THE RIMINI CENTRE FOR ECONOMIC ANALYSIS

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# CONVERGENCE OF EUROPEAN BUSINESS CYCLES: A COMPLEX NETWORKS APPROACH

# Convergence of European Business Cycles: A Complex Networks Approach

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## Abstract

We examine the co-movement patterns of European business cycles during the period 1986-2011, with an obvious focal point the year 1999 that marked the introduction of the common currency, the euro. The empirical analysis is performed within the context of *Graph Theory* where we apply a rolling window approach in order to dynamically analyze the evolution of the network that corresponds to the GDP growth rate cross-correlations of 22 European economies. The main innovation of our study is that the analysis is performed by introducing what we call the *Threshold-Minimum Dominating Set* (T-MDS). We provide evidence at the network level and analyze its structure and evolution by the metrics of *total network edges*, *network density*, *isolated nodes* and the cardinality of the T-MDS set. Next, focusing on the country level, we analyze each individual country's *neighborhood set* (economies with similar growth patterns) in the pre- and post-euro era in order to assess the degree of convergence to the rest of the economies in the network. Our empirical results indicate that despite few economies' idiosyncratic behavior, the business cycles of the European countries display an overall increased degree of synchronization and convergence in the single currency era.

Key words: Business cycles, convergence, Graph Theory, complex economic networks, rolling window, Threshold-Minimum Dominating Set

## 1. Introduction

On February 7, 1992, the Maastricht[1] treaty was signed by the 12 leaders of the members of the European Community. This established the European Union and set the foundations for the introduction of a common currency, the euro. The political and monetary integration of Europe was partly motivated by the Optimum Currency Area (OCA) theory of Mundell (1961). In this work, Mundell described an OCA as a region where the advantages of the circulation of a single currency among two or more nations

[1] Officially "the Treaty on European Union"

are greater than the disadvantages of abolishing the sovereign currencies. Some of the advantages from the adoption of a single currency include: a) elimination of the exchange rate risk, b) reduced transaction costs and c) increased price transparency and comparability since all commodities are priced in a single currency and d) efficient allocation of labor and capital within the monetary union. Nonetheless, the adoption of a single currency does not come without associated costs and tradeoffs (Frankel, 1999; Kenen, 2000). One of the main disadvantages of abdicating the national currency is that monetary policy can no longer be used at the country level: the mechanism that allows national economies to absorb macroeconomic shocks by adjusting the money supply seizes to exist. The other significant cost is often referred to as the "one size does not fit all" problem: for a country that is in the contractionary phase of the economic cycle a loose monetary policy is preferable to a tight one in order to stimulate its economy. The opposite is true for an economy that operates within an inflationary gap. Thus, the synchronization of the participating countries' business cycles is important for the implementation of an overall efficient monetary policy. In the opposite case, the common monetary policy is inefficient and may even be destabilizing. Consequently, business cycle synchronization should be considered as a prerequisite for a successful and efficient monetary union.

The Eurozone is the first and only international example of the creation of such a common currency area. For this reason, there is a wide (and ever growing) literature that deals with the issue of business cycle convergence in Europe. However, the empirical results are not conclusive and thus a consensus has not been reached. Some representative studies include Artis and Zhang (1997) that examine the evolution of correlations between the cyclical component of 15 countries before and after the launch of the Exchange Rate Mechanism (ERM) in Europe. The authors provide evidence in favor of business cycle convergence of ERM countries with Germany and decoupling from the U.S. business cycle for the period following the ERM. Massmann and Mitchell (2004) report an overall convergence between a set of 12 European countries during the period 1960-2001, despite some divergence patterns in the beginning of the 1990s that were mainly induced by the unification of Germany in 1989. Altavilla (2004) applies a Markov switching model on the EMU members and concludes that the establishment of a common currency in Europe has led to increased business cycle synchronization between the EMU economies. Montoya and de Haan (2008) use data on an alternative economic aggregation level in Europe, namely, the 53 NUTS1[2] areas and conclude that despite small signs of divergence during the mid-1980s and early 1990s, the areas under consideration present increased convergence at the full period examined i.e. 1975-2005. Cancelo (2012) applies a rolling window correlation coefficient for the time period 2004-2010 to uncover the evolution of convergence within a selected set of 14 European plus 3

[2] NUTS (Nomenclature of territorial units for statistics) is a hierarchical system that divides the total economic region of Europe in three levels of aggregates for statistical economic analysis purposes.

external countries after the 2007 crisis. He concludes that during the crisis the Eurozone countries have in general increased the alignment of their business cycles with the non-Eurozone countries while Greece, Ireland, Spain and Portugal present more idiosyncratic cycles in the aftermath of the crisis. Gogas (2013) using three alternative methodologies examines the business cycle co-movement of 12 European countries before and after the establishment of a common currency in 1999 and provides evidence in favor of business cycle convergence after the introduction of the euro. Inklaar and de Haan (2001) build on the work of Artis and Zhang (1999) using the same dataset and methodology. However, instead of considering two time periods (pre- and post-ERM), they divide the original sample in four sub-periods and apply the correlation coefficient. Their results contradict those of Artis and Zhang (1999) since the coefficient is found to fluctuate throughout the four periods under consideration. Silva (2009) examines the status of convergence between 26 European economies before and after the emergence of the EMU and argues that no uniform outcome can be derived regarding business cycle synchronization within Europe as some economies tend to move closer through time while others seem to diverge.

In this paper we work within a Graph Theory context, to empirically examine the evolution of business cycle synchronization of 22 European countries throughout a time period of 26 years (namely 1986-2011), using as a mid-point the year of the introduction of the euro in 1999. We construct the *complex network* that is associated to the GDP growth rate similarity of the selected economies and then analyze its topology with the use of standard network metrics and the *Threshold - Minimum Dominating Set* (T-MDS). We perform our empirical analysis within a rolling window framework which allows us to obtain a dynamic view of the evolution of the GDP growth rates network of the 22 European countries and provide empirical evidence on whether their business cycles seem to converge after the introduction of the common currency.

The foundations of Graph Theory were first established by Euler (1741) when he tried to solve the famous "*seven bridges of Konigsberg*" problem in mathematics. He was trying to find a unique path that drives through the seven bridges that connected the individual parts of the town of Konigsberg. Since this "introductory" study, Graph Theory was popularized and applied in diverse scientific fields including path-rooting problems (Plotkin, 1995), metabolic-biological networks (Weng *et al*, 1999; Schuster *et al*, 2000), social network analysis (Milgram, 1967; Freeman, 1979), technological networks (Watts and Strogatz, 1998; Amaral *et al*, 2000), etc. Lately, Graph Theory has been integrated in the analysis of complex economic systems (Garlaschelli *et al*, 2007; Schiavo *et al*, 2010) and more specifically financial networks (Bonanno *et al*, 2004; Tumminello *et al,* 2010; Bowden, 2012), stock market networks (Vandewalle *et al*, 2001; Tse *et al*, 2010), the banking sector (Minoiu and Reyes, 2013; Papadimitriou *et al*, 2013), etc.

The first contribution of our work is that it attempts to implement a new methodological context for the analysis of business cycle synchronization that departs from classical econometric models and utilizes *network analysis* tools to investigate possible convergence patterns. In the relevant literature we find only two more studies that use *network analysis* for the examination of business cycle convergence; namely, Gomez *et al* (2012) and Caraiani (2013). However, Caraiani (2013) presents a static image based on the correlations between GDP growth rates for the full period under consideration. He does not attempt to show the evolution of the business cycle through time as we do in this study, so that no inference on whether the cycles converge or diverge after the monetary union can be drawn. Gomez *et al* (2012) present a dynamic analysis based on the application of a rolling window correlation coefficient, nonetheless, they use the Minimum Spanning Tree (MST) methodology that possesses inherent weaknesses when applied to economics networks: the corresponding algorithmic calculation imposes unnecessary restrictions in the optimization procedure that may result in sub-optimal solutions.

