UB Riskcenter Working Paper Series

University of Barcelona

Research Group on Risk in Insurance and Finance www.ub.edu/riskcenter

Working paper 2014/03 \\ Number of pages 33

Causality and contagion in EMU sovereign debt markets

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CAUSALITY AND CONTAGION IN EMU SOVEREIGN DEBT MARKETS*

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Revised version
February 2014

Abstract

This paper contributes to the literature by applying the Granger-causality approach and endogenous breakpoint test to offer an operational definition of contagion to examine European Economic and Monetary Union (EMU) countries public debt behaviour. A database of yields on 10-year government bonds issued by 11 EMU countries covering fourteen years of monetary union is used. The main results suggest that the 41 new causality patterns, which appeared for the first time in the crisis period, and the intensification of causality recorded in 70% of the cases, provide clear evidence of contagion in the aftermath of the current euro debt crisis.

Keywords: Sovereign bond yields, Granger-Causality, Contagion, Euro area.

JEL Classification: E44, F36, G15, C52

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1. Introduction

From the introduction of the euro in January 1999 until the collapse of the US financial institution Lehman Brothers in September 2008, sovereign yields of euro area issues moved in a narrow range with only very slight differences across countries (see Figures 1 and 2). Nevertheless, following the Lehman Brothers collapse severe tensions emerged in financial markets worldwide, including the euro zone bond market. In fact, not only did the period of financial turmoil turn into a global financial crisis, but it also began to spread to the real sector, with a rapid, synchronized deterioration in most major economies. This financial crisis put the spotlight on the macroeconomic and fiscal imbalances within European Economic and Monetary Union (EMU) countries which had largely been ignored during the period of stability when markets had seemed to underestimate the possibility that governments might default (see Beirne and Fratzscher, 2013). Furthermore, in some EMU countries, problems in the banking sector spread to sovereign states because of their excessive debt issues made in order to save the financial industry; eventually, the global financial crisis grew into a full-blown sovereign debt crisis. Indeed, since 2010, Greece has been bailed out twice and Ireland, Portugal and Cyprus have also needed bailouts to stay afloat. These events brought to light the fact that the origin of sovereign debt crises in the euro area varies according to the country and reflects the strong interconnection between public and private debt (see Gómez-Puig and Sosvilla-Rivero, 2013) [1].

In this scenario, some of the research to date has focused on the analysis of interactions between the sovereign market and the financial sector [see Mody (2009), Ejsing and Lemke (2009), Gennaioli *et al.* (2013), Broner *et al.* (2011), Bolton and Jeanne (2011) and Andenmatten and Brill (2011)]. Other researchers have discussed transmission and/or contagion between sovereigns in the euro area context [see Kalbaska and Gatkowski

[1] Moro (2013) and Aizenman (2013) offer a literature review on the Eurozone economic and financial crisis.

(2012), Metiu (2012), Caporin *et al.* (2013), Beirne and Fratzscher (2013) and Gorea and Radev (2014) to name a few]. Finally, a strand of research has examined structural breaks and sovereign credit risk in the Eurozone [see, e. g., Basse *et al.* (2012), Gruppe and Lange (2013) and Basse (2013)].

The aim of this paper is to contribute to the last two branches of the literature by examining not only the transmission of sovereign risk, but also the contagion in euro area public debt markets. In the literature there is a considerable amount of ambiguity concerning the precise definition of contagion. There is no theoretical or empirical definition on which researchers agree and, consequently, the debate on exactly how to define contagion is not just academic, but also has important implications for measuring the concept and for evaluating policy responses. Pericoli and Sbracia (2003) note five definitions of contagion used in the literature. Two of them have been predominantly used in empirical studies to analyze it in financial markets and have been adopted in common usage by governments, citizens and policymakers. The first defines contagion depending on the channels of transmission that are used to spread the effects of the crisis, whilst the second defines it depending on whether the transmission mechanisms are stable through time.

Masson (1999) and Kaminsky and Reinhart (2000) apply the first definition, which argues that contagion arises when common shocks and all channels of potential interconnection are either not present or have been controlled for. So, the term contagion will only be applied when a crisis in one country may conceivably trigger a crisis elsewhere for reasons unexplained by macroeconomic fundamentals[2] – perhaps because it leads to shifts in

[2] The theory of "monsoonal effects" suggests that financial crises appear to be contagious because underlying macroeconomic variables are correlated. In this context, several important papers have focused on the macroeconomic causes of crises, for example, Eichengreen *et al.* (1996).

market sentiment, or changes the interpretation given to existing information. According to the second definition, which was proposed in a seminal paper by Forbes and Rigobon (2002), contagion is a significant increase in cross-market linkages after a shock to one country (or group of countries)[3]. Therefore, if two markets show a high degree of co-movement during periods of stability, even if they continue to be highly correlated after a shock to one market, this may not constitute contagion, but only the outcome of the "interdependence" that has always been present in the markets. The empirical analysis of Forbes and Rigobon definition of contagion implies then the presence of a tranquil, pre-crisis period in order to be able to examine whether a change in the intensity of the transmission has occurred after the shock.

In this paper, we will use an operational approach based on the second of these definitions[4] in order to capture the phenomenon of contagion quantitatively. Besides, among the five general strategies[5] that have been used in the literature, our analysis will be related to one of the most conventional methodologies for testing for contagion: the analysis of cross-market correlations. However, we not only investigate changes in cross-market interdependencies via cointegration analysis, but also explore changes in the existence and direction of causality by means of a Granger-causality approach[6] before and after endogenously (data-based) identified crises. Hence, the definition of contagion that we will explore in the remainder of this paper is the following: an abnormal increase in the number

[3] The distinction between contagion which occurs at times of crisis, and interdependence which is a result of normal market interaction, has become the focal point of many contagion studies: see for example Corsetti *et al.* (2005) or Bae *et al.* (2003).

[4] In a very recent paper, Gómez-Puig and Sosvilla-Rivero (2014), analyze contagion using an approach that is based in the first definition of contagion [(Masson, 1999) and Kaminsky and Reinhart (2000) among others]. Concretely, they examine whether the transmission of the recent crisis in euro area sovereign debt markets was due to fundamentals-based or pure contagion. Their results suggest the importance of both variables proxying market sentiment and macrofundamentals in determining contagion and underline the coexistence of "pure contagion" and "fundamentals-based contagion" during the recent European debt crisis.

[5] Probability analysis, cross-market correlations, VAR models, latent factor/GARCH models, and extreme value/co-exceedance/jump approach (see Forbes, 2012).

[6] Forbes and Rigobon (2002) suggest the use of this methodology when they point out that, if the source of the crisis is not well identified and endogeneity may be severe, it may be useful to utilize Granger-causality tests to determine the extent of any feedback from each country in the sample to the initial crisis country.

or in the intensity of causal relationships, compared with that of tranquil periods, triggered after an endogenously detected shock.

Most studies in the literature investigate changes in cross-market correlations (see, e. g., Syllignakis and Kouretas, 2011); very few explore changes in the existence and direction of causality. Exceptions are studies by Edwards (2000) who focuses on Chile, Baig and Goldfajn (2001) who investigate contagion from Russia to Brazil, Gray (2009) who examines spillovers in Central and Eastern European countries, and both Granger *et al.* (2000) and Sander *et al.* (2003) who investigate spillovers during the Asian crisis. However, a small number of studies have applied a Granger-causality approach to the investigation of changes in the existence and direction of transmission in euro area debt markets. Among them, Kalbaska and Gatkowski (2012) analyze the dynamics of the credit default swap (CDS) market of peripheral EMU countries along with three central European countries (France, Germany and the UK) for the period of 2008–2010, and Gómez-Puig and Sosvilla-Rivero (2013) focus on the existence of possible Granger-causal relationships between the evolution of the yield of bonds issued solely by peripheral EMU countries during the period 1999-2010.

