A MODULARITY DECOMPOSITION MODEL OF EVOLVING INPUT-OUTPUT SECTORIAL STRUCTURE

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Abstract

This paper builds on the network paradigm to model the evolving input-output (IO) economic structure of Greece into a multiplex network (GION) and unveils structural changes during the period 2005-2015, with reference to the 2008 economic crisis. The results illustrate that the GION resembles to a composition of windmill graphs, it is more clustered at the neighborhood scale, with a tertiary sectorial orientation, a solid performance of the trade and transportation industries, inelastic demand in energy-related economic activities, a neutral profile in communication and manufacturing relevant activities, insufficient connectedness of education, and vulnerable in the construction-related economic activities and the public sector. A major finding describes that the tourism industry is dynamic more due to its dependence on the supportive economies than the intrinsic industrial productivity. The time-series and community detection analysis provide insights into distinguishing three stages in the GION's evolution: the pre-crisis period (2005-2007), with a centralized topology in terms of outgoing connectivity and degree inequalities; the on-crisis period (2008-2010), with a decentralized topology and a tendency to reduce degree inequalities; and the post-crisis period (2011-2015), with a new state of centralized topology illustrating a recovery process. The analysis also reveals a diversified configuration in the Greek economy compared to the three-sector classical breakdown, composed of "tourism" and "transportation and energy" sector-like components, and the traditional secondary and tertiary sectors. Overall, the analysis shapes a "balloon" waiving pattern in the network evolution and reveals solid and fragment-favorable economic interactions in the GION's structure, promoting network analysis to the input-output structural modeling.

Keywords: input-output networks, structural analysis, community detection, economic crisis, Greece

JEL classification: R00, R15

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1. <u>Introduction</u>

Input-output (IO) analysis is a quantitative technique for studying the interdependence of production sectors in an economy (Leontief, 1966). An IO table records the financial flows (Giannakis et al., 2024) among sectors over a stated time period, usually a year, including the distribution of the sectorial output throughout the economy and the disaggregation of the value of production to intermediate consumption of inputs and value added (Miller and Blair, 2009). Traditional tools of IO analysis have been used for analysing the structure of the economy including multiplier and linkage analysis (Lenzen, 2001; Giannakis and Mamuneas, 2022). Another important development in IO analysis over the last decades has been the structural decomposition analysis, focusing on decomposing changes in economic phenomena (Oosterhaven and Van Der Linden, 1997; Chen et al., 2015). However, most of these applications focus on the impacts derived by changes in certain sectors (Temel and Phumpiu, 2021; Li and Wu, 2022). According to Xu and Liang (2019), a more complete study of the structure of the economy as an integrated system requires a more "holistic" approach. This drives into considering the network structure of the economy, which can better portray the complex sectorial interactions and explain the observed aggregate patterns (Dominguez et al., 2021). In particular, IO tables have been used to analyse the topology of sectorial interrelationships and their impacts on national economies (Costa et al., 2022), while network science (Barabasi, 2013) can be employed to evaluate the IO structure of the economy through modelling network communities and identifying the central nodes across the sectors (Dominguez et al., 2021).

A profound knowledge of how sectors are interrelated and interconnected (Dionysopoulou et al., 2021; Todri and Papajorgji, 2023; Giannakis et al., 2024; Pham et al., 2024) is important for understanding the structure of the economy (Lincaru et al., 2010; Alexiadis et al., 2015; Kokkinou et al., 2018; Xu and Sam, 2021; Ruxho and Ladias, 2022), which usually determines its functionality in response to disruptions (Xu and Liang, 2019; Carvalho, 2014). As Hulten (1978) noted, only the sales of the sector (as a share of output) are important for the transmission of sectorial shocks to the aggregate economy. However, apart from the lower properties of the sectorial interdependencies, the more complex properties of the IO network (ION) structure can explain such cascading effects in the system (Acemoglu et al., 2012). Therefore, understanding the topological properties of sectorial interactions and interrelationships, and how these properties may vary over time, can play a defining role in explaining how sectorial shocks propagate throughout the economy and possibly lead to large aggregate fluctuations (Carvalho, 2014; Baqaee and Farhi, 2019). Further, the analysis of the distribution of inter-sectorial linkages rather than the distribution of sectors can explain which sectorial linkages are more prone to volatility amplification or reduction (Joya and Rougier, 2019). Similarly, the structure of IONs can explain the dynamics of national economies in periods of economic growth (Duan, 2012) or decline. Contreras and Fagiolo (2014) argue that the extent and heterogeneity of recessionary impacts depend on whether the shock alters the structure of sectorial interrelationships. Also, Joya and Rougier (2019) support that two topological characteristics of a sector, namely, its local density and centrality, as well as the asymmetry property of the whole network determine whether a sectorial shock can generate aggregate fluctuations.

As far as shocks are concerned, the global economic crisis of 2008, which originated in the United States of America, was an economic shock that was immediately spread across Europe. Although in the early mid-2000s it was one of the fastest-growing economies in the Eurozone, with an annual growth rate of 4.2% (Eurostat, 2022), Greece was the worst-hit country (Xanthos et al., 2012; Pnevmatikos et al., 2019; Sdrolias et al., 2022) within the European Union, having cumulatively lost almost 26% of its GDP during the period 2008-2015 (Eurostat, 2022). This unprecedented economic disruption has significantly affected the productive-web (Polyzos et al., 2013; Delgado and Sequeira, 2023) and the industrial mix (Giannakis and Bruggeman, 2017; Uzsayilir and Baycan, 2023) of the country. Thereby, it is evident that significant structural changes have taken place in the country during and the economic recovery period. From an empirical standpoint, Greece suggests an interesting case to study whether the features of the ION structure of the national economy and their evolution overtime can explain the drivers of resilience (Xanthos and Dulufakis, 2023) and recovery of the economy to the negative shock.

Getting inspired from (i) the peculiar case of Greece, in terms of its vulnerability to the 2008 economic crisis (Polyzos et al., 2013; Giannakis and Bruggeman, 2017; Zheng et al., 2021), and (ii) the recent literature on unveiling topological features from the IO inter-sectorial economic structures (Cerina et al., 2015; Rio-Chanona et al., 2017; Dominguez and Mendez, 2019; Giammetti et al., 2020; Dominguez et al., 2021; Costa et al., 2022), this paper explores the structural transformation in Greece during the pre- and post-crisis period 2005-2015, by using the network paradigm in the modelling of the diachronic inter-sectorial economic structure of the country. As dynamic changes of network structures through the use of a series of IO tables (valued at constant prices) can provide valuable insights for the structure of the economy, we transform the 11 annual IO tables (IOTs) over the period 2005-2015 into graphs (network models) and study their topological features over-time. The contribution of this paper is twofold; first, it goes beyond the current empirical ION studies by constructing a multilayer instead of single layer model of the Greek IO economic structure. Second, the paper develops a novel community detection method based on modularity decomposition from complex network analysis, aiming to contribute to the IO literature by uncovering fixed (stable) and commuting (periodical or unstable) inter-sectorial connections in the evolution of the Greek IO economic structure.

2. LITERATURE REVIEW

Although the network analysis is a modern conceptualization in the IO modelling, it has been increasingly applied in the IO relevant research. In particular, Cerina et al. (2015) used the world IO database to analyse the global, regional and local network properties of the world ION and document its evolution over time. Similarly, del Rio-Chanona et al. (2017) studied the world ION, focusing on the relative importance that countries and sectors have. The findings of the study showed that the political and geographical circumstances can play an important role in communities' definition, while sectors were separated into two different groups: one defined by renewable resources and the other by non-renewable resources. Further, Dominguez and Mendez (2019) studied the ION structure of the Japanese economy, using the eigenvector community-detection algorithm of Newman (2006). The results revealed the existence of two ION structures, namely (i) a densely-connected group of service-related sectors including finance, real estate, transportation, health and welfare-related services (stationary community), and (ii) a group of all remaining industries (transitional community).

The authors Giammetti et al. (2020) studied the properties of the European production network, to identify the key sectors in the complex structure of the UK-EU trade relationships that were involved in the Brexit process. The findings of the study indicate that few industries located in core countries, and specifically in the UK and Germany, were dominant in the production network. Next, Dominguez et al. (2021) empirically studied sectorial productivity convergence patterns through the IO structure of the Japanese economy and its network representation over the period 2003-2012. The authors found two dominant communities: the first community consisting of service-related sectors, while the second community consisting of high-tech manufacturing industries. Finally, Costa et al. (2022) studied the transmission mechanisms of domestic and foreign shocks across the Italian business system through the analysis of domestic inter-industrial relationships. A new taxonomy of Italian business sectors was proposed based on the speed and the extent of their capacity of transmitting impulses across the domestic system.

As is evident, current approaches of network analysis of IOTs mainly focus on the world IO configuration (Cerina et al., 2015; del Rio-Chanona et al., 2017), the European Union (Giammetti et al., 2020; Giannakis et al., 2024), along with some national cases, such as the Japanese (Dominguez and Mendez, 2019; Dominguez et al., 2021) and the Italian (Costa et al., 2022) economy, providing insights into identifying key sectors and major communities in the IO economic structures. In the case of Greece, just a couple of papers building on the network paradigm to study the IO economic structure are available in the literature. In particular, the work of Garcia-Muniz and Ramos-Carvajal (2015) was the first that applied a network approach in the Greek IO economic structure of the period 2000-2010, based on multilevel indicators capturing the influence, immediacy, and transmission capacity of industries, to study the relational structure and the robustness of the economic system. The authors claim that the economic structure of the country shifted from an agricultural and low-medium technological configuration in 2000 to an economy with a significant industrial sector in 2010, detecting limitations for 40% of Greek sectors in the diffusion of their possible impacts in the economy. Although this study was the first inspired by the network paradigm to conceive Greek IOTs as network structures, the overall network approach is somehow unorthodox from the network science perspective, since it builds on unconventional network measures that are more relevant to stochastic processes than complex network analysis. More recently, Reyes and Garcia-Muniz (2016) extended a stochastic model of social network structure to analyse the role of different technological intensity sectors in the Greek economy, between 2005 and 2010. The social network structural model constructed probabilistic distributions of inter-industry connectivity to explore the sectors' ability either to preserve consistency or to change its economic structure by potentially creating new connections. The results showed that the Greek IO economic structure was relatively dispersed, the industries lacked systematic connectivity patterns, and the overall economy lacked a clear specialization, while the tertiary sector was crucial in weaving the economic structure and manufacturing industries were linked through more complex connectivity patterns.