The second innovation is the introduction of the *Threshold-Minimum Dominating Set* (T-MDS) methodology. The T-MDS is an essential improvement of the MDS optimization tool (MDS has so far been successfully applied in wireless computer networks; see Cheng *et al*, 2003 and Wu *et al*, 2006). We enhance the MDS methodology by introducing a thresholding step to remove all the uninformative edges of the network. The resulting network and the identified *T-MDS nodes* are used to describe the evolution of business cycle convergence patterns in Europe.

The rest of this study is organized in the following way: in Section 2 we present the selected data set. In Section 3 we describe the methodological context. In Section 4 we deliver our empirical analysis while in Section 5 we briefly summarize the paper and conclude.

## 2. The Data Set

In order to study whether the business cycles of the 22 European economies converged or moved further apart after the introduction of the euro, we gather data on their real Gross Domestic Product (GDP). These are annual series that span the period from 1985 to 2011. Thus, we include 14 years before the introduction of the euro (1985-1998) and 13 years of the post-euro era (1999-2011). The rolling windows are constructed such that the first window spans a period entirely before the introduction of the euro, while the last window lies entirely within the euro era. The 22 countries included in the study are presented in Table 1.

**Table 1**: The 22 European countries involved in the study

| Eurozone | Non-Eurozone |
|---|---|
| Austria | Bulgaria |
| Belgium | Denmark |
| Cyprus | Hungary |
| Finland | Latvia |
| France | Romania |
| Germany | Sweden |
| Greece | United Kingdom |
| Ireland | |
| Italy | |
| Luxembourg | |
| Malta | |
| Netherlands | |
| Portugal | |
| Slovak Republic | |
| Spain | |

These are 15 Eurozone countries and 7 European countries that do not participate in the monetary union but have close ties to it. We decided to include these 7 countries motivated by Tinbergen's (1962) gravity model of trade and the consequent endogeneity hypothesis of Frankel and Rose (1998). According to these studies, increased trade between a group of countries is expected to induce business cycle synchronization. Real GDP levels are obtained from the World Bank's database in annual frequency. From these data we get the annual GDP growth rates that are used for the rest of our analysis. Figure 1 depicts the growth rates of the 22 countries for the period 1986-2011.

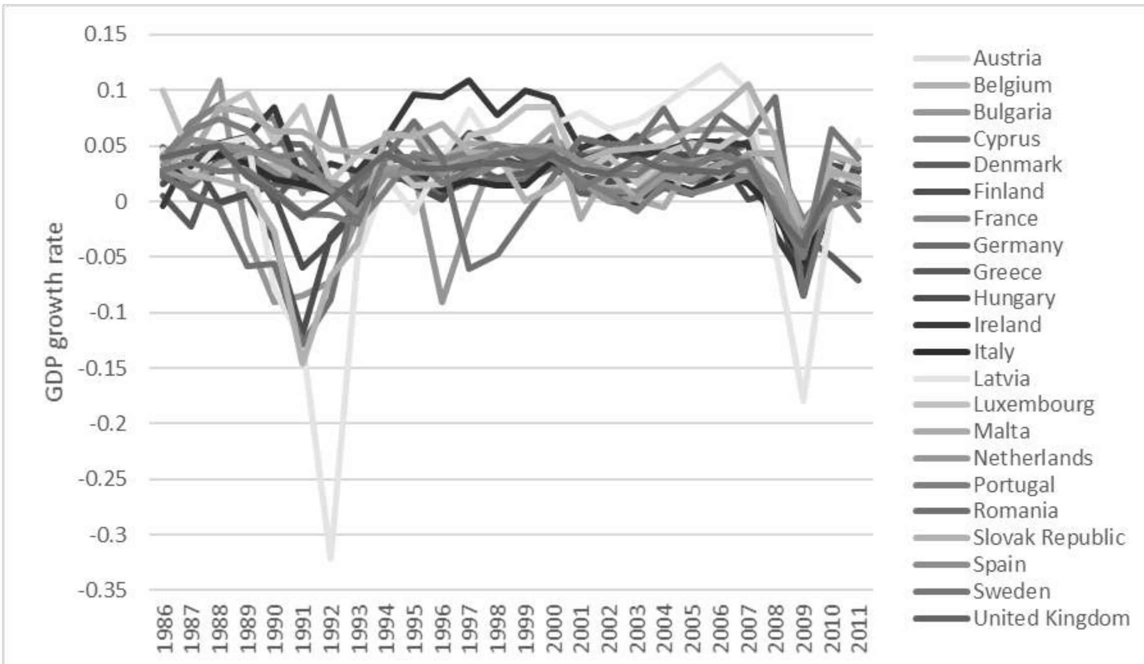


**Figure 1**. GDP Growth Rates of 15 Eurozone and 7 non-Eurozone European countries

## 3. The Methodology

### *3.1. Network construction*

In representing a complex economic system as a network or more formally, a graph (*G*), economic agents are defined as nodes (*N*) and the similarity of the nodes in terms of the selected variable takes the form of edges (*E*) that link these nodes; in mathematical terms $G = (N, E)$. In this study, the nodes of the network represent the 22 European countries and the edges that connect them represent the cross-correlations of the GDP growth rates using the Pearson correlation coefficient $r_{i,j}$ that is calculated as follows:

$$r_{i,j} = r_{j,i} \triangleq \frac{cov(GDP_i, GDP_j)}{\sqrt{var(GDP_i)var(GDP_j)}} . \tag{1}$$

The correlation coefficient takes values in [-1,1]: values near -1 indicate a strong negative correlation while values close to 1 indicate a strong positive correlation. A value of $r \cong 0$ implies no correlation.

We then construct the Threshold-Minimum Dominating Sets (T-MDS) using a rolling window approach and examine the evolution of the network's topology through time employing six alternative network metrics: the total number of edges, the network density, the number of dominant and isolated nodes, the T-MDS size and the node degree. The implementation of a rolling window introduces a dynamic feature to our analysis.

*3.2. Threshold-Minimum Dominating Set*

In order to identify the Threshold-Minimum Dominating Set (T-MDS) we first consider the classic Minimum Dominating Set (MDS) concept. We start by giving the definition of a simple dominating set:

**Definition 1:** A *dominating set* of a graph *G* is a subset of nodes $DS \subseteq N$ such that every node $\notin DS$ is connected to at least one element of the *DS* by one or more edges i.e. $\forall i \notin DS, \exists\, j \in DS : e_{ij} \in E$.

The definition of the *DS* describes such a subset of *N* that every node in the network is either adjacent to a *DS* node or is a *DS* node itself. Thus, since the network is constructed based on the calculation of pairwise correlations, the behavior of any non-*DS* node **can** be represented by the behavior of its adjacent *DS* nodes.

We create *n* binary variables $x_i, i = 1, \ldots, n$ one for each node of the network such that

$$x_i = \begin{cases} 0, & if\ i \notin DS \\ 1, & if\ i \in DS \end{cases},$$

to represent the node's membership status in the DS. The variables can be represented in the vector form $\mathbf{x} = [x_1, x_2, \ldots, x_n]$.

The DS assumption takes the mathematical form of:

$$x_i + \sum_{j \in \mathrm{B}(i)} x_j \geq 1, i = 1, \ldots, n, \tag{2}$$

where $\mathrm{B}(i)$ stands for the neighboring node set of node $i$. Equation (2) implies that each network node can be either a) a Dominating Set node $(x_i = 1)$ or b) adjacent to one or more DS nodes $(\exists j \in \mathrm{N}(i): x_j = 1)$.

