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Measuring spillover effects in Euro area financial markets: a disaggregate approach

Dimitrios P. Louzis

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Abstract This study examines the return (price) and volatility (uncertainty) spillovers among the money, stock, foreign exchange and bond markets in the Euro area. The analysis is conducted in a disaggregated manner with respect to the bond and stock indices and utilizes the generalized forecast error variance decomposition framework of a VAR model proposed by Diebold and Yilmaz (Int J Forecast 23:57–66, 2012). The asymptotic distribution of the generalized forecast error variance decomposition components and the corresponding standard errors are also derived. Our empirical results, based on a data set covering a twelve-year period (2000–2012), suggest a high level of total return and volatility spillover effects throughout the sample period. Stock markets across the Euro area countries are identified as the main transmitters of price spillovers, with the periphery countries transmitting the largest amount of spillovers during the crisis periods. Stock markets also play a key role in uncertainty transmission, but now, the propagation mechanism includes the core Euro area countries, which transmit volatility spillovers diachronically. The money, FX and bond markets are constant receivers of spillovers, with the exception of the Greek bonds, which transmitted spillovers during the peak of the Greek sovereign debt crisis in 2011–2012.

Keywords Asset markets · Spillovers · Vector autoregressive · Euro area · Financial crisis

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D. P. Louzis (✉)
Financial Stability Department, Bank of Greece, 3 Amerikis Str., 10564 Athens, Greece
e-mail: dlouzis@aueb.gr; dlouzis@bankofgreece.gr

1 Introduction

The examination of financial market interconnectedness is of crucial importance for the understanding of financial crises and their propagation mechanisms, and it is also critical in terms of systemic risk identification and financial stability preservation (Hartman et al. 2004). It is evident that exogenous output shocks are more likely to spread worldwide if the transmission mechanism entails asset price spillovers or confidence channels, threatening the economies that are more vulnerable to adverse economic developments (IMF 2007).

The recent developments in the Euro area economies and the unfolding sovereign debt crisis in Southern Europe have highlighted the significance of measuring and monitoring the spillover effects across national markets and asset classes. Ideally, a policy maker would like to have a macroprudential toolkit, which would enable him to answer questions such as: What is the current level of spillover effects in financial markets? How much of the spillover effects can be attributed to a specific market (or country) or to what extent does a specific market transmit (receive) spillover effects to (from) other markets? What is the behavior of spillover effects during economic downturns, and how can we use spillover measures to predict the future evolution of specific market indicators? Answers to these questions could provide useful guidance for policy actions that aim at monitoring, controlling or even predicting, through early warning indicators, contagion effects across markets or countries. Contagion, in turn, may lead to widespread financial instability and economic contraction (In 2007).[1]

Spillover effects in financial markets have been extensively investigated in the extant literature. One strand of the literature examines the return or volatility spillovers across countries for identical assets. Although the majority of the studies focus on international equity markets (recent examples on equity volatility spillovers include Engle et al. (2012) for East Asia countries, Zhou et al. (2012) for Chinese and world equity markets, Diebold and Yilmaz (2009) for a worldwide analysis), there are also plentiful works regarding other market sectors. Recently, Claeys and Vasicek (2012) and Antonakakis and Vergos (2012) studied the sovereign bond yield spillover effects in the European Union countries. Christiansen (2007) and Skintzi and Refenes (2006) studied volatility spillovers in the bond markets, whereas In (2007) examined volatility spillover effects across international swap markets (UK, US, and Japan). The currency markets have also been widely studied in terms of volatility spillovers (e.g., see Antonakakis 2012; Budak et al. 2011 and references therein).

However, Ehrmann et al. (2011) examined financial transmission among different asset classes, i.e., money, FX, bond and stock markets, within and between the USA (US) and the Euro area. The authors concluded that domestic shocks have the strongest impact on asset price changes, but there are also significant international spillover effects within and across the market classes. They also found evidence of the intensification of spillover effects during recessions. In the same vein, Diebold and Yilmaz (2012) studied volatility spillover effects among commodities, FX, bond and stock markets for the USA. The authors proposed a novel approach for the construction

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[1] For a discussion on policy measures regarding financial contagion, see Dornbusch et al. (2001).

of *total* and *directional* spillover indices based on the generalization of their work in Diebold and Yilmaz (2009). Their framework builds on a generalized decomposition of the forecast error variance of a vector autoregressive (VAR) model. A significant feature of this approach is that the empirical results are independent of the ordering of the variables. The researcher can also identify specific variables as transmitters or receivers of spillovers. The empirical findings of Diebold and Yilmaz (2012) suggest that spillovers across markets were strengthened during the recent global financial crisis, and the stock market is identified as the key transmitter of spillovers, especially after the collapse of Lehman Brothers in September 2008. The Diebold and Yilmaz (2012) methodology has also been applied by Duncan and Kabundi (2013), who investigated the domestic and foreign sources of volatility spillovers in the South African asset classes.

Against this background, the present study examines both the return (price) and volatility (uncertainty) spillover effects among the money, FX, bond and stock markets in the Euro area, implementing the methods of Diebold and Yilmaz (2012). In particular, we construct spillover indices to investigate the average level of interconnectedness in the Euro area asset markets. We also examine the behavior of spillover effects throughout a sample period of 10 years (2002–2012), including both the global financial (2007–2009) and the ongoing European debt (2010…) crisis. We expect an intensification of spillovers during the crisis periods, but we are also interested in examining the level of interconnectedness in the Euro area financial markets diachronically.

Moreover, we compute directional spillover indices to identify the key contributors to the total spillover effects during both crisis and calm periods. Directional spillover indices will enable us to study whether stock markets transmit the greatest amount of spillovers to other markets, as evidenced in Diebold and Yilmaz (2012), during the latest debt crisis in Southern Europe.

Furthermore, studying the Euro area spillover effects might be challenging in terms of the variables chosen. An aggregate approach, i.e., using composite indices for the Euro area, would most likely lead to a significant loss of information.[2] Therefore, we choose to proceed with a disaggregate approach and incorporate into the analysis the majority of the stock and bond indices of the Euro area countries. A country-level analysis is also performed to ensure the robustness of our results.

Finally, the identification of statistically significant generalized forecast error variance (GFEV hereafter) decomposition components may accommodate the analysis for locating possible spillover propagation channels. Hence, we derive the asymptotic distribution of the GFEV decompositions and provide estimates of their standard errors, as in Lutkepohl (1990).

The rest of the paper is organized as follows. Section 2 presents the econometric methodology implemented in the study. In Sect. 3, we provide the description of the data set, and in Sect. 4, we present the empirical results. Finally, Sect. 5 summarizes and concludes this paper.

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[2] For an aggregate approach, see Ehrmann et al. (2011) and Louzis (2013).

2 Econometric methodology

We measure the spillover effects using the approach introduced by Diebold and Yilmaz (2009) and generalized in Diebold and Yilmaz (2012) (DY hereafter). In DY, the authors employ the generalized VAR framework of Koop et al. (1996) and Pesaran and Shin (1998) to construct spillover indices. Hence, first we define the GFEV decompositions of a VAR model. In particular, we assume that the data generation process of an N-variable vector $\boldsymbol{y}_t$ is a pth-order (covariance) stationary VAR:

$$\boldsymbol{y}_t = \sum_{i=1}^{p} \boldsymbol{\Pi}_i \boldsymbol{y}_{t-i} + \boldsymbol{\varepsilon}_t, \text{ with } \boldsymbol{\varepsilon}_t \sim \text{i.i.d } (0, \boldsymbol{\Sigma}_\varepsilon) \tag{1}$$

where $\boldsymbol{\Pi}_i$ are the $(N \times N)$ coefficient matrices, and $\boldsymbol{\varepsilon}_t$ is the vector of identically and independently distributed errors with a mean, $E(\boldsymbol{\varepsilon}_t) = 0$ and covariance matrix, $E\left(\boldsymbol{\varepsilon}_t \boldsymbol{\varepsilon'}_t\right) = \boldsymbol{\Sigma}_\varepsilon$. A stationary VAR(p) model can be rewritten as an infinite moving average process, MA (∞), i.e., $\boldsymbol{y}_t = \sum_{i=0}^{\infty} \boldsymbol{\Theta}_i \boldsymbol{\varepsilon}_{t-i}$, with $\boldsymbol{\Theta}_i$ being the $(N \times N)$ moving average coefficients matrix. The $\boldsymbol{\Theta}_i$ coefficient matrices can be obtained using the following recursion: $\boldsymbol{\Theta}_i = \boldsymbol{\Pi}_1 \boldsymbol{\Theta}_{i-1} + \boldsymbol{\Pi}_2 \boldsymbol{\Theta}_{i-2} + \ldots + \boldsymbol{\Pi}_p \boldsymbol{\Theta}_{i-p}$ with $\boldsymbol{\Theta}_0 = \boldsymbol{I}_N$ being an $(N \times N)$ identity matrix and $\boldsymbol{\Theta}_i = 0$ for $\forall i < 0$.

Generally, the forecast error variance decomposition is a standard tool in structural VAR analysis because it enables the analyst to compute the proportion of the H-step forecast error variance of variable i, which is accounted for by innovations in variable j (Lutkepohl 1990). Typically, the computation of the forecast error variance decompositions relies on the orthogonalized errors of the MA representation and their corresponding impulse responses.[3] Koop et al. (1996) and Pesaran and Shin (1998) propose an alternative method for the calculation of the forecast error variance decomposition based on the generalized impulses. In practical applications, the GFEV decomposition measures have the advantage of being invariant to variable reordering in the VAR model (Pesaran and Shin 1998). The H-step GFEV decomposition is defined as:

$$d_{ij,H} = \frac{\sigma_{ii}^{-1} \sum_{h=0}^{H-1} \left(\boldsymbol{e'}_i \boldsymbol{\Theta}_h \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_j\right)^2}{\text{MSE}_{i,H}} \tag{2}$$

where $\text{MSE}_{i,H} := \sum_{h=0}^{H-1} \left(\boldsymbol{e'}_i \boldsymbol{\Theta}_h \boldsymbol{\Sigma}_\varepsilon \boldsymbol{\Theta'}_h \boldsymbol{e}_i\right)$ is the mean square error (forecast error variance) of an H-step forecast of the ith variable, σ_{ii} is the ith diagonal element of $\boldsymbol{\Sigma}_\varepsilon$ and $\boldsymbol{e}_i$ is a selection vector, whose ith element takes the value of one, and all other elements are zeroes. The asymptotic distribution for the GFEV components in Eq. (2) is derived in the Appendix.