Therefore, our study contributes to this literature by applying a Granger-causality approach to 10-year sovereign yields[7] of both peripheral and central EMU countries[8] on an extended time period spanning from the inception of the euro in January 1999, well before the global financial and sovereign debt crises, until December 2012. But, unlike previous studies in the literature (see Sander *et al.*, 2003 o Kalbaska and Gatkowski, 2012), we do not set a

[7] Our analysis focuses on 10-year yields instead of CDS since CDS data are not available for all the countries in the study until late 2008 - only one year before the onset of the euro sovereign debt crisis.

[8] Gómez-Puig and Sosvilla-Rivero (2013) report data of consolidated claims on an immediate borrower basis provided by the Bank for International Settlements by nationality of reporting banks as a proportion of total foreign claims on each country. These data suggest that the problems of peripheral countries can trigger contagion which may affect not only other peripheral countries but also central EMU countries, since some of these banks (mostly German and French banks) are highly exposed to the debt of peripheral countries.

specific breakpoint based on *a priori* knowledge of the potential break date. In our analysis, we use two techniques that take into consideration that the timing of the break is unknown and allow the data to indicate when regime shifts occur. Thus, break dates that identify the shock triggering contagion are determined endogenously by the model in each of the potential pair-wise causal relationships[9].

The rest of the paper is organized as follows. The next section explains the econometric methodology. The dataset used to analyze causality is described in Section 3. Section 4 presents the empirical findings, whilst Section 5 offers some concluding remarks.

2. Econometric methodology

2.1 Testing for causality

Granger's (1969) causality test is widely used to test for the relationship between two variables. A variable X is said to Granger-cause another variable Y if past values of X help predict the current level of Y better than past values of Y alone, indicating that past values of X have some informational content that is not present in past values of Y. This definition is based on the concept of causal ordering: two variables X and Y may be contemporaneously correlated by chance, but it is unlikely that the past values of X will be useful in predicting Y, giving all past values of Y[10].

[9] In the analysis we only analyze shock transmission between pairs, considering in each test that only one country is responsible of spreading the shock. Unlike previous crisis, since in the euro area sovereign debt crisis several peripheral countries entered a fiscal crisis at roughly the same time, it is very difficult to identify the country responsible of the origin of the shock.

[10] Granger causality is not identical to causation in the classical philosophical sense, but it demonstrates the likelihood of this causation more forcefully than contemporaneous correlation (Geweke, 1984).

Granger-causality tests are sensitive to lag length and, therefore, it is important to select the appropriate lengths[11]. Otherwise, the model estimates will be inconsistent and the inferences drawn may be misleading (see Thornton and Batten, 1985). In this paper, we use Hsiao's (1981) generalization of the Granger notion of causality. Hsiao proposed a sequential method to test for causality, which combines Akaike (1974)'s final predictive error (FPE, from now on) and the definition of Granger-causality (Canova 1995, 62-63). Essentially, the FPE criterion trades off the bias that arises from underparameterization of a model against the loss in efficiency that results from its overparameterization.

Consider the following models,

$$Y_t = \alpha_0 + \sum_{i=1}^{M} \delta_i Y_{t-i} + \varepsilon_t \qquad (1)$$

$$Y_t = \alpha_0 + \sum_{i=1}^{M} \delta_i Y_{t-i} + \sum_{j=1}^{N} \gamma_j X_{t-j} + \varepsilon_t \qquad (2)$$

where X_t and Y_t are covariance-stationary variables [i.e., they are I(0) variables]. The following steps are used to apply Hsiao's procedure for testing causality:

i) Treat Y_t as a one-dimensional autoregressive process (1), and compute its FPE with the order of lags m_i varying from 1 to M. Examine the FPE

$$FPE_Y(m_i, 0) = \frac{T + m_i + 1}{T - m_i - 1} \cdot \frac{SSR}{T}$$

where T is the total number of observations and SSR is the sum of squared residuals of OLS regression (1). Choose m_i for the value of m that minimizes the FPE, say m, and denote the corresponding value as FPE_Y (m, 0).

ii) Treat Y_t as a controlled variable with m number of lags, and treat X_t as a manipulated variable as in (2). Compute again the FPE of (2) by varying the order of lags n_i of X_t from 1 to N. Examine the FPE

[11] The general principle is that the smaller lag length has smaller variance but runs a risk of bias, while larger lags will reduce the bias problem but may lead to inefficiency.

$$FPE_Y(m_i, n_i) = \frac{T + m_i + n_i + 1}{T - m_i - n_i - 1} \cdot \frac{SSR}{T}$$

Choose the order n_i which gives the smallest FPE, say n, and denote the corresponding FPE as FPE_Y (m,n).

iii) Compare FPE_Y (m, 0) with FPE_Y (m,n) [i.e., compare the smallest FPE in step (i) with the smallest FPE in step (ii)]. If FPE_Y (m,0)-FPE_Y (m,n)>0, then X_t is said to cause Y_t. If FPE_Y (m,0)-FPE_Y (m,n)<0, then Y_t is an independent process.

iv) Repeat steps i) to iii) for the X_t variable, treating Y_t as the manipulated variable.

When X_t and Y_t are not stationary variables, but are first-difference stationary [i.e., they are I(1) variables] and cointegrated (see Dolado *et al.*, 1990), it is possible to investigate the causal relationships from ΔX_t to ΔY_t and from ΔY_t to ΔX_t, using the following error correction models:

$$\Delta Y_t = \alpha_0 + \beta Z_{t-1} + \sum_{i=1}^{M} \delta_i \Delta Y_{t-i} + \varepsilon_t \qquad (3)$$

$$\Delta Y_t = \alpha_0 + \beta Z_{t-1} + \sum_{i=1}^{M} \delta_i \Delta Y_{t-i} + \sum_{j=1}^{N} \gamma_j \Delta X_{t-j} + \varepsilon_t \qquad (4)$$

where Z_t is the OLS residual of the cointegrating regression ($Y_t = \mu + \lambda X_t$), known as the error-correction term. Note that, if X_t and Y_t are I(1) variables but are not cointegrated, then β in (3) and (4) is assumed to be equal to zero.

In both cases [i.e., X_t and Y_t are I(1) variables, and they are or they are not cointegrated], we can use Hsiao's sequential procedure substituting Y_t with ΔY_t and X_t with ΔX_t in steps (i) to (iv), as well as substituting expressions (1) and (2) with equations (3) and (4).

2.2 Stability Diagnostics

In the conventional Granger-causality analysis, the relationship between two variables is assumed to exist at all times. However, in a context of financial crisis, parameter non-constancy may occur and may generate misleading inferences if left undetected (see, Bai and Perron, 1998, 2003; Perron, 1989; Zivot and Andrews, 1992). Furthermore, the pre-testing issue in early studies may induce a size distortion of the resulting test procedures (Bai, 1997). Thus, it is desirable to let the data select when and where regime shifts occur (i. e., we need to test for the null hypothesis of no structural change *versus* the alternative hypothesis that changes are present). To this end, we first identify a single structural change using the Quandt–Andrews one-time unknown structural break test. We then use the procedure suggested by Bai (1997) and Bai and Perron (1998, 2003) to detect multiple unknown breakpoints in order to obtain further evidence of the existence of the breakpoints previously detected endogenously. These breakpoints allow the identification of pre-crisis and crisis periods for each pair-wise causal relationship which, as explained in the Introduction, are needed for the detection of a possible contagion episode according to our operational definition based on Forbes and Rigobon (2002) approach.

2.2.1 Quandt-Andrews Breakpoint Test

A particular challenge in empirical time series analysis is to determine the appropriate timing of a potential structural break. In a traditional Chow (1960) test[12], we have to set a specific breakpoint based on *a priori* knowledge about the potential break date. In our analysis, however, we do not assume any prior knowledge about potential break dates, but we make use of a data-based procedure to determine the most likely location of a break. In particular, we use the Quandt–Andrews unknown breakpoint test, originally introduced by

[12] The basic idea of the breakpoint Chow test is to fit the equation separately for each subsample and to see whether there are significant differences in the estimated equations. A significant difference indicates a structural change in the relationship.

Quandt (1960) and later developed by Andrews (1993) and Andrews and Ploberger (1994). The idea behind the Quandt-Andrews test is that a single Chow breakpoint test is performed at every observation between two dates, or observations (τ_1 and τ_2). The *k* test statistics from those Chow tests are then summarized into one test statistic for a test against the null hypothesis of no breakpoints between τ_1 and τ_2.