We can identify many *DS*'s for every network. Nonetheless, we are only interested in the minimum sized ones:

**Definition 2**. The Minimum Dominating Set (MDS) is the *DS* with the smallest cardinality.

This condition is satisfied through the next equation:

$$\min_{\mathbf{x}} f(\mathbf{x}) = \sum_{i=1}^{n} x_i. \tag{3}$$

Thus, the calculation of the MDS is reduced to minimizing Equation (3) under the constraints in (2).

The MDS can adequately describe the collective behavior of an entire network by using only a minimum required set of nodes. By studying these nodes a researcher is able to understand the topology of their neighboring ones. Nevertheless, in a correlation-based economics network low correlation edges represent nodes with dissimilar behavior and should not be taken into account in the identification of the MDS. For example, if two countries represented by two nodes are linked with an edge displaying a correlation value of *p=0.2*, in our case they should not be considered adjacent since they are practically uncorrelated. We overcome this inadequacy of the classic MDS optimization procedure in economics networks by imposing a threshold on the correlation values.

**Definition 3:** *We call a* ***Threshold – Minimum Dominating Set*** *the two step methodology for the identification of the most representative nodes of a network, defined as:*

**Step 1.** *A thresholding on the edges' weights leading to the elimination of all edges that correspond to low correlation values.*

**Step 2.** *The identification of the MDS nodes on the remaining network.*

The thresholding procedure may lead to the appearance of *isolated nodes*, (i.e. nodes without any edges connecting them to the rest of the network) and a smaller interconnected network. The second step of Definition 3 identifies the nodes we call *dominant nodes*: the nodes that can efficiently represent the collective behavior of the interconnected network since every network node must be either an element of the dominant nodes' set or directly connected to one or more dominant nodes. The definition of the Threshold-Minimum Dominating Set requires that every isolated node must be included in it. As a result, the T-MDS is composed from the union of the isolated and the dominant nodes sets: T-MDS = $I \cup C$, where $I$ and $C$ are the sets of the isolated and the dominant nodes respectively. However, it is crucial to distinguish the subset of the *isolated nodes* from the *dominant nodes*: the two subsets have entirely different and independent features and thus their topological characteristics should not be examined as a cohesive network. The countries that correspond to isolated nodes exhibit highly idiosyncratic macroeconomic behavior and thus cannot represent (or be represented by) any other country.

According to the above, the T-MDS is a) by construction an improvement over the simple MDS calculation, as by introducing the thresholding step only the relevant in terms of similarity edges remain and are used in the optimization algorithm of the T-MDS and b) in comparison to the widely used in the literature Minimum Spanning Tree (MST) methodology, it does not impose any unnecessary restrictions (no-loop) in the algorithmic calculation for applications in economics networks as the MST does. The MST, results in a network partition that may include uninformative and rather misleading edges (low correlation values) due to the no-loop restriction.

*3.3. Network metrics*

The *degree* of a node in a graph is the number of edges incident to it, given by the following equation:

$$k_i = |B(i)|. \tag{4}$$

In a network of *n* nodes the maximum node degree is $n-1$ and the minimum degree is 0 indicating an isolated node. In our analysis, the node degree describes the country integration in the network: a high node degree indicates that the specific country is well integrated into the network; conversely a low node degree indicates that the respective country presents an idiosyncratic business cycle and has failed to align its economy with most of the network's countries.

*Density* is a Graph Theory metric that describes how well connected a network is, calculated through the following equation:

$$d = \frac{\frac{\sum_{i=1}^{n} k_i}{2}}{\frac{n(n-1)}{2}} = \frac{\sum_{i=1}^{n} k_i}{n(n-1)}. \tag{5}$$

Thus, the network density is calculated by dividing the number of actual edges existing in the network to the maximum theoretical number of edges that a complete network of $n$ nodes would contain. The metric of network density takes values in [0, 1]: values near zero indicate a sparse network with a small number of edges while greater values refer to a more connected network with the case of $d = 1$ representing a complete network where every node is connected to every other. For the purposes of our analysis, the value of network density indicates the similarity degree of the selected economies' GDP growth rates: the more synchronized the economies' business cycles are the higher the density value will be. On the other hand if the European economies present asynchronous GDP growth cycles then a rather sparse network should be observed.

In any arbitrary network the T-MDS size can take values between two extreme instances; if the network is *complete* (every node is connected to every other) the T-MDS size will be 1 with every node being a possible unique MDS node; on the other end, if the network is totally disconnected (all nodes are isolated) the T-MDS size will equal the number of the nodes in the network. As described above, small T-MDS cardinality values indicate a rather dense network and greater T-MDS cardinality values correspond to a sparser network. A dense network by definition exhibits higher correlations between the network's nodes. In our case, a dense network with low T-MDS cardinality provides evidence of business cycle synchronization between the 22 European economies. Therefore, by calculating the T-MDS size for consecutive rolling windows we can observe the dynamic evolution of the European countries' GDP growth rates co-movement. An intertemporally "shrinking" T-MDS indicates that more edges survive the threshold and that the GDP growth rate correlations are getting stronger and the business cycles are converging. On the contrary, an expanding T-MDS size would indicate that GDP growth rate correlations are weaker and the network is becoming less connected as fewer edges are able to "survive" the given threshold providing evidence that the business cycles diverge.

The metric of density provides collective information for a network: by calculating it for rolling windows we can observe the dynamic transition of the network of the business cycles of the European economies under consideration. Increasing over time density values will indicate a denser network with a higher co-movement of business cycles while smaller density values will stress divergence among the European countries.

On the other hand, the metric of node degree provides a more disaggregated picture of the co-movement patterns: By studying the node degree for each individual economy through time we can infer on the process of its individual business cycle integration to the rest of the network. If the node degree is found to increase along the rolling window, then this provides evidence in favor of increased convergence to the rest of the network. On the other hand, a decreasing node degree will indicate that the respective country is diverging from the rest of the network GDP growth rate pattern.

### *3.4. Rolling window analysis and threshold level selection*

We apply the Threshold-Minimum Dominating Set methodology and calculate the network's metrics within a rolling window approach. By doing this, we move from a static network analysis and introduce a dynamic feature that is necessary for the scope of this study and study the evolution of GDP growth rate correlations intertemporally.

With respect to the selection of the size of the rolling window, in general, narrow windows may induce error in the estimation of the correlation coefficient while wider ones limit the number of total windows that can be used to examine the intertemporal evolution of the network. In the empirical section of this study we decide to use a rolling window with size 13. This window a) is wide enough for meaningful correlation calculations and b) has the benefit that the first and last windows, 1986-1998 and 1999-2011, represent periods entirely within the pre- and post-euro era respectively.

The level of the imposed threshold determines the selected significance under which two countries will be considered practically uncorrelated and their business cycles divergent. The threshold selection should not be considered a trivial step: Raising the threshold level induces a stricter rule and is likely to cause the appearance of more isolated nodes. On the contrary, a low threshold will allow more edges to "survive" and consequently more nodes to integrate into the network. However, this will also allow for the existence of edges that are not only non-informative but they are rather misleading as described above. In determining the threshold we should keep in mind two things: first, the threshold should be sufficiently high as to highlight the strong positively correlated business cycles. Secondly, it is apparently crucial that the threshold level remains the same in both network instances (pre- and post-euro) so that we can infer meaningful results of the selected metrics. In this study, after testing various alternative threshold levels (available ad hoc) that produce qualitatively similar results, we report the empirical results for the case of threshold level of $p = 0.75$.

## 4. The Empirical Results

As discussed above, we analyze the network of the 22 European countries using a rolling window of size 13 that results in a total of 14 consecutive windows and a threshold of $p = 0.75$. Thus, we create 14 T-MDS networks and for each one of these we report six alternative metrics.

### *4.1. Network results*

In Table 2, for each window from the first column we report the following metrics on the network's topology: the number of total edges in the network, the network density, the number of Dominant and Isolated Nodes and finally in the last column the T-MDS size.

