integrated with the Swedish market. Both the trace and the maximum eigenvalue tests show that the stock markets of Estonia, Latvia and Lithuania share long-run relationships with Sweden independently over the whole sample, which shows that shocks in the Swedish stock market could be reflected in the dynamics of the Baltic stock markets.

As previously, the robustness of the existence of cointegration is also tested using information criteria. The results are shown in Table 7 and only verify the results of the individual long-term relationships.

The adjustment to shocks is analysed by the vector error correction estimates, which are presented in Table 8. The results of the estimations of the VECMs show that if the stock markets drift away from the equilibrium path, the disequilibrium is corrected through the Baltic States. The adjustment is neither statistically nor economically significant for Sweden, as is illustrated by the adjustment parameter of the cointegration relationship.

The insignificance of the adjustment parameters of the cointegration relationships for Sweden implies that the direction of causality goes from Sweden to each of the Baltic States. The results from the error correction show that the speed of adjustment is highest for Latvia given the estimated coefficients in the cointegration equation, while the adjustments for Estonia and Lithuania are somewhat slower. The estimated spillovers from the stock market shocks of Sweden are largest for the

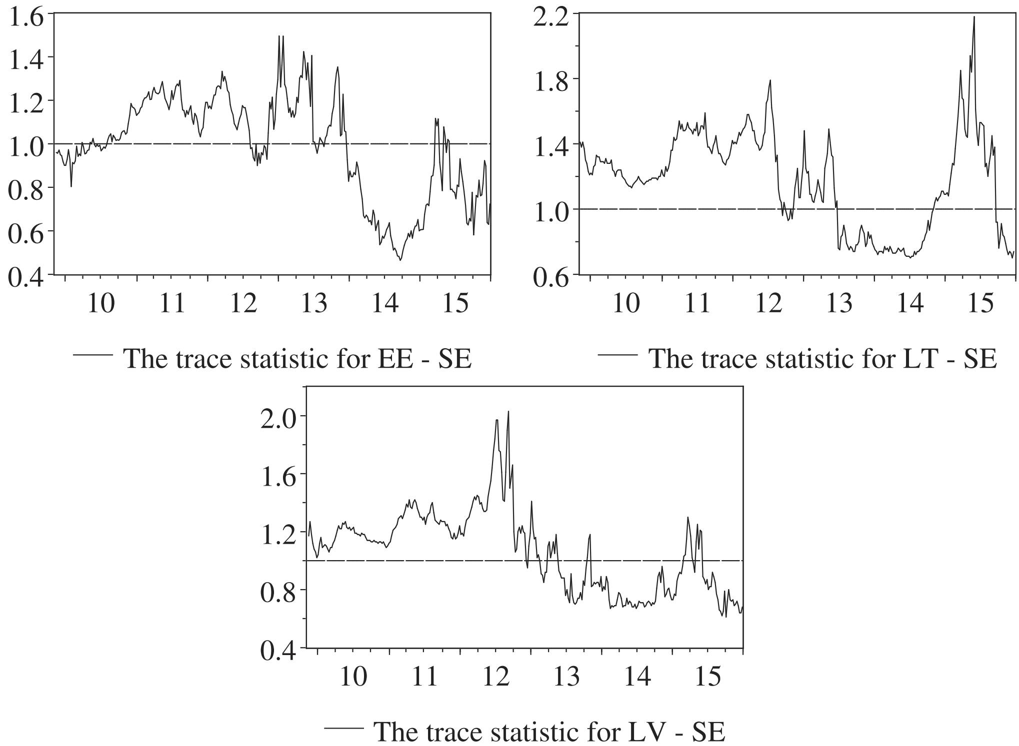

FIGURE 3 Cointegration results for the rolling window for the Baltic States individually and Sweden. Source: Authors' calculations. The lines represent the trace statistics λtrace found by Equation (2), which have been calculated rolling over subsequent sub-samples for the null hypothesis r = 0. The window size is 200 weeks, which is approximately 4 years. Model: constant and trend in the cointegrating term and constant in the VAR equation. Results presented here show the lag intervals determined by the Hannan and Quinn's information criterion: for EE 3, for LT 2, for LV 3. The trace statistics have been normalized with their 5% critical values. Values above one indicate a rejection of the null hypothesis that the number of cointegrating vectors is zero and indicate the presence of a long-run relationship

Latvian stock market, but they are transmitted over to the other two Baltic markets as well.

4.3 | Cointegration results—Discussion of robustness

The cointegration estimation conducted on rolling windows is applied in order to assess the robustness of the finding that the Baltic States share a common long-run relationship with Sweden rather than with other countries. The relationships between the Baltic markets and peers are also studied using the standard Johansen cointegration methodology on rolling sub-samples of 200 observations. First, the relationships are studied in a group setting and then pairwise.

The panels in Figure 2 show the trace statistics found with the rolling-window approach over sub-samples using Equation (2). The trace statistics are scaled with their 5% critical values. Values above one indicate a rejection of the null hypothesis and show evidence of cointegration. These values are then plotted on figures where the end dates of the window are shown so that the first date on the figure characterizes the scaled trace statistic, which is calculated for the previous 200 observations.

The cointegration analysis for the Baltic States individually with Sweden over the whole sample is complemented with the rolling-window approach. Figure 3 presents results that indicate that the stock markets of the Baltic States are all cointegrated with the Swedish stock market over the sub-samples, too.

5 | CONCLUSION

Using standard cointegration analysis, this paper studies the extent of integration of the financial markets in the Baltic States with those in developed Western Europe, proxied by selected stock market indices for the euro area and Sweden and the transmission of shocks to the Baltic region. The data used in the empirical examination are the weekly returns of the stock market indices. The sample covers the period between December 30, 2005 and December 25, 2015. The study is complemented by a rolling-window cointegration analysis over consequent sub-samples.

Both full-sample and rolling-window analysis identify long-run equilibrium relationships between the Baltic and Swedish markets. This result is similar to that of Harrison and Moore (2009), who also show the existence of cointegration between selected stock markets in the CEE and the developed markets of Europe from 2001 onwards.

The bivariate results of the cointegration analysis only add more support for the cointegration between Sweden and the Baltics, as all the Baltic indexes are separately integrated with their Swedish counterpart. Furthermore, there is no integration at all with other stock markets despite the preparations and accession of the Baltic States to the single currency union.

The results from the VECM analysis indicate clearly that the Baltic States are exposed to shocks from Sweden and the shifts in the Swedish market will bring about adjustment also in the Baltic markets. It is also worth keeping in mind that the existence of integration between the financial markets of the Baltics and Sweden will also pass through any negative shocks from Sweden.

The fact that the shocks from Western Europe seem not to be transmitted to the Baltics also argues against the integration of financial markets within the euro area. However, these results indicate that the Baltic States could potentially offer diversification benefits to the stock markets of the euro area. It remains for further studies to analyse whether the Baltic States, which have all joined the euro area, are moving closer to the euro-area stock markets over time or whether the long-run relationships with Sweden are there to stay and what the driving forces are behind the integration.