DY use this framework to eliminate the dependence of the spillover effects on the ordering of the variables. Nonetheless, because the shocks to each variable are not orthogonalized, the sum of each row of a GFEV decomposition matrix does not add to

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[3] Cholesky decomposition of $\boldsymbol{\Sigma}_\varepsilon$ is used to orthogonalize the errors, and the corresponding impulse responses (see Lutkepohl (1990), Lutkepohl (2005, Sect. 2.3.3) and references therein)

unity, i.e., $\sum_{j=1}^{N} d_{ij,H} \neq 1$.[4] Thus, the first step in the DY methodology is to normalize each element of the decomposition matrix, $d_{ij,H}$, by dividing with the row sum:

$$\tilde{d}_{ij,H} = \frac{d_{ij,H}}{\sum_{j=1}^{N} d_{ij,H}}, \text{ with } \sum_{j=1}^{N} \tilde{d}_{ij,H} = 1 \text{ and } \sum_{i,j=1}^{N} \tilde{d}_{ij,H} = N \tag{3}$$

because $0 \leq 100 \times \tilde{d}_{ij,H} \leq 100$, we can interpret each element of the normalized decomposition matrix as the percentage (%) of the forecast error variance of variable i, which is attributed to innovations of variable j (Duncan and Kabundi 2013). Note also that because we have used row sum normalization, the column sum of the normalized decomposition matrix does not add to unity, i.e., $\sum_{i=1}^{N} \tilde{d}_{ij,H} \neq 1$.[5]

Using the normalized elements of the decomposition matrix, $\tilde{d}_{ij,H}$, we construct the *Total Spillover* (TS) index, which captures the level of cross-market spillovers. This is achieved by measuring the contribution of spillovers of shocks to the total forecast error variance, across all N variables. The TS index, based on H-step ahead forecasts, is given by:

$$\text{TS}_H = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \tilde{d}_{ij,H}}{\sum_{i,j=1}^{N} \tilde{d}_{ij,H}} \times 100 = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \tilde{d}_{ij,H}}{N} \times 100 \tag{4}$$

In a spillover analysis, it is also crucial to examine the direction of spillover effects from and toward a specific market or country. The *Directional Spillover* (DS) indices measure the spillover effects received by market i *from* all other markets j for $i \neq j$:

$$\text{DS}_{i \leftarrow j,H} = \frac{\sum_{j=1, i \neq j}^{N} \tilde{d}_{ij,H}}{N} \times 100 \tag{5}$$

The corresponding index that measures the spillover effects transmitted by market i *to* all other markets j is defined as:

$$\text{DS}_{i \rightarrow j,H} = \frac{\sum_{j=1, i \neq j}^{N} \tilde{d}_{ji,H}}{N} \times 100 \tag{6}$$

From Eqs. (5) and (6), we calculate the *Net Spillover* (NS) index for market i as:

$$\text{NS}_{i,H} = \text{DS}_{i \rightarrow j,H} - \text{DS}_{i \leftarrow j,H} \tag{7}$$

Positive values of the $\text{NS}_{i,H}$ index imply that market i transmits spillover effects to all other markets, j, whereas negative values indicate that market i is a receiver of spillover effects from all other markets, j.

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[4] The spillover measures proposed in Diebold and Yilmaz (2009) use the Cholesky factorization of $\boldsymbol{\Sigma}_{\varepsilon}$ to orthogonalize the errors. However, their method suffers from variable reordering.

[5] The elements of the decomposition matrix can also be normalized in terms of a column sum, as in Zhou et al. (2012).

3 The data set

The global financial crisis and the ongoing sovereign debt crisis in the Euro zone periphery countries have highlighted the differences in the Euro area national economies and their financial markets. In particular, the Euro area is a single currency market with a common monetary policy stance, but it also consists of a diverse set of countries in terms of economic growth and creditworthiness. Moreover, the national financial markets in the Euro area diverge substantially in terms of depth and reputation. These issues are expected to be taken into consideration when we study the spillover effects in the Euro area. Therefore, we circumvent an aggregate approach, which may lead to a significant loss of information, and we follow a disaggregate approach, at least with regard to the stock and bond markets.[6]

Table 1 presents the indices and the sources used for the money, FX, bond and stock markets. We employ the majority of the Euro area stock indices, as well as the S&P 500 index, to account for the spillover effects of the US stock market to the Euro area markets. In the same vein, Ehrmann et al. (2011) found that the US asset markets explain a relatively large proportion of the asset price movements in the Euro area financial markets.[7] As far as the bond markets are concerned, we use the total return sovereign bond indices of Bloomberg, which refer to maturities greater than 10 years and are commonly used in related studies (e.g., see Kim et al. 2006; Baur and Lucey 2009).[8] We employ the bond indices for the Euro periphery countries (Greece, Ireland, Italy, Portugal and Spain), and we construct a market value-weighted subindex consisting of investment grade countries (Austria, France, Germany and Netherlands).[9]

For the money market, we use the Euro OverNight Index Average (EONIA) rate, which is regarded as an efficient proxy for the monetary policy stance in the Euro area (Gerlach and Lewis 2013; Ciccrelli et al. 2010; Hristov et al. 2012). Ciccrelli et al. (2010) argued that the EONIA rate is an appropriate measure of monetary policy stance in the Euro area during both calm and turbulent periods because it reflects both standard (official refinancing rate) and nonstandard (credit enhancement measures) ECB monetary policy practices. Gerlach and Lewis (2013) also pointed out that overnight rates are more efficient measures of monetary policy than repo rates.[10] Finally, we follow Ehrmann et al. (2011) and use the EURO/USD exchange rate for the currency market.

The sample period spans from 1.7.2000 to 7.13.2012 and covers over a decade of financial history, including both the global financial crisis (2007–2009) and the

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[6] We would like to thank two anonymous reviewers for this suggestion.

[7] We would also like to thank an anonymous reviewer for proposing the incorporation of the US stock market into the analysis.

[8] Total return bond indices assume that coupon payments are reinvested in the bonds.

[9] Un-reported results show that grouping investment grade countries in a single index does not alter the main findings of the paper.

[10] The authors explain that overnight rates have fallen well below repo rates after the collapse of Lehman Brothers, although the ECB could have prevented this sharp fall. Therefore, they interpret this decline as an expression of monetary policy and use overnight rates as a proxy for the ECB's monetary policy stance.

Table 1 Data and sources

Market/country		Index	Bloomberg ticker
Money market	–	EONIA rate	–
FX market	–	Eur/Usd	EURUSD Curncy
Stock markets	Ireland	ISEQ	ISEQ Index
	Portugal	PSI General	BVLX Index
	Greece	ASE	ASE Index
	Spain	IBEX 35	IBEX Index
	Italy	FTSE MIB	FTSEMIB Index
	France	CAC 40	CAC Index
	Belgium	BEL20	BEL20 Index
	Austria	ATX	ATX Index
	Germany	DAX	DAX Index
	Neth	AEX	AEX Index
	USA	S&P 500	SPX Index
Bond markets	Ireland	Total Return Bloomberg/EFFAS government bond indices, 10 years+	IEG5TR Index
	Portugal		PTG5TR Index
	Greece		GCG5TR Index
	Spain		SPG5TR Index
	Italy		ITG5TR Index
	Inv. Grade (Portfolio of France Austria Germany Netherlands)		FRG5TR Index, ATG5TR Index, GRG5TR Index, NEG5TR Index

EONIA rate was downloaded from http://www.euribor-ebf.eu/euribor-eonia-org/eonia-rates.html

ongoing sovereign debt crisis in the Southern European countries (2010…). The asset prices are sampled at a weekly frequency (Friday-to-Friday) to circumvent day-of-the-week and nonsynchronous trading effects (Skintzi and Refenes 2006). Volatility series are estimated using a GARCH$(1, 1)$ model that utilizes squared returns. Although realized or daily range volatility estimators are more efficient volatility estimators than squared returns, we cannot use them because they require intra-daily data that are not available for a number of indices used in the study (e.g., see Andersen et al. 2003; Parkinson 1980).

Overall, the stock markets have on average negative returns, except for Portugal and Austria, whereas the bonds average returns are positive, with the exception of Greece. Moreover, the stock market volatility is on average higher than the bond market volatility, as expected. The Portuguese stock market and the Greek bond market are the most volatile among the stock and bond markets, respectively. We refer to Appendix B (Electronic supplementary material) for a detailed presentation of the descriptive statistics

4 Empirical results

We produce the spillover measures presented in Sect. 2 using a VAR(2) model ($p = 2$) and a forecast horizon of 10 weeks ($H = 10$). The lag specification of the VAR model is selected by minimizing the Bayesian Information Criterion, whereas the forecasting horizon is commonly used in similar studies (e.g., see Diebold and Yilmaz (2012); Nikolakakis 2012).

The remainder of Sect. 4 is organized as follows: In Sect. 4.1, we present the results for the disaggregate analysis in the Euro area, and in Sect. 4.2, the analysis is repeated for each of the countries included in our sample. Finally, Sect. 4.3 presents the dynamics of the spillover measures relying on rolling sample techniques.

4.1 Euro area spillover analysis

We begin the spillover analysis by examining the standard errors of the GFEV in order to provide some insights regarding the statistical significance of the GFEV decompositions.[11] The full details of the standard error results are reported in Appendix C (Electronic supplementary material), while here we present a synopsis of the main results.

Overall, the empirical findings give evidence of statistically significant GFEV decompositions, under the two standard errors criterion, only for the volatility series. A possible explanation is that volatilities can be more accurately forecasted compared with returns; thus, they produce statistically significant GFEV decompositions. Moreover, volatility shocks in the stock markets of the core Euro area countries, such as France, Germany or Austria, as well as Italy, significantly contribute toward the forecast error variances of the EUR/USD, the EONIA rate, other major stock markets (e.g., France, Germany, and US) and Irish bonds. A similar conclusion can be drawn for the periphery bond markets (Ireland, Portugal, Greece, Spain and Italy) and the EUR/USD exchange rate. Finally, the Greek bond index is the only significant contributor to its own forecast error variance, indicating the idiosyncratic nature of the Greek sovereign debt crisis.[12]

4.1.1 Spillover tables

Although the GFEV decompositions give an indication of market interlinkages, they are not easily interpreted because they are not normalized as the spillover measures of DY. For this reason, we investigate return and volatility interlinkages relying on DY's spillover measures presented in Tables 2 and 3, respectively. Each *ij* entry of the

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[11] The GFEV decompositions are defined as in Eq. (2), and the standard errors are derived from the results in Appendix A. The ijth component of the table shows, in *absolute terms*, the portion of the forecast error variance of the variable i that is attributable to innovations of variable j.

[12] However, these results can be quite misleading if the true GFEV component is zero (see the discussion in the Appendix and Lutkepohl (1990, 2005)). As pointed out in Lutkepohl (2005, p. 125), the standard errors should be "regarded as rough indications of the sampling uncertainty," which limits their value in terms of formal hypothesis testing.