**Table 2**: Rolling window T-MDS analysis

| Time window | Network edges | Network density | Dominant nodes | Isolated nodes | T-MDS size |
|---|---|---|---|---|---|
| 1986-1998 | 22 | 0.095 | 4 | 7 | 11 |
| 1987-1999 | 22 | 0.095 | 5 | 6 | 11 |
| 1988-2000 | 31 | 0.134 | 5 | 4 | 9 |
| 1989-2001 | 32 | 0.139 | 4 | 5 | 9 |
| 1990-2002 | 26 | 0.113 | 7 | 4 | 11 |
| 1991-2003 | 26 | 0.113 | 6 | 4 | 10 |
| 1992-2004 | 32 | 0.139 | 5 | 4 | 9 |
| 1993-2005 | 42 | 0.182 | 3 | 5 | 8 |
| 1994-2006 | 14 | 0.061 | 5 | 7 | 12 |
| 1995-2007 | 14 | 0.061 | 5 | 9 | 14 |
| 1996-2008 | 27 | 0.117 | 3 | 8 | 11 |
| 1997-2009 | 132 | 0.571 | 2 | 1 | 3 |
| 1998-2010 | 121 | 0.524 | 3 | 0 | 3 |
| 1999-2011 | 115 | 0.498 | 3 | 1 | 4 |

The empirical results show that as we move from the first window (1986-1998) to the last (1999-2011) the network is becoming much denser: the number of edges in column 2 gradually increases from 22 to 115, revealing a convergence pattern between the business cycles of the European economies. With time, more edges are able to survive the given threshold. The number of network edges and the T-MDS size remains relatively stable for the windows 1986-1998 to 1996-2008. After that in the last three windows of 1997-2009, 1998-2010 and 1999-2011 the number of edges increases significantly to more than four times the previous level; from 27 to 132, 121 and 115 respectively. Using a formal Chow break-point test, the null hypothesis of no breaks in the 1997-2009 window is rejected with probability $p = 0.000$. Moreover, in the same windows, the number of T-MDS nodes decreases sharply from 11 to 3, 3, and 4 respectively providing evidence of an increased synchronization of the 22 European economies. Figure 2 depicts these results.

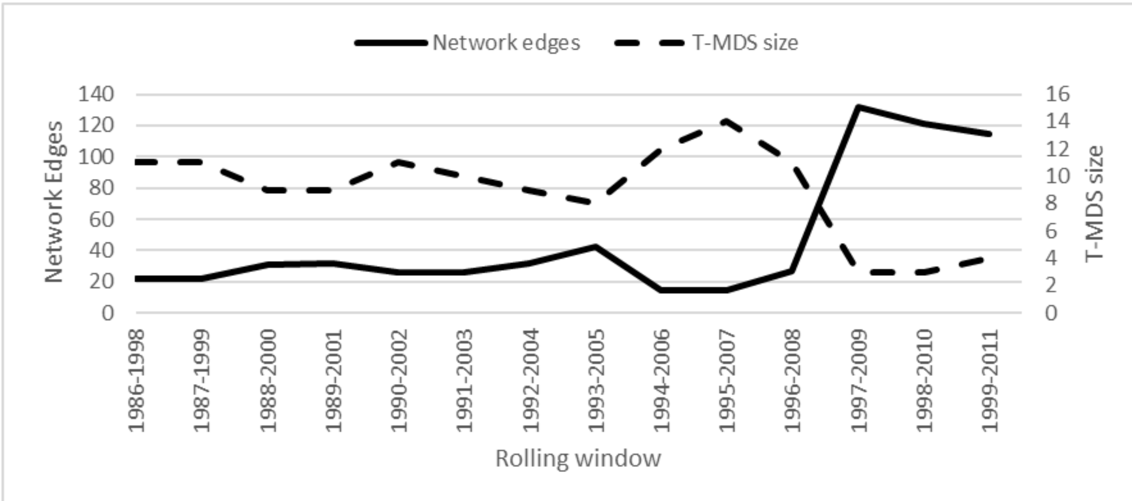


**Figure 2**. Evolution of the number of network edges and the T-MDS size along the rolling window

As the T-MDS is the sum of the dominant and the isolated nodes, the observed decrease in the T-MDS size is mainly driven by the decrease in the number of isolated nodes. The isolated nodes indicate economies with an entirely idiosyncratic business cycle behavior. The number of isolated nodes falls from 7 in the first window of 1986-1998 to 1, 0 and 2 in the last three windows respectively.

Moreover, the metric of the network density reported in the third column of Table 2 starts with a relatively low value of 0.095 (approximately 10%), remains relatively stable in most window instances, and increases sharply reaching the value of 0.498 in the last window. This result indicates that the GDP growth rate network of the 22 European economies has reached a high level of interconnectedness in recent years, while it had reached an even greater percentage of 57.1% in the 1997-2010 window frame. In total, the network's density in the last three windows is more than five times higher than it was in the first window.

The dynamic evolution of all these metrics provides evidence in support of a higher degree of business cycle co-movement. The 22 European countries seem to converge in terms of real GDP growth rates.

Interpreting these results, we must highlight two important issues: a) this results may be driven in part by the manifestation of the recent financial crisis that reduced the real GDP growth rates of most European economies. Nonetheless, the corresponding windows where the cross-country real GDP correlations are calculated include data for 13 years and thus the effects of the crisis in 2008-2009 are significantly dampened. b) Our last window that spans the period 1999-2011, covers entirely the post-euro era as the common currency was introduced in 1999 for the Eurozone countries with the exception of Greece which entered the Eurozone in 2001.

*4.2. Country specific results*

In this section we move from the general network metrics and focus to a country-level analysis. These results are of course qualitatively the same as the ones in Table 2. Table 3 reports the node degree for each country and for all rolling windows used. It is interesting to note here that the first window spans a period entirely before the introduction of the common currency, while the last window lies entirely within the euro era. We report the same information in an optical illustration in Figure 3, depicted the rolling node degree of each country individually, across all 14 windows. We observe that, in general, the node degree metric for each country although relatively stable for the first 10 windows, rises sharply in the last 3 windows. More specifically, the node degree for the 22 European countries increased by an average 8.5 degrees from the initial window of 1986-1998 to the final one of 1999-2011. This of course provides evidence in support of real GDP growth rate convergence in the post-euro era.

