Volatility Co-movements and Spillover Effects within the Eurozone Economies: A Multivariate GARCH Approach using the Financial Stress Index

Abstract

The Eurozone crisis is one the most important economic event in recent years. At its peak, the effects of the crisis have put at serious risk the outcome of the euro project, exposing the inherent weaknesses and vulnerabilities of the monetary union. As the degree of economic and financial integration of these countries is significant, we aim to investigate in details the potential cross-covariance and spillover effects between the Eurozone economies and financial markets. In order to do this, we employ financial stress indexes, as systemic risk metrics in a multivariate GARCH model. This method is able to capture markets' dependencies and volatility spillovers and is employed on a single market level as well as on the full spectrum of Eurozone markets. The empirical results have shown the important and intensive stress transmission on banking and money markets. Moreover, the role of peripheral countries as stress transmitter is verified, but only for particular periods. The significant spillover effects from core countries are also evident, indicating their important role in the Euro Area and its overall financial stability. The "decoupling" hypothesis is empirically verified, underling the gradually decreasing intensity of spillovers between Euro Area countries. Overall, this paper exhibits the complex structure of spillover effects for Eurozone, along with a clustering effect in the most recent times.

JEL Classifications: C43, C58, G01, G15

Keywords: Financial Crisis, Volatility Spillover Effects, Systemic Risk, GARGH-BEKK model

1. Introduction

There is no doubt that the recent Eurozone financial and sovereign crisis is one of the most important economic events of the last decade. It created an unprecedented reaction, in terms of unconventional monetary and fiscal policies from the global and local policy makers. Starting from the US, after the collapse of Lehman Brothers, governments provided state funds for the rescue of insolvent financial institutions and for the stabilization of the financial system in general. The size of this intervention is vast, with ECB's total assets reaching almost 21% of Euro Area GDP in 2015 (as opposed to 9% in 2007), while similar situation prevails in the rest of the world (for instance, FED holds assets equal to 25% of US GDP, with outright purchases being almost 99% of these assets). At the peak of the crisis, US authorities spent almost 20 trillion US dollars for rescuing banks, while in Europe, governments spent almost 312 billion euros for bailing out financial institutions and 2.92 trillion euros for implicit guarantees (Fratzscher, *et al.*, 2016; Hryckiewicz, 2014; Kizys *et al.*, 2016). The main reason to proceed to such a large scale bail out programs, for financial institutions as well as for a number of heavily indebted countries in the Eurozone case, was the heightening uncertainty for the already identified financial, fiscal and real economic meltdown. Furthermore, the lack of a consistent and supra-national macro-prudential and crisis mitigating framework, leads to even more uncertainty.

Bearing all the above in mind and, given the lack of conclusive and clear cut evidence for the potential risk transmission channels within the Eurozone economies, we aim to shed further light in the issue of volatility co-movement and spillover effects among the EMU countries. In contrast to the existing literature, we move beyond the usual focus on sovereign and, sometimes, banking risk channels. Instead, we try to investigate a full set of potential volatility transmission channels, by implementing a number of financial stress indices for a wide group of financial markets.

This paper contributes to the literature in several dimensions. As implied in the previous paragraph, we provide a detailed account of potential spillover effects for a wide number of Eurozone countries and financial markets. We do not limit this research to sovereign or banking risks only. Instead, a broader and inclusive approach is adopted, by studying the effects of the banking sector, along with the money, equity and bond markets. Financial stress indexes, which are aggregate metrics of systemic risk and potential instability in the markets, are used as proxies of these market conditions.

Additionally, the econometric modelling is based on multivariate GARCH-BEKK models, which is another innovative characteristic to this research area.

The empirical work is conducted into two directions: “within” each one of the markets, we produce financial stress indexes for the banking sector, money, equity and bond markets and “between” all of the above markets and countries. This cross-market approach is another novel feature of this study, providing further decomposed evidence for the Eurozone crisis spillover effects. Additionally, the empirical modelling is also materialized on a regional analysis, where regional (core – periphery) stress indices are used, together with sub-sample analysis. The latter is useful, in order to identify changing patterns to the stress transmission channels due to the crisis outbreak. The findings from the baseline model are further reinforced by a range of robustness checks and further evidence analysis. Alternative volatility specifications are employed, along with additional multivariate GARCH modelling approaches, together with alternative sets of financial stress indices.

Our findings show that multiple channels of interconnectedness exist in Eurozone, with an eminent role for banking and money markets. The direction of these spillover effects is towards both types of countries, core and peripheral, depending to the time period in some cases. Even though the most heavily affected countries from the Eurozone crisis (Greece, Spain, Portugal and Ireland) are occasionally among the major contributors of volatility transmission, they are also receivers of such effects from core economies. The structure of transmission channels indicates the existence of clusters of countries, in the sense that countries are more vulnerable and exposed to spillovers from their own group (core or periphery). In the course of the Eurozone crisis, we can also identify the flight to quality and flight to liquidity phenomena taking place, as the clustering effect is more prominent after the outbreak of the Euro Area crisis. The asymmetric nature of the results is also verified by a battery of alternative modelling specifications and robustness checks.

The structure of this paper is as follows. First, a section where we discuss some relevant papers examining the Eurozone volatility spillovers or contagion issues is provided. Thereafter, a description of our financial stress indices and their components, along with the aggregation method, is presented. Moreover, the GARCH-BEKK modeling approach is analyzed. Section 4 is where the estimations outcome is discussed, for the market, country and regional level. Part 5 provides further evidence and robustness tests for our main findings. The last section concludes and provides some discussion on the potential policy recommendations stemming from this work.