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ORCID

Kersti Harkmann https://orcid.org/0000-0003-2712-5789

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Optimal currency hedge and the carry trade

Fabio Filipozzi
Department of Financial Markets, Eesti Pank, Tallinn, Estonia and Estonian Business School, Tallinn, Estonia, and

Kersti Harkmann
Department of Economics and Finance, Tallinna Tehnikaulikool Majandusteaduskond, Tallinn, Estonia and Department of Financial Markets, Eesti Pank, Tallinn, Estonia

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Abstract

Purpose – This paper aims to investigate the efficiency of different hedging strategies for an investor holding a portfolio of foreign currency bonds.

Design/methodology/approach – The simplest strategies of no hedge and fully hedged are compared with the more sophisticated strategies of the ordinary least squares (OLS) approach and the optimal hedge ratios found by the dynamic conditional correlation-generalised autoregressive conditional heteroskedasticity approach.

Findings – The sophisticated hedging strategies are found to be superior to the simple strategies because they lower the portfolio risk in domestic currency terms and improve the Sharpe ratios for multi-asset portfolios. The analyses also show that both the OLS and dynamic hedging strategies imply holding a limited carry position by being long in high-yielding currencies but short in low-yielding currencies.

Originality/value – The performance of multi-currency portfolios is examined using more realistic assumptions than in the previous literature, including a weekly frequency and a constraint of no short selling. Furthermore, carry trades are shown to be part of an optimal portfolio.

Keywords Optimal hedge ratios, Portfolio risk hedging, Carry trade, Dynamic hedge, Currency hedge

Paper type Research paper

1. Introduction

The total global holdings of foreign exchange reserves at the end of the first quarter of 2019 were US$12tn (IMF, 2019). The bulk of global reserves has traditionally been held in the top seven most popular currencies, and the US$ and the euro have been the principal currencies for those reserves (Morahan and Mulder, 2013). Recent data show that the reserves are largely invested in government bonds with a credit rating of at least investment grade, and the US$ and the euro remain the dominant currencies (Alekasir *et al.*, 2019). The daily trading turnover on foreign exchange markets has grown steadily over the years, like the accumulation of the global holdings of foreign reserves has, and it averaged US$5.1tn in April 2016 (Bank for International Settlements, 2016).

The question of whether the foreign exposure in a portfolio of global government bonds should be fully hedged or whether it is possible for the risk-minimising investor to find an optimal level of hedge has not been clearly answered and remains a topic of debate. It is typically shown, however, that hedging currency exposure reduces the volatility of bond portfolios and might improve the risk-return trade-off.

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We investigate how effective hedging policy is for official institutions such as central banks for whom preserving the value of the reserves is extremely important, which makes them risk-minimising investors by nature. The size of the reserves held by these institutions has increased steadily since the early 2000s and they represent a notable portion of the wealth of many countries.

Given that official reserves are mostly invested in fixed income securities (Alekasir *et al.*, 2019), we will focus on a bond portfolio and from the viewpoint of an investor based in the euro area. Data from Alekasir *et al.* (2019) show that most central banks use the US$ and their own domestic currency to measure the performance of their foreign portfolios. Taking the euro as the base currency allows the results and conclusions from our analysis to be used and expanded on by institutions in the euro area and beyond.

The currencies chosen are those that constitute the typical portfolio of an official institution, which are the US dollar (US$), the Japanese Yen (JPY), the UK pound sterling (GBP), the Australian dollar (AU$), the Canadian dollar (CA$), the Norwegian krone (NOK) and the Swiss franc (CHF). We start by finding the degree of hedging needed to minimise the variance of return of the portfolios and then we compare the results.

Our paper contributes in two ways to the literature on currency heading, which is surveyed in Section 2. First, we conduct our analysis on a multi-currency portfolio, while the existing literature mainly focuses on single assets without constructing portfolios (Chang *et al.*, 2013; Lai, 2019).

We develop the analysis by using time-varying hedge ratios computed using the dynamic conditional correlation-generalised autoregressive conditional heteroskedasticity (DCC-GARCH) method by Engle (2002). The DCC-GARCH makes it possible to account for the time-varying and autoregressive nature of the volatilities of both bonds and currencies present in the portfolio and, at the same time, to take into account the presence of conditionality in the correlations between the portfolio components. The idea of the DCC-GARCH model is that the conditional covariance matrix between the portfolio components can be decomposed into conditional standard deviations and a correlation matrix. In the case of dynamic conditional correlation (DCC), both the conditional standard deviations estimated from univariate generalised autoregressive conditional heteroskedasticity (GARCH) models and a correlation matrix are varying over time. Then, the time-varying hedge ratios are found by using the estimated time-varying conditional covariance matrix.

This approach allows for interdependence between the carry trades and optimal hedging to be disentangled. This has not been covered in previous academic research. Second, we make our analysis closer to real applicable situations by imposing a rule of no short selling of currencies. We use a weekly hedging strategy rather than the daily hedging strategy that is often used in previous literature (Opie *et al.*, 2012; Lai, 2019). This analysis will show that with assumptions that are closer to reality, both no hedge and full hedge are sub-optimal strategies, and investors can achieve a better risk-adjusted return by optimising their currency exposure, either statically or dynamically.

The rest of the article is organised as follows. Section 2 summarises the related literature. Section 3 presents the data and the methodology. Section 4 provides the empirical results of the analyses. Section 5 discusses our findings and draws comparisons with the results in the literature. Finally, Section 6 provides final comments.

2. Related literature

The literature review covers the literature since the 1980s and is organised along three dimensions that the literature has centred on when analysing whether, how and how much currency risk should be hedged. The first of these lines looks at the composition of the portfolio and whether a single strategy could work for all investors (Perold and Schulman, 1988; Black, 1989); the second looks at whether the investment horizon of the investors is short or long (Froot, 1993; Carcano, 2007; Campbell *et al.*, 2010; Schmittmann, 2010); and the third considers the complexity of the hedging strategy and whether it is static or dynamic (Kroner and Sultan, 1993; Ku *et al.*, 2007; Schmittmann, 2010; Caporin *et al.*, 2014; Cho *et al.*, 2019). The main question is the same in all cases, i.e. whether investors should accept the currency risk in their portfolio, or whether this risk should be reduced or even eliminated. We first consider the theoretical literature, and then we review the findings from the empirical literature.

Whether and by how much currency exposure should be hedged was initially addressed theoretically by Perold and Schulman (1988) and Black (1989). The early theoretical discussion centred on the universality of hedging strategies and whether all investors should apply the same strategy, whatever the asset classes in their portfolio. Early studies tend to conclude that simple, universal hedge ratios are optimal for all portfolios (Perold and Schulman, 1988; Black, 1989). Black (1989) went as far as to derive a universal formula for hedging. While these approaches are attractive because of their simplicity, their conclusions have been challenged in the more recent literature (Opie and Riddiough, 2019; Laborda, 2018; de Boer *et al.*, 2019). It was subsequently shown that the 100% hedge ratio might not be optimal for reducing the volatility of the portfolio returns mainly because of cross correlations between different currencies, and that the optimal hedge ratios differ depending on the asset classes and currency pairs, implying that there is no universal hedge ratio. In our analysis, we will take the simpler approach as a starting point, using 0% and 100% fixed hedging ratios, and we will compare them with more sophisticated approaches to hedging.