**Table 3**. Rolling window node degree

| | 86-98 | 87-99 | 88-00 | 89-01 | 90-02 | 91-03 | 92-04 | 93-05 | 94-06 | 95-07 | 96-08 | 97-09 | 98-10 | 99-11 | Convergence Degree |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Austria** | 2 | 2 | 4 | 3 | 2 | 3 | 4 | 7 | 3 | 4 | 5 | 16 | 16 | 14 | 12 |
| **Belgium** | 3 | 3 | 3 | 4 | 3 | 3 | 6 | 7 | 1 | 1 | 2 | 15 | 14 | 14 | 11 |
| **Bulgaria** | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 2 | 7 | 7 | 6 |
| **Cyprus** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 11 | 13 | 12 | 12 |
| **Denmark** | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 0 | 1 | 3 | 17 | 16 | 16 | 16 |
| **Finland** | 5 | 5 | 5 | 6 | 6 | 6 | 5 | 10 | 2 | 2 | 7 | 17 | 17 | 16 | 11 |
| **France** | 4 | 4 | 5 | 5 | 4 | 5 | 7 | 9 | 4 | 4 | 6 | 17 | 16 | 16 | 12 |
| **Germany** | 1 | 1 | 1 | 1 | 1 | 0 | 4 | 8 | 1 | 1 | 1 | 13 | 8 | 8 | 7 |
| **Greece** | 0 | 0 | 2 | 1 | 1 | 1 | 2 | 3 | 0 | 0 | 0 | 10 | 3 | 1 | 1 |
| **Hungary** | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 1 | 0 | 0 | 11 | 9 | 9 | 6 |
| **Ireland** | 0 | 1 | 1 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 15 | 15 | 14 | 14 |
| **Italy** | 4 | 4 | 5 | 3 | 2 | 2 | 3 | 5 | 1 | 0 | 4 | 17 | 16 | 16 | 12 |
| **Latvia** | 1 | 1 | 2 | 2 | 2 | 2 | 4 | 2 | 0 | 0 | 0 | 14 | 13 | 11 | 10 |
| **Luxembourg** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 6 | 15 | 14 | 14 | 14 |
| **Malta** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| **Netherlands** | 1 | 2 | 3 | 6 | 1 | 2 | 3 | 5 | 3 | 4 | 3 | 14 | 13 | 12 | 11 |
| **Portugal** | 3 | 3 | 5 | 3 | 3 | 2 | 4 | 5 | 2 | 2 | 3 | 10 | 11 | 9 | 6 |
| **Romania** | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 2 |
| **Slovak Republic** | 4 | 4 | 3 | 3 | 4 | 4 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | -2 |
| **Spain** | 4 | 4 | 8 | 7 | 5 | 3 | 4 | 4 | 2 | 2 | 5 | 17 | 16 | 16 | 12 |
| **Sweden** | 3 | 2 | 4 | 5 | 5 | 5 | 5 | 6 | 2 | 2 | 4 | 16 | 10 | 9 | 6 |
| **United Kingdom** | 5 | 4 | 5 | 6 | 5 | 5 | 2 | 0 | 0 | 0 | 2 | 15 | 12 | 12 | 7 |

*The last column of Table 3 contains the total convergence degree of each country calculated as the difference between the first and last rolling window instances*