For the unknown break date, Quandt (1960) proposed likelihood ratio test statistics for an unknown change point, called Supremum test, while Andrews (1993) supplied analogous Wald and Lagrange Multiplier test statistics for it. Then Andrews and Ploberger (1994) developed Exponential (LR, Wald and LM) and Average (LR, Wald and LM) tests. These tests are calculated by using individual Chow Statistics for each date of the data except for some trimmed portion from both ends of it. While the Supremum test finds the date that maximizes Chow Statistics, the most possible break point, the Average and Exponential tests use all the Chow statistic values and are only informative about the existence of the break but not about its date[13].

We set a search interval $\tau \in [0.15, 0.85]$ for the full sample *T* to allow a minimum of 15% of effective observations contained in both pre- and post-break periods. These tests allow us to determine a structural change with unknown timing endogenously from the data after examining each date of the data except for some trimmed portion from both ends of it.

2.2.2 Multiple Breakpoint Tests

Bai and Perron (1998) develop tests for multiple structural changes. Their methodology can be disentangled in two separate and independent parts. First, they propose a sequential method to identify any number of breaks in a time series, regardless of their statistical

[13] Andrews (1993) and Andrews and Ploberger (1994) provide tables of critical values, and Hansen (1997) provides a method to calculate *p*-values.

significance. Second, once the breaks have been identified, they propose a series of statistics to test for the statistical significance of these breaks, using asymptotic critical values.

The sequential procedure is as follows:

i. Begin with the full sample and perform a test of parameter constancy with unknown break.

ii. If the test rejects the null hypothesis of constancy, determine the breakdate, divide the sample into two samples and perform single unknown breakpoint tests in each subsample. Add a breakpoint whenever in a subsample null is rejected.

iii. Repeat the procedure until all of the subsamples do not reject the null hypothesis, or until the maximum number of breakpoints allowed or maximum subsample intervals to test is reached.

For a specific set of unknown breakpoints $(T_1,...,T_p)$, we use the following set of tests developed by Bai and Perron (1998, 2003) to detect multiple structural breaks: the sup *F* type test, the double maximum tests, and the test for ℓ versus $\ell+1$ breaks. First, we consider the sup *F* type test of no structural breaks ($p=0$) versus the alternative hypothesis that there are $p=k$ breaks. Second, we use the double maximum tests, *UD*max and *WD*max, testing the null hypothesis of no structural breaks against an unknown number of breaks given some upper bound *m**. Finally, the sup $F_T\left(\ell+1/\ell\right)$ test, which is a sequential test of the null hypothesis of ℓ breaks against the alternative of $\ell+1$ breaks. The test is applied to each segment containing the observations $\hat{T}_{i-1}$ to $\hat{T}_i$ $i=1,\ldots,(\ell+1)$. To run these tests it is necessary to decide the minimum distance between two consecutive breaks, *h*, which is obtained as the integer part of a trimming parameter,

ε, multiplied by the number of observations T (we use $\varepsilon = 0.15$ and allow up to four breaks).

2.3 Testing for Causality Intensification

As stated above, Granger causality measures precedence and information content. Therefore, the statement "X Granger causes Y" implies that past values of X provide relevant and valuable information about the future behaviour of Y that is not present in past values of Y.

Since the statistic we use to detect Granger-causality is FPE_Y (m,0)-FPE_Y (m,n), we can compute this statistic before and after the endogenously identified breakpoint, and thus assess the intensification or reduction in the causal relationship for those pairs in which we have found Granger-causality in both periods. Therefore, we take an increase of Granger causality as an amplification of the statistical predictability of one time series for another as evidence of an intensification in the transmission mechanism between them.

To this end, for each pair-wise relationship where we find causality both in the tranquil and in the crisis periods, we compare FPE_Y (m,0)-FPE_Y (m,n) in these periods. If this statistic is higher in the crisis than in the tranquil period, we can conclude that an intensification in the causal relationship has taken place. Indeed, this result shows that in the crisis period, even though the uncertainty is by definition higher, the X_t (or ΔX_t) in equation (2) [or in equation (4)] contains relatively more useful information for forecasting the Y_t (or ΔY_t) which is not contained in past values of Y_t (or ΔY_t), than during the pre-crisis period. Conversely, if this statistic is lower in the crisis period than in the tranquil one, we can infer a reduction in the causal relationship, since the extra lagged variables are less useful now for providing information about the future behaviour of the yield under study during the crisis period than during the pre-crisis period.

In doing so, we are first evaluating the "forecast conditional efficiency" in the terminology of Granger and Newbold (1973, 1986) [or "forecast encompassing" according to Chong and Hendry (1986) and Clements and Hendry (1993)] of the manipulated variable X_t (or ΔX_t) in equation (2) [or equation (4)] for each period, by examining whether X_t (or ΔX_t) contains useful information for forecasting the Y_t (or ΔY_t) which is not contained in past values of Y_t (or ΔY_t), and then comparing them and assessing the relative gains in forecast accuracy in each period.

3. Data

We use daily data of 10-year bond yields from January 1st 1999 to December 31st 2012 collected from Thomson Reuters Datastream for EMU-11 countries: both central (Austria, Belgium, Finland, France, Germany and the Netherlands) and peripheral countries (Greece, Ireland, Italy, Portugal and Spain).

[Insert Figure 1 and Figure 2 here]

Figure 1 plots the evolution of daily 10-year bond yields for each country in our sample, whilst Figure 2 displays the evolution of their spread against the German bund. A simple look at these figures allows us to identify two periods, although the breakpoint is not the same in all countries. Between January 1999 and summer 2008, the 10-year bond yields of different countries were evolving simultaneously, and spreads presented only small differences across countries. Only at the end of this period, following the collapse of Lehman Brothers in September 2008, did the major tensions emerging in the financial markets worldwide affect the euro area sovereign debt market since, in a context in which the crisis had already reached the real sector, the problems in the banking sector began to spread to euro area sovereign states.

The descriptive statistics of the 10-year government bond yields in EMU countries during the sample period, (not reported here to save space, but available from the authors upon request) suggest that the mean is not significantly different from zero for the first differences and that normality is strongly rejected for both the levels and first differences. Our results also indicate the presence of heteroskedaticity, in line with the findings by Favero and Missale (2012) and Groba *et al.* (2013) among many others.

4. Empirical results

4.1 Preliminary analysis

As a first step, we tested for the order of integration of the 10-year bond yields by means of the Augmented Dickey-Fuller (ADF) tests. Then, following Cheung and Chinn (1997)'s suggestion, we confirm the results using the Kwiatkowski *et al.* (1992) (KPSS) tests, where the null is a stationary process against the alternative of a unit root. The results, not shown here to save space but available from the authors upon request, decisively reject the null hypothesis of non-stationarity in the first regressions. They do not reject the null hypothesis of stationarity in first differences, but strongly reject it in levels, in the second ones. So, they suggest that both variables can be treated as first-difference stationary.

As a second step, we tested for cointegration between each of the 55 pair combinations[14] of EMU-11 yields using Johansen (1991, 1995)'s approach. The results suggest[15] that only

[14] Recall that the number of possible pairs between our sample of EMU-11 yields is given by the following formula $\frac{n!}{r!(n-r)!} = \frac{11!}{2!(11-2)!} = 55$

[15] The results are not presented, either, to save space but are available from the authors upon request.

for the Austria-Finland, Austria-France, Finland-France, Finland-Netherlands, Greece-Ireland, Greece-Portugal, Ireland-Italy, Ireland-Portugal, Italy-Netherlands and Italy-Portugal cases does the trace test indicate the existence of one cointegrating equation at least at the 0.05 level. Therefore, for these pairs we test for Granger-causality in the first difference of the variables, with an error-correction term added [i. e., equations (3) and (4)], whereas for the remaining cases, we test for Granger-causality in the first difference of the variables, with no error-correction term added [i. e., equations (3) and (4) with β=0]

4. 2. Detecting structural breakpoints

As we explained above, in order to detect contagion in the euro area sovereign debt markets, we need to identify a tranquil or pre-crisis period. To do so, unlike previous studies, we do not set a specific breakpoint based on *a priori* knowledge about the potential break date; first we apply the Quandt-Andrews breakpoint test and let the data select when regime shifts occur in each potential causal relationship, and later we confirm the identified breakpoint by using the tests developed by Bai and Perron (1998, 2003) to detect multiple structural breaks[16]. Table 1 shows that 70% of the total break dates (77 out of the 110 cases analysed) can be explained by some of the following five triggering events[17]: (1) the increase in the ECB interest rates by 25 basis points on July 3rd 2008; (2) the Lehman Brothers collapse on September 15th 2008; (3) the admission by Papandreou's government that its finances were far worse than in previous announcements in November 2009; (4) Greece's request for financial support on April 23rd 2010; and (5) Ireland's request of financial support on November 21st 2010.