In the search for an investor-specific hedging ratio, recent articles have focused on the nature of the asset classes included in the portfolio, and in particular on their volatility and cross-correlation. Haefliger *et al.* (2002), de Roon *et al.* (2012) and Glen and Jorion (1993) have looked at this and concluded that portfolio composition is indeed relevant for the hedging strategy. More recently Ackermann *et al.* (2016) and de Boer *et al.* (2019) both confirm that not only the covariance between different asset classes, but also the changes in covariances through time and through different business cycles are important when deciding the hedging strategy. These authors focus more on the relation between stocks and bonds while we will focus only on bonds, but we will see that the volatility and correlations are also relevant for how effective the hedging strategy is for a bonds-only portfolio.

The second line of enquiry considers the investment horizon of the investor. If exchange rates are mean reverting, hedging in theory should improve the risk/return profile of the portfolio in the short term by reducing volatility, but not in the long term, because the reduction in volatility will not compensate for the cost of hedging, which increases with the investment horizon. This problem has been analysed by Froot (1993) and Carcano (2007), and their studies confirm the hypothesis of hedging only being efficient in the short horizon. Campbell *et al.* (2010) and Schmittmann (2010) combine the question of volatility and cross-correlation with the time horizon question, and reach the conclusion that some hedging can be optimal in the long term as well. We will follow an approach similar to that of Campbell *et al.* (2010) and Schmittmann (2010).

Finally, the third theoretical question centres around the hedging method. Calculating hedging ratios has become increasingly complex over time, starting from pure no hedge vs full hedge, going on to ordinary least squares (OLS) regression hedging (Kroner and Sultan, 1993; Schmittmann, 2010), and then to more sophisticated approaches. Kroner and Sultan (1993) use an error-correction model together with the GARCH model, Cho *et al.* (2019) use

DCC, Ku *et al.* (2007) use constant conditional correlation and DCC models in addition to their OLS and error-correction models, Caporin *et al.* (2014) use DCC and several other multivariate GARCH models and Lien *et al.* (2002) add a constant-correlation vector GARCH model as well. Alvarez-Diez *et al.* (2016) have gone a step further when analysing the hedging strategy as they focus not on volatility but on the value-at-risk and conditional value-at-risk of the portfolios.

The main theoretical idea behind this line of research is that more complex models are able to capture different characteristics of the distribution of the returns of assets and currencies, and this makes the calculation of the hedging ratio more precise. We use the OLS and DCC approaches here, and we find that they can indeed give better strategies than simpler models. While OLS is a straightforward way to address the correlations between bonds and currencies, the DCC approach is used here because it makes it possible to model the time-varying nature of the correlations. The DCC method gives good results for risk-adjusted return in line with the recent literature, such as Ackermann *et al.* (2016). The effectiveness of dynamic hedging strategies derives from the finding that the time variation of correlations is important for the building of multi-asset portfolios.

In the empirical results of the previous literature, different articles use different asset classes, currencies, investment horizons and optimisation strategies, but some main common conclusions can be drawn that are relevant for our research. Firstly, there is a general consensus that currency exposure stemming from equity investment should not be hedged, while the exposure that comes from bond investment should be hedged (Haefliger *et al.*, 2002; Campbell *et al.*, 2010). We will focus here only on bonds, and we will address the question of whether no hedging is an optimal strategy. The second conclusion is that the time horizon is important, and hedging can be too costly for longer horizons (Froot, 1993). Thirdly, more sophisticated hedging methods can improve the risk/return profile of the portfolio (Opie *et al.*, 2012; Caporin *et al.*, 2014).

An important line of enquiry that has not received much attention but that is closely related to our article focuses on the role of carry in the choice of strategy and the empirical results of the different hedging strategies. Baltas (2017), Laborda (2018) and Opie and Riddiough (2019) find that both the classical currency carry factor and carry factors for other asset classes can not only improve the total risk-adjusted performance of a multi-asset portfolio, but can also be a useful input in the decision of a multi-currency portfolio about hedging currency.

Our article differs by trying to fill gaps in three directions. Firstly, while there is a strong indication that hedging either optimally or fully reduces the volatility of bond portfolios, there is no clear answer as to what the optimal level of hedge should be for bond portfolios, nor to the question of how to determine the optimal level of hedge. Most earlier studies analyse the issue by looking at single assets without addressing the construction of portfolios (Choudhry, 2004; Ku *et al.*, 2007; Chang *et al.*, 2013; Lai, 2019), or by considering only stocks or stocks and bonds in conjunction when the portfolio problem is approached (Carcano, 2007; Caporin *et al.*, 2014). The dynamic hedging of bond portfolios is not addressed in detail, as studies such as Choudhry (2004), Ku *et al.* (2007) and Lien (2009) focus on stocks and foreign currency and on the use of futures as hedging instruments. Furthermore, we seek to shed light on the relationship between the hedging strategy and the currency carry trades. Secondly, most of the available research uses daily hedging strategies that may not be feasible in practice (Opie *et al.*, 2012; Kroner and Sultan, 1993), particularly for institutional investors with large portfolios. Thirdly, hedging is done using futures in the vast majority of the literature (Kroner and Sultan, 1993; Ku *et al.*, 2007; Caporin *et al.*, 2014) and there are very few investigations that use forward contracts, which could be considered a limitation [1]. A method built on the Engle's (2002) DCC method has found some support for dynamic hedging but in general there is not enough evidence to conclude that using dynamic hedging helps to make the hedge more effective.

3. Research methodology

3.1 Data and descriptive statistics

The currencies chosen are those that are included in the typical portfolio of an official institution. We gathered data for the currencies of the USA (US$), Australia (AU$), Canada (CA$), Norway (NOK), Switzerland (CHF), Great Britain (GBP) and Japan (JPY). Data from Reuters are used for the forward rates of the CA$ and for the AU$. We do not consider here the volume or quantity effects. We do not consider the part of the portfolio invested in euros because we consider this to be in a domestic portfolio. This approach is justified for two reasons. The first is that we use the euro as the currency in which the performance of the foreign portfolio is measured. We use a fully foreign portfolio from the perspective of a euro-based investor to study the hedging of pure foreign portfolios in detail without the influence of euro-denominated assets. The second reason is that the motivation for an official institution such as a central bank to hold foreign assets is different from their motivation for investing in domestic assets. For an official euro-based institution as we understand it in our analysis, the foreign portfolio would consist only of assets denominated in foreign currency.

The data are gathered in weekly frequency from the Bloomberg generic quotation end of day mid-price. The data cover the period from 7 January 2000 to 26 January 2018 [2]. We take as a starting point the launch of the euro currency (1999), but the first year of the sample is used as the first stage estimation window for the DCC model, so all the results and statistics are reported from the period starting at the beginning of 2000. We use the indexes produced by Citigroup for the fixed income investment, taking the total return index level with weekly frequency for each country with the Friday closing price for the World Government Bond Index for the three to five year maturity sector, measured in local currency. Table 1 reports the weekly returns, the standard deviation of the returns and the return/risk ratio between the two main statistics for the series used in our analysis.