Table 2 Returns spillover table for the Euro area financial markets

		Money market	FX market	Stock markets							
		EONIA ($j = 1$)	Eur/Usd ($j = 2$)	Ireland ($j = 3$)	Portuga l ($j = 4$)	Greece ($j = 5$)	Spain ($j = 6$)	Italy ($j = 7$)	France ($j = 8$)	Belgium ($j = 9$)	Austria ($j = 10$)
Money market	EONIA ($i = 1$)	0.00	0.02	8.03	13.65	6.00	8.23	10.43	10.15	7.65	7.49
FX market	Eur/Usd ($i = 2$)	0.00	0.24	7.55	12.32	5.96	8.68	10.79	10.37	7.78	7.51
Stock markets	Ireland ($i = 3$)	0.00	0.03	11.51	11.92	6.56	8.18	10.24	9.64	7.59	8.12
	Portugal ($i = 4$)	0.00	0.06	6.88	33.36	4.14	5.39	7.66	7.10	5.44	7.26
	Greece ($i = 5$)	0.00	0.08	6.60	10.46	16.78	8.02	9.76	8.95	6.95	7.85
	Spain ($i = 6$)	0.00	0.05	7.63	14.08	5.69	9.02	10.76	9.91	7.53	7.88
	Italy ($i = 7$)	0.00	0.04	7.29	13.55	7.51	8.59	11.66	9.86	7.18	7.46
	France ($i = 8$)	0.00	0.04	7.69	11.23	7.04	8.62	10.76	10.82	7.81	7.78
	Belgium ($i = 9$)	0.00	0.05	7.39	13.67	6.41	8.10	10.37	9.60	9.52	7.97
	Austria ($i = 10$)	0.00	0.12	7.69	11.14	8.06	8.24	10.02	9.08	7.55	13.62
	Germany ($i = 11$)	0.00	0.05	7.21	10.55	6.78	9.10	11.03	10.43	7.62	7.50
	Neth ($i = 12$)	0.00	0.03	7.64	14.13	7.09	7.91	10.12	9.84	7.63	7.57
	USA ($i = 13$)	0.00	0.04	8.35	11.61	7.69	8.37	10.40	9.96	7.77	8.30
Bond markets	Ireland ($i = 14$)	0.00	0.08	7.27	13.02	8.45	8.56	10.52	9.68	7.26	8.20
	Portugal ($i = 15$)	0.00	0.05	7.80	12.05	6.69	8.32	10.52	9.81	7.87	8.39
	Greece ($i = 16$)	0.00	0.14	6.70	11.78	10.52	8.11	9.75	8.81	6.96	8.58
	Spain ($i = 17$)	0.00	0.05	7.88	13.45	6.42	8.36	10.48	9.87	7.68	8.45
	Italy ($i = 18$)	0.00	0.05	7.45	16.35	7.42	8.05	10.05	9.41	6.94	7.50
	Inv.Grade ($i = 19$)	0.00	0.07	7.40	13.00	7.94	8.79	10.67	9.72	7.37	8.38
	To	0.00	1.06	134.45	**227.96**	126.39	147.63	184.34	172.20	132.59	142.19
	Net	−100.00	−98.69	45.96	**161.32**	43.17	56.65	96.01	83.02	42.10	55.81

Table 2 continued

		Stock markets			Bond markets						**From**
		Germany ($j = 11$)	Neth (j=12)	USA ($j = 13$)	Ireland ($j = 14$)	Portugal ($j = 15$)	Greece ($j = 16$)	Spain ($j = 17$)	Italy ($j = 18$)	Inv.Grade ($j = 19$)	
Money market	EONIA ($i = 1$)	11.05	10.65	6.30	0.01	0.03	0.04	0.03	0.05	0.19	**100.00**
FX market	Eur/Usd ($i = 2$)	11.22	10.96	6.17	0.03	0.03	0.07	0.04	0.06	0.20	99.76
Stock markets	Ireland ($i = 3$)	10.12	9.99	5.65	0.03	0.02	0.24	0.01	0.01	0.13	88.49
	Portugal ($i = 4$)	7.77	7.50	7.21	0.01	0.01	0.03	0.03	0.04	0.10	66.64
	Greece ($i = 5$)	9.49	9.12	5.12	0.06	0.06	0.53	0.01	0.01	0.14	83.22
	Spain ($i = 6$)	10.56	10.17	6.33	0.03	0.02	0.21	0.01	0.01	0.12	90.98
	Italy ($i = 7$)	10.39	9.95	6.00	0.04	0.03	0.24	0.02	0.02	0.16	88.34
	France ($i = 8$)	10.94	10.68	5.81	0.06	0.05	0.45	0.03	0.03	0.14	89.18
	Belgium ($i = 9$)	10.04	10.34	6.02	0.05	0.04	0.31	0.02	0.02	0.11	90.48
	Austria ($i = 10$)	9.37	9.43	5.16	0.03	0.02	0.28	0.02	0.01	0.16	86.38
	Germany ($i = 11$)	12.23	10.68	5.92	0.11	0.11	0.44	0.07	0.06	0.13	87.77
	Neth ($i = 12$)	10.69	10.81	6.24	0.01	0.01	0.07	0.02	0.03	0.17	89.19
	USA ($i = 13$)	10.66	10.43	6.05	0.01	0.01	0.16	0.01	0.02	0.16	93.95
Bond markets	Ireland ($i = 14$)	10.35	9.82	6.01	0.12	0.06	0.41	0.03	0.02	0.15	99.88
	Portugal ($i = 15$)	10.50	10.32	5.74	0.28	0.72	0.50	0.14	0.13	0.17	99.28
	Greece ($i = 16$)	9.19	8.81	5.31	0.44	0.43	3.85	0.25	0.21	0.15	96.15
	Spain ($i = 17$)	10.52	10.30	6.15	0.03	0.02	0.13	0.04	0.03	0.14	99.96
	Italy ($i = 18$)	10.33	9.63	6.44	0.01	0.01	0.11	0.03	0.04	0.17	99.96
	Inv.Grade ($i = 19$)	10.34	9.89	5.94	0.03	0.02	0.24	0.02	0.02	0.16	99.84

Table 2 continued

	Stock markets			Bond markets						**From**
	Germany ($j = 11$)	Neth (j=12)	USA ($j = 13$)	Ireland ($j = 14$)	Portugal ($j = 15$)	Greece ($j = 16$)	Spain ($j = 17$)	Italy ($j = 18$)	Inv.Grade ($j = 19$)	
To	183.51	178.67	107.52	1.26	0.98	4.46	0.76	0.77	2.68	Total
Net	95.74	89.48	13.58	−98.62	−98.30	−91.69	−99.20	−99.18	−97.15	92.08

The *ij*th element of the table is computed as in Eq. (3) and shows the proportion of a 10-step forecast error variance of variable i (rows), which is accounted for by innovations in variable j (columns). Table entries are normalized with respect to their row sum, i.e., the sum of row elements adds to 100. The diagonal elements ($j = i$) are the *own variance shares* estimates, which show the fraction of the forecast error variance of market i which is due to its own shocks. The column "**From**" shows the total spillovers received by a particular market from all other markets, while the row "**To**" shows the spillover effects directed by a particular market to all other markets. The measure "**Total**" shows the level of total spillovers in the Euro area markets

Table 3 Volatilities spillover table for the Euro area financial markets

		Money market	FX market	Stock markets							
		EONIA ($j = 1$)	Eur/Usd ($j = 2$)	Ireland ($j = 3$)	Portugal ($j = 4$)	Greece ($j = 5$)	Spain ($j = 6$)	Italy ($j = 7$)	France ($j = 8$)	Belgium ($j = 9$)	Austria ($j = 10$)
Money market	EONIA ($i = 1$)	0.00	0.02	4.17	2.95	0.90	1.84	15.84	5.73	17.47	13.90
FX market	Eur/Usd ($i = 2$)	0.00	0.03	4.65	2.21	1.39	2.08	15.51	5.62	17.35	15.44
Stock markets	Ireland ($i = 3$)	0.00	0.02	5.15	3.17	0.98	1.86	15.29	5.56	17.41	15.22
	Portugal ($i = 4$)	0.00	0.02	4.56	3.85	1.08	1.93	15.70	5.58	16.95	14.58
	Greece ($i = 5$)	0.00	0.04	4.37	3.36	1.67	2.09	16.01	5.70	16.12	14.44
	Spain ($i = 6$)	0.00	0.01	4.12	2.60	0.85	1.74	15.75	5.62	17.51	15.30
	Italy ($i = 7$)	0.00	0.02	3.75	2.97	0.99	1.94	19.71	5.63	16.50	12.00
	France ($i = 8$)	0.00	0.01	3.12	0.87	0.55	1.69	15.50	6.43	18.51	12.05
	Belgium ($i = 9$)	0.00	0.01	3.78	2.28	0.79	1.60	14.06	5.35	23.55	13.60
	Austria ($i = 10$)	0.00	0.01	4.16	2.12	0.93	1.76	14.02	5.38	16.17	22.05
	Germany ($i = 11$)	0.00	0.01	3.33	1.73	0.79	1.65	14.70	5.81	14.45	10.52
	Neth ($i = 12$)	0.00	0.01	3.86	2.24	0.94	1.83	15.20	5.90	17.52	12.84
	USA ($i = 13$)	0.00	0.02	3.95	2.56	0.89	1.82	15.84	5.73	17.18	14.29
Bond markets	Ireland ($i = 14$)	0.00	0.02	4.19	2.44	0.93	1.99	16.71	5.82	16.45	14.02
	Portugal ($i = 15$)	0.00	0.06	3.44	1.62	1.80	2.21	15.60	5.46	14.97	14.70
	Greece ($i = 16$)	0.00	0.18	2.01	1.01	2.43	1.73	6.57	2.76	5.88	12.03
	Spain ($i = 17$)	0.00	0.07	4.92	3.34	1.69	2.32	16.10	5.34	14.90	18.04
	Italy ($i = 18$)	0.00	0.02	3.92	2.62	1.06	1.84	15.01	5.81	16.56	13.69
	Inv.Grade ($i = 19$)	0.00	0.03	4.13	2.85	1.22	2.01	16.08	5.78	16.62	14.23
	To	0.02	0.57	70.43	42.96	20.21	34.22	269.46	98.58	288.53	250.90
	Net	−99.98	−99.40	−24.42	−53.19	−78.12	−64.04	189.17	5.02	212.08	172.96

Table 3 continued

		Stock markets			Bond markets						**From**
		Germany ($j = 11$)	Neth ($j = 12$)	USA ($j = 13$)	Ireland ($j = 14$)	Portugal ($j = 15$)	Greece ($j = 16$)	Spain ($j = 17$)	Italy ($j =$ 18)	Inv.Grade ($j = 19$)	
Money market	EONIA ($i = 1$)	18.72	12.87	4.92	0.05	0.02	0.37	0.04	0.18	0.01	**100.00**
FX market	Eur/Usd ($i = 2$)	16.21	11.72	3.53	0.33	0.30	3.11	0.12	0.36	0.03	99.97
Stock markets	Ireland ($i = 3$)	17.59	12.36	4.78	0.06	0.03	0.26	0.04	0.20	0.01	94.85
	Portugal ($i = 4$)	17.53	12.20	5.13	0.10	0.07	0.41	0.07	0.23	0.02	96.15
	Greece ($i = 5$)	17.81	11.97	4.79	0.15	0.12	0.97	0.09	0.26	0.03	98.33
	Spain ($i = 6$)	18.48	12.72	4.66	0.07	0.03	0.28	0.05	0.20	0.01	98.26
	Italy ($i = 7$)	18.10	12.46	4.72	0.14	0.09	0.68	0.06	0.21	0.02	80.29
	France ($i = 8$)	22.55	14.24	3.62	0.09	0.06	0.43	0.05	0.23	0.01	93.57
	Belgium ($i = 9$)	17.34	12.78	4.43	0.04	0.02	0.17	0.03	0.15	0.01	76.45
	Austria ($i = 10$)	16.71	11.91	3.97	0.06	0.04	0.44	0.04	0.22	0.01	77.95
	Germany ($i = 11$)	29.26	12.55	4.52	0.05	0.04	0.35	0.05	0.17	0.02	70.74
	Neth ($i = 12$)	20.45	14.16	4.36	0.06	0.03	0.31	0.05	0.20	0.02	85.84
	USA ($i = 13$)	19.07	12.84	5.04	0.08	0.05	0.37	0.05	0.21	0.02	94.96
Bond markets	Ireland ($i = 14$)	18.88	12.42	4.29	0.36	0.16	0.89	0.09	0.29	0.03	99.64
	Portugal ($i = 15$)	15.30	10.70	3.06	0.89	1.27	8.02	0.24	0.59	0.06	98.73
	Greece ($i = 16$)	4.06	3.74	1.11	2.21	2.37	50.07	0.58	1.12	0.15	49.93
	Spain ($i = 17$)	12.39	10.63	3.76	0.71	0.90	3.94	0.28	0.61	0.07	99.72
	Italy ($i = 18$)	21.19	12.86	4.91	0.04	0.03	0.17	0.05	0.21	0.02	99.79
	Inv.Grade ($i = 19$)	18.35	12.42	4.67	0.16	0.14	0.93	0.08	0.27	0.03	99.97