2. Eurozone Crisis and Modeling of Spillover Effects

The study of contagion and spillover effects among markets and countries is a topical research area in recent years, given the current multi-faceted crisis in Eurozone. Recently, the interest is focused on the potential deleterious effects of the global financial crisis. For the case of Europe, most researchers have focused on the issues of sovereign risk transmission. For instance, Bruttin and Saure (2015) employ SVAR analysis of sovereign CDS for eleven Eurozone countries. They find that exposure to Greek sovereign debt and Greek banks assets are sources of intensive transmission of risk. On the other hand, Kohonen (2014) uses ten-year government bond yield differentials for the peripheral Euro Area countries, again into a SVAR framework. Here, the author suggests that there was a default risk transmission from the Greek bonds, but only at the beginning of the crisis. The also suggest that this was not the only risk channel within the countries under scrutiny. More recently, VAR modeling in the spirit of the work developed by Diebold and Yilmaz (2012, 2014) has been used to examine the financial spillover effects between different groups of markets or economies. For instance, Apostolakis and Papadopoulos (2014, 2015) study the effects between the G7 banking, securities and foreign exchange markets, identifying some interrelations within them. Antonakakis and Vergos (2013) examine sovereign risk transmission for some Eurozone countries, showing that most of them are mostly responsive to their own government bond yield variations. Using a range of econometric techniques, Caporin *et al.* (2013) indicate that contagion effects were not that intensive, even though peripheral countries went through serious difficulties because of their heightening fiscal burden. On the other hand, Metiu (2012) identifies strong contagion effects for the period 2008-2012, using the canonical contagion model. Overall, literature shows a lack of consensus on the actual distress transmission effects among the Eurozone countries.

Another popular type of models to identify spillover effects is the multivariate volatility models. Audige (2013) employs a smooth transition conditional correlation (STCC-GARCH) model, with long term governmental bond yields, in order to check for spillover effects from the Greek crisis. The author identifies contagion effects from Greece to Ireland and Portugal in 2010, while such effects weaken after that period. In a similar vein, Grammatikos and Vermeulen (2012) examine the transmission of financial and sovereign debt shocks through the Eurozone stock markets, for the period 2007–2010. In order to do this, GARCH modeling of stock returns are employed, with the US markets effects taken into consideration. They split EMU into three groups of countries, namely the North, South and Small economies. Their findings show strong crisis transmission from US non-financials to European non-financials, with the financial entities from both sides of the world showing not significant interconnections. Moreover, Greek CDS spreads seem to play a much more important role in the period after the Lehman collapse, but not for the non-financial firms. Another interesting paper is by Dajcman (2012), who uses a flight-to-quality indicator to examine the co-movements of stock returns with bond yields for Germany and the most debt ridden Euro Area economies. The results, using a DCC modeling approach, are concurrent with Kohonen (2014) and Caporin et al. (2013). Also, the flight-to-quality indicator has higher value prior to 2010, indicating increasing uncertainty for investors, who turned towards the safe haven of German Bunds.

3. Data and Methodology

3.1 Financial Stress Index Construction

The analysis of the financial stress is accomplished by creating aggregated financial stress indexes (FSIs). These indexes provide information on the financial markets conditions, based on a range of stand-alone indicators representing important market features. Our focus is on Eurozone crisis and, thus, our sample consists of eleven Eurozone economies: Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal and Spain. Our interest is in the calculation of four market-level indicators, along with a systemic risk index for each individual country. The four markets for which financial instability indexes are provided are the banking sector, money, equity and the bond market. The reason is that these are the markets that exhibited the biggest uncertainty and distress level during the Eurozone crisis. Banks were highly distressed and a number of defaults or near defaults take place in the

European banking system the last few years. Money market, as it is later shown, predominantly represents the interbank funding and liquidity conditions. It is evident from the recent financial events that these were major issues for European economies. Finally, stock markets are also important, while bond markets have to do with sovereign risk issues, together with sustainable long term funding and investments to the private sector.

The data used to develop our FSIs are retrieved on a weekly frequency. The reasons are twofold: first, we aim to explore the transmission channels existing between different markets and different countries. In this way, the implemented analysis accounts for possible transmission channels on both a country level, through the aggregated country FSIs, and on a specific market of a country, through the aggregated market FSIs. Finally, we aim to investigate the cross-market spillover effects. Secondly, we employ multivariate GARCH modeling and, henceforth, there is a necessity to employ high frequency data. For this reason, the variables chosen are restrained to those that can be collected in such time frequency. Table 1 summarizes the variables included in the financial stress indices of the economies in our sample. The time period covered is from January 2001 until the 20th of September 2013. In total, there are 664 observations covering the pre- and post-crisis period. We do not use daily data in order to avoid potential mismatches in public holidays and trading days (Yiu *et al.*, 2010). In this way, a uniform dataset is created, without any discrepancies in the countries' series used. The choice of variables relies on the relevant financial stress literature, covering a broad range of individual indicators that provide useful information for the markets. On the other hand, the fact that this study aims to examine a range of economies limits somehow the total number of variables that can be uniformly picked for the sample.

[Table 1 here]

Getting into more details, the banking sector index comprises of seven variables, while five variables are used in the case of money and equity markets and four for the case of bond market. Focusing to the banking market, variables representing banks' sensitivity to market conditions, along with their level of profitability and risk level there are included. Dividend yield is negatively related to fundamentals of banking institutions and, thus, excessive dividend yields can be a signal of increasing default risk for them. On the same time, market value is also important, since its size directly affects the stability of the market. Increasing uncertainty can lead to a significant adverse effect to market value, which is also tied to these institutions' book value. Thus, their financial health is at stake. A strong indicator of instability for banks is the turnover by volume. This increases, according to market sentiment and the perceived level of risk and uncertainty by the investors. Profitability is also an important metric here, represented by the P/E ratio. Here, since banks' operational efficiency and profitability is indicated by higher values for the aforementioned ratio, we impose a negative sign to this variable (so, higher P/E ratio coincides with increasing financial stress). Finally, the last three variables here (realized volatility of banks equity index, beta coefficient of the same index and the (negative) stock returns) depict the risk perception and the volatility level of this market. In accordance to the stock market bubble literature, increasing stock prices reflect imbalances building up, while a swift decrease in prices is evidence of a market crash (Grimaldi, 2010).

The aggregate index for the money market sector includes some of the most important liquidity, credit and counterparty risk indicators. TED spread (the difference between the 3-month Euribor and the respective Treasury bill of the same maturity) is one of these measures, reflecting the flight to quality and flight to liquidity phenomena. It is expected to observe increasing values for this spread, in periods of worsening financial conditions. In such times, interbank funding markets seize to operate smoothly, while the risk perception reaches unprecedented levels. In the same line of thought, inverted term spread is incorporated, as indicator of interest rate setting expectations, along with the representation of default risk and increasing information asymmetry in money markets. Moreover, the spreads of the main refinancing rate from the short term governmental bills yield is another indicator of deteriorating liquidity conditions. Negative values in these spreads coincide with higher financial stress and, hence, the need to incorporate them in our aggregate index with a negative sign. Finally, the treasury bill realized volatility depicts the market volatility risk.