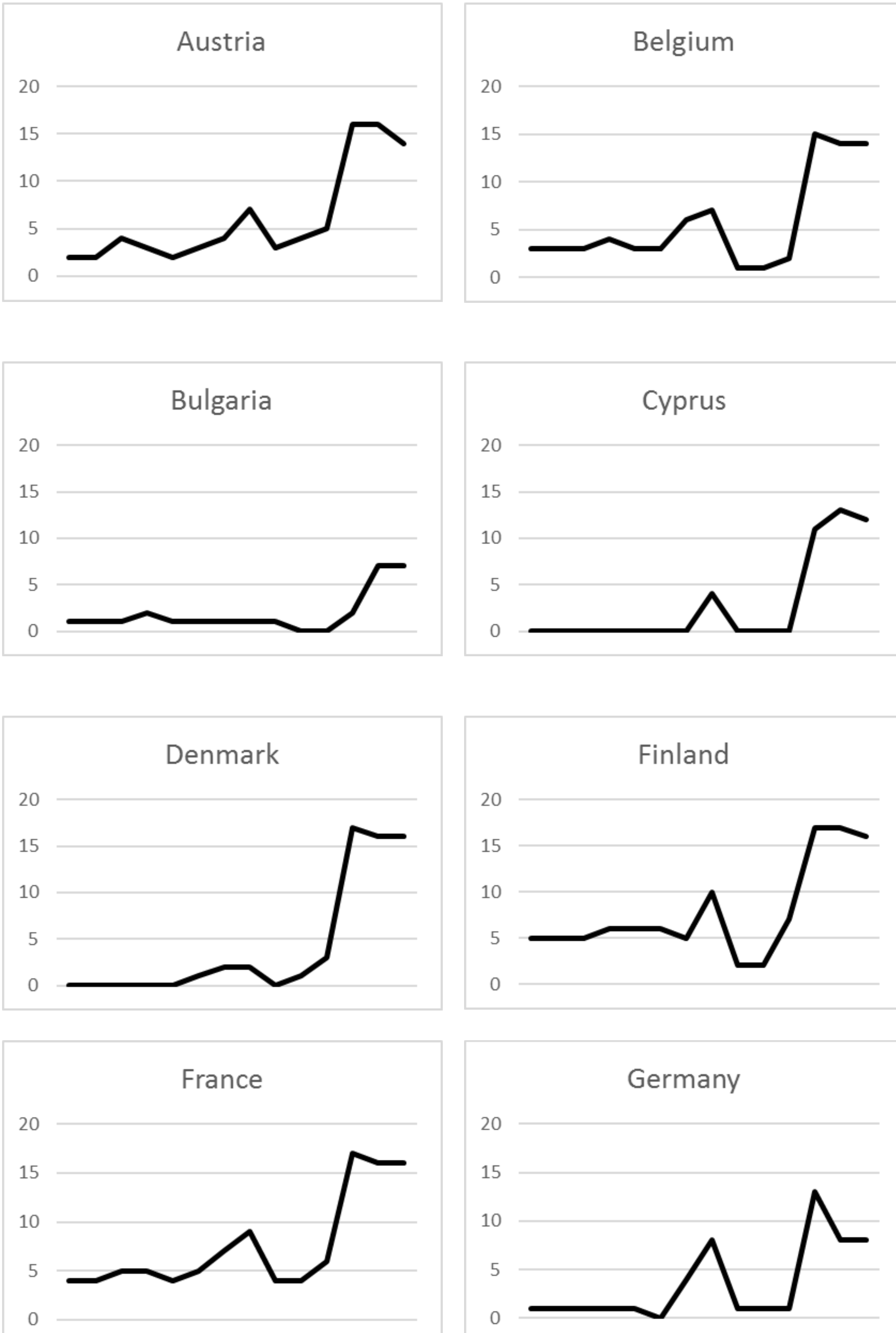


**Figure 3**. Rolling node degree of each country

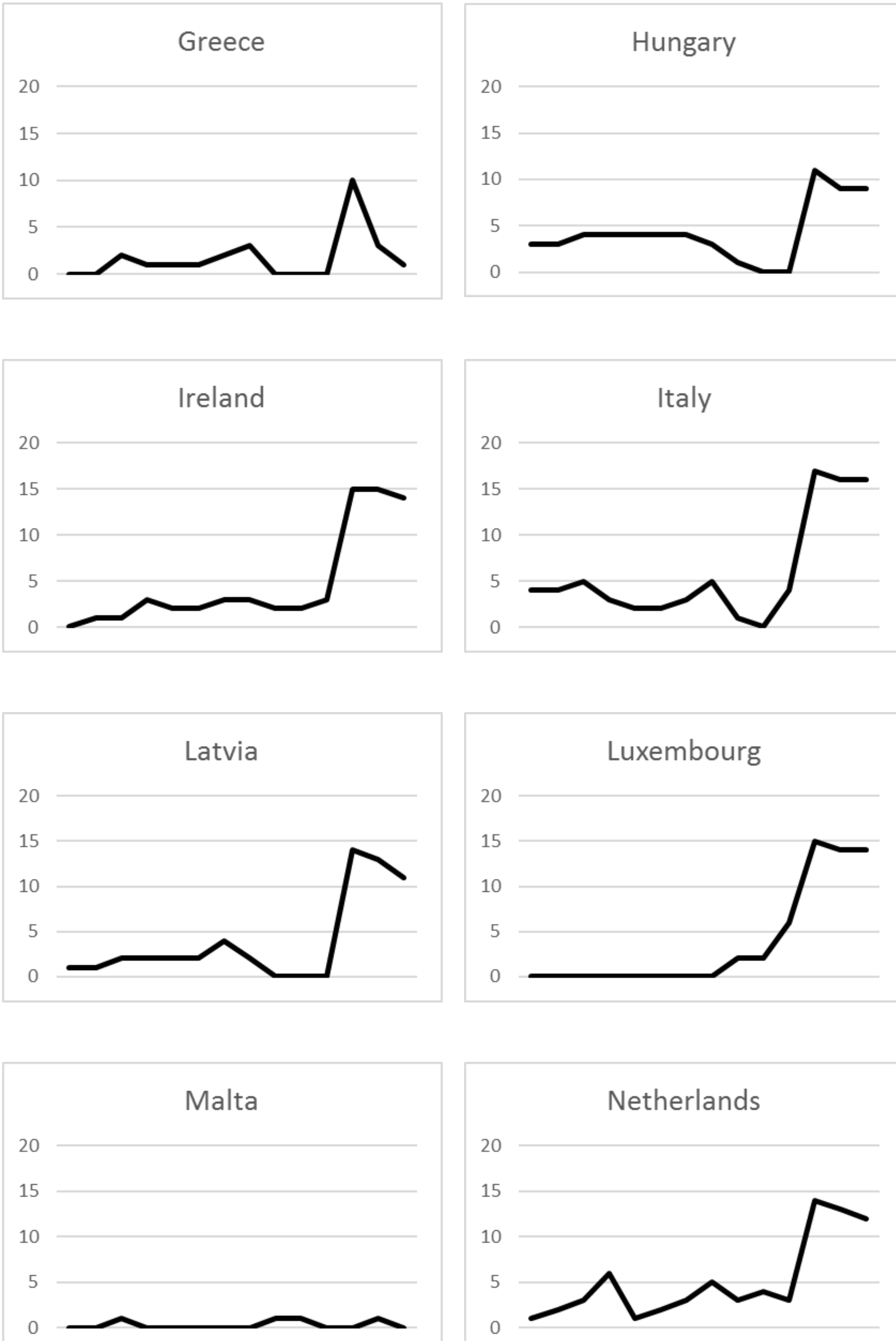


**Figure 3** (continued). Rolling node degree of each country

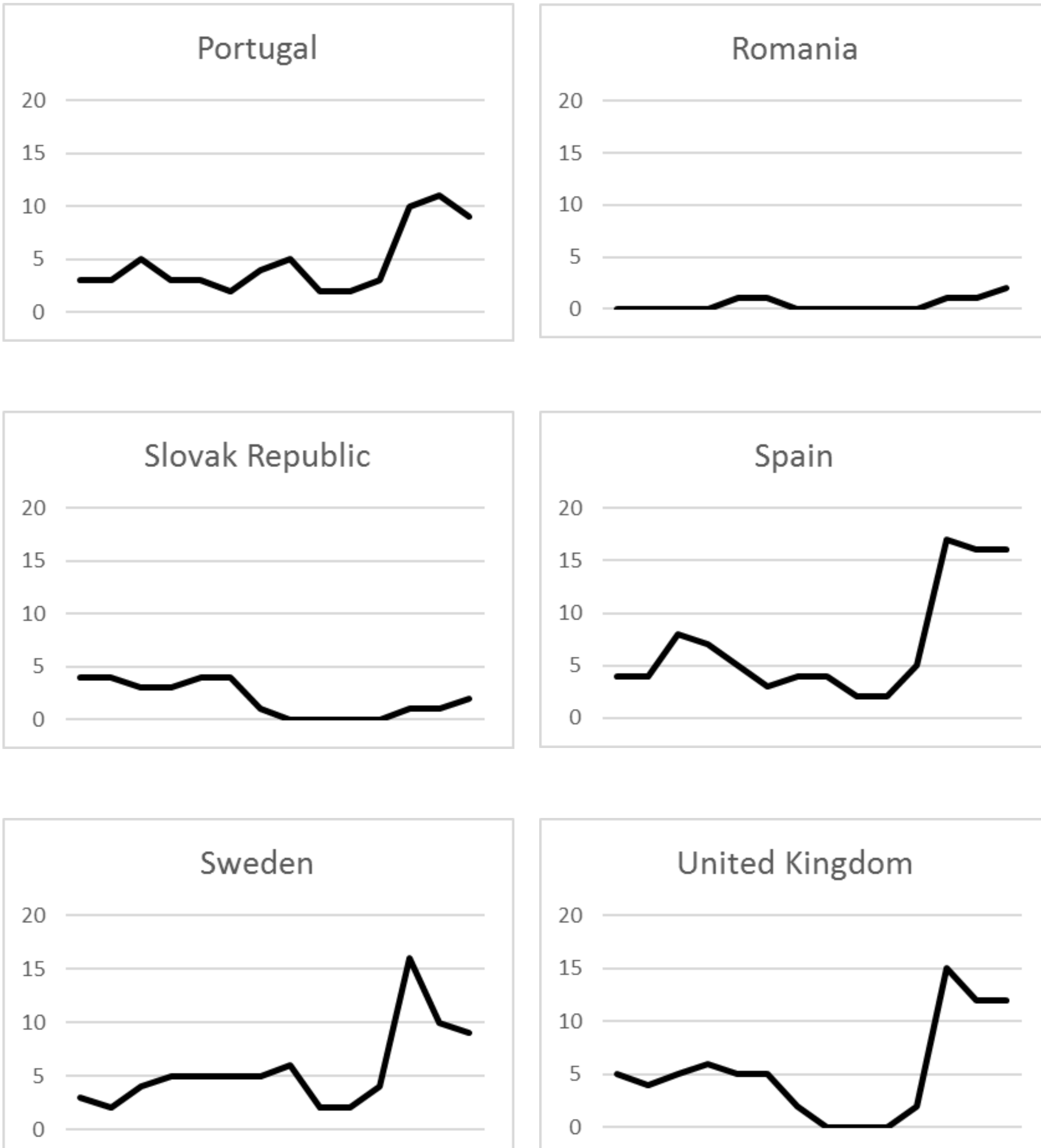


**Figure 3** (continued). Rolling node degree of each country

At the country level, some examples of this synchronization are: Austria that started with a node degree of 2, indicating that its business cycle coincided with only 2 other countries from the 22 in our sample. Nonetheless, Austria's node degree rose to 14 in the last euro-era window implying a significant degree of business cycle synchronization with the rest of the 22 European countries. Similarly, for Spain the node degree was 4 in the first window and rose to 16 and Denmark, Finland and France that started with a node degree of 0, 5 and 4 respectively, show a node degree of 16 in the last window. Although most countries' topological features exhibit a momentum towards a higher degree of business cycle synchronization, there are also few counter-examples: the Slovak republic, moved from 4 to 2 and Malta maintained a 0 node degree implying no convergence. An interesting case is that of Greece: it starts with a completely idiosyncratic business cycle with node degree 0 that remains relatively stable until it rises sharply to 10 in the 1997-2009 window (the end of 2009 marks the unfolding of the Greek debt crisis) and then it falls to 3 and 1 in the last two windows. This divergence of Greece in the last windows may be a result of the manifested fiscal crisis in the country that started in 2009. The best momentum towards convergence from the first to the last window is exhibited by Denmark that demonstrates a 16 node degree increment followed by Ireland and Luxemburg with 14 and Austria, Cyprus, France, Italy and Spain by 12. In Table 4 we summarize these results by ranking the 22 countries by the degree of convergence momentum. The same information is graphically illustrated in Figure 4.