Apart from these two distinguishable works, all other relevant research in the Greek IO literature are mainly empirical and provide interesting case studies of diverse sectorial foci of the Greek IO economic configuration including applications on tourism (Briassoulis, 1991), construction (Caloghirou et al., 1996), agriculture (Giannakis and Efstratoglou, 2011) and energy (Karagianni and Pempetzoglou, 2004). More recently, Pnevmatikos et al. (2019) used a hybrid IO modeling and causative-matrix analysis approach to study the inter-sectorial linkages in the Greek economy and detect structural changes in Greece at the pre-crisis period (2000-2010). The analysis showed that (i) most of the sectors (and particularly the tertiary ones) increased their gross output; (ii) the technological changes were smaller than those captured due to the change in the final demand; and (iii) the effects on final demand were increasingly internalized. Finally, Polyzos and Tsiotas (2020) complemented the previous work by studying the structural changes in Greece for the succeeding (post-crisis) period 2010-2015. The analysis showed that the Greek IO structure neither experienced sharp technological nor hierarchical changes, while the transportation and energy industries (sectors) were found more resilient. As is evident in the previous review, the 2008 economic crisis is a point of interest in the IO analysis of the Greek economy. Yet there is an insufficient integration in the relevant literature of network analysis, which has already been proven effective for unveiling topological features from the inter-sectorial IO economic structures.

3. METHOD AND DATA

The methodological framework of the study builds on a multilevel consideration that consists of five discrete steps, the first two concerning data manipulation and graph modeling, while the last three network and empirical analysis. At the first step (s#1), we deflate the 11 available IOTs of the period 2005-2015, on the basis year 2020, and we afterwards convert them into graph models (IO Networks - IONs). At the second step (s#2), we construct an average ION model by computing the averages across the annual values for each element in the connectivity matrix. At the third step (s#3), we compute the major complex network measures of the annual and average ION models and we study their evolution, to detect significant changes in the ION economic structure of Greece. At the fourth step (s#4), we apply a community detection analysis to the average and annual ION models and we develop a novel intersection model from the communities of the annual IONs. Finally, at the fifth step (s#5), we compare the community structure between the average and the intersection IONs to detect fixed and commuting interactions in the IO economic structure of Greece.

3.1. Graph modelling and Data

The database for the construction of the multilayer GION was extracted from the Organization for the Economic Co-operation and Development (OECD, 2018) and regards annual sales and purchases flows of industry outputs, measured in million US$, current prices, for the period 2005-2015. The available IO Tables (IOTs) were further deflated on the basis year 2020, using inverse average (inter-sectorial) inflation rates extracted from the Hellenic Statistical Authority (ELSTAT, 2021). This collection of annual IOTs is conceived as a collection of connectivity matrices of network structures (Dominguez et al., 2021), due to their by definition square structure. Within this context, the family of annual IOTs constructs a multilayer graph model $M(\Gamma,X=\emptyset)$ (Kivela et al., 2014; Boccaletti et al., 2014), the Greek Input-Output Network (GION), consisting of eleven (11) directed layers (IO Networks - IONs) $\Gamma=\{G_p\}=\{V_p,\ E_p \mid p=1,\ldots,11\}$ without interlayer connections $X=\{E_{ij}\subseteq V_i\times V_j\}=\emptyset$, where $G=(V, E)$ denotes a graph with V set of nodes and E set of edges (links). In each layer $G_p=(V_p, E_p)$, nodes ($i \in V_p$) represent n=35 industrial sectors (industries) of the IO economic structure in Greece (shown in Table A_1, in the appendix) and links ($ij \in E_p$) their industrial transactions. Provided that all layers are constructed by the same node set, namely $V_1 = V_2 = \ldots = V_{11}$, the multilayer GION can be seen as a multiplex network. Each GION's layer $G_p \in M$ is a directed and weighted graph expressed by a weighted connectivity matrix

$$W_p = \left\{ w_{ij}^{(p)} \right\}$$

where weights represent the annual sales and purchases between producers and consumers within the economy of Greece, for a year p.

Finally, in the multilayer configuration of GION, we include an additional layer (AION), which is constructed by averaging the available annual layers, according to the formula:

$$AION = \frac{1}{p}\sum_{i=1}^{p=11} W_p = \left\{ \frac{1}{p}\sum_{i=1}^{p=11} w_{ij}^{(p)} \right\} \quad (1),$$

where W_p is the weighted connectivity matrix of year (layer) p, as previously defined. The average layer is denoted as *AION* and provides a magnitude of scale for the Greek IO economic structure of the period 2005-2015.

3.2. Network Analysis

After the multilayer graph modeling, topological analysis applies to unveil patterns of hierarchy (Tsiotas and Kallioras, 2025) and relevant topological information in the GION configuration. The topology of the GION is studied additively, namely is approximated by using a set of network measures, each capturing a topological aspect (such as connectivity, intermediacy, path length, clustering, centrality, etc.). The measures of network topology considered in this paper are shown in Table 1.

Table 1

Nomenclature and measures of network topology used in analysis of GION

Measure	Description	Math Formula	Reference
Graph	A pair set consisting of a node-set V and an edge-set E. In graph $G(V,E)$, n expresses the number of nodes and m the number of links.	$G(V,E)$	Newman (2010); Barthelemy (2011)
Graph density (ρ)	The fraction of the existing connections (m) to the number of the possible connections. It expresses the probability to meet a link between two randomly chosen nodes in the network.	$\rho = m \Big/ \binom{n}{2} = \frac{2m}{n\cdot(n-1)}$	Newman (2010)
Network diameter (dG)	The longest path $p(i,j)$ in the network.	$d(G) = \max\left\{ p(i,j) \mid i,j \in V \right\}$	Koschutzki et al. (2005).
Node Degree (k)	The number of graph edges being adjacent to a given node i. It expresses the number of interacting industries of a node.	$k_i = m(i) = m_i = \sum_{j\in V(G)} \delta_{ij} = \sum_{j\in V(G)} \delta_{ij}$, where $\delta_{ij} = \begin{cases} 1, \text{ if } e_{ij} \in E(G) \\ 0, \text{ otherwise} \end{cases}$	Newman (2010)
In-degree (k–)	The number of incoming edges being adjacent to a given node i. It expresses the number of sellers of an industry.	$k_i - = m_i - = \sum_{j\in V(G)} \delta_{ij} -$, where $\delta_{ij} = \begin{cases} 1, \text{ if } e_{ij} \in E(G) \\ 0, \text{ otherwise} \end{cases}$	Newman (2010); Barthelemy (2011)
Out-degree (k+)	The number of outgoing edges being adjacent to a given node i. It expresses the number of buyers of an industry.	$k_i - = m_i - = \sum_{j\in V(G)} \delta_{ji} -$, where $\delta_{ij} = \begin{cases} 1, \text{ if } e_{ji} \in E(G) \\ 0, \text{ otherwise} \end{cases}$	Newman (2010)
Node strength (s)	The sum of weights (w_{ij}) of the links (e_{ij}) being adjacent to a given node i. The δ_{ij} operator is the Kronecker delta function yielding a true output for links belonging to graph G. It	$s_i = s(i) = \sum_{j\in V(G)} \delta_{ij} \cdot d_{ij}$, where $d_{ij} = w(e_{ij})$ in km	Newman (2010); Barthelemy (2011)

Measure	Description	Math Formula	Reference
	measures the volume of imports (incoming) and exports (outgoing) of an industry.		
Closeness Centrality (*CC*)	Is computed on the average path-lengths $d(i,j)$ originating from a given node $i \in V$ to all other nodes $j \in V$ in the network. It measures accessibility.	$CC(i) = \frac{1}{n-1} \cdot \sum_{j=1, i \neq j}^{n} d_{ij} = \overline{d}_i$	Koschutzki et al. (2005).
Betweenness Centrality (*CB*)	The proportion that is defined by $\sigma(i)$ shortest-paths that pass through a given node i to the total shortest-paths σ in the network. It expresses intermediacy.	$CB(i) = \sigma(i)/\sigma$	Koschutzki et al. (2005)
Eccentricity ($e(u)$)	The longest path $p(u,j)$ in the network from a given node $u \in V$.	$e(u) = \max\{p(u,j) \mid j \in V\}$	Koschutzki et al. (2005).
Local Clustering Coefficient ($C(i)$)	The probability a node i to have $E(i)$ neighbors connected. It is computed on the number of triangles configured by node i to the number of the total triplets $k_i(k_i-1)$ shaped by this node.	$C(i) = \frac{E(i)}{k_i \cdot (k_i - 1)}$	Newman (2010)
Modularity (Q)	Objective function expressing the potential of a network to be subdivided into communities. In the mathematical formula, g_i is the community of node $i \in V(G)$, $[A_{ij} - P_{ij}]$ is the difference of the actual minus the expected number of edges falling between a particular pair of vertices $i,j \in V(G)$, and $\delta(g_i,g_j)$ is an indicator function returning 1 when $g_i=g_j$.	$Q = \frac{\sum_{i,j}[A_{ij} - P_{ij}] \cdot \delta(g_i, g_j)}{2m}$	Blondel et al. (2008); Fortunato (2010)
Average path length $\langle l \rangle$	The average of the path length $d[p(i,j)]$ computed for all accessible pairs (i,j) of network nodes.	$\langle l \rangle = \frac{\sum_{v \in V} d(p(i,j))}{n \cdot (n-1)}$	Barthelemy (2011)

By definition, IOTs are connective graphs including one component and thus all network measures are well-defined in this study, raising no issues of insufficient connectivity (Koschutzki et al., 2005). In general, comparisons of network measures in a multilayer context can apply through a double axis (Tsiotas and Polyzos, 2018): (*i*) in reference to theoretical values, to detect similarities of the empirical network (being under examination) with a null model of already known properties; and (*ii*) between different layers (for the same measure), able to provide insights into the changes in the topological aspect that the measure represents for the certain layers (in this study: years). Further, In a multilayer networks' context, collections of scores for a network measure across the layers may generally provide a data series (representing different states of a measure), where empirical analysis can apply to the variables composed of each series (Tsiotas and Ducruet, 2021). In the case of GION, where each layer corresponds to an annual IOT, the cross-layer collections of a network measure defines a time-series illustrating the evolution of a certain topological aspect (this that is represented by the network measure) during the period 2005-2015. Within this context, the empirical analysis in this paper builds on the idea of applying independent-samples *t*-tests to compare the means between different time periods. Further, instead of applying *t*-tests, this paper alternatively constructs error bars of 95% confidence intervals (CIs), for obtaining visualized (instead of tabulated) results. In terms of interpretation, when the error bars overlay, the population parameters expressed by the mean values between groups are considered as statistically the same, implying that the performance of the populations represented by these groups is equivalent. On the contrary, when the error bars do not overlay, the population parameters expressed by the mean values are considered as statistically different, implying that the performance of the populations represented by these groups is different.