[Insert Table 1 here]

[16] We compute the breakpoint tests using a statistic which is robust to heteroskedasticity, since we estimate our original equations with Newey and West (1987) standard errors.
[17] In order to save space, the numerical results of Quandt-Andrews and Bai-Perron tests are not reported in Table 1, but they are also available upon request.

These results suggest that not only can most of the breakpoints be explained by systemic shocks, but that more than half of them (60 out of 110) are directly connected to the euro sovereign debt crisis (triggering events 4 to 5). Besides, 69 out of the 110 breakpoints (i. e., 63%) occur after November 2009, after Papandreou's government had disclosed that its finances were far worse than previously announced[18], with a yearly deficit of 12.7% of GDP, four times more than the euro area's limit (and more than double the previously published figure), and a public debt of $410 billion. We should recall that this announcement only served to worsen the severe crisis in the Greek economy, and the country's debt rating was lowered to BBB+ (the lowest in the euro zone) on December 8th. These episodes marked the beginning of the euro area sovereign debt crisis.

Furthermore, it is also notable that all break dates, including the 30% which are not related to one of the five triggering events mentioned above[19], occur between January 2008 and December 2010, suggesting that systemic rather than idiosyncratic factors explain euro area sovereign debt market turmoil. Therefore, since the precise regime shift date changes depending on the causal relationship, our analysis improves on previous studies by using in each relationship the breakpoint obtained from the Quandt–Andrews and Bai-Perron tests.

4. 3. Changes in the number of Granger-causal relationships

Given the evidence presented in the previous sub-section, in ten relationships (Austria-Finland, Austria-France, Finland-France, Finland-Netherlands, Greece-Ireland, Greece-Portugal, Ireland-Italy, Ireland-Portugal, Italy-Netherlands and Italy-Portugal) we test for Granger-causality in the first difference of the variables, with an error-correction term

[18] These results are in line with Gómez-Puig and Sosvilla-Rivero (2014) who find that none of the variables measuring global (world) market sentiment was statistically significant, suggesting that shifts in local (country-specific) or regional (European) rather than global market sentiment are behind euro area debt crisis transmission.
[19] We make use of equality tests to formally evaluate the null hypothesis that the mean and variance in the pre-crisis and crisis periods are equal against the alternative that they are different. The results (not shown here to save space, but available from the authors upon request) indicate strong evidence that they differ across periods.

added. In all other cases, we test for Granger-causality in the first difference of the variables, with no error-correction term added. The causal relationships resulting from the estimated FPE statistics for the pre-crisis and crisis periods jointly with the break dates resulting from the Quandt–Andrews and Bai-Perron tests are shown in Tables 2 and 3[20].

[Insert Table 2 and Table 3 here]

The changes in causal relationships in the crisis period compared to the pre-crisis period are illustrated in Figures 3 and 4 (grey arrows represent relationships that did not exist before the breakpoint, whilst discontinuous arrows reflect relationships that disappear with the crisis).

[Insert Figure 3 and Figure 4 here]

Specifically, Table 2 and Figure 3 present the evolution of the causality running from EMU peripheral countries. The behaviour of causality running from EMU peripheral to central countries is displayed in Panel A of Table 2 and Figure 3a; whilst Panel B of Table 2 and Figure 3b show the evolution of causality running within EMU peripheral countries. Likewise, Table 3 and Figure 4 present the changes in causality running from EMU central countries. Panel A of Table 3 and Figure 4a illustrate the evolution of causality running from EMU central to peripheral countries while Panel B of Table 3 and Figure 4b report how causality running within EMU central countries has evolved during the two periods.

As can be seen, for the four subsamples of countries, the number of causal relationships increases as the financial and sovereign debt crisis develops in the euro area. If we focus on the evolution of causality between EMU peripheral and EMU central countries (Panels A of Tables 2 and 3 and Figures 3a and 4a), it can be observed that in the pre-crisis period causality is higher if EMU central countries are triggers rather than EMU peripheral

[20] These results were confirmed using both Wald statistics to test the joint hypothesis $\hat{\gamma}_1 = \hat{\gamma}_2 = ... = \hat{\gamma}_n = 0,$ and the Williams-Kloot test for forecasting accuracy (Williams, 1959). These additional results are not shown here to save space, but are available from the authors upon request.

countries. In particular, our results indicate the existence of 19 causal relationships in the first case (Figure 4a) and 10 in the second (Figure 3a). Two interesting findings are worth pointing out: (1) in the pre-crisis period, the evolution of Greek sovereign yields does not Granger-cause that of other EMU central countries, and (2) the Netherlands' yield behaviour is not Granger-caused by the evolution of yields of any EMU peripheral country (see Figure 3a).

During the crisis period, even though the number of causal relationships detected increases in both directions, they are more frequent when EMU peripheral countries are the triggers. We find 27 out of 30 causal relationships when the EMU peripheral countries are the triggers (Figure 3a), whilst the number of causality linkages rises from 19 to 24 if the triggers are EMU central countries (Figure 4a). Interestingly, Greece now Granger-causes Austria, Belgium, Finland and France while Netherlands' yield behaviour is caused by the Spanish and the Irish one. Moreover, another relevant finding is that with the crisis, four causal relationships from central to peripheral countries disappear: Austria-Ireland, Belgium-Greece, France-Portugal and Netherlands-Ireland, suggesting a temporal disconnection between them.

Panel B of Table 2 and Figure 3b, which show the results regarding causal relationships running within EMU peripheral countries in the two periods under study, also suggest that their number is boosted as the financial and sovereign debt crises expand in the euro area. We find evidence of 14 relationships in the pre-crisis period (Figure 3b) and 20 in the crisis period. In the pre-crisis period the exceptions are: a) Greece-Ireland, where there is no evidence of Granger-causality in either direction, and b) some relationships where we do not find unidirectional Granger-causality: from Greece to Italy and Spain, and from

Portugal and Spain to Ireland. Nevertheless, we find evidence of bidirectional causality in all the relationships during the crisis period.

Finally, Panel B of Table 3 and Figure 4b present the results regarding causality running within EMU central countries in the two periods. From these results it can be inferred that the number of causal relationships also increases in the crisis period, since we find evidence of bidirectional causality in all 15 relationships (Figure 4b). Hence, causality linkages increase from 21 to 30 during the crisis compared to the pre-crisis period.

4. 4. Changes in the intensity of Granger-causal relationships

As mentioned above, for each of the 60 cases where we find causality in both the tranquil and the crisis periods, we compare FPE_X (m,0)-FPE_X (m,n) in the two periods. If this statistic is higher in the crisis than in the tranquil period, we can conclude that the causal relationship has intensified. Conversely, if this statistic is lower in the crisis period than in the tranquil one, we can infer a reduction in the causal relationship.

In the last column in Tables 2 and 3, we report the results of this exploratory exercise. As can be seen, even though in the aftermath of the crisis there is an increase in volatility (see Figure 1), we obtain evidence of causality intensification with respect to the more stable pre-crisis period[21]. The causing yields improve the forecast accuracy of the caused yields during the crisis period compared with the tranquil period, indicating that after the detected breakpoint they carry even more useful informational content about the future behaviour of the caused yields.