**Table 4**. Total Country Convergence Degree

| Country | Convergence Degree | Country | Convergence Degree |
|---|---|---|---|
| Denmark | 16 | Latvia | 10 |
| Luxembourg | 14 | United Kingdom | 7 |
| Ireland | 14 | Germany | 7 |
| Spain | 12 | Sweden | 6 |
| Italy | 12 | Portugal | 6 |
| France | 12 | Hungary | 6 |
| Cyprus | 12 | Bulgaria | 6 |
| Austria | 12 | Romania | 2 |
| Netherlands | 11 | Greece | 1 |
| Finland | 11 | Malta | 0 |
| Belgium | 11 | Slovak Republic | -2 |

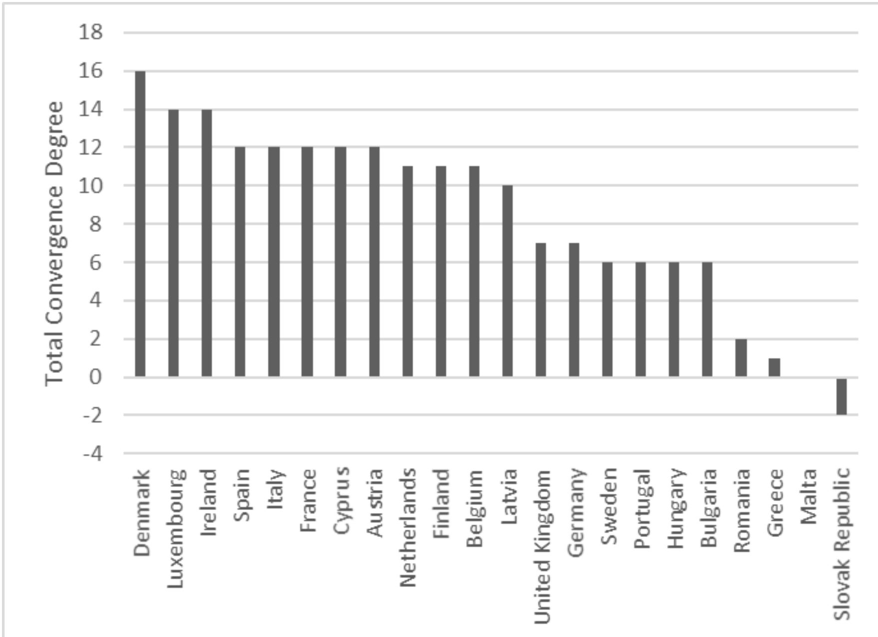


**Figure 4**. Total country convergence degree

*4.3. Neighborhood specific results*

In Table 5 we provide a detailed list of each country's neighbors for the first (1986-1998) and the last window (1999-2011). The same information is illustrated in network form in Figures 5a and 5b. By doing this, we can analyze the evolution of the neighborhoods' formation in time. In the last column of Table 5 we mark with bold in the 1999-2011 window the countries that remain neighbors for each country both in the first and the last window. In general, each country's neighbors in the 1986-1998 window remain in its neighborhood for the final 1999-2011 window as well. Exceptions to this finding are: a) the U.K. for Bulgaria, b) the Slovak republic for Finland, Hungary, Sweden and the U.K and c) Bulgaria for the U.K. Only the Slovak republic forms an entirely different neighborhood in the last window: from one with Finland, Hungary, Sweden and the U.K to one that includes only Bulgaria and Romania. This last finding might be explained by the gravity model of trade (Tinbergen, 1962) and the consequent "endogeneity hypothesis" of Frankel and Rose (1998) according to which increased trade is expected to induce increased business cycle convergence.

From Figures 4a and 4b we observe that in the pre-euro period, Germany forms a separate sub-network together with Austria and the Netherlands. However in the single currency era, while all three countries become well connected with several countries, Germany still remains uncorrelated with Greece, Portugal and Spain. These three southern European countries were severely hit by debt crises in recent years and required large rescue funds from the E.U., the I.M.F. and the E.C.B. in the effort to avoid a default. From a policy perspective this finding highlights and may explain the difficulty of those crisis ridden countries to recover. Germany is the most influential member of the

E.U. due to the size of its economy and its central political role. The German business cycle is not correlated to the three southern countries as indicated by the lack of any edge connecting them. As a result, and especially during the above mentioned debt crises, the implemented by the ECB monetary policy cannot be efficient to Greece, Portugal and Spain.

**Table 5**. Node degree and set of neighbors of each node before and after the adoption of euro

| | Window 1986 - 1998 | | Window 1999 - 2010 | |
|---|---|---|---|---|
| **Country** | **Degree** | **Neighbors** | **Degree** | **Neighbors** |
| Austria | 2 | Germany, Netherlands | 14 | Belgium, Cyprus, Denmark, Finland, France, **Germany**[3], Ireland, Italy, Latvia, Luxembourg, **Netherlands**, Spain, Sweden, U.K. |
| Belgium | 3 | France, Italy, Spain | 14 | Austria, Cyprus, Denmark, Finland, **France**, Germany, Ireland, **Italy**, Portugal, Luxembourg, Netherlands, **Spain**, Sweden, U.K. |
| Bulgaria | 1 | U.K. | 7 | Cyprus, Finland, Hungary, Latvia, Luxembourg, Slovak Republic, Spain |
| Cyprus | 0 | (-) | 12 | Austria, Belgium, Bulgaria, Denmark, Finland, France, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain |
| Denmark | 0 | (-) | 16 | Austria, Belgium, Cyprus, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Luxembourg, Netherlands, Portugal, Spain, Sweden, U.K. |
| Finland | 5 | Hungary, Latvia, Slovak Republic, Sweden, U.K. | 16 | Austria, Belgium, Bulgaria, Cyprus, Finland, France, Germany, **Hungary**, Ireland, Italy, **Latvia**, Luxembourg, Netherlands, Portugal, Spain, **U.K**. |
| France | 4 | Belgium, Italy, Portugal, Spain | 16 | Austria, **Belgium**, Cyprus, Denmark, Finland, Germany, Hungary, Ireland, **Italy**, Latvia, Luxembourg, Netherlands, **Portugal**, **Spain**, Sweden, U.K. |
| Germany | 1 | Austria | 8 | **Austria**, Belgium, Denmark, Finland, France, Italy, Netherlands, Sweden |
| Greece | 0 | (-) | 1 | Spain |
| Hungary | 3 | Finland, Slovak Republic, U.K. | 9 | Bulgaria, Denmark, **Finland**, France, Ireland, Latvia, Netherlands, Spain, **U.K**. |
| Ireland | 0 | (-) | 14 | Austria, Belgium, Cyprus, Denmark, Finland, France, Hungary, Italy, Latvia, Luxembourg, Netherlands, Portugal, Spain, U.K. |
| Italy | 4 | Belgium, France, Portugal, Spain | 16 | Austria, **Belgium**, Cyprus, Denmark, Finland, **France**, Germany, Hungary, Ireland, Latvia, Luxembourg, Netherlands, **Portugal**, **Spain**, Sweden, U.K. |
| Latvia | 1 | Finland | 11 | Austria, Bulgaria, Denmark, **Finland**, France, Hungary, Ireland, Italy, Luxembourg, Spain, U.K. |
| Luxembourg | 0 | (-) | 14 | Austria, Belgium, Cyprus, Denmark, Finland, France, Ireland, Italy, Latvia, Netherlands, Portugal, Spain, Sweden, U.K. |
| Malta | 0 | (-) | 0 | (-) |
| Netherlands | 1 | Austria | 12 | **Austria**, Belgium, Cyprus, Denmark, Finland, France, Germany, Ireland, Italy, Luxembourg, Portugal, Spain |
| Portugal | 3 | France, Italy, Spain | 9 | Belgium, Cyprus, Denmark, **France**, Ireland, **Italy**, Luxembourg, Netherlands, **Spain** |
| Romania | 0 | (-) | 2 | Bulgaria, Slovak Republic |
| Slovak Republic | 4 | Finland, Hungary, Sweden, U.K. | 2 | Bulgaria, Romania |
| Spain | 4 | Belgium, France, Italy, Portugal | 16 | Austria, **Belgium**, Bulgaria, Cyprus, Denmark, Finland, **France**, Greece, Hungary, Ireland, **Italy**, Latvia, Luxembourg, Netherlands, **Portugal**, U.K. |
| Sweden | 3 | Finland, Slovak Republic, U.K. | 9 | Austria, Belgium, **Finland**, France, Germany, Italy, Luxembourg, Portugal, **U.K.** |
| United Kingdom | 5 | Bulgaria, Finland, Hungary, Slovak Republic, Sweden | 12 | Austria, Belgium, Denmark, **Finland**, France, **Hungary**, Ireland, Italy, Latvia, Luxembourg, Spain, **Sweden** |