3.3. Community detection and community membership intersection

After the network measures computation, we apply a community detection analysis both to the AION and the GION's layers separately, by using the modularity optimization algorithm proposed by Blondel et al. (2008). This is a heuristic algorithm, which divides the graph into communities by their (binary or weighted) node connectivity, under the requirement to maximize the within-communities and minimize the between-communities connectivity (specifically the sum of actual minus the expected number of edges falling in the communities). In the case of weighted networks, the modularity function is expressed by the following relation:

$$Q = \frac{1}{2m}\sum_{i,j}[A_{ij} - \frac{k_i \cdot k_j}{2m}] \cdot \delta(g_i, g_j) \quad (2),$$

where Q is the modularity function; A_{ij}, m, and $\delta(g_i,g_j)$ are the arguments defined in Table 1; and $k_i = \sum_j A_{ij}$ is. Due to the heuristic architecture of this algorithm, we run the community detection analysis several times (is set to 30 iterations) and we keep the mode (most frequent) of the modularity score and its corresponding modularity classification (community membership). In terms of interpretation, the modularity algorithm produces communities that are dense in connectivity within and sparse between. The nodes included in a community can be considered as relevant to the extent they are more strongly interconnected than other nodes in the network. In this paper, we apply the community detection algorithm of Blondel et al. (2008), to the form it is available in the open source software of Bastian et al. (2009).

At the final step of the methodological framework, we develop a novel set theoretic community model of the GION's layers. The model is defined by the intersections of the modularity classification distributions (the nominal community labeling of all network nodes) across the annual layers of the GION. This model allows distinguishing the fixed members in the GION's communities during the period 2005-2015 and thus detecting the diachronically stable sectorial interconnections in the multilayer network's structure. Finally, after configuring the fixed communities' set, we compare at the fifth step the community configuration between the average and the intersection IONs to detect fixed and commuting interactions in the IO economic structure of Greece.

4. RESULTS AND DISCUSSION

4.1. Network Analysis

■ Network measures and layouts

In the first part of the analysis, we compute the network measures of the multilayer GION (composed of AION and the *Γ* family) and the results are shown in Table 2. As it can be observed, the GION is a connected, directed, and highly dense network; including –on average– the 97.9% of the K_{35} complete graph's connectivity. This result is in line with relevant empirical findings (Cerina et al., 2015) stating that, at national level, IONs are highly dense and complete. Moreover, during the period 2005-2015, the number of the GION's links ranged from 1167 to 1186. This high scale of magnitude is responsible driving into high levels the relevant degree-based network measures (average degree, min degree, in- and out-degree, etc.). The average strength of the GION is 5611.7m US$, interpreting that (in the 35-node structure of the GION's economy) each industry is interconnected to the others with an amount of purchases over 5.6 billion US$, on average. As far as clustering is concerned, we can observe a considerable difference of magnitude between average and global clustering coefficient (by converting the average and global clustering coefficients to undirected measures, to be comparable), expressing that clustering at the neighborhood scale is almost 4 times than this at the global scale.

In terms of pattern recognition, this clustering divergence usually describes a property of windmill graphs (Estrada, 2016), at which nodes are not mutually interconnected but linked each other via a super-hub. However, the case of the Greek IO economy is even more complex, since 5 out of 35 industries can be considered as super-hubs (enjoying a degree of

k=70) at all years in the period 2005-2015, and particularly the sectors: 20T21 (Chemicals and pharmaceutical products), 24 (Manufacture of basic metals), 35T39 (Electricity, gas, water supply, sewerage, waste and remediation services), 49T53 (Transportation and storage), and 69T82 (Other business sector services). Within this context, the GION's topology may suggest a composition of windmill graph models, implying that, at the certain level of resolution (35 sectors), *the IO structure of the Greek economy may operate more as an aggregation of sub-economies than a fully integrated economic system*. This interpretation can be also satisfactorily supported by the scores of the modularity measures, illustrating that the GION's structure diachronically consists of 4-5 communities, which is equal to the number of the diachronic super-hubs. Finally, in terms of path length, we can observe that the GION enjoys an average path length of $\langle l \rangle = 1.022 \sim 1$, which indicates that the majority of paths are direct connections, interpreting a very high level of efficiency. Also, the GION has a diameter $d(G)$=2 steps of separation, which also implies a high level of efficiency and expresses that the most distant industrial sectors in the network are far just one additional link from directedness.

Table 2

Network measures of the GION, for the period 2005-2015

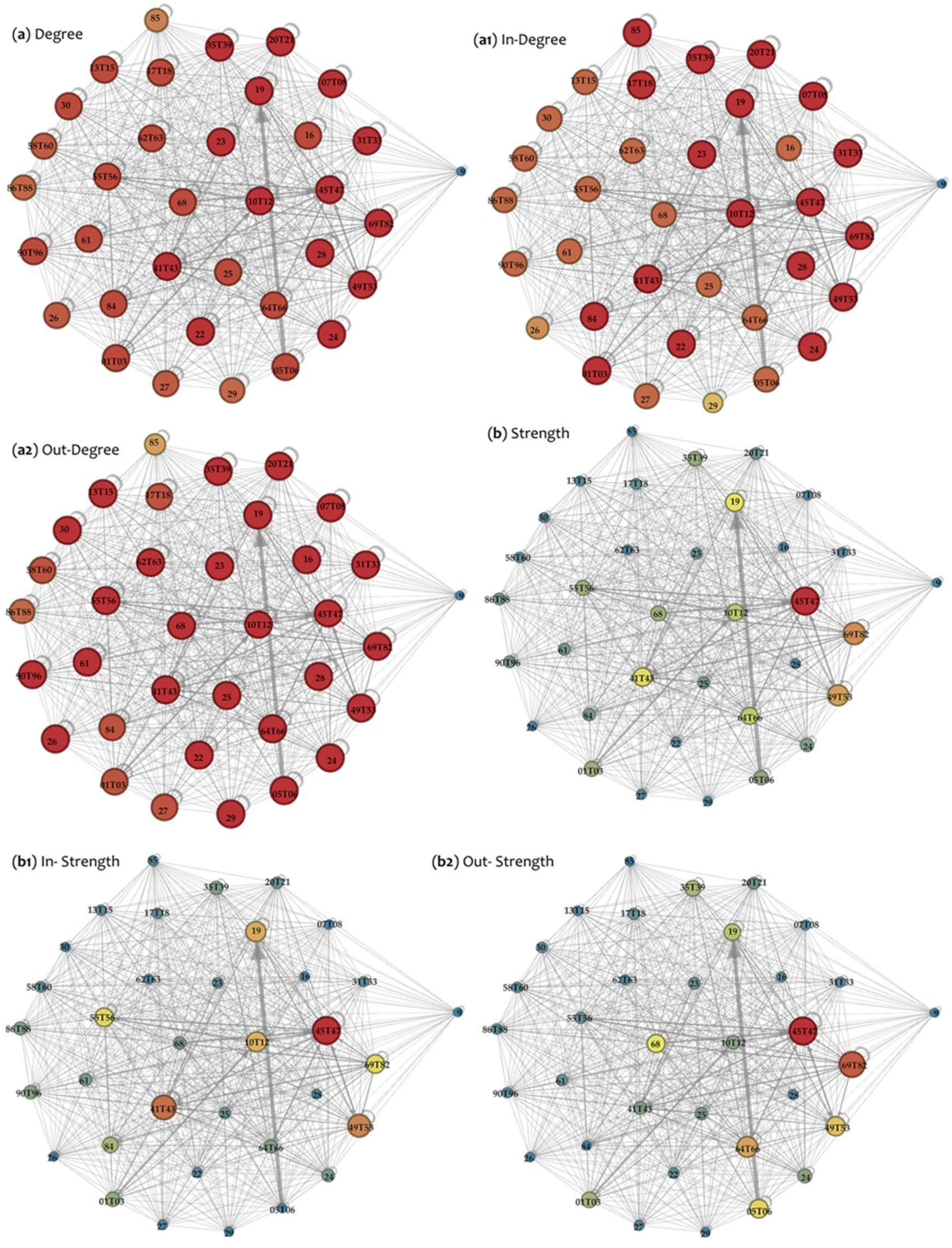
		GION's Layer										
Network Measure	**AION**	**G_1 (2005)**	**G_2 (2006)**	**G_3 (2007)**	**G_4 (2008)**	**G_5 (2009)**	**G_6 (2010)**	**G_7 (2011)**	**G_8 (2012)**	**G_9 (2013)**	**G_{10} (2014)**	**G_{11} (2015)**
Nodes	35						35[(a)]					
Edges	1199	1173	1179	1181	1186	1183	1184	1176	1169	*1167*[(b)]	1172	1172
Average Degree (und[(c)])	34.257	33.514	33.686	33.743	33.886	33.8	33.829	33.6	33.4	*33.343*	33.486	33.486
Min degree (dir[(d)])	49	43	41	43	47	46	47	44	42	41	43	*40*
Degree Range	21	27	29	27	*23*	24	*23*	26	28	29	27	30
In-degree Range	7	12	13	11	11	10	*9*	12	13	14	13	15
Out-degree Range	14	15	16	16	*14*	*14*	*14*	*14*	15	15	*14*	15
Average Strength	5611.7	5772.1	6322.4	7176.0	7281.0	6547.3	5672.2	5215.6	4664.1	4694.2	4642.72	*3741.8*
CB Range	1.144	0.292	0.214	0.214	*0.172*	1.800	1.683	2.112	2.575	2.736	2.349	2.498
CC Range	0.412	0.206	0.176	0.176	*0.147*	0.412	0.412	0.412	0.441	0.441	0.412	0.441
Net Diameter (dir)	2						2					
Net Diameter (und)	2						2					
Graph Density[(e)] (dir)	0.979	0.958	0.963	0.964	0.969	0.966	0.967	0.960	0.954	*0.953*	0.957	0.957
Modularity	0.39	0.379	*0.349*	0.367	0.401	0.359	0.399	0.425	0.428	0.425	0.431	0.425
Communities	4	*4*	*4*	*4*	*4*	5	5	5	5	5	*4*	*4*
Connected Components	1						1					
Avg. Clust. Coefficient (dir)	0.98	0.961	0.965	0.967	0.97	0.968	0.968	0.958	0.958	*0.957*	0.961	0.962
Clust. Coefficient (und)	0.12	0.123	0.124	0.123	*0.122*	*0.122*	*0.122*	0.124	0.124	0.124	0.123	0.123
Avg. Path Length (und)	1.022	*1.013*	1.039	1.037	1.033	1.035	1.034	1.047	1.047	1.049	1.045	1.045