3.2 Methodology

In the traditional portfolio optimisation framework, investors maximise the return of their portfolio by changing the weights of the possible asset classes under the constraint of the

Currency	AU$	CA$	CHF	GBP	JPY	NOK	US$
Bond return in local currency							
Mean	0.105%	0.080%	0.046%	0.087%	0.019%	0.086%	0.081%
SD	0.445%	0.386%	0.274%	0.366%	0.160%	0.404%	0.456%
Return/risk	0.236	0.208	0.169	0.238	0.120	0.212	0.178
Exchange rate return							
Mean	0.027%	0.004%	0.039%	−0.030%	−0.015%	−0.013%	−0.013%
SD	1.496%	1.384%	1.050%	1.177%	1.684%	1.001%	1.394%
Return/risk	0.018	0.003	0.037	−0.025	−0.009	−0.013	−0.009

Notes: Return/risk ratio is the ratio between the mean and the standard deviation for each currency
Source: Bloomberg, Thomson Reuters and authors' calculations. The period covered is from 7 January 2000 to 26 January 2018 (weekly frequency)

Table 1. Bond and exchange rate weekly returns

maximum amount of risk or volatility they are ready to accept. Although we partly follow the literature discussed above (Glen and Jorion, 1993; Caporin *et al.*, 2014), we deviate from this approach in a couple of ways. Firstly, we focus only on one part of the portfolio choice. We consider an investor with institutional constraints that require the investor to invest a given amount in fixed income securities. The second deviation from the traditional mean variance optimisation framework is that our investor minimises the variance of the portfolio instead of maximising the return under a maximum risk constraint. This is the typical approach to portfolio optimisation when focusing on optimal hedging of currency risk (Kroner and Sultan, 1993; Schmittmann, 2010). The objective function minimised by our investor would therefore be:

$$\underset{h}{min}\, Var(r_h) = \underset{h}{min}\;\; Var(r_u - h_t[f_t - e_t]) \tag{1}$$

where r_h represents the return of the optimally hedged portfolio, r_u is the foreign-currency return of the unhedged portfolio, e_t is the change in the exchange rate between the domestic and the foreign currencies, f_t is the return for period t from the hedging position, and h_t is the hedge ratio. This is in line with the analysis by Schmittmann (2010). The optimal hedge is given by the slope coefficient of the following regression, which is also used for the OLS estimations of hedge ratios:

$$r_{u,t} = \alpha + \beta\,(e_t - f_t) + \varepsilon_t \tag{2}$$

The coefficient β is the optimal hedge ratio estimated as: $\beta = \frac{Cov\left(r_{u,t}, e_t - f_t\right)}{Var(e_t - f_t)}$.

In the time-invariant framework, it is assumed that the covariance-variance matrices are constant over time and so only one optimal hedge ratio exists. However, it is well documented in the literature that changes in the variance of asset returns might lead to incorrect conclusions about the constant hedge ratios as the regular OLS approach ignores the time-varying nature of the variance–covariance structure of financial time series. We address this concern using Engle's (2002) DCC approach, which takes changes in volatility into account by fitting GARCH models onto the individual variables. These adjustments might improve the quality of the optimal hedge ratio because of its dynamic nature, as the hedging ratios are no longer constant but change over time as the covariance–variance matrix is also time-variant.

The DCC-GARCH model follows the steps proposed in Engle (2002) and is built for the return series used with time-varying means, variances and covariances. This model can be applied for each currency and it takes into account the time-varying nature of the volatilities and correlations. Firstly, the mean equations for the unhedged return $r_{u,t}$ at time t and at cost $\eta_t = (e_t - f_t)$ for the net hedge at time t are estimated with the following equations:

$$r_{u,t} = \mu_{r_u,t} + \varepsilon_{r_u,t} \tag{3}$$

where $\mu_{r_u,t}$ is the constant term that is the expected value of the conditional $r_{u,t}$ and $\varepsilon_{r_u,t}$ is the residual term. The mean equations for the net hedge cost η_t at time t are estimated by:

$$\eta_t = \mu_{(e_t - f_t),t} + \varepsilon_{(e_t - f_t),t} \tag{4}$$

where η_t is the expected value of the conditional $\mu_{(e_t - f_t),t}$ and $\varepsilon_{(e_t - f_t),t}$ is the residual term. Then the conditional variances are estimated by the GARCH(1,1) models:

$$h_{r_u,t} = \omega_{r_u} + \delta_{r_u} \varepsilon^2_{r_u,t-1} + \gamma_{r_u} h_{r_u,t-1} \tag{5}$$

$$h_{\eta_t,t} = \omega_{\eta_t} + \delta_i \varepsilon^2_{\eta_t,t-1} + \gamma_{\eta_t} h_{\eta_t,t-1} \tag{6}$$

where ω_i is the constant, δ_i is the autoregressive conditional heteroskedasticity effect and γ_i is the GARCH effect. A positive parameter of γ_i shows clustering and persistence of volatility. Thirdly, the dynamic covariance is found by:

$$h_{r_u \eta_t,t} = \rho_{r_u \eta_t,t} \sqrt{h_{r_u,t}} \sqrt{h_{\eta_t,t}} \tag{7}$$

The model parameters are found using the maximum likelihood method. The dynamic optimal hedge ratio can be found by:

$$\beta_t = h_{r_u \eta_t,t} / h_{\eta_t,t} \tag{8}$$

A way to assess the effectiveness of hedging that uses the OLS and DCC-GARCH method hedge ratios is to compare the Sharpe ratios of the hedged portfolio with those of an alternative portfolio. This can be done by taking the *z*-statistic approach used in Kim (2012), which was developed by Jobson and Korkie (1981) and further developed by Memmel (2003), in which we calculate the Sharpe ratios for the portfolios and test whether the difference is statistically significant from the null hypothesis of no difference between the ratios. The *z*-statistic can be found by:

$$z = \frac{Sharpe_{r_h} - Sharpe_{r_u}}{\sqrt{\frac{1}{N}\left[2 - 2\tilde{\rho} + \frac{1}{2}\left(Sharpe^2_{r_u} + Sharpe^2_{r_h} - 2Sharpe_{r_u} Sharpe_{r_h} \tilde{\rho}^2\right)\right]}} \tag{9}$$

The Sharpe ratios are calculated as $Sharpe_{r_h} = \frac{\tilde{\mu}_{r_h} - r_f}{\tilde{\sigma}_{r_h}}$ and $Sharpe_{r_u} = \frac{\tilde{\mu}_{r_u} - r_f}{\tilde{\sigma}_{r_u}}$, where $\tilde{\mu}_{r_h}$ and $\tilde{\mu}_{r_u}$ are the mean returns of the hedged and unhedged portfolios, r_f is the risk-free interest rate, which is assumed to equal zero for the sake of simplicity in our analysis, $\tilde{\sigma}_{r_h}$ and $\tilde{\sigma}_{r_u}$ are the standard deviations of the return of the hedged and unhedged portfolios, respectively, while N is the number of observations and $\tilde{\rho}$ is the correlation between the returns of the hedged and unhedged portfolios. The test statistic is asymptotically normally distributed (Jobson and Korkie, 1981; Memmel, 2003).