[3] The countries that are strongly correlated in both time periods are highlighted with bold font

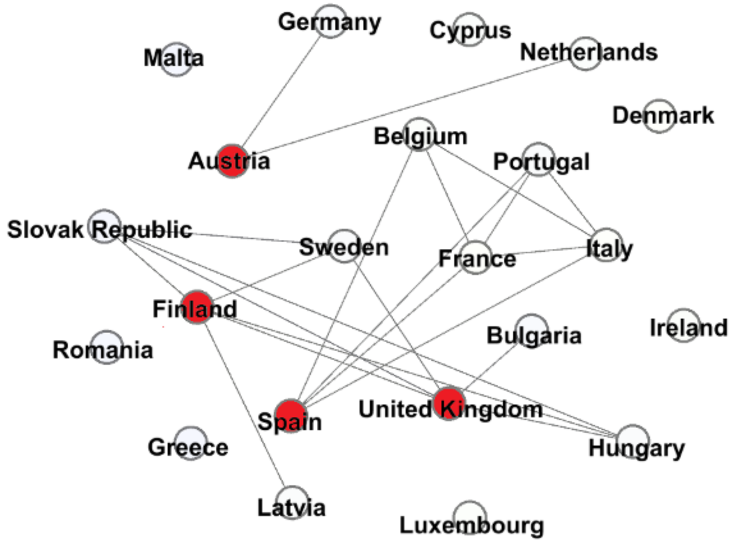


**Figure 5a**. Network topology and dominant nodes (colored nodes) for the pre-euro period (1986-1998)

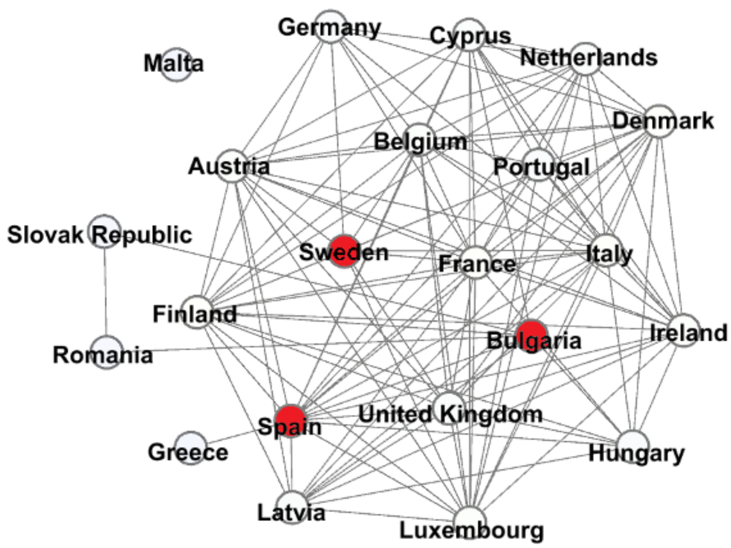


**Figure 5b**. Network topology and dominant nodes (colored nodes) for the post-euro period (1999-2011)

It is also interesting to observe the integration course of the European countries after dividing them in Eurozone participants and non-Eurozone ones. We observe that the countries participating in the Eurozone have increased their real GDP growth rate synchronization far more than the non-Eurozone ones. The exceptions from this pattern are Denmark and the U.K. who are very well connected in the post-euro period with node degrees of 16 and 12 respectively. These countries had formerly met the convergence criteria but decided not to adopt the euro for political and internal reasons that are beyond the scope of this paper. On the other hand, Bulgaria, Hungary, Latvia and Romania are among the most recent E.U. entrants. However, within a brief period of time, they have managed to converge to the other Eurozone members. This indicates that they may constitute good candidates to join the monetary union, in terms of business cycle synchronization.

A common empirical finding is that the E.M.U. economies do not present a common, uniform business cycle; rather, they are split in two groups with distinct cycles forming a so-called dominant-periphery status (Canova *et al*, 2007; Aguiar and Soares, 2011; Cancelo, 2012). Our results are in contrast to these studies: we observe that periphery countries become strongly correlated with many E.U. dominant countries after the adoption of the euro. This is more obvious for Italy, Ireland and Spain which in the 1990-2011 period appear to be among the most well-connected (synchronized) countries. Finally, we examined the convergence evolution between the euro-newcomers and the rest of the network. This was motivated by the work of Savva *et al* (2010), who argue that since the early 1990s, all E.U. newcomers and negotiating counties included in the study have substantially increased their business cycle convergence with the "old" E.M.U. members, However, our results are mixed and a uniform conclusion cannot be drawn since: a) Malta displays an atypical business cycle both in the pre-euro as well as in the post-euro period, b) Slovakia is the only country with a smaller node degree in the single currency area than before, while c) only Cyprus displays significant convergence in the post-euro period.

## 5. Conclusion

In this study we examined the business cycle synchronization between a set of 22 European economies in terms of their real GDP growth rate. In doing so, we employ Graph Theory and more specifically the Threshold-Minimum Dominating Set (T-MDS) methodology and provide evidence using various Graph Theory metrics. The T-MDS is an improvement over the standard MDS methodology as it introduces a thresholding step to eliminate uninformative and possibly misleading links between nodes. Neither the T-MDS nor the MDS have ever been used before in the analysis of macroeconomic issues and especially the business cycle synchronization. Only the MST methodology has been used previously in this type of analysis but the algorithmic optimization procedure of the MST imposes restrictions that are both unnecessary and most importantly inappropriate for this analysis. In the effort to analyze and derive inference on the dynamic evolution of the 22 European countries' GDP growth rates co-movement we generate the T-MDS networks on a rolling window basis.

All network metrics used provide strong evidence in support of an increased real GDP growth rate synchronization between the 22 European countries in the post-euro era. The network's topology does not show any significant change over the first 11 windows (from 1986-1998 to 1996-2008). We find few edges, low density, many isolated economies (nodes) and a high T-MDS set cardinality. All these network metrics depict a network that remains relatively sparse will a low degree of interconnectivity (correlations) between the 22 economies from which many exhibit idiosyncratic behavior. Nonetheless, this image changes radically in the last three windows of our study, namely, 1997-2009, 1998-2010 and finally the 1999-2011 window that covers entirely the post-euro era. In these windows the interconnectivity (network edges) of the 22 economies quadruples, network density is more than five times higher, the T-MDS cardinality decreases to one third and the isolated economies reduce significantly from 7 in the pre-euro era (1986-1998) to only 1. All these findings provide evidence in support of an increased real GDP growth synchronization in the post-euro era.

The country specific analysis provides, in general, the same qualitative results. All of the countries increase their connectivity (correlation) to the others economies' real GDP growth rates. The neighborhoods where the 22 economies belong before the introduction of the euro increase in cardinality in the post-euro era as their business cycles become synchronized. The only exceptions are Malta that remains unchanged with no neighbors and the Slovak republic that exhibits a decreasing convergence.

Another finding of macroeconomic policy-making significance is emphasized through our methodological context. We observe that Germany, which constitutes the major economy of Europe, has been displaying a constant atypical, uncorrelated business cycle with Greece, Portugal and Spain (i.e. the countries that have been more severely affected by the fiscal crisis). If the countries of the South are to be benefited from a mutually efficient monetary policy of all Eurozone members then the proper policies should be applied in order to induce convergence between the business cycles of these countries and the one of Germany (and ideally to the entire network).

Finally, it is evident from our empirical analysis that, in general, the countries that participate in the Eurozone have increased their real GDP growth rate correlations far more than the non-Eurozone ones. The exceptions are Denmark and the U.K. where the increased convergence may be explained by Tinbergen's (1962) gravity model of trade and the endogeneity hypothesis of Frankel and Rose (1998).

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