As far as topological layouts are concerned, we can observe in Fig.1a that the majority of the AION's are –on average– highly connected nodes (of degree $k_i \geq 65 \mid 9 \neq i=1, 2, \ldots, 35$) enjoying a similar incoming and outgoing connectivity, except industry 9 (Mining support service activities), which is the lowest connected node with a degree k_9=49. However, we can observe in Fig.1b that only 7 out of 35 nodes have a relatively high strength (exceeding 2 billion US$), which are the sectors: 45T47 (Wholesale and retail trade; repair of motor vehicles | s_{45T47}=5.0215 billion US$); 69T82 (Other business sector services | s_{69T82}=3.5749 billion US$); 49T53 (Transportation and storage | s_{49T53}=3.2584 billion US$); 41T43 (Construction | s_{41T43}=2.6037 billion US$); 19 (Coke and refined petroleum products | s_{19}=2.5711 billion US$); 64T66 (Financial and insurance activities | s_{64T66}=2.1743 billion US$); and 10T12 (Food products, beverages and tobacco | s_{10T12}=2.1134 billion US$). This outcome is in line with the tertiary specialization of the Greek economy (Sdrolias et al., 2022), both in terms of volume and number of strong sectors. In particular, the top-five exporting industries (sellers) are (for more details see Table A_2, Appendix): 45T47 (Wholesale and retail trade; repair of motor vehicles), 69T82 (Other business sector services), 64T66 (Financial and insurance activities), 49T53 (Transportation and storage), 05T06 (Mining and extraction of energy producing products); whereas the top-5 importing industries (purchasers) are: 45T47 (Wholesale and retail trade; repair of motor vehicles), 41T43 (Construction), 49T53 (Transportation and storage), 19 (Coke and refined petroleum products), and 10T12 (Food products, beverages and tobacco). Amongst these nodes, only the trade (45T47) and transportation (49T53) industries belong to both groups, illustrating a solid performance.

Further, in terms of trade balance (defined by the difference exports–imports), the top-5 industries are: 05T06 (Mining and extraction of energy producing products), 64T66 (Financial and insurance activities), 69T82 (Other business sector services), 68 (Real estate activities), and 35T39 (Electricity, gas, water supply, sewerage, waste and remediation services); with an average difference ranging from 3.896 to 13.071 billion US$. This outcome (*i*) illustrates the *importance of the energy-related economic activities, due to their inelastic demand* (Labadeira et al., 2017; Sdrolias et al., 2022); and (*ii*) it further *reveals the tertiary specialization of the Greek IO economic structure* (Pnevmatikos et al., 2019; Polyzos and Tsiotas, 2020; Sdrolias et al., 2022). On the other hand, the bottom-5 (most deficient) industries are 41T43 (Construction), 55T56 (Accommodation and food services), 84 (Public administration and defense; compulsory social security), 10T12 (Food products, beverages and tobacco), 19 (Coke and refined petroleum products), with a deficit from –15.016 to –4.446 billion US$. This outcome (*i*) accredits the finding of Sdrolias et al. (2022) that *the construction-related economic activities were the most vulnerable in the Greek economy due to the 2008 economic crisis*; (*ii*) *captures the diachronic administrative lag of the public sector* in Greece (Spanou, 2008; Tzannatos and Monogios, 2013); and (*iii*) reveals a striking finding that *the tourism industry* (55T56) – which has an average share of ~15-20% in the national GDP (Kalantzi et al., 2017; Sdrolias et al., 2022) – *owes its dynamism more to its dependence on the supportive economies than to its intrinsic productivity*. Finally, the 5-null nodes (most neutral, with the closest to zero trade balance) are the industries: 29 (Motor vehicles, trailers and semi-trailers), 62T63 (IT and other information services), 31T33 (Other manufacturing; repair and installation of machinery and equipment), 9 (Mining support service activities), 58T60 and (Publishing, audiovisual and broadcasting activities); with values of trade-balance ranging from –389.495 to +249.804 million US$. This outcome highlights the importance of communication and manufacturing relevant activities in terms of their supportive (balanced) role in the Greek IO structure.

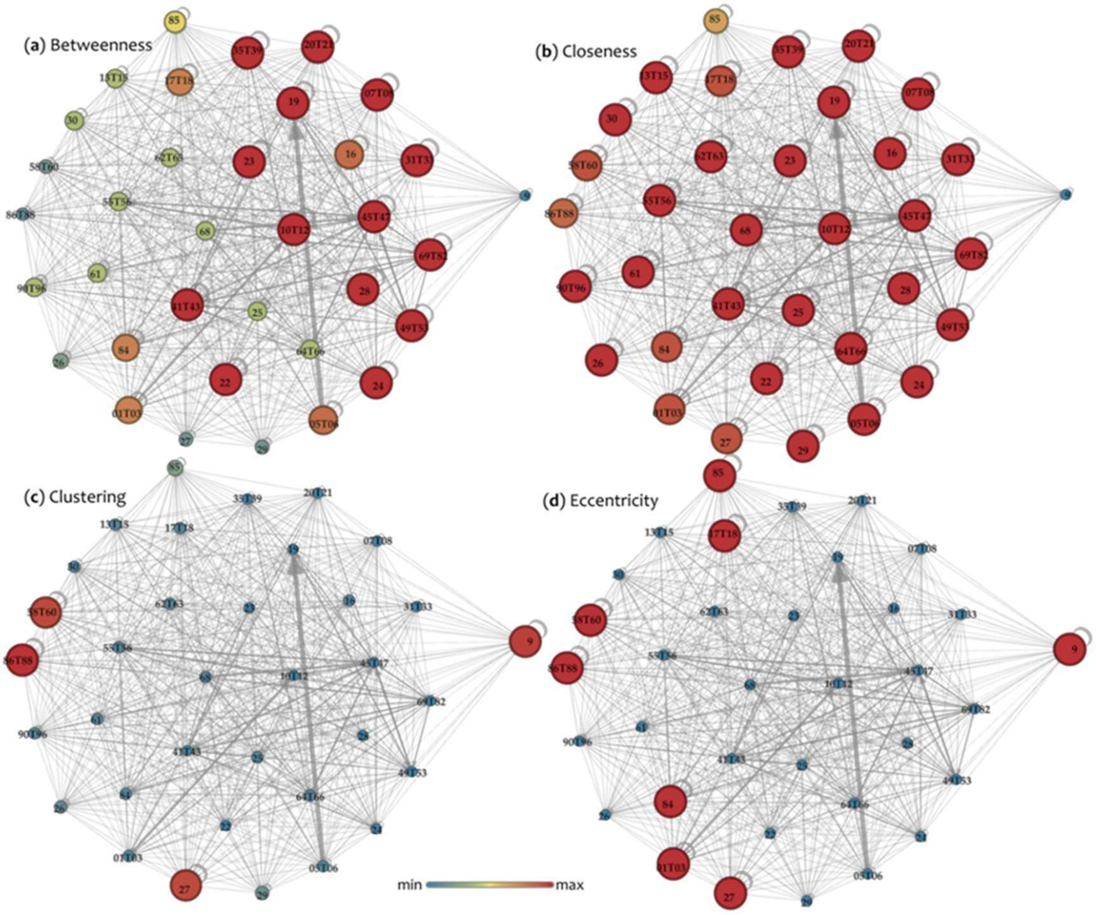
Next, in terms of centrality, we can observe in Fig.2a that almost half (14 out of 35) of the AION's nodes enjoy a high betweenness, and in particular the industries (for more details see Table A_3, Appendix): 45T47 (Wholesale and retail trade; repair of motor vehicles), 69T82 (Other business sector services), 49T53 (Transportation and storage), 41T43 (Construction), 19 (Coke and refined petroleum products), 10T12 (Food products, beverages and tobacco), 35T39 (Electricity, gas, water supply, sewerage, waste and remediation services), 24 (Manufacture of basic metals), 20T21 (Chemicals and pharmaceutical products), 23 (Other non-metallic mineral products), 22 (Rubber and plastics products), 31T33 (Other manufacturing; repair and installation of machinery and equipment), 28 (Machinery and equipment n.e.c.), and 07T08 (Mining and quarrying of non-energy producing products). *This observation can support the assumption about the windmill structure of the GION*, since less than the half nodes undertake the major traffic of this network, although almost all of the GION's nodes are highly connected ones.