4. Empirical results

Using the methodology presented in the previous section, we first find the optimal hedge ratios and then use them to analyse the performance of portfolios with different hedging strategies in comparison to the performance of the zero hedge and full hedge portfolios. We also conduct a constrained optimisation [3] for the standard OLS (with robust standard errors) approach, and for the constrained dynamic hedge ratios, we use a ceiling of 100% whenever the dynamic hedge exceeds 100%. Table 2 reports the hedge ratios we found for the four different cases (the average across the sample is used for the DCC hedge ratios).

The results for the hedge ratios are quite similar across the four methods for AU$ and CA $. All the hedge ratios remain under 100%, whichever method is used to find them. The hedge ratios for the remaining currencies, with the exception only of US$, are consistently above 100% in unconstrained regressions, but are forced to 100% when constrained. A comparison of the hedge ratios for different currencies reveals that the hedge ratios for the US$ are not very different from the fully hedged ratio. The differences in the degree of hedge ratios between the JPY, the CHF, the GBP and the NOK on one side and the AU$ and CA$ on the other side are notable.

Japan and Switzerland are the two countries that have the lowest return on the fixed income index, with a weekly return of 0.019% for Japan and 0.046% for Switzerland (Table 1), and they also have the lowest yield to maturity (not reported here). The AU$ is at the other end of the spectrum, with a realised fixed income return of 0.105%. This suggests that the optimal hedge ratios are inversely correlated with the level of interest rates, an indication that the carry trade strategy is embedded in the portfolios with optimal hedge ratios.

The average optimal dynamic hedge ratios are very close to the constant hedge ratios. Nevertheless, Figure 1 shows that the time-varying hedge ratios (marked as DCC for a given currency) for a portfolio of several assets move by a large amount against the constant hedge ratios (marked as OLS for that same currency in the figure). This is especially clear for the CHF, for which the movement was caused by the Swiss Central Bank abandoning the CHF peg to the euro in 2015.

Using the hedge ratios from Table 2, we compare the results of various portfolios. Table 3 summarises the return and risk characteristics of the different portfolios. The unhedged return (RU) represents the return of the bond indexes translated into local currency, which is the euro in our case, without hedging. Next are the fully hedged returns (RH), where 100% of the currency exposure is hedged, and then come two unconstrained portfolio returns (OLS and DCC) found using the optimal hedge ratios of the OLS approach and the DCC-GARCH approach [4].

There is clear evidence that volatility is lower in all the hedged portfolios than in the unhedged portfolio returns. The returns of the equally weighted unhedged portfolio are around three times as volatile as those of the hedged portfolios. Hedging also improves the risk–return profile significantly.

A comparison of the statistics of optimal portfolios shows the best return/risk ratio to be given by the strategies of the OLS approach and the optimal hedge ratios found by the DCC-GARCH approach. The statistics for the portfolios are worse with the constrained hedge ratios, but they are still better than those of the unhedged or fully hedged portfolios. The analysis of the efficiency of the hedging strategy has been enhanced using the hedge effectiveness (HE) measure, which represents the relative reduction of the risk in the portfolio when optimal hedging strategies are used. The HE statistics confirm the conclusion drawn using the return/risk ratios.

Portfolio	AU$ (%)	CA$ (%)	CHF (%)	GBP (%)	JPY (%)	NOK (%)	US$ (%)
Constant hedge (OLS)	77.75	61.81	121.41	106.58	139.06	104.27	95.49
Constant hedge (OLS) constrained	75.52	76.88	100.00	100.00	100.00	100.00	100.00
Average dynamic hedge (DCC)	75.89	61.95	113.99	108.78	145.35	103.68	93.88
Average dynamic hedge (DCC) constrained	75.71	61.89	98.08	96.55	99.89	95.16	88.48

Notes: The period covered is from 7 January 2000 to 26 January 2018, weekly frequency. The R^2 for the first estimation (OLS) is 0.913 and for the second (OLS constrained) it is 0.899
Source: Authors' calculations

Table 2.
Optimal hedge ratios

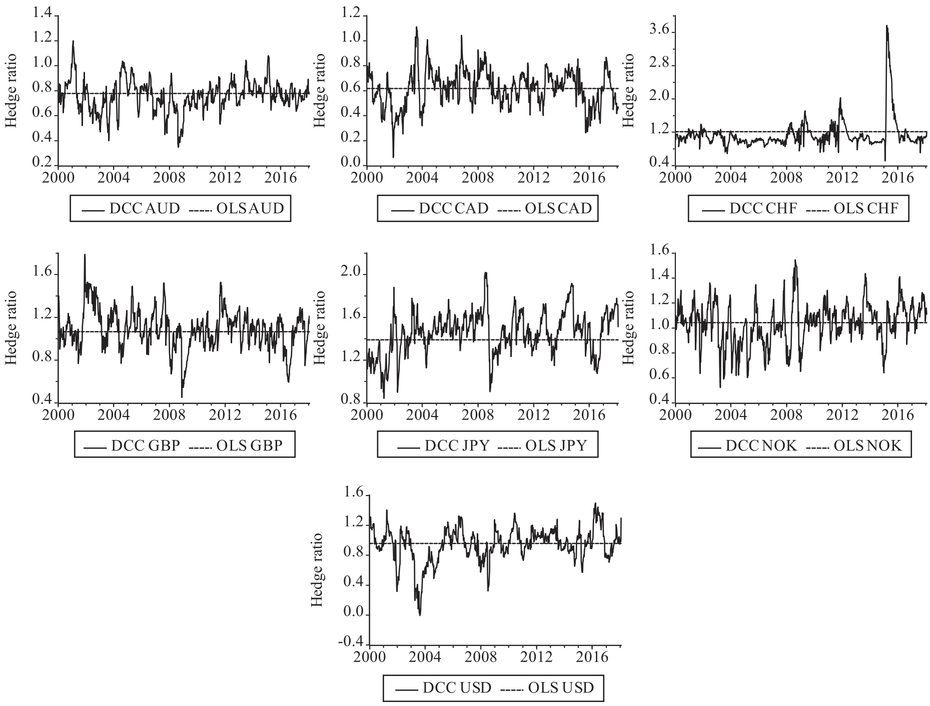


Figure 1. Constant and time-varying hedge ratios for the seven-asset portfolio

Note: The second axes show the time-varying hedge ratios estimated with the DCC model and the constant hedge ratios estimated with the OLS model. The value 1 corresponds to a 100% hedge ratio
Source: Authors' calculations. The period covered is from 7 January 2000 to 26 January 2018

To explain the economic meaning of the analysis better, we have translated the results of hedging into annualised outcome. While the returns for the portfolios with different hedging strategies do not change much in economic terms, staying between 3.54% and 3.76%, the annualised standard deviations of returns are much more diverse between portfolios, varying from 6.16% for the unhedged portfolio to 1.8% for the OLS and DCC portfolios. If we translate these figures into value at risk terms, supposing normality of the distribution of returns, the unhedged portfolio loses 6.3% or more in 5% of the cases, while both the OLS and DCC portfolios have a 95% probability of having a positive return.