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[21] Note that, in contrast to tests for contagion based on cross-market correlation measures, we do not need to adjust for the shift in volatility from the tranquil period to the crisis period.

Regarding the causal relationships running from EMU peripheral to EMU central countries, an increase in causality after the endogenously identified crisis is detected in six of the 10 possible cases (Panel A of Table 2). As for the causality linkages going from EMU central to EMU peripheral countries, in 10 out of the 15 cases where we find causality both in the tranquil and in the crisis period, we find that the relationship intensifies (Panel A of Table 3). With regard to the causal relationships within EMU peripheral countries, we find evidence of significant relative rise in causality after the crisis in 12 out of the 14 possible cases (Panel B of Table 2). Finally, when examining the causal relationships within EMU central countries we conclude that they increase after the crisis in 14 of the 21 possible cases (Panel B of Table 3).

4.5. Contagion assessment

From the above analysis we can conclude that, in the crisis period, not only do we find some new causality patterns which had been absent before its start, but also an intensification of causality in 70% of the cases which would allow us to establish that those linkages may be purely crisis-contingent.

Specifically, causal relationships running from EMU peripheral countries record an important increase in the crisis period: not only relationships within peripheral countries (Figure 3b shows six new linkages), but also causal relationships running from EMU peripheral to EMU central countries (Figure 3a displays 17 new causality patterns). This suggests that the problems of peripheral countries can spill over not only to other peripheral countries but also to EMU central countries since some of these banks (mostly German and French banks) are highly exposed to the debt of peripheral countries (see Gómez-Puig and Sosvilla-Rivero, 2013). Moreover, several studies show that sovereign bond yields are not only driven by country-specific risk factors but that they are also significantly affected by global risk factors [see Groba *et. al.* (2013) and Dieckmann and Plank (2011) among them]. These global risk factors reflect global investors' risk aversion, since in times of uncertainty, they become more risk averse and the "flight-to-safety" motive favors bonds of countries that are generally regarded to have a low default risk (e.g. during the crisis Germany experienced one of its lowest yields' levels in history). Therefore, an increase in the Granger-causality of bond yields from peripheral to central countries might also reflect a general increase in investors' risk aversion which might have driven an increase of yields in those countries. Indeed, 10-year yields spreads over Germany of Austrian, Finish, French and Dutch government's bonds achieved a maximum level of 183, 83, 189 and 84 basis points (in November 2011 in the first three countries and in April 2012 in the case of the Netherlands, see Figure 2) while the credit rating provided by the three most important agencies (Moody's, Standard & Poor's and Fitch) at the same date was, like in Germany, the highest one. The reason behind sovereign risk rise in central countries, triggered by the behaviour of peripheral countries, can be related to herding behavior or panic among investors which leads to what is named by the literature as "pure contagion" (see Gómez-Puig and Sosvilla-Rivero, 2014). Besides, the fact that tensions in sovereign debt markets also spread to EMU central countries is also stressed by the nine new linkages that appear (see Figures 4a and 4b) both in the causal relationships running from EMU central to EMU peripheral countries and between EMU central countries.

In our view, these 41 new causality patterns out of the 101 causal relationships that exist in the crisis period within the 11 euro area countries analyzed (which were absent before the break date, determined endogenously for each causal relationship), together with the intensification of the causal relationship in 42 of the 60 cases in which we find causality both in the tranquil and in the crisis period, can be considered an important operative measure of contagion consistent with both our definition and the literature, as they represent additional linkages during crisis periods in excess of those that arise during non-crisis periods; see for example, Forbes and Rigobon (2002), Masson (1999), Pericoli and Sbracia (2003) or Dungey *et al.* (2006).

5. Conclusions

This paper has three main objectives: to test for the existence of possible Granger-causal relationships between the evolution of the yield of bonds issued by both peripheral and central EMU countries, to determine endogenously the breakpoints in the evolution of those relationships and to detect contagion episodes according to an operative definition: an abnormal increase in the number or in the intensity of causal relationships compared with that of tranquil periods, triggered by an endogenously detected shock.

The most important results that emerge from our analysis are the following: (1) Around two thirds out of the total endogenously identified breakpoints occur after November 2009, when Papandreou's government revealed that its finances were far worse than previous announcements, suggesting that most of the breakpoints can be explained by systemic shocks directly connected to the euro sovereign debt crisis. (2) The number of causal relationships increases as the financial and sovereign debt crisis unfolds in the euro area, and causality patterns after the break dates are more frequent when EMU peripheral countries are the triggers. (3) In the crisis period we find evidence of 101 causal relationships: 41 represent new causality linkages and 60 are patterns that already existed in the tranquil period. However, we find an intensification of the causal relationship in 42 out of the 60 cases. In our opinion, these 41 new causality patterns, together with the intensification of the causal relationship in 70% of the cases can be considered an important operative measure of contagion that is consistent with the definition we have proposed.

Regarding policy implications, our results seem to indicate that EMU has brought about strong interlinkages of the participating countries which are reasonable within a group of countries that share an exchange rate agreement (a common currency in the case of the euro area) and where financial crises tend to be clustered (see Beirne and Fratzscher, 2013). Therefore, we consider that our results might have some practical meaning for investors and policymakers, as well as some theoretical insights for academic scholars interested in the behaviour of EMU sovereign debt markets. Our methodology could be used as a tool to provide information regarding the drivers and the time-varying intensity of crisis transmission, in the euro area sovereign debt markets, after a shock, which is an important question that can help policymakers to react in the future in order to avoid another.

Finally, it should be noted that our analysis is devoted to bivariate series analysis. The extension to multivariate series analysis is reserved for future research. In view of the encouraging results of the present study, some optimism about the benefits from implementing this analysis seems justified.

Acknowledgements

The authors thank the editor and two anonymous referees for useful comments and suggestions on a previous draft of this article, substantially improving the content and quality of the article. This paper is based upon work supported by the Government of Spain and FEDER under grant number ECO2010-21787-C03-01 and ECO2011-23189. Simón Sosvilla-Rivero thanks the Universitat de Barcelona & RFA-IREA for their hospitality. The authors are very grateful to Petros Migiakis from the Bank of Greece for his comments and suggestions on an early draft. Responsibility for any remaining errors rests with the authors.

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Figure 1. Daily 10-year sovereign yields in EMU-11 countries: 1999-2012