The conditions in the equity markets are captured by five variables. The (negatively signed) stock returns is an indication of investors' sentiment and lack of trust to listed firms' fundamentals. In periods of increasing financial stress, higher volatility is expected in the stock markets. Then, market value is included and the dividend yield as well. The rationale is similar to the case of the banking sector, emphasizing the level of default risk, as well as the lack of credibility and funding sources in the market. The P/E ratio is included again in a similar fashion, while the realized volatility of the general equity market index is indicative of the historical risk perception on each equity market.

Turning now to the bond market case, we employ the sovereign bond spread, vis-à-vis German bond yield, which is considered as a safe haven for bond market investors. This is a strong and popular indicator of the perceived sovereign risk of the countries under investigation. Then, the realized volatility of the long term governmental bond yields is used, as another variable illustrating the markets' risk aversion. Moreover, the corporate bond spread (defined as the yield difference between corporate bonds and government bonds of the same maturity) is a factor showing the default risk and the financial obstacles that firms face. Government bond duration is also included. It is expected that decreasing credit ratings and increasing concerns for the countries solvency, will lead to lower duration for their bonds (Lee *et al.*, 2011). Hence, decreasing duration represents increasing financial stress and uncertainty.

The FSIs are computed, following the variance-equal aggregation method. Based on this approach, an equal weight is attributed to all variables in each of the markets. In this way, the market - level indices are computed (equation 1), while the same approach is followed for the country – wide (equation 2) and regional ones (equation 3). Before the aggregation, each one of the single indicator is standardized. That is, its mean value is subtracted by each observation and, then, divided by its standard deviation, avoiding mis-measurement issues. All series are expressed as deviations from their long run mean value. Based on the above, the original discrepancies in variables units disappear. The variance – equal approach is frequently used in the relevant literature (Cardarelli *et al.*, 2011). The reason for this is the simplicity of the relevant calculations the effective representation of the prevailing financial conditions in the markets. The indexes are presented in figure 1, where their fluctuations through time follow the major financial events.

$$FSI_t^{market\ i} = \sum_{j=1}^{l} \frac{1}{l} \cdot x_{jt}^{i\ standardized} \qquad (1)$$

$$FSI_t^{country\ i} = 0.25 \cdot \left\{ FSI_t^{bank} + FSI_t^{money} + FSI_t^{equity} + FSI_t^{bond} \right\} \quad (2)$$

$$FSI_t^{region\ i} = \sum_{j=1}^{n} \frac{1}{n} \cdot FSI_t^{country^i\ j} \quad (3)$$

[Figure 1 here]

It should be noted here that an additional reason for constructing this set of stress indices is the lack of an appropriately developed dataset for the countries and financial markets that we examine. Individual researchers or institutions, such as the IMF or ECB, have sporadically being involved in the study and development of similar measures. Still, the composition, types of market characteristics and the detailed coverage of the Euro Area markets diversifies this work from the rest[1].

3.2 Volatility Transmission Models

Ambition of this paper is the empirical investigation of potential interdependencies and spill-over effects of financial distress in the Euro Area, on a market, country and regional level. As a concept, it is closer to the "meteor showers" hypothesis of Engle et al. (1990), than the idea of contagion as developed by other economists (for instance, Forbes and Rigobon, 2002). The multivariate GARCH family of models has been extensively applied in the past for the examination of spill-over effects between financial data providing a reliable mechanism for examining the significance, the magnitude and the direction of potential interrelationships of the second moment of time series data.

The mean equation of the FSIs (*kxT: k series, T weeks*) under consideration is modeled through an unstructured VAR(p^*) equilibrium specification:

$$\Delta FSI_t = c_0 + \sum_{i=1}^{p^*} L_i \cdot \Delta FSI_{t-i} + \varepsilon_t \quad (4)$$

[1] In section 5, we experiment with the CISS index, which is a sovereign risk index created by ECB, as a robustness check.

where, ΔFSI is the vector of the first log differences of k response times series variables at time t, c_0 is a constant vector of offsets with k elements, L_i are kxk matrices for each lag ($i=1\ldots,p^*$) and ε_t is a vector of serially uncorrelated innovations.

For the purposes of our analysis we apply the full BEKK model of Engle and Kroner (1995), the parameterization of which ensures a positively definite variance covariance matrix, mitigating the estimation process of the parameter set. This is an alternative to the multivariate VEC model, proposed by Bollerslev *et al.* (1988), ensuring the positive definiteness of the conditional variance matrix H_t (Bauwens *et al.*, 2006). The residuals of the mean equation are assumed to follow a T-student distribution with zero mean and a time-varying variance conditional on the past informational set Ω_{t-1}:

$$\varepsilon_t \left| \Omega_{t-1} \sim T - Student(0, H_t) \right. \qquad (5)$$

The k-dimension full BEKK GARCH(p,q) conditional volatility specification has the following form:

$$H_t = C_0^{'} C_0 + \sum_{j=1}^{p} A_j^{'} \varepsilon_{t-j} \varepsilon_{t-j}^{'} A_j + \sum_{j=1}^{q} B_j^{'} H_{t-j} B_j \qquad (6)$$

where, C_0 is the constants matrix, A and B are parameter matrices, ε_{t-1} is the innovation matrix (lagged disturbance vector) and H_{t-1} is the lagged variance covariance matrix. The constants matrix is restricted to be a lower triangular matrix, while the A and B parameter matrices are not restricted. As emphasized by Bollerslev (2010), this quadratic parameterization guarantees that the covariance matrix is positive definite, while the number of parameters to be estimated is more compact, compared with its initial version proposed by Bollerslev *et al.*(1988)[2].

The relationship between the k FSIs' volatilities is captured by the elements of A and B matrices. The elements of A matrix's coefficients depict the effects of lagged innovations to the conditional variance covariance matrix. As it is commonly said in the relevant literature, matrix A provides information on "news effect", while matrix B

[2] In this way, model's convergence is more easily achieved. See, among others, Bauwens *et al.* (2006) and Brooks (2008).

captures the "volatility spillover" effect (Kim *et al.*, 2012). Both effects can provide important insights for the potential volatility transmission channels of financial distress within the Euro Area.