The variance ratio test lets us assess whether the variances of different portfolios are significantly different. The variance of the unhedged portfolio is indeed significantly higher than the variance of the fully hedged portfolios. The fully hedged portfolio risk is also significantly higher than the risks of the unconstrained OLS and DCC portfolios. Comparing the variances of the OLS and DCC optimal hedge ratio portfolios does not reveal a conclusive result to show that one ratio is significantly better than the other. We can only conclude that the constant optimal hedge ratio produces lower portfolio variance than fully hedging the portfolio does.

Evidence from the Sharpe ratios suggests that neither full hedging nor no hedging is optimal, as the return/risk trade-off can be significantly improved with optimal hedging.

Portfolio	RU	RH	OLS	DCC	OLS constrained	DCC constrained
Mean	0.071%	0.068%	0.071%	0.070%	0.070%	0.067%
SD	0.854%	0.288%	0.249%	0.254%	0.271%	0.281%
Return/risk	0.083	0.236	0.285	0.276	0.258	0.238
HE against RU		88.63%	91.50%	91.15%	89.93%	89.17%
HE against RH			25.25%	22.22%	11.46%	4.80%
Sharpe ratio test						
vs RU		3.89***	5.25***	5.01***	5.34***	5.68***
vs RH			3.27***	2.04**	2.17**	0.31
vs DCC			0.81			
Variance ratio test						
vs RU		0.11***	0.09***	0.09***	0.10***	0.11***
vs RH			0.75***	0.78***	0.89**	0.95
vs DCC			0.96			

Notes: RU represents the fully unhedged portfolio and RH represents the fully hedged portfolio. The hedging ratio for each currency has been found for OLS using the OLS method and for DCC using the dynamic coefficient correlation method. The last two columns report the statistics for the portfolios found with the same methods, but with the hedging ratio for each currency capped at between 0% and 100%. HE measures the relative risk reduction in a hedged portfolio against the no hedge portfolio or against a fully hedged portfolio. The test statistics are shown for the equality of the Sharpe ratio tests of Jobson and Korkie (1981). Superscripts *** and ** indicate the rejection of the null hypothesis of equal Sharpe ratios at the 1% and 5% levels. For the variance ratio test, the test statistics are shown, and *** and ** indicate the rejection of the null hypothesis of equal variances at the 1% and 5% levels
Source: Authors' calculations. The period covered is from 7 January 2000 to 26 January 2018, weekly frequency

Table 3.
Multiple asset portfolio returns with optimal hedge ratios

This is particularly the case for the OLS, the DCC and the OLS constrained portfolios. In their variance and Sharpe ratio tests, the OLS and DCC portfolios have very similar results. It can be seen that the optimal portfolios have better risk-adjusted returns because they combine the benefits of a reduction in volatility with the positive effect of keeping a small open currency position in the high-yielding currencies, especially AU$, against an opposite small position in the low-yielding currencies, which are JPY and CHF. This conclusion is confirmed by the results shown in Table 4, where the exchange rate contribution to the overall portfolio performance is shown.

Exchange rate contribution	RU (%)	RH (%)	OLS (%)	DCC (%)	OLS constrained (%)	DCC constrained (%)
Mean	0.002	−0.004	0.000	−0.001	−0.003	−0.004
SD	0.825	0.103	0.152	0.121	0.186	0.171

Notes: RU represents the fully unhedged portfolio and RH represents the fully hedged portfolio. The hedging ratio for each currency has been found for OLS using the OLS method and for DCC using the dynamic coefficient correlation method. The last two columns report the statistics for the portfolios found with the same methods, but with the hedging ratio for each currency capped at between 0% and 100%. The contribution of the exchange rate exposure to the overall portfolio performance is reported, but the interest rate contribution is the same for all the portfolios and so is not reported
Source: Authors' calculations. The period covered is from 7 January 2000 to 26 January 2018

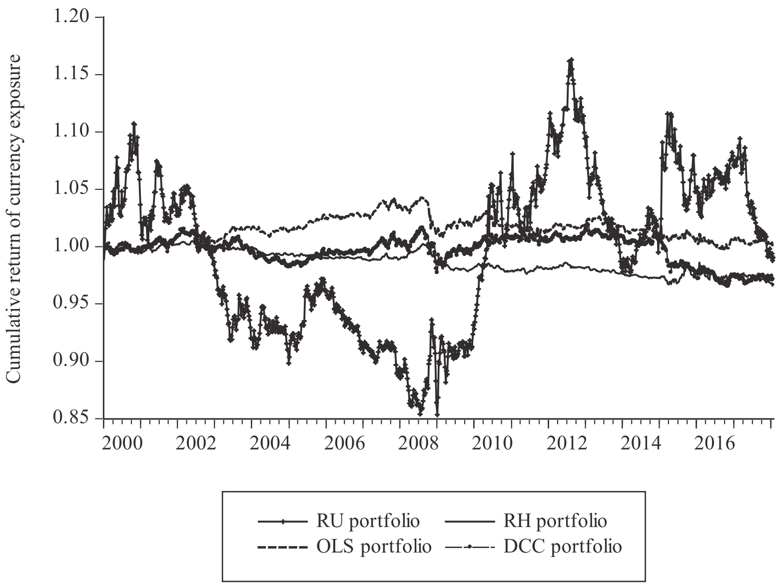
Table 4.
Portfolio performance contribution

The total return and risk of each portfolio can be divided into two components of the interest rate and the exchange rate. The first is the same for each portfolio, while the second differs because the hedge ratios are different for the six portfolios, ranging from 0% for RU to 100% for RH, and the cost of hedging is also different as it is proportional to the hedging level. Table 4 reports only the return and risk stemming from the exchange rate component of the six portfolios.

The return of the currency exposure, whether positive or negative, is small for each portfolio and makes a relatively small contribution to the overall return of the portfolios. At the same time, the contribution to risk in the standard deviation can be quite high, depending on the hedging strategy adopted. The open currency positions add volatility for the unhedged portfolio RU, while the contribution to portfolio volatility is much lower for all the other portfolios. The optimal hedge ratios help to keep the volatility under control, while at the same time the loss from the hedging activity is marginal when compared to the total returns, as reported in Table 3.

Figure 2 depicts the cumulative return of the currency exposure for the four portfolios. The currency exposure is not only volatile, but is also able to have a substantial negative impact on the overall portfolio result, which is especially clear for the unhedged portfolio.

Fully hedged currency exposure reduces the volatility of the portfolio, but there is a constant cost from the hedge. The OLS and DCC portfolios allow the benefit of reduced volatility to be combined with the ability to run a small carry exposure, which recovers the hedging costs.



Note: Y-axis represents the cumulative return of the portfolios
Source: Authors' calculations. The period covered is from 7 January 2000 to 26 January 2018, weekly frequency

Figure 2.
The return attribution of the portfolios' currency exposure

To ascertain the robustness of our results, we compute the hedging ratios and portfolio returns for the same time period using monthly instead of weekly data. The results are reported in Table 5.