Table 3 continued

	Stock markets			Bond markets						**From**
	Germany ($j = 11$)	Neth ($j = 12$)	USA ($j = 13$)	Ireland ($j = 14$)	Portugal ($j = 15$)	Greece ($j = 16$)	Spain ($j = 17$)	Italy ($j =$ 18)	Inv.Grade ($j = 19$)	
To	**310.71**	213.39	75.22	5.31	4.51	22.09	1.78	5.69	0.55	***Total***
Net	**239.97**	127.56	−19.75	−94.33	−94.22	−27.84	−97.94	−94.11	−99.43	90.27

The *ij*th element of the table is computed as in Eq. (3) and shows the proportion of a 10-step forecast error variance of variable i (rows), which is accounted for by innovations in variable j (columns). Table entries are normalized with respect to their row sum, i.e., the sum of row elements adds to 100. The diagonal elements ($j = i$) are the *own variance shares* estimates, which show the fraction of the forecast error variance of market i which is due to its own shocks. The column "**From**" shows the total spillovers received by a particular market from all other markets, while the row "**To**" shows the spillover effects directed by a particular market to all other markets. The measure "**Total**" shows the level of total spillovers in the Euro area markets so-called *spillover tables* is an estimate of the contribution to the ith market's forecast error variance generated by shocks to market j (see Eq. (3), i.e., $100 \times \tilde{d}_{ij,10}$).[13]

Overall, the results show that the stock markets are the dominant component in the spillover analysis, meaning that they tend to be the greatest contributor to all other market forecast error variances. Nevertheless, the interpretation of the results can be greatly facilitated if we focus on the aggregate measures of directional and total spillover effects, which are thoroughly described in Tables 2 and 3. The key empirical findings are summarized below.

The most sticking feature of Tables 2 and 3 is the high level of the approximate "**Total**" spillover index, indicating a high level of interconnectedness in the Euro area financial markets. In particular, total spillovers are 92.08 and 90.27 % for the returns and volatilities, respectively, implying that more than 90 % of the total forecast error variance across all markets is attributed to spillover effects. The fact that the total spillover indices are much higher than the one reported in the DY study for the US asset markets (stocks, bonds, FX and commodities) may be interpreted as follows. First, we employ a large number of highly correlated stock and bond markets, and as a result, the spillovers within these markets tend to increase the value of the total spillover indices (DY used only the S&P 500 and the 10 years Treasury Note indices). Second, our sample includes two crisis periods (the global financial crisis in 2008 and the Euro debt crisis in 2010), which potentially contributes to the increase in the total spillovers. In the country-level analysis presented in Sect. 4.2, we expect much lower total spillovers among the four asset classes.

Furthermore, the "**Net**" spillover results for the returns (Table 2) indicate that both the Euro area and the US stock markets are net transmitters of return shocks. On the other hand, all other market segments are net receivers of stock market spillovers. The Portuguese stock market is identified as the main net transmitter of return shocks, followed by the Italian and the German stock markets. These findings also verify the evidence of Ehrmann et al. (2011), who found significant transmissions of the US asset return shocks toward the Euro area financial markets.

The picture is slightly different regarding the net volatility spillover results (Table 3). The central European stock markets, along with the Italian stock market, are the main net transmitters of volatility spillovers, whereas the rest of the markets are net receivers of volatility shocks. DY also found that the stock market volatility is the greatest net spillover contributor in the US financial system. This empirical evidence reveals that the stock markets in the core Eurozone countries, and especially the German stock market, form the main propagation mechanism of uncertainty transmission throughout the Euro area financial markets. In contrast, the periphery stock markets, irrespective of being or not being under the IMF/ECB/EC support mechanism (i.e., Ireland, Portugal and Greece vs Spain), are net receivers of uncertainty shocks.

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[13] For example, the element in column 5 ($j = 5$) row 11 ($i = 11$), i.e., $\tilde{d}_{511,10}$, shows that 6.78 % (0.79 %) of Germany's stock market return (volatility) forecast error variance is due to shocks to the Greek stock market. By contrast, the $j = 11, i = 5$ element shows that 9.49 % (17.81 %) of the Greek stock market return (volatility) forecast error variance is attributable to the German stock market return (volatility) innovations.

A possible explanation for these findings could be the different level of market capitalization for each of the countries examined. Although it is difficult to establish a robust statistical relationship, the data available do not support a positive relation between market capitalization and positive net spillover effects.[14] Therefore, one possible interpretation of the results may be related to the expectations encapsulated in specific stock markets regarding the prospects of the Euro zone economy as a whole. For instance, an increase in the German stock market volatility may be translated by investors as an increase in the uncertainty regarding the prospects of the entire Euro area economy. This common belief creates a mechanism that diffuses the uncertainty to other stock markets and market segments in the Euro area.

Another remarkable result is that the Greek bond index and the US stock market are, on average, net receivers of uncertainty shocks. Nonetheless, an investigation of the dynamics of net spillovers is required to locate possible shifts and investigate diachronically the behavior of net spillover effects for both markets (see Sect. 4.3).

Overall, from the results synopsis presented above, the following conclusions can be drawn: First, the total spillover indices indicate a high level of interconnectedness in the Euro area financial markets. Second, stock markets transmit the largest amount of return and volatility spillovers toward the money, FX and bond markets. Third, the central European stock markets, and especially Germany, transmit volatility spillovers to all other market segments, including the periphery stock markets (except for Italy). This finding implies that investors translate changes in the stock market volatility of the core countries as changes in the level of uncertainty regarding the Euro zone economy prospects, resulting in uncertainty diffusion. Finally, because the spillover tables give a picture for the average spillover effects, a dynamic analysis is required to locate possible spillover shifts.

4.2 Country-level analysis

The empirical analysis of Sect. 4.1 is repeated on the country level to study the spillover effects among the domestic stock and bond indices and the common Euro zone money market and FX rates. The analysis can also be considered as a robustness check for the main findings of Sect. 4.1.

Appendix D (Electronic supplementary material) presents, for each of the ten countries under examination, the GFEV decompositions along with their standard errors for the returns and volatility series. The empirical evidence suggests that the contributions of stock price movements to the EONIA rate forecast error variance are significant across all countries. This outcome could be considered as an indication that the monetary policy stance of the ECB is affected by domestic stock market sentiment. This is also in line with the theoretical argument of Mishkin (2001), who states that stock price movements have an important impact on the aggregate economy and should be considered by central banks when they make monetary policy decisions.

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[14] For example, the USA and the Spanish stock market capitalization as a percentage of GDP for 2012 is 119 and 74 %, respectively, whereas the German and Italian stock market capitalization is only 44 and 24 %, respectively. The data for the stock market capitalization as % of GDP are obtained from the World Bank database: http://data.worldbank.org/indicator/CM.MKT.LCAP.GD.ZS.

However, volatility results reveal a large number of significant contributions among the FX, stock and bond markets across countries. The EONIA uncertainty shocks also significantly contribute to other market forecast error variances in the case of Ireland (FX, stocks, and bonds), Portugal (FX, stocks) and Spain (FX). However, the GFEV components between the stock and bond markets in Greece and Portugal are statistically insignificant. A possible interpretation is that the severe sovereign debt crisis and the resulting uncertainty in the domestic bond markets diminished the contribution of the stock market volatility shocks.

4.2.1 Spillover tables

Once again, we rely on DY's spillover measures for a formal spillover analysis. The spillover results presented in Tables 4 and 5 are in accordance with the empirical findings of Tables 2 and 3. Stock markets are identified as the only (net) transmitter of price and volatility spillovers across all countries, implying that all other markets are (net) receivers of price and volatility shocks. The only exception is the Greek bond market, which transmits volatility spillovers to the rest of the markets (see Table 5). This is probably the result of the Greek sovereign debt crisis and the consequent uncertainty generated by the Greek government bonds. Furthermore, the financial markets in the core Euro area economies are more interconnected compared with the smaller Euro area economies in terms of both return and volatility spillovers. This indicates the relative importance of the stock and bond markets of these economies in the configuration of the common money market and FX rates.[15]

The return spillover results in Table 4 show that total spillover indices range between 33.59 and 57.93 % across countries, which is much lower than the total spillover index reported in Table 2, as expected. The total volatility spillover indices in Table 5 span from 50.17 to 74.92 % across countries and are also lower than the total spillover index in Table 3.

Nonetheless, the total volatility spillover estimates are much higher than the ones reported in DY for the US financial markets, indicating a higher level of interconnectedness in the Euro area financial markets. Additional factors that potentially increase the total volatility spillovers in the Euro countries are (a) the sample period, which includes two crises, (b) the asset classes examined, which differ from those in DY, (money market rate instead of commodities) and (c) the squared returns used by the GARCH model, which is a noisier volatility estimator than the daily range volatility estimator used by DY (see also Sect. 3)

4.3 Rolling sample spillover indices

Spillover tables give an overview for the "average" spillover effects over the full sample and cannot depict the financial evolution or the financial crises (Diebold and Yilmaz 2009, 2012). Therefore, we use a 2-year (or 104 weekly observations) rolling sample

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[15] The average total return (volatility) spillover index for Germany, France, Italy, Spain and the Netherlands is 50.50 % (71.57 %), whereas for Belgium, Austria, Greece, Portugal and Ireland, it is 44.65 % (63.62 %).