For encountering more efficiently the leptokurtic distributional form of the FSI series we use the T-Student distributional (ν degrees of freedom) form in the MLE estimation process:

$$
\begin{aligned}
likelihood &= T \cdot \left\{ log\left(\Gamma\left(\frac{v+1}{2} \right) \right) - log\left(\Gamma\left(\frac{v}{2} \right) \right) \right\} - \\
&- \frac{1}{2} \cdot \left\{ \sum_{t=1}^{T} log\left(h_t \cdot \pi \cdot (v-2) \right) - (v+1) \cdot \sum_{t=1}^{T} log\left(1 + \frac{\varepsilon_t^2 / h_t}{v-2} \right) \right\}
\end{aligned} \tag{7}
$$

As the required number of parameters for the VAR(p^*) - Full BEKK Multivariate GARCH(p,q) model, of a k-dimensional dataset (kxT), is equal to $k+k^2p^*+(k/2)(k+1)+pk^2+qk^2$ plus the degrees of freedom of the T-student distribution, we choose the parsimonious representation of one lag for both the VAR and GARCH specifications resulting to $(3k+7k^2)/2$ parameters for estimation.

3.2.1 Market Level

Our first research aim is the investigation of the financial distress spillover effects on a market level across countries, i.e. the Banking sector, the Money market, the Equity market and the Bond market. Considering the high dimensionality of the parameter set and the ensuing computational procedures, we examine the transmission channels using all possible pairwise combinations with the estimation of bivariate full BEEK models instead of running a 11-dimensional multivariate GARCH model.

Consequently, with 11 countries in our dataset, 55 different pairwise samples are under investigation for each of the four markets, having excluded the case of examining own effects. Thus, the volatility specification of the 55 VAR(1) - Full BEKK - GARCH(1,1) models of each market would be represented by the following equations:

$$H_t = C_0^{'} C_0 + \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}^{'} \begin{pmatrix} \varepsilon_{1,t-1}^2 & \varepsilon_{1,t-1}\varepsilon_{2,t-1} \\ \varepsilon_{2,t-1}\varepsilon_{1,t-1} & \varepsilon_{2,t-1}^2 \end{pmatrix} \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} + \begin{pmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{pmatrix}^{'} H_{t-1} \begin{pmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{pmatrix} \quad (8)$$

$$\begin{aligned} h_{11,t} &= c_{11} + \alpha_{11}^2 \varepsilon_{1,t-1}^2 + \alpha_{21}^2 \varepsilon_{2,t-1}^2 + 2\alpha_{11}\alpha_{21}\varepsilon_{1,t-1}\varepsilon_{2,t-1} \\ &\quad + \beta_{11}^2 h_{11,t-1} + \beta_{21}^2 h_{22,t-1} + 2\beta_{11}\beta_{22} h_{12,t-1} \\ h_{22,t} &= c_{22} + \alpha_{12}^2 \varepsilon_{1,t-1}^2 + \alpha_{22}^2 \varepsilon_{2,t-1}^2 + 2\alpha_{12}\alpha_{22}\varepsilon_{1,t-1}\varepsilon_{2,t-1} \\ &\quad + \beta_{12}^2 h_{11,t-1} + \beta_{22}^2 h_{22,t-1} + 2\beta_{11}\beta_{22} h_{21,t-1} \end{aligned} \quad (9)$$

In this framework the transmission channels between country's market FSIs are examined through the 55 estimations of coefficients α_{21}, β_{21} and a_{12}, b_{12}. The former two coefficients represent the volatility spillover from the second country's market FSI to that of the first one while the latter two represent the opposite direction effect. It should be noted that we investigate the transmission channels based on the squared innovations (ε_{t-1}^2) and variances (h_{t-1}) of equation (9) and this implies that the coefficients' sign would not affect the direction, the significance and the economic justification. However, the transmission channels are further examined, for the regional case, by the adoption of the "News Impact Surface" approach as a robustness check.

3.2.2 National Level

At a national level (equation 2) we adopt a similar approach estimating 55 VAR(1) - Full BEKK models. Coefficients α_{21}, β_{21} and a_{12}, b_{12} reflect the potential distress transmission channels between EU countries for all possible pairwise combinations between the 11 examined countries. Thus the 55 estimated α_{21} and β_{21} coefficients examine the effect of the second series on the first one for all possible 55 pairwise coefficients while the 55 estimated a_{12} and b_{12} coefficients examine the opposite direction effect.

3.2.3 Regional Analysis

The regional analysis refers to the distress index of equation (3); that is the core and periphery countries' FSI per se and by market. Thus, our sample consists of five series for the core region and five for the periphery one, i.e. total, bank, money, equity and bond. The 10 regional series result to 45 potential pairwise combinations having excluded the effect of a series to itself (main diagonal). Thus, in this part of the analysis we examine the potential transmission channels between and/or within regions, i.e. core banking with periphery banking, core banking with core bond, core banking with periphery equity etc. Moreover, the regional transmission channels are further examined by the adoption of the "News Impact Surface" approach as a robustness check. In this aspect, we aim to examine whether a past shock in a region's financial distress index (FSI) affects the forecasted volatility of another region's FSI. This is implemented within a multivariate Full-BEKK-GARCH framework allowing for asymmetric dynamic covariance responses due to past and current shocks in one of the determinant series.

4. Discussion of Results

4.1 FSI Descriptive Statistics

Table 2 provides several descriptive statistics for the FSIs across markets (Panel A-D) and countries (Panel E). These statistics refer to the first four moments of the series, their normality, autocorrelation, heteroscedasticity and stationarity. According to the standard deviation of the series, the Banking and Equity FSIs embed the higher risk. Most of the series exhibit a positive skewness, while their distributions are leptokurtic. Further evidence of non-normal distributional forms for the FSI series is provided by the high J-B statistic. Moreover, the Ljung-Box statistics (Q, Q^2) are in favour of serially correlated series, exhibiting higher order correlations and non-linear dependencies. The only exception is the Dutch bond market FSI, while the Ljung-Box Q^2 test fails to provide relevant evidence for the cases of Greece, Portugal and Spain (in the case of the bond markets). The same holds for the money market FSIs of Greece and Finland. Nevertheless, the aforementioned are limited exceptions to the general conclusion of the autocorrelation existence. The Engle's ARCH test coincides with the previous findings, underlying the necessity of employing a time varying volatility model for the implementation of our empirical work that aims to study the spillover effects of financial stress among the Euro Area. Finally, the ADF test for the first log differences of FSIs could not accept the existence of a unit root.