Fig.1. Topological layout of the AION's degree-based network measures



As far as closeness is concerned, we can observe in Fig.2b that almost all nodes are highly central, except industries: 9 (Mining support service activities) and 85 (Education); which are the most distant from the others respectively 1.41 and 1.14 steps. As far as education (85) is concerned, this outcome raises a concern about the level of connectedness of education with the production structures of the Greek economy (Hyz, 2011; Korres et al., 2018), towards promoting national and regional economic development. Finally, for the measures of clustering (Fig.2c) and eccentricity (Fig.2d), we can observe similar topological patterns in their layouts. In terms of clustering, industries: 86T88 (Human health and social work), 27 (Electrical equipment) and 58T60 (Publishing, audiovisual and broadcasting activities), and 9 (Mining support service activities); are the most clustered in AION, implying that they belong to neighborhoods that are more highly mutually interconnected and thus they more concisely enjoy flow circulation at the neighborhood scale. These nodes, along with industries: 85 (Education), 01T03 (Agriculture, forestry and fishing), 17T18 (Paper products and printing), and 84 (Public administration and defence; compulsory social security); also have the highest eccentricity, implying that they are the most distant from the functional center of the AION. Through a joint consideration, these outcomes imply that nodes (industries) of high eccentricity are more likely to be also highly clustered, but this observation addresses avenues of further research.

Fig.2. Topological layout of the AION's centrality measures

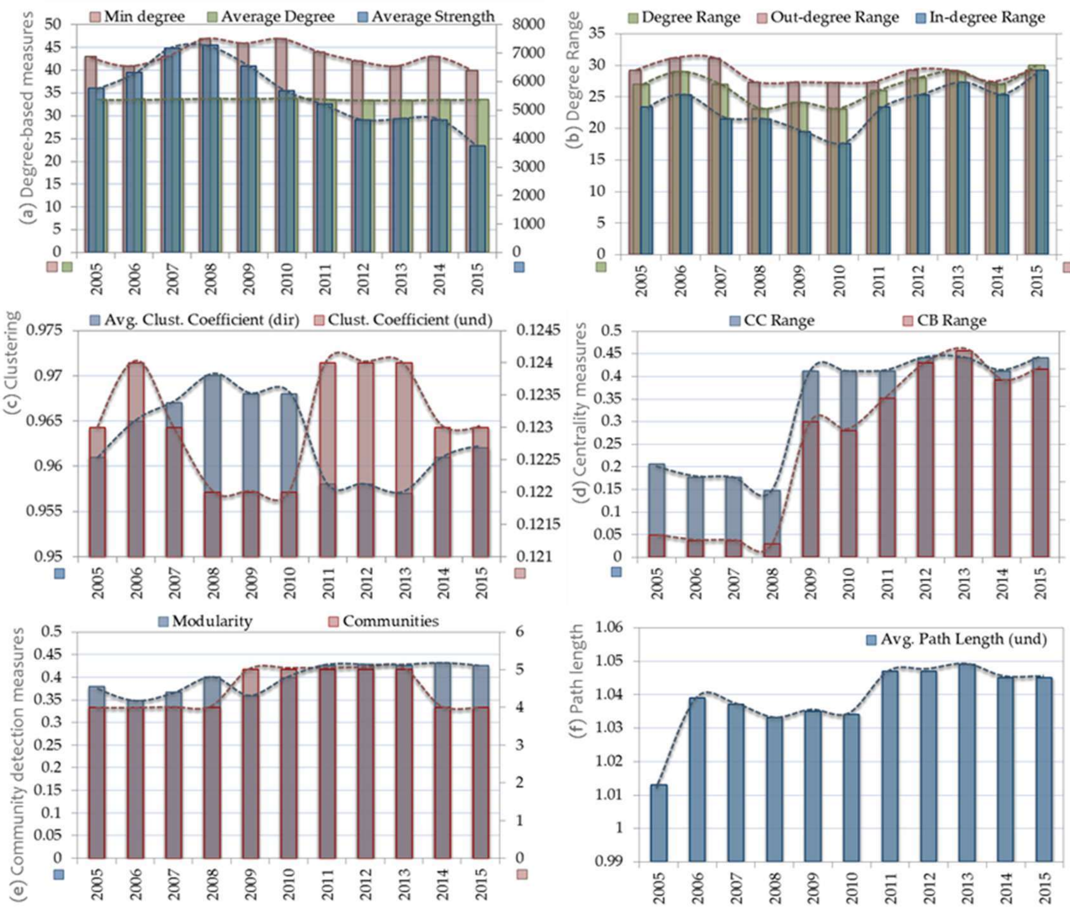


■ Time-series analysis

In this part of the analysis, we examine the available information in Table 1 within a time-series context. As it can be observed, in 15 out of 19 cases, the network measures that are numerically closer to the AION's values are included in the period 2008-2010. Provided that this period is: (*i*) the core of the 2008 economic crisis in Greece (Polyzos et al., 2013) and (*ii*) structurally, the (spatial) middle interval of the time-series body; this observation allows broadly assume that the GION's performance is described by monotonicity (similar to this of one-dimensional 1d-lattice) or periodicity, where in both cases the arithmetic mean and barycenter coincide. In terms of interpretation, this observation suggests that, in the period 2008-2010, the GION's topology can be seen as a representative of the whole period 2005-2015, implying that the 2008 economic crisis in Greece affected the scale of the GION's topological measures on a longer-term basis. To obtain a deeper structural picture, we examine the time-series of the GION's topological measures at the bar-charts shown in Fig.3. According to Fig.3a, the GION's degree-based measures started declining after 2009 (although slightly on average, see Table 2 for the detailed time-series), illustrating a loss of connectivity in the network structure due to the 2008 economic crisis. As Fig.3b shows that the range in these degree-based measures increased after 2009, we can complementary note that this loss of connectivity has caused an increase in the inequalities of the GION's connections, due to the 2008 economic crisis. A combined consideration of Fig.3a and Fig.3b interprets that, in the period after the economic crisis, the GION's connectivity decreased amongst sectors, while degree inequalities (as expressed by the degree range) increased. By assuming that the concave Williamson's curve of regional inequalities (Cappello, 2016) can be also insightful (through an analogy) in the GION's structural context, this observation may imply that the economic crisis forced the pair-wise relationship between average node connectivity and sectorial inequalities to shift backwards in the first quadrant (from righter to more left positions), towards the vertical axis of the curve's symmetry. Within a broader interpretation, this backwards' shift illustrates that the 2008 economic crisis forced GION to move into a state of more downgraded network structure, reducing thus connectivity from the lower connected nodes (industries) and thus favoring a more centralized network structure.

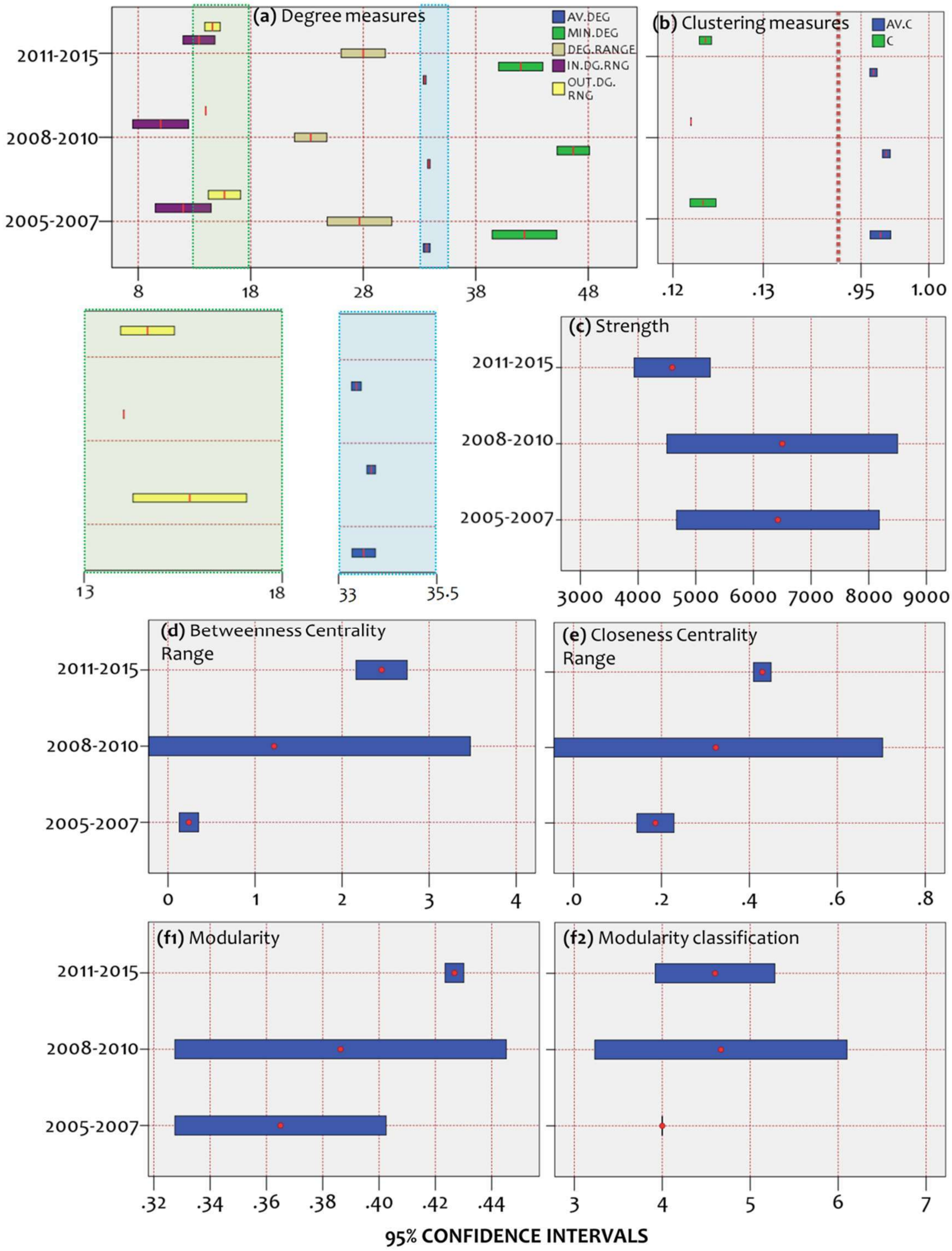
Next, Fig.3c illustrates the time-series of the GION's clustering (average and global clustering coefficient), where we can observe a contrary performance at the emergence of the 2008 economic crisis. In particular, in the three first years (2005-2007) we can observe a proportional evolution of the two measures, while in the next period 2008-2010 the global clustering coefficient inclined and the average clustering coefficient increased. This contrary behavior uncovers a resilience mechanism of the GION against the shock of the 2008 economic crisis, according to which clustering (peripheral connectivity) shifted from the global to the neighborhood scale, illustrating a sectorial localization of the GION's economic structure. In the succeeding period 2011-2013 this picture reverses, where the GION's economic structure regains its sectorial extraversion and simultaneously reduces its local structure. Finally, in the last two years 2014-2015, the GION's clustering appeared almost to return to a performance similar to this of 2005-2007. As far as network centrality is concerned, we can observe in Fig.3d that the ranges (max–min) of betweenness and closeness centrality have similarly evolved during the period 2005-2015. In particular, up to 2008, the ranges of both measures inclined, illustrating a convergence of inequalities in terms of intermediacy and closeness in the GION's structure, while afterwards increased, expressing a concordant increase of the inter-sectorial inequalities. In terms of network topology, this outcome implies that the 2008 economic crisis caused GION to move into a more centralized network structure, favoring more the privileged nodes according to "the rich get richer" growth model.