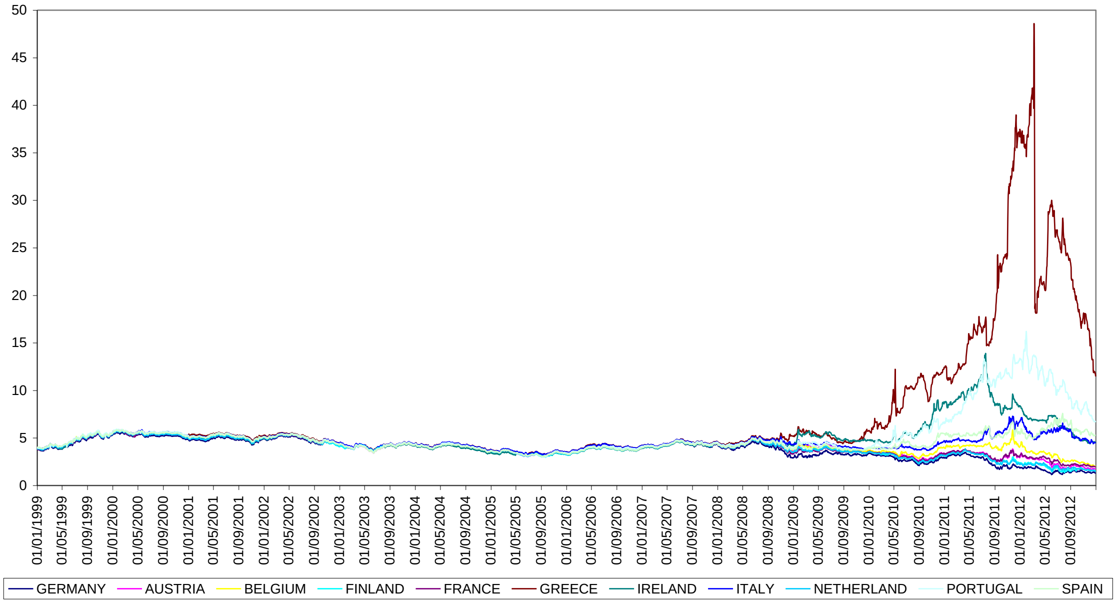


Figure 2. Daily 10-year sovereign yield spreads over Germany: 1999-2012

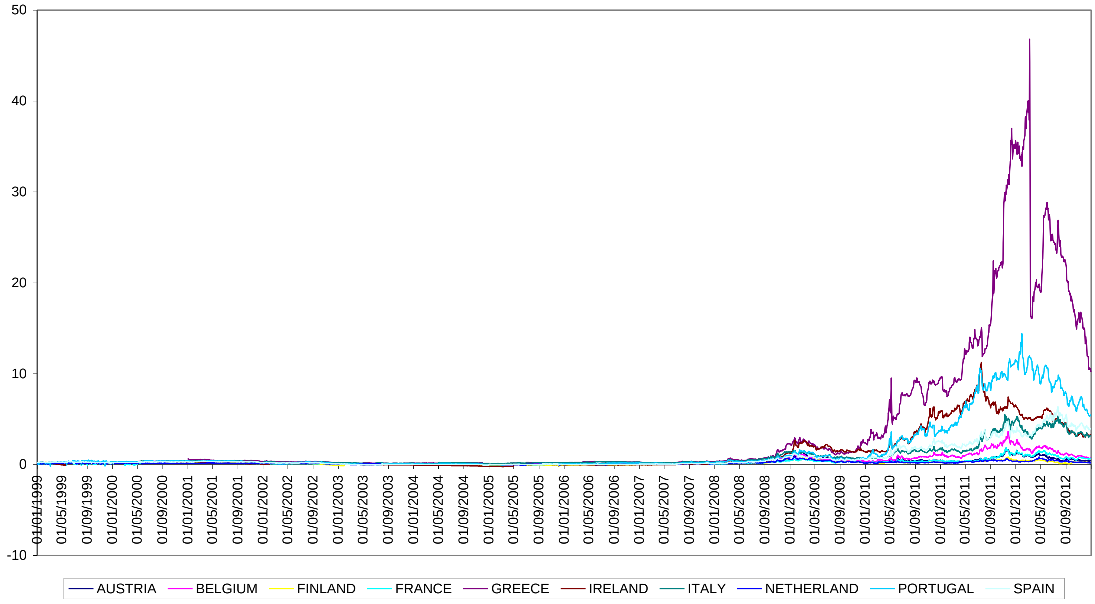


Figure 3: Causal relationships from EMU Peripheral countries.

Figure 3a: Causal relationships from EMU Peripheral to Central countries

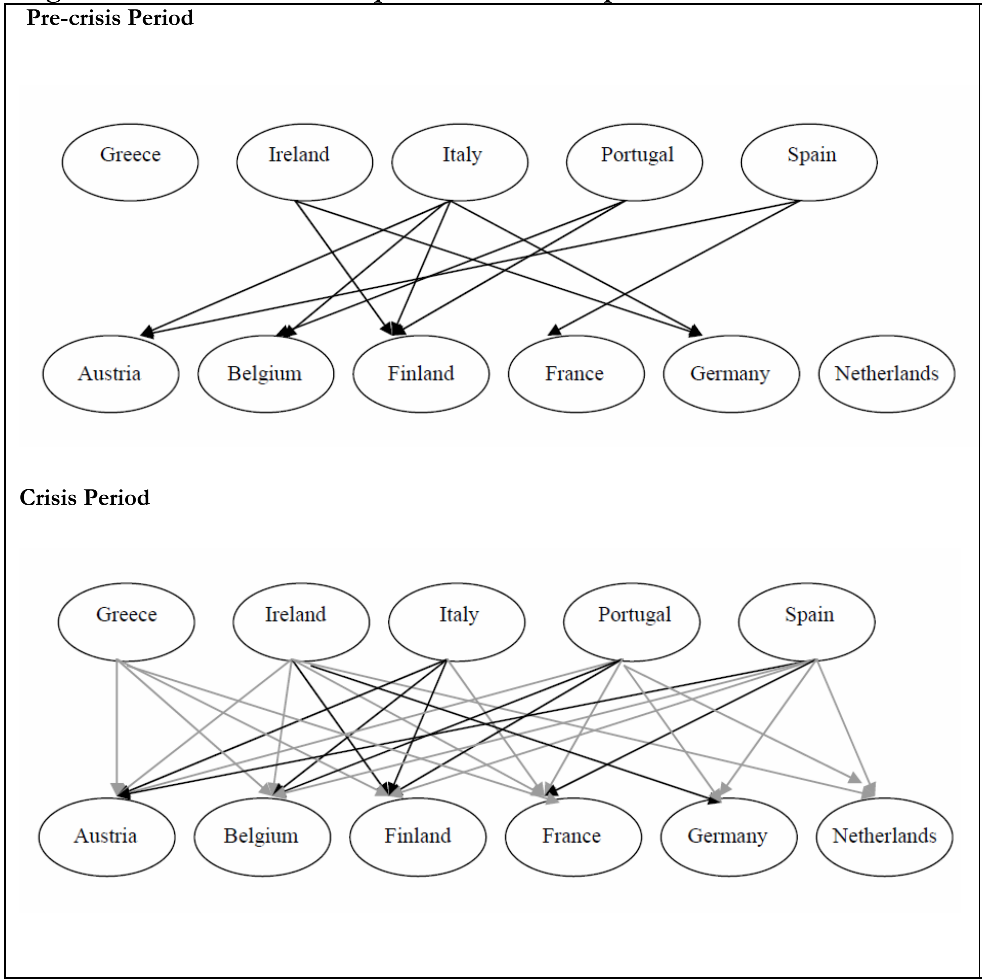


Figure 3b: Causal relationships within EMU Peripheral countries

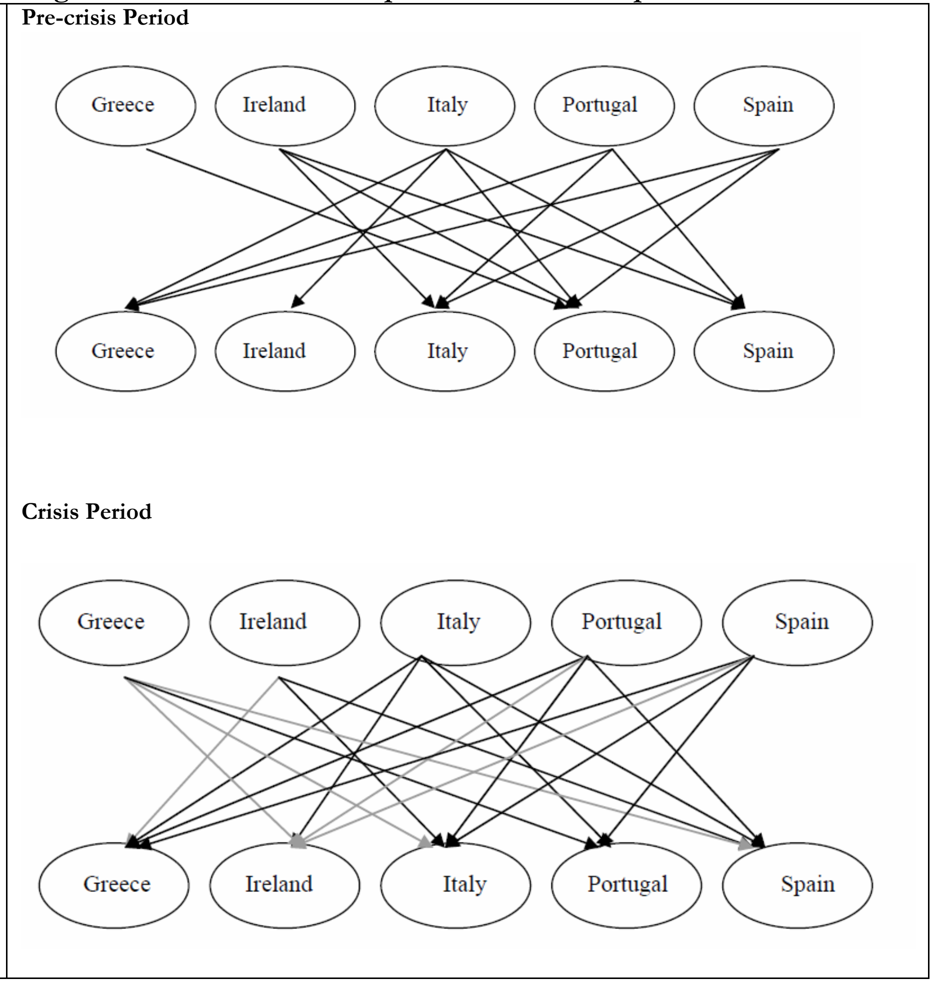
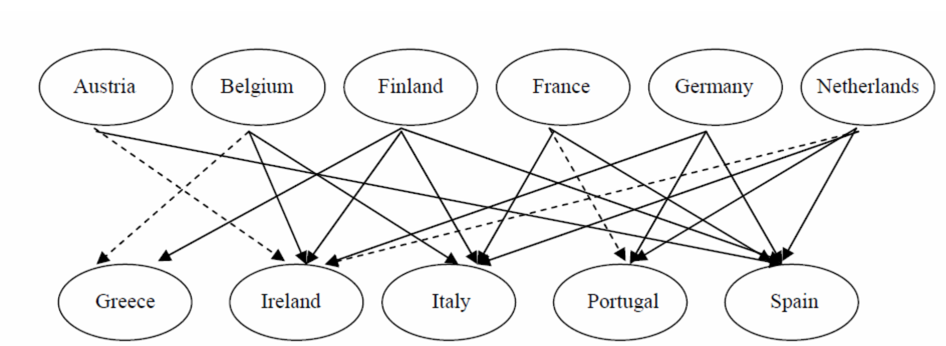