[Table 2 here]

4.2 Transmission Channels across Markets

We commence the analysis of the econometric results from the banking sector. Tables 3.A and 3.B present the outcome of the estimation in this case. Banking market, along with the money market are the most interconnected sectors, in the sense that a range of significant interactions can be identified, both for news surprises as well as for spillover effects coefficients. The prominent role of the peripheral economies is evident. Ireland, together with the Italian and Portuguese banking sectors are the major volatility risk recipients and transmitters. Similar vulnerability is indicated for the case of Austria, even though, on a more limited size compared to the aforementioned cases. French banking system contributes to the heightening stress transmission to the rest. It is interesting to underline that peripheral banking systems are more exposed to effects from banks of the same group of countries, as it is the case for the major Euro Area economies. This is an indication of a fragmentation, in terms of potential vulnerability transmission effects. It can also be an indication of divergent policies and response reactions to the crisis outbreak from banks and governments in the common currency area. The Greek case does not seem to constitute a serious threat in this particular market.

[Table 3.A – 3.B here]

Money market volatility spillovers are depicted in tables 4.A and 4.B. The main recipients of the relevant effects are, mainly, Greece, Ireland and Finland (for the case of "news effects" coefficients), with France, Ireland and Portugal (apart from Italy) to take the lead in the volatility transmission risks. Nevertheless, the strong statistical results are accompanied by small parameter values. Greek case is rather distinctive for the "news surprises" effect, something reasonable given that Eurozone crisis has escalated due to the economic event taken place in this particular case. The decreasing significance of Greece as volatility transmitter, as indicated in the second panel of Table 4, shows that more vulnerability and uncertainty stemmed from other markets. Given the nature of money market stress indicators, representing funding, liquidity and interbank markets considerations, also contributes to understand the substantial number of statistically significant α_{ij} coefficients in this market case. Again, countries clustering can be observed, as weaker economies are more exposed to spillover effects from their peers, as it is the case for core countries' money markets.

[Table 4.A – 4.B here]

A very different situation appears in the case of equity markets' spillovers. In essence, the identified links are limited. In both the cases of cross-innovations and variance volatility transmission parameters, few statistically significant results exist. In the case of information shocks, there is no a market with prominent role. There are effects from the Greek stock market, as well as Spain and Belgium. In terms of the persistence parameters (Table 5.B), some interactions can be identified, with Belgium being the most eminent towards its core peer markets. In contrast to the previous cases, a clear pattern in core-periphery disaggregated effects is not that evident here. Overall, this lack of significant effects in the equity markets could, probably be a sign of the, rather limited, financial risk propagation taken place through that market in the Eurozone case.

[Table 5.A – 5.B here]

The last market examined is the bond market, incorporating effects and risk transmission from, both, sovereign and corporate risks. It is fair to say that there are some effects identified in this market, but not significantly more and different compared to the previous cases. In case of news surprises, shocks can found from, both, major economies (such as Germany and Belgium or Austria), as well as from smaller economies, like Greece and Spain. Nevertheless, the most significant results, both for the propagation and receival of spillover effects, come from Germany (Table 6.A). For the case of spillover effects, Greece is a major receiver, with several other economies contributing as risk transmitters to the rest of the markets examined. On average, the news effect is much more prominent in this market, compared to the results shown for the beta coefficients. A clear pattern cannot be established, in terms of the direction of the effects. The regional analysis that follows can probably shed some more light in this market case. Some interesting insights are also provided by the sub-sample analysis presented in section 5.4.

[Table 6.A – 6.B here]

4.3 Transmission Channels across Countries

Tables 7 depicts the country-wide financial stress spillovers. According to these findings, the most heavily affected countries are those with the strongest spillovers to the rest of the Euro Area countries. Especially Ireland, Belgium and France present significant news and volatility spillover effects to the rest of the economies. The previously mentioned countries (except Greece) exhibit spillover effects to the rest of the sample economies. On the same time, Ireland and France are also the main recipients of financial stress spillovers. It is interesting to notice that Germany is highly immune to financial stress transmission in this respect. Again, a clear pattern cannot be established here, in relation to potential transmission channels. This can be due to the fact that the effects here are, essentially, influenced by the nature of the used dataset (country indexes are the average values of the market specific indicators for the set of markets used for each economy). In total, debt ridden countries do not seem to lead the effects here, while they are also the major recipients of transmission effects from, both, peripheral as well as the major Euro Area economies.

[Table 7.A – 7.B here]

4.4 Transmission Channels across Regions

In order to further examine the interconnections and spillover effects between the Euro Area core and peripheral economies, we proceed to a core-periphery empirical investigation. As before, our estimation strategy is the same. We employ GARCH-BEKK modelling framework, using financial stress indices in our dataset. This time, the systemic risk indexes are regional ones, representing the Euro core and periphery.

In order to construct them, we use the average of the indices used for the countries before: the core countries and the GIIPS (Greece, Ireland, Italy, Portugal and Spain) for the peripheral indicators. In this section, we present the results for the whole period, while in the robustness checks we also proceed to a pre- and post-crisis examination.

According to our results, the prominent role of banking sector and bond markets in the Euro Area is verified. These two are the main markets where substantial risk transmission channels are identified. Additionally, the intensity of information flow ("news effect", table 8.A) is evident to both directions and with marginally greater impact from the periphery to core countries. In fact, this is more pronounced for the core countries' banking sector, which used to be one of the major creditors for peripheral European countries. However, these findings need to be further investigated throughout the crisis period (sub-sample analysis), as this will indicate the potential impact of the Eurozone crisis outbreak to these spillover channels.