Fig.3. Time-series of the GION’s (a) degree-based measures, (b) degree range, (c) clustering, (d) centrality range, (e) community detection measures, and (f) average path length. In cases where double vertical axes are applicable, colored boxes on the bottom of each axis are used as references to the corresponding time-series.



In terms of community structure, we can observe in Fig.3e that the period 2009-2013 was critical for the GION’s community configuration, where the number of communities changed from 4 to 5. This change implies that the 2008 economic crisis caused a restructure to the GION’s community configuration, driving this multilayer network into to a more localized structure composed of more –in number– communities. This observation complements a previous outcome about the GION’s clustering, although it illustrates that the localization kept longer than in the case of clustering. Finally, in terms of average path length, we can observe in Fig.3f two levels of magnitude in the time-series’ body, defined by a cutting point of the year 2010. This dichotomous approach describes that the 2008 economic crisis made the GION’s inter-sectorial communication more distant, an observation which (in conjunction with the previous findings) supports the assumption about the overlaid windmill structure of GION (where centrality and distant connectivity can coexist). According to the previous time-series consideration, we can overall observe three critical periods in the 11-year period of the GION’s structure, defined by the cutting points of the years 2008 (where degree, clustering, centrality, and modularity changed) and 2011 (where clustering, centrality and path-length measures seem to change). To detect whether these changes between the periods *A* (pre-crisis: 2005-2007), *B* (on-crisis: 2008-2010), and *C* (post-crisis: 2011-2015), are significant ones, we construct error bars of 95% CIs, which provide a visualization of an independent samples *t*-test for the comparison of means between groups. When CIs overlay, no significant difference between the groups’ means exist.

Fig.4. Network measures with significant differences between the pre-crisis (<2009) and on-crisis (≥2009) periods and the four-community ([2005,2008]U[2014,2015]) and five community ([2009,2013]) periods



To better supervise the results of Fig.4, we construct the auxiliary Table 3, summarizing significant inequalities *i*>*j* in the corresponding cells *ij*. As it can be observed in Fig.4 and Table 3, period *A* has a significantly higher degree range (R_k) and out-degree (k_+) than the period *B*, whereas it has a significantly higher average strength (<*s*>) than the period *C*. These results imply that the pre-crisis period (2005-2007) is described by a higher level of outgoing connectivity and degree inequalities than the on-crisis period (2008-2010), illustrating a more extraverted (open) structure due to the pre-crisis welfare. Also, period *A* (2005-2007) is described by a higher volume of inter-sectorial transactions (average strength) than the period *C* (2011-2015), also illustrating its “welfare” compared to the post-crisis times. Next, period *B* has a significantly higher minimum degree ($k_{\min}$) than period A, illustrating a tendency (it may imply a homeostatic mechanism against the crisis) of GION to reduce degree inequalities by improving connectivity of lowest connected nodes, at the time that the shock of 2008 economic crisis applied. We can also make a similar observation through the comparison of periods B and C, where period B has a significantly higher average ($<k>$) and minimum degree ($k_{\min}$) than period C, illustrating that degree inequalities and average connectivity reduced at the post-crisis period (thus favoring a more decentralized - peripheral topology), as previously observed. Finally, period C has a significantly higher betweenness (R_{CB}) and closeness (R_{CC}) centrality range than period A, along with higher scores in modularity. These results are in line with the previous findings (Fig.3d) illustrating the centralized network structure of GION in the post-crisis period. Also, period C has a significantly higher degree range (R_k), in-degree ($k_{–}$) and out-degree (k_{+}) than period B, implying that after the crisis shock the GION's structure started recovering by becoming more connected.

Table 3

Tabulation of the significant differences extracted by the error bar analysis

	A:2005-2007	B:2008-2010	C:2011-2015
A:2005-2007		$R_k^{(*,**)}$ (95%CI); $k(+)$ (90%CI)	$<s>$ (90%CI)
B:2008-2010	$k_{\min}$ (95%CI)		$<k>$ (95%CI); $k_{\min}$ (95%CI); $<s>$ (90%CI)
C:2011-2015	R_{CB} (95%CI); R_{CC} (95%CI); Q (95%CI); Q_{class} (90%CI)	R_k (95%CI); $k_{(–)}$ (95%CI); $k_{(+)}$ (90%CI)	

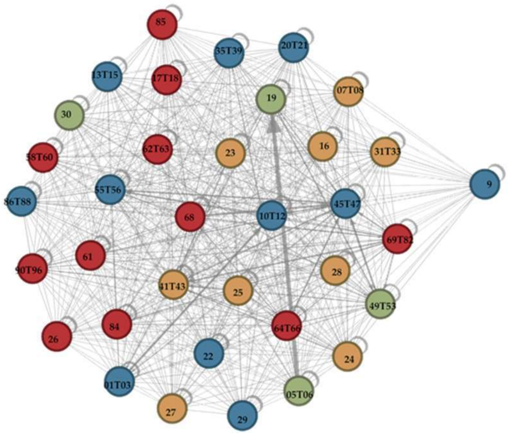
[*]. Cases ij imply that the average of i is significantly greater than the average of j ($i>j$) at the confidence level shown in brackets

[**]. $R(\cdot)$: range; $<\cdot>$: average; $\min\{\cdot\}$: minimum; CI: confidence interval; k: degree, s: strength; CB: betweenness; C: closeness; Q: modularity; Q_{class}: modularity classification

4.2. Community detection

In the final part of the study, we apply a community detection analysis based on the modularity optimization algorithm of Blondel et al. (2008), to detect communities of dense inner connectivity in the GION. To do so, we separately detect community structure in the AION and the GION's layers, separately, and we further construct the interlayer community intersection model, described in relation (2). First, the results of the analysis applied to the AION's community structure are shown in Fig.5 and in Table A_4 (see Appendix) in more detail. As it can be observed, the AION's structure can divide into 4 communities of size 11, 4, 9, and 11 industries, respectively. Based on their composition, we can observe that the first community (g_1) has apparently a diverse semiology, as is composed of sectors included in all major sectors of the 3d sectorial structure, such as: agriculture (01T03) and food products (10T12); mining support service (9); wearing apparel (13T15); chemicals and pharmaceutical (20T21), and plastic (22) products; motor vehicles (29); electricity, gas, water supply, sewerage, waste, and remediation services (35T39); trade (45T47); accommodation and food services (55T56); and human health and social work (86T88). However, all these industries are broadly related to tourism, which is a major industry in the Greek economy (Briassoulis, 1991; Polyzos et al., 2013; Giannakis and Bruggeman, 2017; Sdrolias et al., 2022) and is considered by many national researchers as the "fourth sector" as complementary to the three-sector classical breakdown. Within this context, the composition of the first community in the AION provides insights into an integration of the broader "tourism sector" in Greece. The second community (g_2) has semiology related to transportation (30, 49T53) and supportive energy products (05T06, 19), highlighting the importance and integration of transportation in the GION's sectorial structure. Next, the third community (g_3) has a broader manufacture semiology consisting of industries related to non-energy mining (07T08), construction (16, 23, 41T43), manufacturing (24, 25, 31T33), and electrical (27, 28) products and equipment. This community can be seen as a more representative to the semiology of secondary sector in terms of the three-sector classical breakdown. Finally, the fourth community (g_4) is composed of industries that are related to education (85, 17T18), communication and IT (26, 58T60, 61), arts (90T96), public administration (84), real estate (68), and relevant business activities (69T82), which can be seen as a representative of the services (tertiary) sector within the context of the three-sector classical breakdown. Overall, the AION's community configuration *allows distinguishing a diversified configuration in the Greek economy compared to the three-sector classical breakdown*, composed of a *manufacture* (the secondary, size: 9), *tertiary* (size: 11), *tourism* (the secondary, size: 11), and *transportation and energy* (size: 4) sector-like components.