In line with the results found with weekly frequency, the unhedged portfolio exhibits the worst volatility and return/risk ratio, followed by the fully hedged portfolios. The unconstrained optimised portfolios offer a better return/risk combination, followed by the constrained optimised portfolios. The results of the variance ratio and the Sharpe ratio tests reinforce the conclusions drawn using weekly data. The variance ratio and the Sharpe ratio tests show that the optimised methods of OLS and DCC, whether unconstrained or constrained, are better than both the fully hedged and the fully unhedged portfolios.

In addition to the monthly analysis, we also performed a test of robustness against different regimes. There have been several different regimes in financial markets in the past 20 years; one of the most important events that affected the markets was the bankruptcy of Lehman Brothers, which we have used as a regime-shift event to split the sample on 12 September 2008. Table 6 reports the results for the robustness check with two regimes [5].

The general conclusion as shown does not change, as RU, the fully unhedged portfolio, is still by far the worst in terms of the return and risk trade-off. Taking the fully hedged portfolio (RH) as a benchmark in both the full sample and the two sub-samples, OLS and DCC represent an improvement over the return of RH, with unconstrained portfolios performing better than the constrained one. Even so, the two samples are different. In the

Portfolios	RU	RH	OLS	DCC	OLS constrained	DCC constrained
Mean	0.282%	0.329%	0.304%	0.320%	0.294%	0.282%
SD	1.740%	0.883%	0.557%	0.560%	0.679%	0.713%
Risk/return	0.162	0.372	0.545	0.572	0.432	0.395
HE against RU		74.26%	89.75%	89.65%	84.77%	83.19%
HE against RH			60.19%	59.78%	40.84%	34.68%
Sharpe ratio test		RH	OLS	DCC	OLS constrained	DCC constrained
vs RU		4.99***	9.91***	10.47***	9.53***	10.66***
vs RH			5.93***	6.72***	2.59**	0.72
vs DCC			−2.42			
Variance ratio test		RH	OLS	DCC	OLS constrained	DCC constrained
vs RU		0.26***	0.10***	0.10***	0.15***	0.17***
vs RH			0.40***	0.40***	0.59***	0.65***
vs DCC			0.99			

Note: RU represents the fully unhedged portfolio and RH represents the fully hedged portfolio. The hedging ratio for each currency has been found for OLS using the OLS method and for DCC using the dynamic coefficient correlation method. The last two columns report the statistics for the portfolios found with the same methods, but with the hedging ratio for each currency capped at between 0% and 100%. HE measures the relative risk reduction in a hedged portfolio against the no hedge portfolio or against a fully hedged portfolio. The test statistics are shown for the equality of the Sharpe ratio tests of Jobson and Korkie (1981). Superscripts *** and ** indicate the rejection of the null hypothesis of equal Sharpe ratios at the 1% and 5% levels. For the variance ratio test, the test statistics are shown and *** indicates the rejection of the null hypothesis of equal variances at the 1% level
Source: Authors' calculations. The period covered is from 31 January 2000 to 31 January 2018, monthly frequency

Table 5.
Multiple asset portfolio returns with optimal hedge ratios (monthly data)

Portfolios	RU	RH	OLS	DCC	OLS constrained	DCC constrained
7 January 2000–12 September 2008						
Mean	0.060%	0.090%	0.096%	0.093%	0.091%	0.086%
SD	0.703%	0.303%	0.271%	0.269%	0.281%	0.280%
Risk/return	0.086	0.297	0.355	0.347	0.323	0.308
HE against RU		81.44%	85.14%	85.39%	84.04%	84.13%
HE against RH			19.92%	21.27%	14.02%	14.49%
19 September 2008–26 January 2018						
Mean	0.080%	0.475%	0.044%	0.042%	0.050%	0.047%
SD	0.975%	0.273%	0.214%	0.247%	0.259%	0.271%
Risk/return	0.084	0.173	0.207	0.168	0.192	0.174
HE against RU		92.18%	95.17%	93.56%	92.95%	92.28%
HE against RH			38.17%	17.65%	9.81%	1.31%

Notes: Given that dynamic models required an initial period of convergence of the parameters, we present the statistics for the sample starting at the beginnings of 2000 and 2008 for both subsamples. RU represents the fully unhedged portfolio and RH represents the fully hedged portfolio. The hedging ratio for each currency has been found for OLS using the OLS method and for DCC using the dynamic coefficient correlation method. The last two columns report the statistics for the portfolios found with the same methods, but with the hedging ratio for each currency capped at between 0% and 100%. HE measures the relative risk reduction in a hedged portfolio against the no hedge portfolio or against a fully hedged portfolio
Source: Authors' calculations. The period covered is from 7 January 2000 to 26 January 2018, weekly frequency

Table 6. Multiple asset portfolio returns for the sample before and after the bankruptcy of Lehman Brothers

second sample from 2008 to 2009, interest rates are particularly low in the euro area, increasing the cost of both full hedging and optimised hedging considerably, so that while the return of the unhedged portfolio RU is lower than the returns of other portfolios in the first sub-sample, the opposite is true in the second sub-sample. This is because the cost of hedging becomes much higher when relative interest rates are lower. Despite this, both the OLS and DCC hedging strategies are more efficient than the fully hedged portfolio.

5. Analysis and discussion

We discuss the results of our article in more detail in this section, and we compare them with the results in the literature presented in Section 2. We show that portfolios of foreign bond investments are sensitive to foreign currency risk and these risks can only be partially mitigated in multiple asset portfolios. In line with the previous literature on international-fixed income portfolios, such as Carcano (2007), Campbell *et al.* (2010), Schmittmann (2010), de Roon *et al.* (2012) and Caporin *et al.* (2014), we find that different kinds of hedging strategies improve the return/risk profiles in our sample significantly. Unhedged positions perform the worst in terms of the volatility of the portfolios.

The comparison between the fully hedged portfolio and the optimally hedged portfolios found using the OLS and DCC methods shows that these two methods give better results than 100% hedging does for both the volatility of the return and the Sharpe ratio. From the comparison of the OLS and DCC models, we conclude that both methods fulfil the objective of minimising the variance of the portfolio, and that the optimal hedging ratios are similar for both. Our results contradict those of Caporin *et al.* (2014) to some extent, as we cannot conclude that dynamic hedging outperforms the OLS method. This might be because we have used a weekly hedging horizon, which reduces the number of observations but is a much more realistic assumption than the daily hedging horizon, and also because we use a strict bond portfolio.

The finding that the DCC method gives good results for risk-adjusted return is in line with the recent literature, such as Ackermann *et al.* (2016) for example. The effectiveness of dynamic hedging strategies derives from the finding that correlations are important in building multi-asset portfolios, but they change over time. DCC accounts for this in the model, while more recent papers model the dynamics of correlation in a more direct way, such as de Boer *et al.* (2019), where correlation is business cycle dependent, or Ackermann *et al.* (2016), who use the historical correlations of rolling windows. The advantage of using DCC, as also pointed out by Cho *et al.* (2019), is that correlation is built within the model, and does not need to be estimated separately.