Table 4 Returns spillover table on the country level

	EONIA	FX	Stocks	Bonds	**From**
Ireland					
EONIA	0.00	0.60	99.25	0.14	100.00
FX	0.00	85.11	11.26	3.63	14.89
Stocks	0.00	0.01	99.97	0.02	0.03
Bonds	0.00	1.91	17.52	80.57	19.43
To	0.01	2.52	128.03	3.79	Total
Net	−99.99	−12.37	128.00	−29.80	33.59
Portugal					
EONIA	0.00	0.22	99.39	0.38	100.00
FX	0.00	64.64	32.78	2.58	35.36
Stocks	0.00	0.24	99.74	0.03	0.26
Bonds	0.00	0.58	60.60	38.82	61.18
To	0.00	1.04	192.77	2.99	**Total**
Net	−100.00	−34.32	192.50	−46.21	49.20
Greece					
EONIA	0.00	0.75	82.77	16.48	100.00
FX	0.00	49.58	35.09	15.33	50.42
Stocks	0.00	0.49	97.35	2.16	2.65
Bonds	0.00	0.96	19.88	79.16	20.84
To	0.00	2.20	137.74	33.97	**Total**
Net	−100.00	−48.22	135.09	−9.51	43.48
Spain					
EONIA	0.00	1.70	98.25	0.05	100.00
FX	0.00	39.89	58.80	1.30	60.11
Stocks	0.00	0.62	99.29	0.09	0.71
Bonds	0.00	2.41	29.51	68.08	31.92
To	0.01	4.74	186.56	1.44	**Total**
Net	−99.99	−55.37	185.85	−46.75	48.18
Italy					
EONIA	0.01	0.07	99.84	0.09	99.99
FX	0.00	63.94	34.32	1.74	36.06
Stocks	0.00	0.31	99.68	0.01	0.32
Bonds	0.00	1.52	71.86	26.61	73.39
To	0.01	1.90	206.01	1.84	**Total**
Net	−99.98	−34.16	205.69	−50.60	52.44
France					
EONIA	0.00	0.43	98.65	0.92	100.00
FX	0.00	49.02	50.47	0.52	50.98
Stocks	0.00	0.14	98.93	0.93	1.07
Bonds	0.00	0.54	53.05	46.41	53.59

Table 4 continued

	EONIA	FX	Stocks	Bonds	**From**
To	0.01	1.11	202.16	2.36	**Total**
Net	−99.99	−49.87	201.09	−49.05	51.41
Belgium					
EONIA	0.00	0.65	98.92	0.42	100.00
FX	0.00	61.09	38.55	0.36	38.91
Stocks	0.00	0.25	99.64	0.11	0.36
Bonds	0.00	1.26	15.61	83.12	16.88
To	0.00	2.17	153.09	0.89	**Total**
Net	−99.99	−36.74	152.72	−38.15	39.04
Germany					
EONIA	0.00	0.35	97.99	1.66	100.00
FX	0.00	55.26	43.71	1.03	44.74
Stocks	0.00	0.10	98.24	1.66	1.76
Bonds	0.00	0.26	57.95	41.79	58.21
To	0.01	0.71	199.65	4.34	**Total**
Net	−99.99	−44.03	197.89	−46.83	51.18
Austria					
EONIA	0.01	2.20	97.19	0.60	99.99
FX	0.00	38.86	61.00	0.14	61.14
Stocks	0.00	1.02	98.83	0.15	1.17
Bonds	0.00	2.20	67.22	30.57	69.43
To	0.00	5.42	225.41	0.88	**Total**
Net	−99.99	−55.72	224.25	−57.05	57.93
Netherlands					
EONIA	0.00	0.38	98.56	1.06	100.00
FX	0.00	48.38	50.93	0.68	51.62
Stocks	0.00	0.02	98.72	1.26	1.28
Bonds	0.00	0.14	64.28	35.58	64.42
To	0.00	0.54	213.77	3.00	**Total**
Net	−99.99	−51.08	212.49	−51.33	54.33

The *ij*th element of the table is computed as in Eq. (3) and shows the proportion of a 10-step forecast error variance of variable i (rows), which is accounted for by innovations in variable j (columns). Table entries are normalized with respect to their row sum, i.e., the sum of row elements adds to 100. The diagonal elements ($j = i$) are the *own variance shares* estimates, which show the fraction of the forecast error variance of market i which is due to its own shocks. The column "**From**" shows the total spillovers received by a particular market from all other markets, while the row "**To**" shows the spillover effects directed by a particular market to all other markets .The measure "**Total**" shows the level of total spillovers in the Euro area markets

Table 5 Volatilities spillover table on the country level

	EONIA	FX	Stocks	Bonds	**From**
Ireland					
EONIA	0.03	0.06	89.80	10.11	99.97
FX	0.03	0.98	97.35	1.64	99.02
Stocks	0.02	0.24	98.81	0.93	1.19
Bonds	0.08	0.92	24.22	74.77	25.23
To	0.13	1.22	211.37	12.67	**Total**
Net	−99.84	−97.80	210.19	−43.68	56.35
Portugal					
EONIA	0.06	0.45	99.29	0.20	99.94
FX	0.07	2.17	86.11	11.65	97.83
Stocks	0.08	0.48	98.71	0.74	1.29
Bonds	0.00	0.60	1.02	98.38	1.62
To	0.15	1.53	186.42	12.59	**Total**
Net	−99.79	−96.30	185.12	−37.58	50.17
Greece					
EONIA	0.03	0.29	4.29	95.39	99.97
FX	0.00	0.26	7.69	92.05	99.74
Stocks	0.01	1.01	46.21	52.77	53.79
Bonds	0.00	0.27	4.28	95.44	4.56
To	0.01	1.58	16.26	240.21	**Total**
Net	−99.96	−98.17	−37.53	175.69	64.52
Spain					
EONIA	3.43	3.18	63.28	30.11	96.57
FX	0.05	8.23	86.22	5.50	91.77
Stocks	0.03	1.51	94.68	3.79	5.32
Bonds	0.02	3.00	43.53	53.44	46.56
To	0.11	7.69	193.02	39.40	**Total**
Net	−96.46	−84.08	187.70	−20.66	60.05
Italy					
EONIA	0.02	0.08	97.45	2.45	99.98
FX	0.00	0.16	98.81	1.03	99.84
Stocks	0.00	0.05	99.17	0.78	0.83
Bonds	0.00	0.16	92.75	7.08	92.92
To	0.01	0.29	289.02	4.26	**Total**
Net	−99.97	−99.55	288.19	−69.14	73.39
France					
EONIA	0.01	0.24	99.66	0.09	99.99
FX	0.01	1.11	98.55	0.33	98.89
Stocks	0.01	0.25	99.58	0.16	0.42

Table 5 continued

	EONIA	FX	Stocks	Bonds	**From**
Bonds	0.01	0.27	99.47	0.26	99.74
To	0.03	0.76	297.67	0.58	**Total**
Net	−99.97	−98.12	297.25	−74.18	74.76
Belgium					
EONIA	0.01	0.03	99.78	0.18	99.99
FX	0.00	0.08	99.89	0.04	99.92
Stocks	0.00	0.03	99.93	0.04	0.07
Bonds	0.01	0.28	89.14	10.57	89.43
To	0.01	0.33	288.81	0.26	**Total**
Net	−99.98	−99.59	288.74	−72.10	72.35
Germany					
EONIA	0.00	0.03	99.87	0.10	100.00
FX	0.00	0.08	99.81	0.11	99.92
Stocks	0.00	0.03	99.89	0.08	0.11
Bonds	0.00	0.08	99.58	0.34	99.66
To	0.00	0.13	299.26	0.29	**Total**
Net	−100.00	−99.79	299.16	−74.63	74.92
Austria					
EONIA	0.00	0.04	99.96	0.00	100.00
FX	0.00	0.11	99.86	0.03	99.89
Stocks	0.00	0.05	99.93	0.02	0.07
Bonds	0.01	0.21	98.73	1.06	98.94
To	0.01	0.30	298.54	0.05	**Total**
Net	−99.99	−99.59	298.47	−74.67	74.73
Netherlands					
EONIA	0.01	0.05	99.89	0.05	99.99
FX	0.01	0.55	99.24	0.20	99.45
Stocks	0.00	0.05	99.86	0.08	0.14
Bonds	0.00	0.14	99.33	0.53	99.47
To	0.01	0.24	298.46	0.33	**Total**
Net	−99.98	−99.20	298.32	−74.43	74.76

The ijth element of the table is computed as in Eq. (3) and shows the proportion of a 10-step forecast error variance of variable i (rows) which is accounted for by innovations in variable j (columns). Table entries are normalized with respect to their row sum, i.e. the sum of row elements adds to 100. The diagonal elements $(j = i)$ are the *own variance shares* estimates, which show the fraction of the forecast error variance of market i that is due to its own shocks. The column "**From**" shows the total spillovers received by a particular market from all other markets, while the row "**To**" shows the spillover effects directed by a particular market to all other markets.The measure "**Total**" shows the level of total spillovers in the Euro area markets to re-estimate the VAR model on a weekly basis and produce time-varying spillover indices. The time-dependent return and volatility spillover indices are depicted in Fig. 1.

Figure 1 reveals the high level of total spillover effects across the Euro area markets (fluctuating between 89 and 94 %) and the fact that the two indices seem to co-move, at least for most of the sample period. We are also able to locate two spillover cycles that are described below.

The first one covers the period from 2002 to mid-2006, during which both indices moved downwards and reached their minimum values in the first half of 2006. The downward trend probably reflects the underestimation of assets risks and the prosperous financial environment (ECB, Financial Stability Review, 2005; 2006). The second spillover cycle starts in the second half of 2006 and is characterized by a sharp increase of both indices until the collapse of Lehman Brothers in September 2008. The high level of spillover is retained throughout 2010 and 2011, reflecting the unfolding sovereign debt crisis in the periphery countries, whereas there are signs of a spillover de-escalation after May 2012. Both indices reached their maximum value during Lehman's collapse and the period surrounding the agreement between the Greek government and the IMF/ECB/EC. Apart from these general spillover cycles, there are also short-lived spillover spikes during stressful events, such as the Bear Sterns bailout and the Northern Rock bank-run.

Overall, the dynamics of both the returns and volatility spillovers indicate that total spillovers are intensified during periods of financial or economic stress, but there is no clear upward or downward trend during our sample. Moreover, the debt crisis in the periphery did not increase the level of volatility spillover more than the period following the collapse of Lehman Brothers. Finally, the average level of spillovers in the 2009–2012 period is slightly higher than the 2002–2005 period, indicating that even strong idiosyncratic shocks can only trigger temporary spillover increases above average.

4.3.1 Net directional spillover indices

The examination of the directional spillover dynamics will enable us to identify possible sources of imbalances and propagation channels in the financial system. Figure 2 presents the net spillovers for the returns across all markets. Positive (negative) values indicate that market i transmits (receives) spillovers to (from) the rest of the j markets.

Figure 2 confirms the results of Table 4 and indicates that stock markets are the key net transmitter of return spillovers throughout the sample period. In particular, all Euro area stock markets transmit spillovers during both crisis periods (global financial and European debt crisis). The US stock market also contributes to the transmission of price shocks to all other markets during the subprime crisis and immediately afterward, as expected. However, it is a net receiver of spillovers during the Euro area sovereign debt crisis.