Fig.5. Modularity classification of the average Input-Output network (AION) of Greece



After the community detection in the AION's structure, we repeat the analysis to each of the GION's layer, resulting to 11 annual community patterns, where each corresponds to a year of the period 2005-2015. By applying the community intersection model of relation (2) to these community patterns, we get 16 groups of industries (fg_i) with fixed interconnectivity in the period 2005-2015, as it is shown in Table A_5 (see Appendix). As it can be observed through comparisons (Table A_4, Appendix), the AION's communities divide as follows in the community intersection model:

(i) community g_1 ("tourism sector") divides into 8 sub-communities $g_1 = \bigcup_i fg_i \,|\, i = 1,4,5,7,10,12-13$

(*ii*) community g_2 (transportation and energy) splits into 2 sub-communities $g_2 = fg_2 \bigcup fg_{11}$

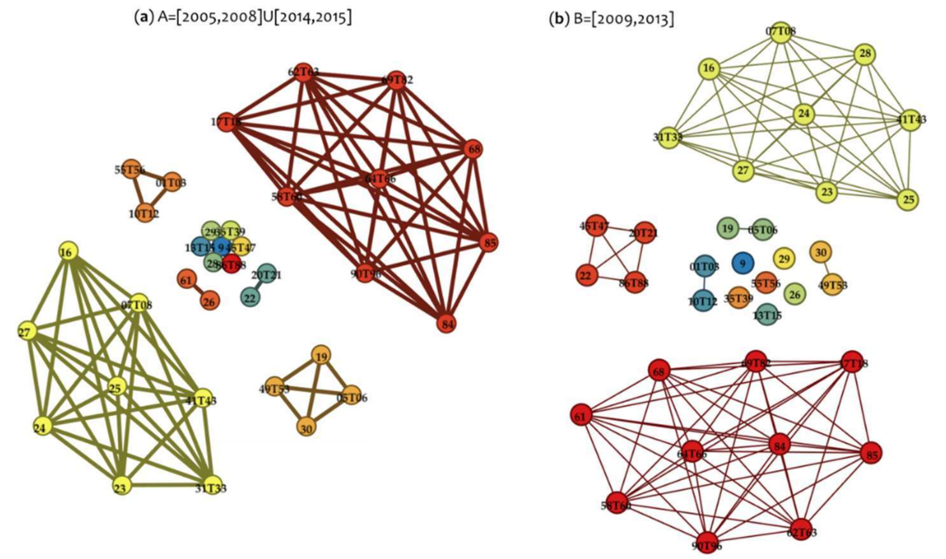
(*iii*) community g_3 (secondary sector) splits into 2 sub-communities $g_3 = fg_3 \bigcup fg_9$ and

(*iv*) community g_4 (tertiary sector) divides into 4 sub-communities $g_4 = \bigcup_i fg_i \,|\, i = 6,8,15,16$

These results allow observing structural coherence between the AION's and interlayer GION's structures, as no sub-communities in the 2005-2015 intersection model include industries from different AION's communities. Namely, all sub-communities produced by the intersection model are parts of the same communities in the AION's community structure. However, in functional terms, this observation implies that the four AION's communities are not that much functionally integrated and can be separated to further substructures (sub-communities). This dis-concordance *can be attributed to the 2008 economic crisis and allows interpreting that this exogenous shock affected*: (*i*) *mainly the broader "tourism sector" in Greece*, dividing it into 8 sub-communities, the biggest in size of which are {01T03, 10T12 | Agriculture and Food products} and {9, 13T15 | Mining support service activities and Textiles}; (*ii*) *afterwards the tertiary sector*, dividing it into 4 sub-communities, where sub-community fg6 is similar to the AION's g4 excluding industries 26 (Computer, electronic and optical products), 61 (Telecommunications), and 86T88 (Human health and social work); and (*iii*) *lastly the other two AION's "sectors"* (secondary sector; transportation and energy), dividing them into 2 sub-communities (dichotomous effect). Overall, the comparison of Tables A_4 and A_5 allows detecting the solid structural components in the AION's community structure, observing that the most concise AION's communities are the secondary sector and transportation and energy, while the most fragment-favorable the tertiary sector and tourism.

Toward a further analysis, we apply the community intersection model to the periods A= $\left[2005,2008\right]\bigcup\left[2014,2015\right]$ (off-crisis) and B=[2009,2013] (on-crisis), which are found of different community structure (4 and 5 communities, respectively) in the analysis of Fig.3e. This approach aims to provide further insights into the diachronically solid components in the GION's economic structure. The results of this analysis are shown in Fig.6 and –in more detail– in Table A_6 (Appendix). Similarly to the previous case, we can observe that these sub-communities are parts of the same AION's communities and not a mix of different memberships. Further, for period *A*, we can observe that the AION's communities divide as follows: (*i*) community g_1 ("tourism sector") divides into 8 sub-communities $g_1=\bigcup_i f_I g_i \mid i=1,4,5,7,10-13$, each consisting of 1-2 industries; (*ii*) community g_2 (transportation and energy) remains solid; (*iii*) community g_3 (secondary sector) divides into 3 sub-communities $g_3=\bigcup_i f_I g_i \mid i=3,9,10$, where the first ($f_I g_3$) is the largest consisting of 8 industries; and (*iv*) community g_4 (tertiary sector) splits into 2 sub-communities $g_4=f_I g_6 \bigcup f_I g_8$, essentially abstracting sub-community {26, 61 | Computer, electronic and Telecommunications}. On the other hand, for period *B*, we can observe that the AION's communities divide as follows: (*i*) community g_1 ("tourism sector") divides into 6 sub-communities $g_1=\bigcup_i f_{II} g_i \mid i=1,4,5,7,11,12$, one consisting of 4 industries and the others of 1-2 industries; (*ii*) community g_2 (transportation and energy) splits into 2 sub-communities $g_2=f_{II} g_2 \bigcup f_{II} g_{10}$, each consisting of 2 industries; (*iii*) community g_3 (secondary sector) splits into 2 sub-communities $g_3=f_{II} g_3 \bigcup f_{II} g_9$, where the first ($f_I g_3$) is the largest consisting of 9 industries; and (*iv*) community g_4 (tertiary sector) splits into 2 sub-communities $g_4=f_{II} g_6 \bigcup f_{II} g_8$, essentially abstracting industry 26 (Computer, electronic and optical products).

Fig.6. Groups of the GION's industries with fixed interconnectivity in the periods: (a) [2005-2008]U[2014-2015] and (b) [2009-2013].



Overall, we can observe that, in period *A* (off-crisis period), the GION's community structure appeared relatively more concrete in transportation and energy, and in agriculture and tourism, which are considered as high resilience industries (Giannakis and Bruggeman, 2017; Sdrolias et al., 2022) due to their inelastic demand. On the contrary, in period *B* (on- and early post-crisis) the GION's community structure turned relatively more concrete in the secondary and tertiary sector (according to the classic sectorial breakdown), which are the sectors enjoying the highest shares in the Greek economy (Sdrolias et al., 2022). This observation, in conjunction with a previous finding, stating that that the 2008 economic crisis caused a restructure to the GION's into to a more localized community structure, imply that industries of inelastic demand may contribute towards structural integration, while industries enjoying highest shares may contribute to structural localization. It can further provide avenues of further research.

5. CONCLUSIONS

This paper used the network paradigm to model the IO economic structure of Greece during the period 2005-2015 into a multiplex network (Greek IO Network - GION). The analysis built on multilayer network modelling and a customized community detection method, to uncover structural changes in Greece with reference to the 2008 economic crisis. The network analysis showed that the GION is a highly dense and efficient, in terms of path length, network, where each industry participates on average to an amount of purchases over 5.6 billion US$. It also appeared more clustered at the neighborhood than at the global scale, illustrating a multilayer composition of windmill graph structures, configuring diachronically 4-5 communities. In terms of strength and trade balance, the volume of purchases revealed (*i*) the tertiary orientation of the Greek economy; (*ii*) a solid performance of the trade and transportation industries; (*iii*) the importance of (the inelastic demand) energy-related economic activities; (*iv*) a neutral profile in communication and manufacturing relevant activities; (*v*) insufficient connectedness of the education industry; and (*vi*) a higher vulnerability of the construction-related economic activities and the public sector. This part of the analysis came up to a finding that the tourism industry in Greece seems to owe its dynamism more to its dependence on the supportive economies (which makes many researchers considering it a broader economic sector) than to its intrinsic productivity.

The time-series analysis showed that the 2008 economic crisis affected on average the scale of the GION's topological measures, illustrating a loss of connectivity in the network structure from the lower connected nodes (industries) and a more centralized network structure. This part of analysis also revealed that the GION's clustering (peripheral connectivity) shifted towards a sectorial localization to recover the external shock, while inequalities in centrality (intermediacy and closeness) initially converged (on-crisis) and afterwards (post-crisis) increased, illustrating that GION moved into a more centralized network structure. Overall, the time-series analysis allowed collectively distinguishing three stages in the examined period of GION's evolution: (*i*) the pre-crisis period 2005-2007, described by considerably high outgoing connectivity, degree inequalities, and inter-sectorial transactions reflecting economic "welfare"; (*ii*) the on-crisis period 2008-2010, described by considerably high minimum degree, illustrating a recovery tendency to reduce degree inequalities by improving connectivity of lowest connected nodes (thus favoring a more decentralized or peripheral topology); and (*iii*) the post-crisis period 2011-2015, described by a considerably high directed degree and centrality ranges, illustrating a GION's recovery activation into increasing connectivity.

Finally, the community detection analysis showed that period 2009-2013 was critical for the GION's structure, where the number of communities changed from 4 to 5, driving this multilayer network into to a more localized structure. The AION's community configuration allowed distinguishing a diversified configuration in the Greek economy compared to the three-sector classical breakdown, since the industries' configuration within the communities illustrated more the existence of "*tourism*" and "*transportation and energy*" sector-like components than the traditional agricultural sector. Additionally, the community detection analysis revealed solid interactions in the GION's structure through time, where the most concise communities appeared the secondary sector and transportation and energy, while the most fragment-favorable the tertiary and tourism sectors. In particular, within a binary on-crisis and off-crisis context, the community detection analysis showed that: (*i*) during off-crisis the GION's community structure appeared relatively more concrete in transportation and energy, agriculture, and tourism group of industries, while (*ii*) during on-crisis it turned relatively more concrete in the secondary and tertiary sector. These findings indicate that industries of inelastic demand may contribute towards structural integration, while industries enjoying highest shares may contribute to structural localization.