Similarly, the banking and bond markets are the most susceptible sectors to financial spillover effects (Table 8.B). The core banks have major effects on all peripheral markets, while the same holds for the peripheral bond stress, transmitting to all core (but not to the equity) financial markets. Moreover, periphery's bond sector is exposed to spillover effects from core markets and economies. On top of the above, both regions are interlinked and exposed to their own sources of distress. These are interesting findings, indicating the complex nature of the interactions between Euro Area markets, indicating the threats posed by both mature and less developed markets in this monetary union.

[Table 8.A – 8.B here]

5. Further Evidence and Robustness Checks

In order to substantiate our previous findings, we extend our analysis in many different ways. First, we use alternative FSIs, by adopting a PCA-based aggregation approach and by using the ECB CISS index for sovereign risk within our modelling framework. Second, we consider the cross-market transmission channels; that is the examination of all possible combinations of countries and markets at the same time (*1484 pairwise cases*). Third, we extend the analysis by recruiting many alternative volatility specifications. This is executed by estimating a 11-dimensional model instead of the pairwise bivariate models, the analysis of potential asymmetries at the volatility specifications and, finally, by testing the optimal lag terms (p, q) for the GARCH models in the aggregated regional analysis. Fourth, our robustness checks accounts for the effect of the financial crisis on the regional distress transmission channels. Finally, we adopt the News Impact Surface approach for a more insightful examination of the core-periphery impact channels. Given the large number of figures and tables produced out of these additional empirical exercises, the detailed results are available as an online appendix.

5.1 Alternative Financial Stress Indices

5.1.1 A PCA-based approach for FSI

In order to test the reliability of our findings, we employ an alternative set of financial stress indices. The difference lies on the aggregation method used to construct the FSIs. A principal components (PCA) approach is used, as opposed to the variance-equal method in the baseline framework. In brief, PCA is a statistical method, transforming a set of correlated variables into a new linear combination of them. It relies on the covariance matrix of these indicators and their eigenvalues for the decomposition of the principal components. In our case, the first principal component and its ensuing factor loadings are used as weights for the final aggregation of the stand-alone indicators. After constructing the new stress indices, we re-estimate our models for, both, country and market level analysis. Overall, the results are similar to the one produced from the baseline model.

5.1.2 European Central Bank's CISS indices

ECB has developed a range of systemic risk indicators, similar in nature to our own FSI dataset. The Composite Indicators of Systemic Risk (CISS) aim to capture systemic risk exposures, as they become evident to a number of markets in Euro Area. In their indexes, Hollo *et al.* (2012) incorporate metrics representing the prevailing market conditions in financial intermediaries, money, securities and foreign exchange markets. Since this particular dataset does not cover the whole spectrum of markets and economies we focus, we decide to examine the potential sovereign risk transmission channels, as documented by the employment of the CISS sovereign risk sub-indices for some core and peripheral European countries. The indices, country-specific as well as the regional ones constructed by use, are shown in figure 2. The indices clearly exhibit a pattern in accordance to the development of the economic events creating havoc in the sovereign debt conditions of, both, core and peripheral European economies.

[Figure 2 here]

We conduct an empirical investigation, using all possible pairwise combinations for examining the sovereign risk transmission channels in Eurozone's core and periphery. A bivariate VAR(1) – Full BEKK GARCH(1,1) model is estimated and the relevant spillover effects are shown in Table 9 of the online appendix. Panel A refers to the news surprises effect while Panel B to the spillover effects per se. The basic outcome of this exercise is the lack of concrete evidence in favour of spillover effects between the countries and peripheries of the sample. Only weak evidence towards regional transmission channels are identified, even though not in the degree indicated to the baseline modelling framework. This weak regional clustering effect is evident when the spillover effects are accounted for.

5.2 Cross-Market Analysis

The second robustness check refers to the consideration of all possible transmission channels of financial distress "between" and "within" the four markets (banks, money, equity and bonds) of the 11 Eurozone countries. Thus, our analysis refers to the country-specific and market FSIs, consisting of the full 55 series of our dataset. All possible pairwise combinations count to 1430, excluding each market's own effect.

The estimated coefficients of all the bivariate Full BEKK-GARCH(1,1) models are used for calculating their joint distributions with respect to their significance. The joint distribution is classified as, either, "causer" or "receiver" of financial stress, depending on the direction of the implied transmission channel between each combination of series. For each of the 55 series, we estimated the percentage of the significant "causer" effect of volatility spillovers to the rest of the series. Similarly, we also obtain the percentage of the significant “receiver” effect of volatility spillovers from the rest of the sample. Bar charts are employed for the provision of more lucid and insightful results[3].

Figure 3 of the appendix represents the causal relationship between all FSIs, either the news impact effect (Panel A) or the spillover effect (Panel B). On the country level, Ireland and Spain seem to have prominent role on the “news” effects. On the other hand, several peripheral economies (Greece, Spain, Ireland), along with France, seem to contribute substantially to financial distress volatility. Moreover, the periphery is more susceptible to such effects. Once again, the importance of banking and bond markets is underlined, with the role of most peripheral economies’ banking systems to be imminent. Again, the major economies are also among the major bond risk transmitters. In the case of equity market, the results are again poor, while the money market case is similar with the previous section analysis.

Overall, the market-level analysis provides some useful insights to the prevailing conditions to Euro Area economies and markets. We find evidence of strong spillover effects among most of the economies under scrutiny. Moreover, the most volatile and vulnerable to risk transmission are the bond and bank markets. A notable exception is the equity markets analysis, where no convincing evidence for volatility spillover is detected. Regarding the main risk spillover propagators, results vary but, again, there is no clear cut evidence whatsoever against a specific country or group of countries as the major financial stress contributors.

5.3 Alternative volatility specifications

As the main body of the analysis is based on bivariate volatility models, our estimations might suffer from an omitted variable bias, since there are third countries or markets that transmit or receive volatility from each examined pair in the estimated bivariate models. For this reason, we employ a multivariate approach for the full set of country level FSIs under consideration. In order to accomplish this task, a 11-dimensional VAR(1) - Full BEKK GARCH(1,1) model is estimated, in accordance to the baseline

[3] The estimated parameters tables are available upon request.

model's characteristics. The resulting estimation consists of 308 estimated coefficients for, both, "news" and persistence effects.