In addition, during the first spillover cycle (2002–2006), the stock markets in Germany, France, Italy, Spain and the Netherlands are the main net transmitters of price spillovers. The picture changes during the 2007–2009 financial crisis, when the stock markets in the periphery countries (Ireland, Greece and Portugal) and smaller Euro

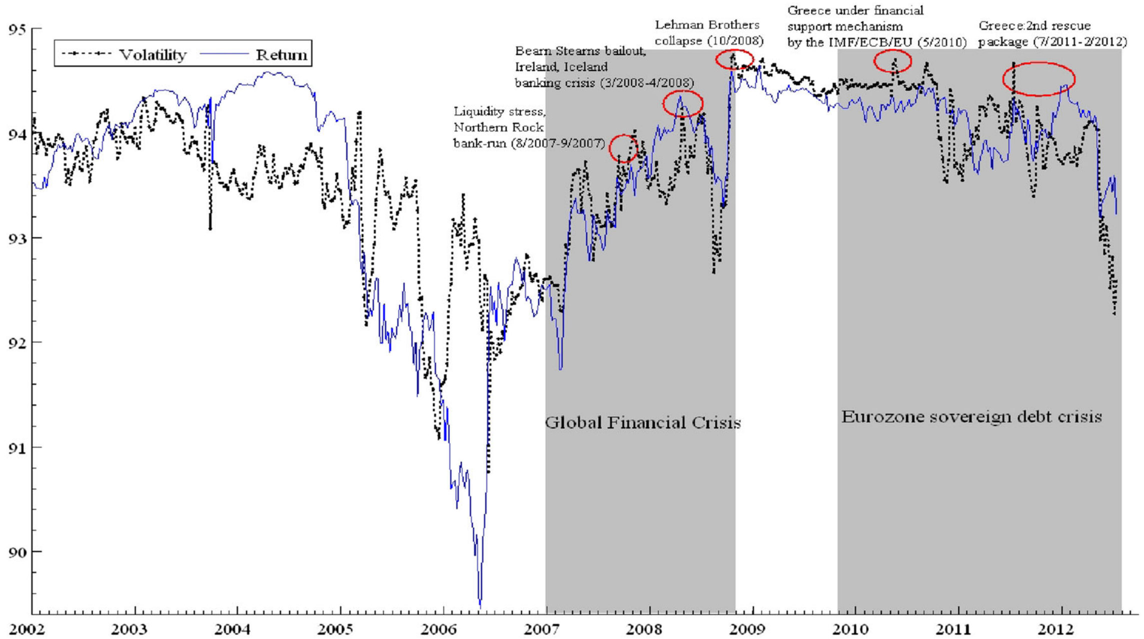

Fig. 1 Total return and volatility spillover indices. **Notes** The figure shows the total return and volatility spillover indices computed as in Eq. (4). A rolling sample of 104 weeks has been used so as to compute the time-dependent total spillover indices. The shaded areas depict the global financial crisis (1/2007–10/2008) and the European debt crisis (10/2009…), while the circles point out specific stressful events. The time periods for the crises are selected on the basis of Brunnermeier (2009) and Louzis and Vouldis (2013) studies

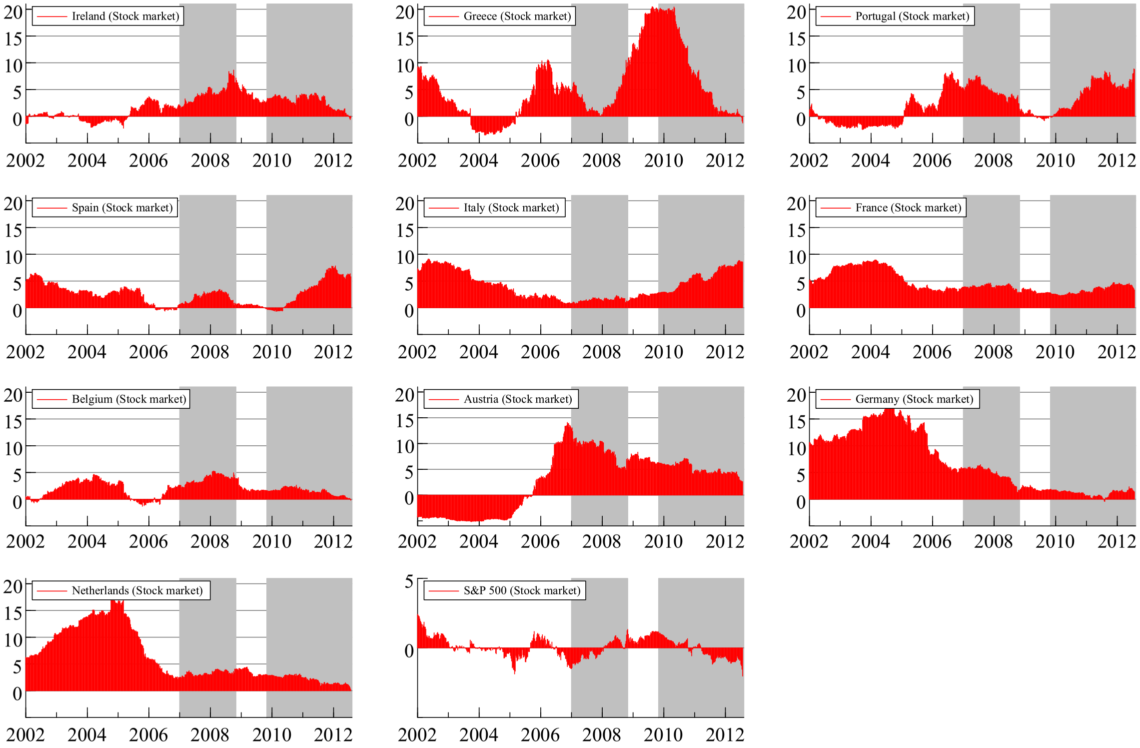

Fig. 2 Net directional return spillover indices. **Notes** The figure shows the net directional return spillover indices computed as in Eq. (7). A rolling sample of 104 weeks has been used so as to compute the time-dependent net spillover indices. The shaded areas depict the global financial crisis (1/2007–10/2008) and the European debt crisis (10/2009…). The time periods for the crises are selected on the basis of Brunnermeier (2009) and Louzis and Vouldis (2013) studies

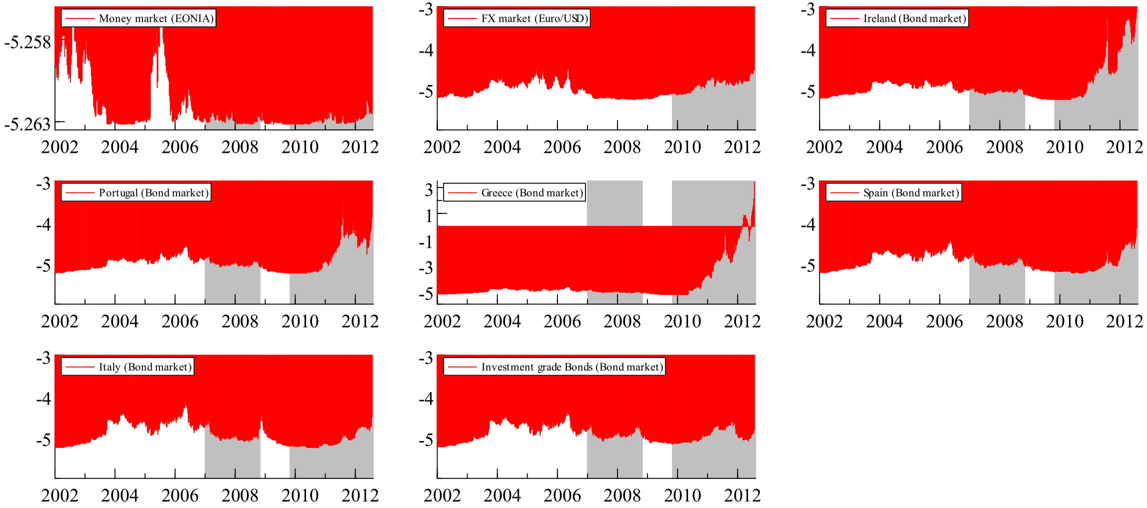

Fig. 2 continued

area economies, i.e., Belgium and Austria, are the main propagation mechanism of stock price shocks. Moreover, during the ongoing debt crisis (2010…), the periphery stock markets transmit the largest amount of spillovers to all other markets. The rest of the asset classes remain net receivers of price shocks during the full sample period. The only exception is the Greek bonds market, which spills over price shocks to other markets after 2012.

Figure 3 depicts the net spillover indices for volatility series that are also in line with the findings in Table 5. The stock markets in Germany, Austria, the Netherlands, Belgium and Italy are the key net transmitters of uncertainty spillovers. With the exception of Austria, this group of stock markets transmits volatility shocks to the rest of the markets throughout the sample period. Surprisingly, the US stock market transmits a small amount of volatility spillovers toward the end of the global financial crisis and at the beginning of the European debt crisis. Nonetheless, the results align with the study of Duncan and Kabundi (2013), who found that a relatively small amount of the US volatility shocks is directed to the South African financial system. Moreover, the money, FX and bond markets are net receivers of uncertainty shocks throughout the sample period. Again, the only exception is the Greek bond index, which spills over a relatively large amount of uncertainty as a result of the sovereign debt crisis.

Overall, the dynamic analysis verifies that stock markets spill over price or uncertainty shocks diachronically. Nonetheless, the core European stock markets make up the main propagation mechanism of uncertainty shocks throughout the sample period. Finally, the empirical evidence suggests that bond markets can also transmit both price and volatility spillovers in cases of severe credit events.

5 Conclusions

This study examines the return (price) and volatility (uncertainty) spillover effects among the main aspects of the Euro area financial system, i.e., among the money, stock, FX and bond markets. We construct spillover tables and indices for a 10-year period (2002–2012) by implementing the generalized forecast error variance decomposition approach of Diebold and Yilmaz (2012). The asymptotic distribution for the generalized forecast error variance decompositions is also derived.

Overall, the empirical results indicate a high level of total return and volatility spillovers throughout the sample period, with sharp but temporary increases observed during external (Lehman Brother collapse) and idiosyncratic (Greek debt crisis) shocks to the Euro area. Nonetheless, the spillovers follow a more general pattern, which may be affected by the corresponding phase of the business cycle.