Figure 4: Causal relationships from EMU Central countries.

Figure 4a: Causal relationships from EMU Central to Peripheral countries

Pre-crisis Period



Crisis Period

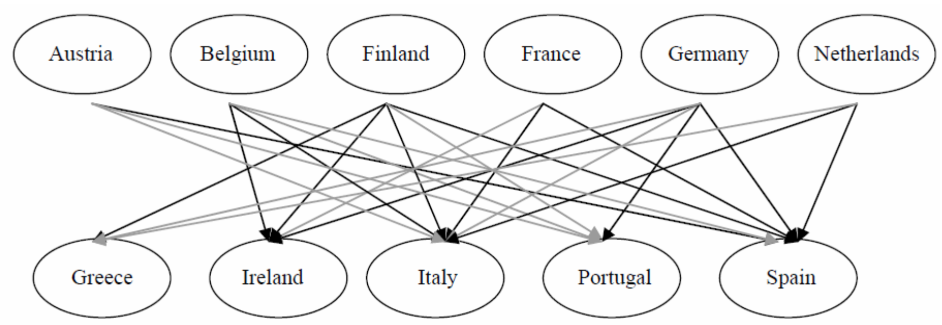
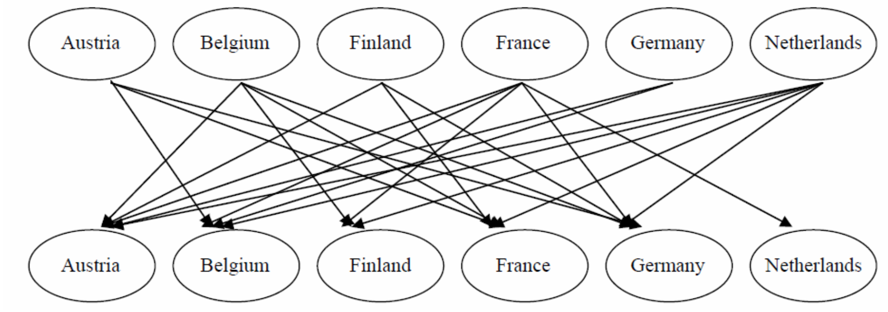


Figure4b: Causal relationships within EMU Central countries

Pre-crisis Period



Crisis Period

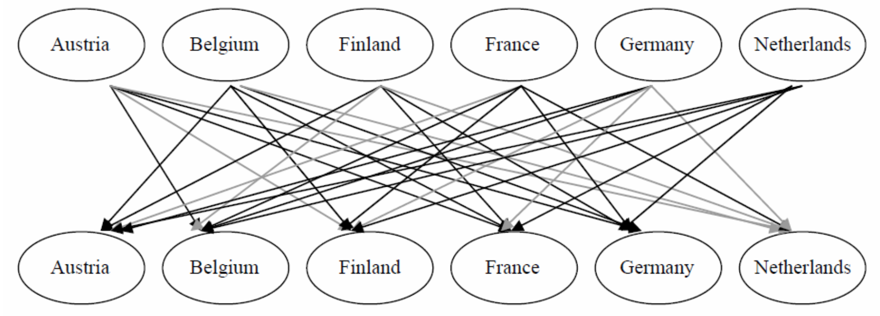


Table 1: Causal relationships' break dates[a]

Causal relationship	Break date	Causal relationship	Break date
Panel A: 07/03/2008: ECB increases interest rates by 25 basis points		**Panel B: 09/15/2008: Lehman Brothers files for bankruptcy**	
PT → NL	07/04/2008	**PT → IT**	09/15/2008
SP → NL	07/04/2008	**PT → GE**	10/08/2008
FR → NL	07/04/2008	**SP → GE**	10/08/2008
GE → FI	07/04/2008	**FR → FI**	10/08/2008
GE → NL	07/04/2008	**SP → IT**	10/08/2008
NL → GE	07/04/2008	**NL → FI**	10/28/2008
IE → NL	07/04/2008	**BE → GE**	11/04/2008
IT → GE	07/04/2008	**IE → IT**	11/14/2008
GR → GE	07/04/2008	**GR → IT**	11/28/2008
GR → NL	07/04/2008		
FR → PT	07/04/2008		
FR→ SP	07/04/2008		
IE → GE	07/04/2008		
BE → NL	07/24/2008		
Panel C: November 2009: Papandreou's government reveals that its finances were far worse than previous announcements		**Panel D: 04/23/2010: Greece seeks financial support**	
BE → PT	11/30/2009	**IT → AT**	05/05/2010
IT → PT	12/03/2009	**FR → IT**	05/07/2010
IT→ SP	12/03/2009	**GE → IT**	05/10/2010
GR → AT	12/21/2009	**GR→ SP**	05/10/2010
PT → FR	12/21/2009	**NL → IT**	05/10/2010
SP → FR	12/21/2009	**IT → NL**	05/10/2010
Panel E: 11/21/2010: Ireland seeks financial support		**SP → AT**	05/10/2010
FI → PT	11/21/2010	**FR → AT**	05/10/2010
FI→ SP	11/21/2010	**FR → BE**	05/11/2010
BE → SP	11/21/2010	**FI → IT**	05/11/2010
FI → IE	11/21/2010	**FI → GR**	05/11/2010
BE → IE	11/21/2010	**AT → GR**	05/11/2010
NL → IE	11/21/2010	**AT → PT**	05/11/2010
AT → BE	11/21/2010	**BE → IT**	05/11/2010
AT → NL	11/21/2010	**BE → GR**	05/11/2010
BE → FR	11/21/2010	**IE → BE**	05/11/2010
FI → FR	11/21/2010	**IE → GR**	05/12/2010
IT → IE	11/21/2010	**IT → GR**	05/12/2010
PT → IE	11/21/2010	**SP → GR**	05/12/2010
SP → IE	11/21/2010		
SP→ PT	11/21/2010		
GE → IE	11/22/2010		
AT → SP	11/23/2010		
AT → IT	11/23/2010		
GE → BE	11/24/2010		
NL → BE	11/24/2010		
NL → FR	11/24/2010		
FI → BE	11/24/2010		
SP → BE	11/24/2010		
GR → BE	11/24/2010		
IT → BE	11/24/2010		
PT → BE	11/24/2010		
AT → FI	11/25/2010		
NL→ SP	11/25/2010		
GE → GR	12/10/2010		
NL → GR	12/10/2010		

[a] Notes: Five triggering events explain 70% of total break dates.
AT, BE, FI, FR, GE, GR, IE, IT, NL, PT, and SP stand for Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal and Spain, respectively.