The results (Table 10 in the appendix) do not differ from the previous findings. There is hardly any statistically significant alpha, while only a few significant spillover effects are identified in the second panel of this table. In fact, most of these effects are own effects, as it is the case for Austria and Netherlands. Moreover, there are some bidirectional effects between countries from the same group, such as Belgium and Finland (core). France and Portugal also seem to transmit financial distress between each other. Overall, these findings should be assessed with caution, as they are computationally sensitive[4].

Further robustness checks are provided for potential asymmetries within the volatility specifications (leverage effect), in the case of regional stress transmission analysis. In order to do so, a range of alternative GARCH models is employed, namely the EGARCH, the GJR and the APARCH models. All these models are extensions to the GARCH model which is our baseline model in this paper. Again, on the basis of the pairwise bivariate framework, we consider the transmission channels between the regional FSIs (i.e. core and periphery FSIs). The asymmetric volatility models are applied using a non-linear two-stage estimation process that involves the orthogonalisation of our pairwise data within a PCA analysis. In the EGARCH model specification (Nelson, 1991), our interest is focused on the θ_1 and θ_2 coefficients with θ_2 representing the leverage effect (when $\theta_2 < 0$ the leverage effect is taken place).

$$ln\left(h_t\right) = a_0 + \theta_1 \cdot \left(\left| \frac{\varepsilon_{t-1}}{\sqrt{h_{t-1}}} \right| - E\left| \frac{\varepsilon_{t-1}}{\sqrt{h_{t-1}}} \right| \right) + \theta_2 \cdot \frac{\varepsilon_{t-1}}{\sqrt{h_{t-1}}} + \beta \cdot ln\left(h_{t-1}\right) \qquad (10)$$

Another popular way to model the asymmetry of positive and negative innovations is the use of indicator functions according to the GJR-GARCH(p,q) model (Glosten *et al.* 1993):

$$h_t = a_0 + \sum_{i=1}^{q}\left(a_i \cdot \varepsilon_{t-i}^2\right) + \sum_{i=1}^{q}\left(\gamma_i \cdot d\left(\varepsilon_{t-i} < 0\right) \cdot \varepsilon_{t-i}^2\right) + \sum_{j=1}^{p}\left(\beta_j \cdot h_{t-j}\right) \qquad (11)$$

[4] In fact, our effort to estimate the same model for the four types of markets examined here brought no success. The only model that worked was this one.

Here, γ_i, i=1..q, are parameters for estimation while d(.) denotes the indicator function (i.e. d(ε_{t-i} < 0) = 1 if ε_{t-i} < 0, and d(ε_{t-i} < 0) = 0 otherwise). The GJR model allows for good news, (ε_{t-i} > 0), and bad news, (ε_{t-i} < 0), to have different effects on the conditional variance. Therefore, in the case of the GJR(0,1) model, good news has an impact of α_1, while bad news has an impact of $\alpha_1+\gamma_1$, meaning that for negative γ_1 the "leverage effect" exists.

According to Ding *et al.* (1993), we also employ the Asymmetric Power ARCH, or APARCH(p,q) model, which includes seven ARCH models as special cases (ARCH, GARCH, A-GARCH, GJR, T-ARCH, N-ARCH and log-ARCH), with the following conditional variance:

$$h_t^{\frac{\delta}{2}} = a_0 + \sum_{i=1}^{q} a_i \cdot \left(\left|\varepsilon_{t-1}\right| - \gamma_{1,i} \cdot \varepsilon_{t-i}\right)^{\delta} + \sum_{j=1}^{p} \beta_j \cdot h_{t-j}^{\frac{\delta}{2}} \qquad (12)$$

This model imposes a Box-Cox power transformation of the conditional standard deviation process and the asymmetric absolute innovations while the leverage effect is captured by the parameter γ1.

The results of this analysis are presented on Table 11 of the Appendix. It is obvious that the leverage effect exists in most cases while the model fit of asymmetric models is marginally better than that of our benchmark GARCH model. However, it reflects the necessary transmission channels adequately (model diagnostics) and, thus, it is preferred for parsimonious reasons.

Finally, we conduct an analysis for the optimal lag structure of the GARCH(p,q) bivariate specification. It is a necessary step, in order to verify the validity and reliability of our chosen specification in the baseline model. Once more, the analysis is performed on the core-periphery case. The evidence (Table 12) is in favour of the GARCH(1,1) model, compared to a higher lagged specification.

5.4 Financial Crisis and its long and short term dynamics

A sub-sample empirical investigation is conducted, in order to identify whether the Eurozone crisis outbreak led to a shifting behaviour in the structure of spillover effects between the Euro Area markets. The estimation process is the same as in the baseline approach, with May 2010 being the cut-off point for the pre- and post-crisis period analysis. The break point coincides with the time Greece sought for financial assistance from its Eurozone partners.

As it can be seen from the Table 13, there is a clear distinction on the interconnections between core and peripheral economies, before and after the crisis outbreak. In the first period, there are significant "news surprises" effects between these two groups of countries, with strong bidirectional links. As it is also evident from Table 13.D, the persistence of these effects is important, especially for the core-to-periphery direction. Interestingly, the situation is rather different in the second half of the examined period (post-crisis time). The number of statistically significant coefficients, for both α_{ij}'s and β_{ij}'s, is significantly lower, while a clustering effect is pronounced. Core economies and markets are susceptible to stress transmission effects from core countries and the same holds for the periphery case. It is a clear indication of market decoupling taking place, while market participants flee from the more vulnerable economies and adjust their portfolio positions towards safer investments (flight to safety and flight to quality phenomena).

Beyond the sub-sample analysis, our aim is to provide some insights to the time varying conditional correlation behaviour of the two regions' markets discussed above. In order to do so, we employ the well-known DCC model, as developed by Engle and Sheppard (2001) and Engle (2002). This MGARCH approach is based on a two-step procedure, where standardized residuals, produced from univariate GARCH models in the first step, are subsequently incorporated to the estimation of the conditional correlation estimator in the second stage. The graphical exposition of the dynamic conditional correlation for the regions and markets of interest is provided in Figure 4 of the appendix. Overall, the total conditional correlation is mild and relatively stable in size, throughout the period under investigation. Also, with the introduction of euro as the common currency for these groups of countries, we can see a significant increase in the conditional correlation for these markets, especially for the money market case. This is logical, given the nature of the money market indicators, which incorporate liquidity, funding and interbank market indicators. All these metrics are expected to be strongly interrelated for countries sharing the same monetary policy. Moreover, the banking sector exhibits an increasing trend in its conditional correlation, an outcome related again with the common currency effect. It is noteworthy the opposite reaction, in terms of the degree of correlation that can be identified for the money market and the bond market of the two regions right before and during the peak of Eurozone crisis. Money market conditional correlation plummets, remaining at fairly low level and with strong swings between positive and negative values, until the end of the sample. On the other hand, bond markets turn from negative into positive correlation, remaining like this from this point onwards. Once more, both markets clearly indicate their importance and their degree of interconnectedness for the two regions under investigation.