Moreover, the stock markets are identified as the key transmitters of price and uncertainty spillovers across the Euro area. Specifically, the stock markets in the periphery countries (i.e., Ireland, Portugal, and Greece) comprise the propagation mechanism of price shocks during financial distress. In contrast, the stock markets in the core Euro area countries (i.e., Germany, Austria, and the Netherlands) and Italy are the main transmitters of uncertainty spillovers diachronically. This phenomenon may imply that investors translate the changes in the stock market volatility of specific countries

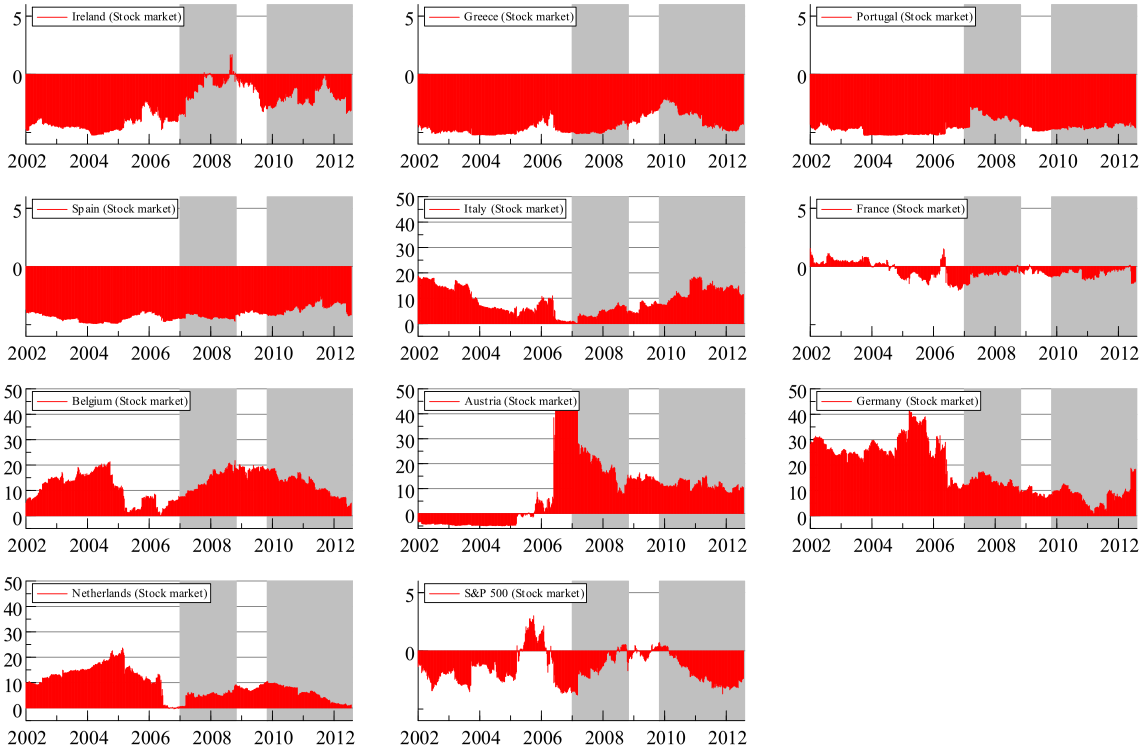

Fig. 3 Net directional volatility spillover indices. **Notes** The figure shows the net directional volatility spillover indices computed as in Eq. (7). A rolling sample of 104 weeks has been used so as to compute the time-dependent net spillover indices. The shaded areas depict the global financial crisis (1/2007–10/2008) and the European debt crisis (10/2009…). The time periods for the crises are selected on the basis of Brunnermeier (2009) and Louzis and Vouldis (2013) studies

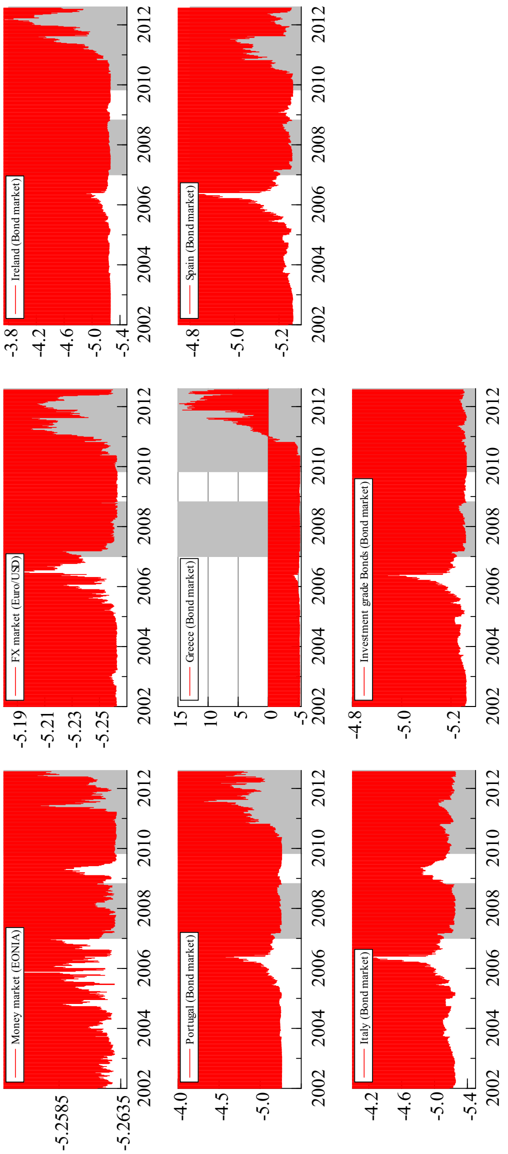

Fig. 3 continued

as changes in the uncertainty regarding the prospects of the whole Euro area economy. This belief makes up the propagation mechanism, which diffuses spillovers to other market segments. Furthermore, the empirical evidence suggests that the bond markets can also diffuse spillovers to other market segments in the case of severe credit events, such as the Greek crisis. Finally, the standard errors for the generalized forecast error variance decompositions reveal that a volatility spillover analysis is more likely to provide statistically significant results compared with an analysis based on return series.

The results presented in this study are of particular interest for both policy makers and investors. From a policy-making perspective, it is of great importance for the preservation of financial stability to identify that shocks to one market will probably create spillovers to other markets because the Euro area financial markets are highly interconnected. Moreover, because stock markets are the main transmitter of price and uncertainty shocks, they should be closely monitored and possibly used in an early warning indicator system. In addition, the fact that sovereign bond markets can play a crucial role in the uncertainty transmission during severe credit events enhances the idea of central policy actions, such as the recent rescue plan by the ECB for buying sovereign bonds through outright monetary transactions (OMT) (ECB 2012), in order to limit widespread contagion effects. Finally, investors can also improve their hedging and portfolio diversification strategies by exploiting the increased knowledge regarding the interconnection of the markets.

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Appendix A: Asymptotic distribution for the generalized forecast error variance decomposition components

In this Appendix, we derive the asymptotic distribution for the generalized forecast error variance decompositions, $d_{ij,H}$, defined in Eq. (2). We rely on the results of Lutkepohl (1990) and use the following standard asymptotic properties of estimators (see Lutkepohl (2005, pp. 692–693)):[16]

(i) Let $\boldsymbol{\beta}$ be an $(N \times 1)$ vector of parameters and $\hat{\boldsymbol{\beta}}$ be its estimate. Then

$$\sqrt{T}\left(\hat{\boldsymbol{\beta}} - \boldsymbol{\beta}\right) \xrightarrow{d} N\left(0, \boldsymbol{\Sigma}_{\hat{\boldsymbol{\beta}}}\right) \tag{8}$$

Where $\rightarrow^{d}$ denotes convergence in distribution, N is a multivariate Normal distribution with a mean vector 0 and covariance matrix $\boldsymbol{\Sigma}_{\hat{\boldsymbol{\beta}}}$, and T is the sample size.

(ii) Let $g\left(\boldsymbol{\beta}\right) = \left(g_1\left(\boldsymbol{\beta}\right), g_2\left(\boldsymbol{\beta}\right), \ldots g_m\left(\boldsymbol{\beta}\right)\right)'$ be a vector-valued continuously differentiable function with $\partial g / \partial \boldsymbol{\beta}' \neq 0$ at $\boldsymbol{\beta}$. Then

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[16] Lutkepohl (1990) provides analytical expressions for the asymptotic distribution of the orthogonalized forecast error variance decomposition measures (see also Lutkepohl (2005, Section 3.7)

$$\sqrt{T}\left(g\left(\hat{\boldsymbol{\beta}}\right)-g\left(\boldsymbol{\beta}\right)\right)\xrightarrow{d}N\left(0,\frac{\partial g}{\partial\boldsymbol{\beta}'}\Sigma_{\hat{\boldsymbol{\beta}}}\frac{\partial g'}{\partial\boldsymbol{\beta}}\right)\tag{9}$$

The necessary notation and definitions are given below:

- $\boldsymbol{\pi} := vec\left(\boldsymbol{\Pi}_1,\ldots,\boldsymbol{\Pi}_p\right) \qquad \left(N^2p\times 1\right)$
- $\boldsymbol{A} := \begin{bmatrix} \boldsymbol{\Pi}_1 & \boldsymbol{\Pi}_2 & \cdots & \boldsymbol{\Pi}_{p-1} & \boldsymbol{\Pi}_p \\ \boldsymbol{I}_N & 0 & \cdots & 0 & 0 \\ 0 & \boldsymbol{I}_N & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \boldsymbol{I}_N & 0 \end{bmatrix} \qquad (Np\times Np)$
- $\boldsymbol{\sigma} := vech\left(\boldsymbol{\Sigma}_\varepsilon\right) \qquad \left(\frac{1}{2}N\left(N+1\right)\times 1\right)$
- $\boldsymbol{J} := [\boldsymbol{I}_N : 0 : \cdots : 0] \qquad (N\times Np)$
- Moreover, $\boldsymbol{D}_N$ is an $\left(N^2\times\frac{1}{2}N(N+1)\right)$ duplication matrix which is defined such that $\boldsymbol{D}_N vech\left(F\right) = vec\left(\boldsymbol{F}\right)$ for any $\boldsymbol{F}$ $(N\times N)$ symmetric matrix.

Based on the above, we can state Proposition 5.1.

Proposition 5.1 *Suppose:*

$$\sqrt{T}\begin{bmatrix}\hat{\boldsymbol{\pi}}-\boldsymbol{\pi}\\ \hat{\boldsymbol{\sigma}}-\boldsymbol{\sigma}\end{bmatrix}\xrightarrow{d}N\left(0,\begin{bmatrix}\boldsymbol{\Sigma}_{\hat{\boldsymbol{\pi}}} & 0\\ 0 & \boldsymbol{\Sigma}_{\hat{\boldsymbol{\sigma}}}\end{bmatrix}\right)$$

Then

$$\sqrt{T}\left(\hat{d}_{ij,H}-d_{ij,H}\right)\xrightarrow{d}N\left(0,\boldsymbol{\omega}_{ij,H}\boldsymbol{\Sigma}_{\hat{\boldsymbol{\pi}}}\boldsymbol{\omega}'_{ij,H}+\bar{\boldsymbol{\omega}}_{ij,H}\boldsymbol{\Sigma}_{\hat{\boldsymbol{\sigma}}}\bar{\boldsymbol{\omega}}'_{ij,H}\right)$$
$$\text{with } i,\, j=1,\ldots,N \text{ and } H=1,2,\ldots$$

Where

$$\begin{aligned}\boldsymbol{\omega}_{ij,H} = \frac{2\sigma_{ii}^{-1}}{MSE_{i,H}^2}\Bigg[&\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)\left(\boldsymbol{e}'_j\boldsymbol{\Sigma}'_\varepsilon\otimes\boldsymbol{e}'_i\right)\boldsymbol{G}_h MSE_{i,H}\\ &-\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)^2\sum_{m=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_m\boldsymbol{\Sigma}_\varepsilon\otimes\boldsymbol{e}'_i\right)\boldsymbol{G}_m\Bigg]\end{aligned}\tag{10}$$

$\boldsymbol{G}_i := \frac{\partial vec(\boldsymbol{\Theta}_i)}{\partial\boldsymbol{\pi}'} = \sum_{m=0}^{i-1}\boldsymbol{J}\left(\boldsymbol{A}'\right)^{i-1-m}\otimes\boldsymbol{\Theta}_m$ *with* $\boldsymbol{G}_0 := \boldsymbol{0}$ *(see Lutkepohl (2005, Section 3.7.2, p. 111))*