Table 2: Causality running from EMU Peripheral countries[b]

Panel A: Causality running from EMU Peripheral to Central countries

	Pre-crisis period	Crisis period	Break date	Causality Changes
IE → AT	**No**	Yes	09/18/2009	New
IE → BE	**No**	Yes	05/11/2010	New
IE → FI	Yes	Yes	01/29/2009	Intensification
IE → FR	**No**	Yes	03/23/2010	New
IE → GE	Yes	Yes	07/04/2008	Reduction
IE → NL	**No**	Yes	07/04/2008	New
IT → AT	Yes	Yes	05/05/2010	Reduction
IT → BE	Yes	Yes	11/24/2010	Intensification
IT → FI	Yes	Yes	07/04/2010	Intensification
IT → FR	**No**	Yes	01/05/2009	New
IT → GE	Yes	Yes	07/04/2008	Reduction
IT → NL	**No**	**No**	05/10/2010	-
GR → AT	**No**	Yes	12/21/2009	New
GR → BE	**No**	Yes	11/24/2010	New
GR → FI	**No**	Yes	07/04/2010	New
GR → FR	**No**	Yes	01/06/2009	New
GR → GE	**No**	**No**	07/04/2008	-
GR → NL	**No**	**No**	07/04/2008	-
PT → AT	**No**	Yes	01/06/2009	New
PT → BE	Yes	Yes	11/24/2010	Intensification
PT → FI	Yes	Yes	07/04/2010	Reduction
PT → FR	**No**	Yes	12/21/2009	New
PT → GE	**No**	Yes	10/08/2008	New
PT → NL	**No**	Yes	07/04/2008	New
SP → AT	Yes	Yes	05/10/2010	Intensification
SP → BE	**No**	Yes	11/24/2010	New
SP → FI	**No**	Yes	07/04/2010	New
SP → FR	Yes	Yes	12/21/2009	Intensification
SP → GE	**No**	Yes	10/08/2008	New
SP → NL	**No**	Yes	07/04/2008	New

Panel B: Causality running within EMU Peripheral countries

	Pre-crisis period	Crisis period	Break date	Causality changes
IE → IT	Yes	Yes	11/14/2008	Intensification
IE → GR	**No**	Yes	05/12/2010	New
IE → PT	Yes	Yes	06/22/2009	Intensification
IE→ SP	Yes	Yes	03/02/2009	Intensification
IT → IE	Yes	Yes	11/21/2010	Intensification
IT → GR	Yes	Yes	05/12/2010	Intensification
IT → PT	Yes	Yes	12/03/2009	Reduction
IT→ SP	Yes	Yes	12/03/2009	Intensification
GR → IE	**No**	Yes	07/05/2010	New
GR → IT	**No**	Yes	11/28/2008	New
GR → PT	Yes	Yes	02/02/2010	Intensification
GR→ SP	**No**	Yes	05/10/2010	New
PT → IE	**No**	Yes	11/21/2010	New
PT → IT	Yes	Yes	09/15/2008	Reduction
PT → GR	Yes	Yes	08/05/2010	Intensification
PT→ SP	Yes	Yes	15/01/2010	Intensification
SP → IE	**No**	Yes	11/21/2010	New
SP → IT	Yes	Yes	10/08/2008	Intensification
SP → GR	Yes	Yes	05/12/2010	Intensification
SP→ PT	Yes	Yes	11/21/2010	Intensification

[b] Notes: AT, BE, FI, FR, GE, GR, IE, IT, NL, PT, and SP stand for Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal and Spain, respectively. Bold values indicate absence of Granger-causality.

Table 3: Causality running from EMU Central countries[c]

Panel A: Causality running from EMU Central to Peripheral countries

	Pre-crisis period	Crisis period	Break date	Causality changes
AT → IE	Yes	**No**	07/05/2010	-
AT → IT	**No**	Yes	11/23/2010	New
AT → GR	**No**	**No**	05/11/2010	-
AT → PT	**No**	Yes	05/11/2010	New
AT → SP	Yes	Yes	11/23/2010	Intensification
BE → IE	Yes	Yes	11/21/2010	Intensification
BE → IT	Yes	Yes	05/11/2010	Intensification
BE → GR	Yes	**No**	05/11/2010	-
BE → PT	**No**	Yes	11/30/2009	New
BE → SP	**No**	Yes	11/21/2010	New
FI → IE	Yes	Yes	11/21/2010	Intensification
FI → IT	Yes	Yes	05/11/2010	Intensification
FI → GR	Yes	Yes	05/11/2010	Intensification
FI → PT	**No**	Yes	11/21/2010	New
FI→ SP	Yes	Yes	11/21/2010	Intensification
FR → IE	**No**	Yes	07/05/2010	New
FR → IT	Yes	Yes	05/07/2010	Intensification
FR → GR	**No**	**No**	05/03/2010	-
FR → PT	Yes	**No**	07/04/2008	-
FR→ SP	Yes	Yes	07/04/2008	Intensification
GE → IE	Yes	Yes	11/22/2010	Reduction
GE → IT	**No**	Yes	05/10/2010	New
GE → GR	**No**	Yes	12/10/2010	New
GE → PT	Yes	Yes	01/08/2008	Reduction
GE→ SP	Yes	Yes	01/14/2010	Intensification
NL → IE	Yes	**No**	11/21/2010	-
NL → IT	Yes	Yes	05/10/2010	Reduction
NL → GR	**No**	Yes	12/10/2010	New
NL → PT	Yes	Yes	08/18/2008	Reduction
NL→ SP	Yes	Yes	11/25/2010	Reduction

Panel B: Causality running within EMU Central countries

	Pre-crisis period	Crisis period	Break date	Causality changes
AT → BE	Yes	Yes	11/21/2010	Intensification
AT → FI	**No**	Yes	11/25/2010	New
AT → FR	Yes	Yes	06/10/2008	Intensification
AT → GE	Yes	Yes	07/01/2008	Intensification
AT → NL	**No**	Yes	11/21/2010	New
BE → AT	Yes	Yes	06/01/2009	Reduction
BE → FI	Yes	Yes	06/04/2010	Intensification
BE → FR	Yes	Yes	11/21/2010	Intensification
BE → GE	Yes	Yes	11/04/2008	Reduction
BE → NL	**No**	Yes	07/24/2008	New
FI → AT	Yes	Yes	05/01/2009	Intensification
FI → BE	**No**	Yes	11/24/2010	New
FI → FR	Yes	Yes	11/21/2010	Intensification
FI → GE	Yes	Yes	07/01/2008	Intensification
FI → NL	**No**	Yes	06/04/2010	New
FR → AT	**No**	Yes	05/10/2010	New
FR → BE	Yes	Yes	05/11/2010	Reduction
FR → FI	Yes	Yes	10/08/2008	Reduction
FR → GE	Yes	Yes	07/01/2008	Intensification
FR → NL	Yes	Yes	07/04/2008	Intensification
GE → AT	Yes	Yes	06/06/2009	Intensification
GE → BE	Yes	Yes	11/24/2010	Intensification
GE → FI	**No**	Yes	07/04/2008	New
GE → FR	**No**	Yes	02/19/2008	New
GE → NL	**No**	Yes	07/04/2008	New
NL → AT	Yes	Yes	01/06/2009	Intensification
NL → BE	Yes	Yes	11/24/2010	Intensification
NL → FI	Yes	Yes	10/28/2008	Reduction
NL → FR	Yes	Yes	11/24/2010	Reduction
NL → GE	Yes	Yes	07/04/2008	Intensification

[c] Notes: AT, BE, FI, FR, GE, GR, IE, IT, NL, PT, and SP stand for Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Portugal and Spain, respectively.
Bold values indicate absence of Granger-causality.

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