5.5 Volatility Surfaces

The usage of impact news surfaces is the last empirical exercise. The purpose of this test is to examine whether and by how much the conditional variance of the ensuing GARCH model is affected by its own lagged innovations, as well as the other market innovations (Kroner and Ng, 1998; Savva, 2009). Additionally, potential asymmetric effects can also be captured, in relation to the potential shocks on the stress transmission volatility of the markets (Martens and Poon, 2001). Once more, the news impact surface for the regional FSIs are constructed and presented in figures 5A and 5B of the appendix for the core and peripheral regions respectively. Undoubtedly, there are bidirectional transmission channels that explain the way periphery and core countries' distress is distributed to each other. A more careful consideration of these figures (and under alternative parametrizations) reveals that there is a tendency for these channels to have a prominent effect from the core countries to the peripheral ones. This is because peripheral positive distress shocks are transmitted to the core countries when their magnitude is big enough. It is noteworthy that some asymmetric behavior can be identified, especially for the case of the core countries conditional variance, as well as for the periphery case (but much milder in this case). More specifically, the conditional variance of core countries' FSI is increasing smoothly (Figure 5.A) while current and past core-periphery distress shocks are taking place. On the other hand, the conditional variance of periphery distress (Figure 5.B) is affected rapidly during turbulent financial conditions within core economies.

6. Concluding Remarks

Our aspiration for this paper is the Eurozone crisis that, when was fully fledged and on its peak, rendered the European economy under severe strains. A prolonged recessionary period is its real economy reflection. Both governments and market participants were alerted for the eventuality of crisis transmission from the most vulnerable EMU economies to the rest. Thus, there is a growing research interest, focusing on the examination of contagion and channels of interconnectedness between the major protagonists of the Euro crisis.

This paper aims to extend the relevant literature in several ways. First of all, our interest is to study the crisis to its fully diverse nature. That is, we do not limit our study only to the sovereign risk or the banking instability issues, as most of the research has done until now. Instead, we try to encapsulate the necessary information into a number of metrics that are able to provide clear cut insights to the crisis and its constituents. In order to do it, we employ a set of financial stress indices. These are aggregate indicators, representing the level of systemic risk in each one of the markets we analyze. These are, the banking sector, money market, equity and bond markets, while we also provide an index for each national economy. The dataset contents and development is rather unique, towards other similar aggregate measures existing in the literature or developed by policy making institutions. The individual indicators used cover several aspects and sources of financial risk, while the degree of disaggregation in countries and markets renders our dataset distinctive. The next important extension is the adoption of a multivariate GARCH framework for the empirical investigation of potential spillover effects among the aforementioned markets. To the best of our knowledge, it is the first time that such a modeling approach is used in conjunction to such successful systemic risk indicators. It is an innovative combination, given the very nature of the financial stress indexes and the ability of the MGARCH type of models to estimate time-varying co-variances. Another important feature of our research is the simultaneous assessment of potential volatility transmission channels between and within the previously mentioned markets and countries. The Eurozone case is analyzed and discussed in a detailed level and markets' decomposition. Moreover, a core – periphery modelling is provided, together with sub-sample analysis to take into account potential changes to spillover effects due to the Eurozone crisis outbreak. A whole battery of robustness checks and further econometric specifications are employed, in order to provide further credibility and substantiate the baseline results produced by our BEKK modelling framework. Finally, our dataset covers the Eurozone crisis until very recently.

The results shed new light into the Euro Area's volatility transmission literature. There is strong evidence that there exist multiple links between the EMU financial markets. Depending on the sector discussed, the main receivers and transmitters of the spillover effects vary. For instance, it is true that the GIIPS countries significantly contribute to the cross-volatility, especially in the case of the country level analysis and the banking and money markets. On the same time, the core is also an important channel of variance volatility transmission, both within the North European countries, but also towards the peripheral ones. Such a, somewhat surprising, result for part of the profession is in accordance to latest findings (Antonakakis and Vergos, 2013; Kohonen, 2014). Moreover, we find strong bidirectional effects between countries of the same group. Equity market, on its single market analysis, does not provide convincing evidence as a sector where volatility spillovers take place. Also, the case of money market is interesting. Given the representation of the interbank funding conditions, along with the relative volatility measures and the yield curve, this sector manifests itself as one which central bankers should pay special attention to. An important finding, directly relevant to policy making decisions, is the one coming from the sub-sample analysis. The decoupling hypothesis for the Euro Area markets clearly holds and it is manifested with the crisis outbreak. The, initially, highly interconnected European markets exhibit a clear disaggregation when the adverse economic events took place in the peripheral economies, leading to markets interacting and being susceptible to effects from their particular group of countries (either, the core or the peripheral ones). Investors seem to fled from the debt ridden economies, looking for alternative and safe investment positions to safer markets (flight to quality and flight to liquidity phenomena). These findings are confirmed by the robustness checks, using alternative volatility specifications, together with techniques verifying the existence of asymmetries in the market under investigation.

We believe that these facts underline the direction towards which macroprudential policies should aim to. Such policies should be formulated in a way to accommodate the multifaceted nature of modern financial systems, taking into account and monitor potential risks and perils that can source to different markets. Moreover, the clustering effect identified in our econometric investigation should be taken into serious consideration from Eurozone policy makers. Divergent policies should be followed and applied to different regions or countries, according to their special characteristics and vulnerabilities and applied on an ad hoc basis, depending on the prevailing market and macroeconomic conditions. The mix of standardized policies, as those currently applied for monitoring and regulating Euro Area banks, together with tailored made, country level prudential policies, can be the appropriate way forward for ameliorating policy responses to future events of economic instability.

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