Our research builds on existing theoretical contributions and in addition tests how the more realistic assumptions of weekly data rather than daily data and hedging with forwards instead of futures affect previous conclusions on optimal hedging strategies. We show most notably that the carry component of dynamic hedging strategies is the main cause of the superiority of dynamic hedging. While the currency carry has been analysed in the literature, it has not been directly related to optimal hedging strategies. Our research helps to shed some light on the link between these two lines of research.

The other main finding of our analysis is that the currency carry has a relevant role in determining the risk/return profile of the hedged portfolios. This result is in line with other recent studies such as Opie and Riddiough (2019) and Laborda (2018). The difference our contribution makes is that the currency carry component emerges naturally as a product of the DCC hedging strategy in our case, while the authors of the other two articles make a deliberate decision to model and forecast currency carry, and they specifically build their portfolios to use the carry properties of different components of the portfolios. The merit of our method is that we do not need any forecast, as it is the DCC model itself that provides time-varying exposure to currencies with positive carry, as a consequence of the optimisation process.

6. Conclusion and perspectives

This paper analyses whether and to what extent foreign bond investments should be hedged to minimise the variance of the overall portfolio. Starting with a comparison of the risk/return profiles of the unhedged and fully hedged portfolios, we proceed to find constant optimal hedge ratios using the conventional minimum variance framework, and we expand the analysis by using the multivariate time series DCC-GARCH approach. We have also taken account of possible short-selling restrictions that may apply.

As discussed in some detail in Section 5, one of the main implications of our study is that when official institutions deal with currency risk in their portfolios, which are typically exposed mainly to fixed income securities, they should not aim to hedge the exchange rate risk fully. More sophisticated hedging strategies based on OLS or DCC-GARCH should be used instead. One reason why more sophisticated strategies are superior is that they have a degree of exposure to a currency carry component, which improves the risk/return profiles of the portfolios. Furthermore, our study shows that this can be applied to real portfolios. The main practical implication of our study is to show that OLS or DCC-GARCH hedging using forwards, with weekly and monthly hedging frequency, is still preferable to simple full hedging or no hedging at all. Official institutions tend to have large portfolios, which means that daily hedging using futures is simply not feasible.

Our research here is admittedly limited to selected currencies, but it can easily be expanded to other currencies. The results of our analysis are reliant on the selected sample, and the benefits of hedging in making the portfolio less volatile might be different in other currencies. Nevertheless, we believe that our analysis fulfils its goal of providing a basis that an institutional investor can use in currency hedging.

The analysis presented here can be expanded in different directions. The investment horizon could be expanded to 20 or 30 years to examine whether the results remain valid with longer horizons and to study in depth the dynamics of the carry trade and its importance for hedging. A comparison of several portfolios with different optimised weights could also help to shed further light on our results. Another possible extension of our analysis would be to apply to the same problem the methods used by previous contributions for accounting for asymmetries in the returns of the currency exposures of the portfolio.

Notes

1. Forward contracts might prove to be more flexible in practice as futures are highly standardised for size and expiration.
2. All data were downloaded on 16 March 2018.
3. We estimated the model with the restriction that the estimated hedge ratio coefficients should be between zero and one.
4. Given that the dynamic models required an initial period of convergence of the parameters, we present the statistics for the sample starting at the beginning of 2000.
5. We have also conducted robustness checks of our results against outliers in the data set and against different specifications of the GARCH model. We found only one significant outlier, which corresponds to the sudden revaluation of CHF in January 2015. This event caused a jump in both the spot and forward values of CHF. To examine the effect of this outlier, we ran our analysis again using a data set with the outlier removed. The differences from the numbers reported in the article are marginal, and therefore we decided not to drop the outlier from our analysis. Alternative specifications of the GARCH model do not change the results to any noticeable extent and so do not affect the conclusions of the paper.

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Corresponding author

Kersti Harkmann can be contacted at: kharkmann@gmail.com

Curriculum vitae

Personal data

Name:	Kersti Harkmann
Date of birth:	01.09.1983
Place of birth:	Tartu
Citizenship:	Estonian

Contact data

Email:	kharkmann@gmail.com

Education

2009– …	Tallinn University of Technology, Department of Economics and Finance, Doctoral studies
2006–2009	Tallinn University of Technology, Department of Economics and Finance, Master of Arts in Social Sciences (Finance and Banking)
2007–2008	Università Umanesimo Latino S.p.A in cooperation with UniCredit S.p.A, New Europe Master in Banking and Entrepreneurship, *Master Specialistico*
2002–2006	Tartu University, School of Economics and Business Administration, Bachelor's degree in Economics and Business Administration (Economics)

Language competence

Estonian	Native language
English	Fluent
Italian	Intermediate

Professional employment

2019– …	Head of Monetary Policy Operations Division, Financial Markets Department, Bank of Estonia
2014	Visiting researcher, Economics and Research Department, Bank of Estonia
2011–2019	Senior specialist, Financial Markets Department, Bank of Estonia
2010–2011	Analyst, Financial Markets Department, Bank of Estonia
2008–2011	Risk Specialist, Financial Markets Department, Bank of Estonia

Publications

Filipozzi, F., and K. Harkmann (2010). The financial crisis in Central and Eastern Europe: The measure and determinants of the exchange market pressure index and the money market pressure index. *Research in Economics and Business: Central and Eastern Europe*, 2(2), 5-36. (ETIS 1.2)

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Elulookirjeldus

Isikuandmed

Nimi:	Kersti Harkmann
Sünniaeg:	01.09.1983
Sünnikoht:	Tartu
Kodakondsus:	Eesti

Kontaktandmed

E-post:	kharkmann@gmail.com

Hariduskäik

2009– …	Tallinna Tehnikaülikool, Majandusteaduskond, Majandusanalüüsi ja Rahanduse instituut, doktoriõpe
2006–2009	Tallinna Tehnikaülikool, Majandusteaduskond, Majandusanalüüsi ja Rahanduse instituut, sotsiaalteaduse magistrikraad (rahandus ja pangandus)
2007–2008	Università Umanesimo Latino S.p.A in cooperation with UniCredit S.p.A, New Europe Master in Banking and Entrepreneurship, *master specialistico*
2002–2006	Tartu Ülikool, Majandusteaduskond, rahvamajandus, sotsiaalteaduse bakalaureuse kraad (majandusteadus, rahvamajandus)

Keelteoskus

Eesti keel	emakeel
Inglise keel	kõrgtase
Itaalia keel	algtase

Teenistuskäik

2019– …	Eesti Pank, finantsturgude osakond, rahapoliitiliste operatsioonide allosakonna juhataja
2014	Eesti Pank, rahapoliitika ja majandusuuringute osakond, majandusuuringute allosakond, külalisuurija
2011–2019	Eesti Pank, finantsturgude osakond, rahapoliitiliste operatsioonide peaspetsialist
2010–2011	Eesti Pank, finantsturgude osakond, analüütik
2008–2011	Eesti Pank, finantsturgude osakond, riskihaldur

Publikatsioonid

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