And

$$\begin{aligned}\bar{\boldsymbol{\omega}}_{ij,H} = \frac{\sigma_{ii}^{-1}}{MSE_{i,H}^2}\Bigg\{\Bigg[&-\sigma_{ii}^{-1}\left(\boldsymbol{e}'_j\otimes\boldsymbol{e}'_j\right)\boldsymbol{D}_N\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)^2\\ &+2\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)\left(\boldsymbol{e}'_j\otimes\boldsymbol{e}'_i\boldsymbol{\Theta}_h\right)\boldsymbol{D}_N\Bigg]MSE_{i,H}\end{aligned}$$

$$-\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)^2 2\sum_{m=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_m\otimes\boldsymbol{e}'_i\boldsymbol{\Theta}_m\right)\boldsymbol{D}_N\Bigg\} \tag{11}$$

Proof To facilitate the calculation of the partial derivatives we define:

- $F_j(\boldsymbol{\sigma}) := \left(\boldsymbol{e}'_i\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_i\right) = \sigma_{ii}$
- $Y_{ij,H}(\boldsymbol{\pi},\boldsymbol{\sigma}) := \sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)^2$

Therefore, we can write:

$$d_{ij,H}(\boldsymbol{\pi},\boldsymbol{\sigma}) = \frac{F_j(\boldsymbol{\sigma})^{-1}Y_{ij,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}{\mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}$$

and

$$\omega_{ij,H} = \frac{\partial d_{ij,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}{\partial\boldsymbol{\pi}'} = \frac{\partial}{\partial\boldsymbol{\pi}'}\left(\frac{F_j(\boldsymbol{\sigma})^{-1}Y_{ij,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}{\mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}\right)$$

Applying quotient differentiation rule we get:

$$\omega_{ij,H} = \left[\frac{\partial\left(F(\boldsymbol{\sigma})^{-1}Y(\boldsymbol{\pi},\boldsymbol{\sigma})\right)}{\partial\boldsymbol{\pi}'}\mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})\right.$$
$$\left.-F(\boldsymbol{\sigma})^{-1}Y(\boldsymbol{\pi},\boldsymbol{\sigma})\frac{\partial\mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}{\partial\boldsymbol{\pi}'}\right]\Big/\mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})^2 \tag{12}$$

Where

$$\begin{aligned}
\text{(i)}\ \frac{\partial\left(F(\boldsymbol{\sigma})^{-1}Y(\boldsymbol{\pi},\boldsymbol{\sigma})\right)}{\partial\boldsymbol{\pi}'} &= F(\boldsymbol{\sigma})^{-1}\frac{\partial}{\partial\boldsymbol{\pi}'}Y(\boldsymbol{\pi},\boldsymbol{\sigma})\\
&= F(\boldsymbol{\sigma})^{-1}\frac{\partial}{\partial\boldsymbol{\pi}'}\left(\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)^2\right)\\
&= 2\sigma_{ii}^{-1}\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)\left(\boldsymbol{e}'_j\boldsymbol{\Sigma}'_\varepsilon\otimes\boldsymbol{e}'_i\right)\frac{\partial vec(\boldsymbol{\Theta}_h)}{\partial\boldsymbol{\pi}'}\\
&= 2\sigma_{ii}^{-1}\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_\varepsilon\boldsymbol{e}_j\right)\left(\boldsymbol{e}'_j\boldsymbol{\Sigma}'_\varepsilon\otimes\boldsymbol{e}'_i\right)G_h
\end{aligned}$$

(ii) $G_i := \frac{\partial vec(\boldsymbol{\Theta}_i)}{\partial\boldsymbol{\pi}'}$
(iii) $\frac{\partial\mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}{\partial\boldsymbol{\pi}'} = 2\sum_{m=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_m\boldsymbol{\Sigma}_\varepsilon\otimes\boldsymbol{e}'_i\right)G_m$. See proof in Lutkepohl (2005, pp. 117)).

Replacing the expressions (i) – (iii) in Eq. (12) and rearranging the terms we get Eq. (10).

Similarly, we write

$$\bar{\omega}_{ij,H} = \frac{\partial d_{ij,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}{\partial \boldsymbol{\sigma}'} = \frac{\partial}{\partial \boldsymbol{\sigma}'}\left(\frac{F_j(\boldsymbol{\sigma})^{-1} Y_{ij,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}{\mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}\right)$$

Applying quotient differentiation rule we get:

$$\bar{\omega}_{ij,H} = \left[\frac{\partial\left(F(\boldsymbol{\sigma})^{-1} Y(\boldsymbol{\pi},\boldsymbol{\sigma})\right)}{\partial \boldsymbol{\sigma}'}\mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma}) - F(\boldsymbol{\sigma})^{-1} Y(\boldsymbol{\pi},\boldsymbol{\sigma})\frac{\partial \mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})}{\partial \boldsymbol{\sigma}'}\right] \Big/ \mathrm{MSE}_{i,H}(\boldsymbol{\pi},\boldsymbol{\sigma})^2 \qquad (13)$$

Where

$$\text{(i)}\quad \frac{\partial\left(F(\boldsymbol{\sigma})^{-1} Y(\boldsymbol{\pi},\boldsymbol{\sigma})\right)}{\partial \boldsymbol{\sigma}'} = \left(\frac{\partial}{\partial \boldsymbol{\sigma}'}\left(F(\boldsymbol{\sigma})^{-1}\right)\right) Y(\boldsymbol{\pi},\boldsymbol{\sigma}) + F(\boldsymbol{\sigma})^{-1}\frac{\partial}{\partial \boldsymbol{\sigma}'} Y(\boldsymbol{\pi},\boldsymbol{\sigma})$$

$$\begin{aligned}\text{(i.a)}\quad \frac{\partial}{\partial \boldsymbol{\sigma}'}\left(F(\boldsymbol{\sigma})^{-1}\right) &= \frac{\partial}{\partial \boldsymbol{\sigma}'}\left(\boldsymbol{e}'_i \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_i\right)^{-1} \\ &= -\left(\boldsymbol{e}'_i \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_i\right)^{-2}\left(\boldsymbol{e}'_i \otimes \boldsymbol{e}'_i\right)\frac{\partial}{\partial \boldsymbol{\sigma}'} vec\left(\boldsymbol{\Sigma}_\varepsilon\right) \\ &= -\left(\boldsymbol{e}'_i \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_i\right)^{-2}\left(\boldsymbol{e}'_i \otimes \boldsymbol{e}'_i\right)\boldsymbol{D}_N\frac{\partial}{\partial \boldsymbol{\sigma}'} vech\left(\boldsymbol{\Sigma}_\varepsilon\right) \\ &= -\sigma_{ii}^{-2}\left(\boldsymbol{e}'_i \otimes \boldsymbol{e}'_i\right)\boldsymbol{D}_N\end{aligned}$$

$$\begin{aligned}\text{(i.b)}\quad \frac{\partial}{\partial \boldsymbol{\sigma}'} Y(\boldsymbol{\pi},\boldsymbol{\sigma}) &= \frac{\partial}{\partial \boldsymbol{\sigma}'}\left(\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i \boldsymbol{\Theta}_h \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_j\right)^2\right) \\ &= 2\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i \boldsymbol{\Theta}_h \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_j\right)\left(\boldsymbol{e}'_j \otimes \boldsymbol{e}'_i \boldsymbol{\Theta}_h\right)\frac{\partial}{\partial \boldsymbol{\sigma}'} vec\left(\boldsymbol{\Sigma}_\varepsilon\right) \\ &= 2\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i \boldsymbol{\Theta}_h \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_j\right)\left(\boldsymbol{e}'_j \otimes \boldsymbol{e}'_i \boldsymbol{\Theta}_h\right)\boldsymbol{D}_N\frac{\partial}{\partial \boldsymbol{\sigma}'} vech\left(\boldsymbol{\Sigma}_\varepsilon\right) \\ &= 2\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i \boldsymbol{\Theta}_h \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_j\right)\left(\boldsymbol{e}'_j \otimes \boldsymbol{e}'_i \boldsymbol{\Theta}_h\right)\boldsymbol{D}_N\end{aligned}$$

Replacing (i.a) and (i.b) in (i) we get:

$$\frac{\partial\left(F(\boldsymbol{\sigma})^{-1} Y(\boldsymbol{\pi},\boldsymbol{\sigma})\right)}{\partial \boldsymbol{\sigma}'} = -\sigma_{ii}^{-2}\left(\boldsymbol{e}'_i \otimes \boldsymbol{e}'_i\right)\boldsymbol{D}_N\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i \boldsymbol{\Theta}_h \boldsymbol{\Sigma}_\varepsilon \boldsymbol{e}_j\right)^2$$

$$+2\sigma_{ii}^{-1}\sum_{h=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_h\boldsymbol{\Sigma}_{\varepsilon}\boldsymbol{e}_j\right)\left(\boldsymbol{e}'_j\otimes\boldsymbol{e}'_i\boldsymbol{\Theta}_h\right)\boldsymbol{D}_N$$

$$\begin{aligned}\text{(ii)}\frac{\partial\mathrm{MSE}_i\left(H\right)}{\partial\boldsymbol{\sigma}'}&=\frac{\partial}{\partial\boldsymbol{\sigma}'}\left(\sum_{m=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_m\boldsymbol{\Sigma}_{\varepsilon}\boldsymbol{\Theta}'_m\boldsymbol{e}_i\right)\right)\\&=\sum_{m=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_m\otimes\boldsymbol{e}'_i\boldsymbol{\Theta}_m\right)\boldsymbol{D}_N\frac{\partial vech\left(\boldsymbol{\Sigma}\right)}{\partial\boldsymbol{\sigma}'}\\&=\sum_{m=0}^{H-1}\left(\boldsymbol{e}'_i\boldsymbol{\Theta}_m\otimes\boldsymbol{e}'_i\boldsymbol{\Theta}_m\right)\boldsymbol{D}_N.\end{aligned}$$

Replacing expressions (i), (ii) in Eq. (13) and rearranging the terms we get Eq. (11). However, we should note that:

(a) The block diagonal structure of the covariance matrix of the asymptotic distribution of $\hat{\boldsymbol{\pi}}$ and $\hat{\boldsymbol{\sigma}}$ in Proposition 5.1 is essential for the simple additive structure of the asymptotic variance of $\hat{d}_{ij,H}$ (Lutkepohl 2005, Remark 3 p.113).

(b) In practical applications of statistical inference the unknown covariance matrices $\boldsymbol{\Sigma}_{\boldsymbol{\pi}}$ and $\boldsymbol{\Sigma}_{\varepsilon}$ are replaced by their estimators (see Lutkepohl 2005, Remark 5 p.114).

(c) The results in Proposition 5.1 should be treated cautiously as far as formal hypothesis testing is concerned. As pointed out in Lutkepohl (2005, Remark 6, p. 114) the asymptotic distribution of $\hat{d}_{ij,H}$ can not be utilized in hypothesis testing if the true value of $d_{ij,H}$ is zero. When $d_{ij,H}=0$ it is easy to show that $\boldsymbol{\omega}_{ij,H}$ and $\bar{\boldsymbol{\omega}}_{ij,H}$ are also zero implying a zero asymptotic variance. In that case estimating $\boldsymbol{\omega}_{ij,H}$ and $\bar{\boldsymbol{\omega}}_{ij,H}$ using standard estimators may result in t-statistics which are not standard normal asymptotically and therefore cannot be used in significance testing.

□

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