Overall, the network analysis applied to the GION revealed a "balloon" waiving pattern in the evolution of the GION's topology implemented in three stages

6. References

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7. APPENDIX

Table A1

The n=35 industries of the input-output tables (IOTs) composing the GION

Industry Code	Description
01T03	Agriculture, forestry and fishing
05T06	Mining and extraction of energy producing products
07T08	Mining and quarrying of non-energy producing products
9	Mining support service activities
10T12	Food products, beverages and tobacco
13T15	Textiles, wearing apparel, leather and related products
16	Wood and of products of wood and cork (except furniture)
17T18	Paper products and printing
19	Coke and refined petroleum products
20T21	Chemicals and pharmaceutical products
22	Rubber and plastics products
23	Other non-metallic mineral products
24	Manufacture of basic metals
25	Fabricated metal products, except machinery and equipment
26	Computer, electronic and optical products
27	Electrical equipment
28	Machinery and equipment n.e.c.
29	Motor vehicles, trailers and semi-trailers
30	Other transport equipment
31T33	Other manufacturing; repair and installation of machinery and equipment
35T39	Electricity, gas, water supply, sewerage, waste and remediation services
41T43	Construction
45T47	Wholesale and retail trade; repair of motor vehicles
49T53	Transportation and storage
55T56	Accomodation and food services
58T60	Publishing, audiovisual and broadcasting activities
61	Telecommunications
62T63	IT and other information services
64T66	Financial and insurance activities
68	Real estate activities
69T82	Other business sector services
84	Public administration and defence; compulsory social security
85	Education
86T88	Human health and social work
90T96	Arts, entertainment, recreation and other service activities

Table A2
Degree ranking in the AION's nodes

Description	Degree*	In-Degree	Out-Degree	Label	Description	Strength*	In-Strength	Out-Strength
Mining and quarrying of non-energy producing products		35	35	45T47	Wholesale and retail trade; repair of motor vehicles	50215.53	24669.87	25545.66
Food products, beverages and tobacco		35	35	**69T82****	**Other business sector services**	35749.93	12897.33	22852.60
Coke and refined petroleum products		35	35	**49T53**	**Transportation and storage**	32584.36	18344.31	14240.05
Chemicals and pharmaceutical products		35	35	41T43	Construction	26037.93	20527.35	5510.58
Rubber and plastics products		35	35	19	Coke and refined petroleum products	25711.03	15078.56	10632.47
Other non-metallic mineral products		35	35	64T66	Financial and insurance activities	21743.57	5539.27	16204.30
Manufacture of basic metals		35	35	10T12	Food products, beverages and tobacco	21134.91	14674.46	6460.44
Machinery and equipment n.e.c.	70	35	35	68	Real estate activities	17086.29	4403.54	12682.75
Other manufacturing; repair and installation of machinery and equipment		35	35	01T03	Agriculture, forestry and fishing	16305.31	7213.85	9091.46
Electricity, gas, water supply, sewerage, waste and remediation services		35	35	55T56	Accomodation and food services	16211.22	12923.66	3287.57
Construction		35	35	**35T39**	**Electricity, gas, water supply, sewerage, waste and remediation services**	14837.23	5470.29	9366.94
Wholesale and retail trade; repair of motor vehicles		35	35	05T06	Mining and extraction of energy producing products	13846.00	387.43	13458.57
Transportation and storage		35	35	**24**	**Manufacture of basic metals**	11418.10	4727.76	6690.34
Other business sector services		35	35	84	Public administration and defence; compulsory social security	9317.31	8929.01	388.30
Agriculture, forestry and fishing		35	34	25	Fabricated metal products, except machinery and equipment	7929.96	3258.61	4671.35
Paper products and printing		35	34	61	Telecommunications	7842.28	4664.24	3178.04
Public administration and defence; compulsory social security		35	34	90T96	Arts, entertainment, recreation and other service activities	7726.35	6046.32	1680.03
Mining and extraction of energy producing products		34	35	86T88	Human health and social work	7586.87	5336.48	2250.39
Wood and of products of wood and cork (except furniture)		34	35	**20T21**	**Chemicals and pharmaceutical products**	6972.05	3157.28	3814.77
Textiles, wearing apparel, leather and related products		34	35	23	Other non-metallic mineral products	5882.81	2178.90	3703.91
Fabricated metal products, except machinery and equipment	69	34	35	17T18	Paper products and printing	5228.74	1943.71	3285.03
Other transport equipment		34	35	58T60	Publishing, audiovisual and broadcasting activities	4386.28	2387.89	1998.39
Accomodation and food services		34	35	22	Rubber and plastics products	3916.49	1596.33	2320.16
Telecommunications		34	35	31T33	Other manufacturing; repair and installation of machinery and equipment	3250.09	1565.58	1684.50
IT and other information services		34	35	13T15	Textiles, wearing apparel, leather and related products	2982.51	2061.20	921.31
Financial and insurance activities		34	35	30	Other transport equipment	2867.66	412.75	2454.90
Real estate activities		34	35	27	Electrical equipment	2706.81	1116.29	1590.52
Arts, entertainment, recreation and other service activities		34	35	16	Wood and of products of wood and cork (except furniture)	2303.04	814.07	1488.97
Electrical equipment	68	34	34	28	Machinery and equipment	2153.67	751.13	1402.54

*. Ranking according to this variable
. Sectors that were hubs for all the period 2005-2015 are shown in **bold

Table A3
Centrality ranking of the AION's nodes

Code	Description	Closeness
5T06	Mining and extraction of energy producing products	
7T08	Mining and quarrying of non-energy producing products	
0T12	Food products, beverages and tobacco	
3T15	Textiles, wearing apparel, leather and related products	
6	Wood and of products of wood and cork (except furniture)	
9	Coke and refined petroleum products	
0T21	Chemicals and pharmaceutical products	
2	Rubber and plastics products	
3	Other non-metallic mineral products	
4	Manufacture of basic metals	
5	Fabricated metal products, except machinery and equipment	
6	Computer, electronic and optical products	
8	Machinery and equipment n.e.c.	
9	Motor vehicles, trailers and semi-trailers	1
0	Other transport equipment	
1T33	Other manufacturing; repair and installation of machinery and equipment	
5T39	Electricity, gas, water supply, sewerage, waste and remediation services	
1T43	Construction	
5T47	Wholesale and retail trade; repair of motor vehicles	
9T53	Transportation and storage	
5T56	Accomodation and food services	
1	Telecommunications	
2T63	IT and other information services	
4T66	Financial and insurance activities	
8	Real estate activities	
9T82	Other business sector services	
0T96	Arts, entertainment, recreation and other service activities	
1T03	Agriculture, forestry and fishing	
7T18	Paper products and printing	
7	Electrical equipment	0.971
8T60	Publishing, audiovisual and broadcasting activities	
4	Public administration and defence; compulsory social security	
6T88	Human health and social work	0.944
5	Education	0.872
	Mining support service activities	0.708

Code	Description	Betweenness
07T08	Mining and quarrying of non-energy producing products	
10T12	Food products, beverages and tobacco	
19	Coke and refined petroleum products	
20T21	Chemicals and pharmaceutical products	
22	Rubber and plastics products	
23	Other non-metallic mineral products	
24	Manufacture of basic metals	
28	Machinery and equipment n.e.c.	1.144
31T33	Other manufacturing; repair and installation of machinery and equipment	
35T39	Electricity, gas, water supply, sewerage, waste and remediation services	
41T43	Construction	
45T47	Wholesale and retail trade; repair of motor vehicles	
49T53	Transportation and storage	
69T82	Other business sector services	
05T06	Mining and extraction of energy producing products	
16	Wood and of products of wood and cork (except furniture)	0.961
01T03	Agriculture, forestry and fishing	
17T18	Paper products and printing	0.877
84	Public administration and defence; compulsory social security	
85	Education	0.600
13T15	Textiles, wearing apparel, leather and related products	
25	Fabricated metal products, except machinery and equipment	
30	Other transport equipment	
55T56	Accomodation and food services	
61	Telecommunications	0.439
62T63	IT and other information services	
64T66	Financial and insurance activities	
68	Real estate activities	
90T96	Arts, entertainment, recreation and other service activities	
26	Computer, electronic and optical products	0.256
29	Motor vehicles, trailers and semi-trailers	0.185
27	Electrical equipment	
58T60	Publishing, audiovisual and broadcasting activities	0.171
86T88	Human health and social work	0.103
9	Mining support service activities	0.000

Table A4

Industries included in the communities (g_i) of the AION (2005-2015)

Code	Description	Community
01T03	Agriculture, forestry and fishing	g_1
9	Mining support service activities	
10T12	Food products, beverages and tobacco	
13T15	Textiles, wearing apparel, leather and related products	
20T21	Chemicals and pharmaceutical products	
22	Rubber and plastics products	
29	Motor vehicles, trailers and semi-trailers	
35T39	Electricity, gas, water supply, sewerage, waste and remediation services	
45T47	Wholesale and retail trade; repair of motor vehicles	
55T56	Accomodation and food services	
86T88	Human health and social work	
05T06	Mining and extraction of energy producing products	g_2
19	Coke and refined petroleum products	
30	Other transport equipment	
49T53	Transportation and storage	
07T08	Mining and quarrying of non-energy producing products	g_3
16	Wood and of products of wood and cork (except furniture)	
23	Other non-metallic mineral products	
24	Manufacture of basic metals	
25	Fabricated metal products, except machinery and equipment	
27	Electrical equipment	
28	Machinery and equipment n.e.c.	
31T33	Other manufacturing; repair and installation of machinery and equipment	
41T43	Construction	
17T18	Paper products and printing	g_4
26	Computer, electronic and optical products	
58T60	Publishing, audiovisual and broadcasting activities	
61	Telecommunications	
62T63	IT and other information services	
64T66	Financial and insurance activities	
68	Real estate activities	
69T82	Other business sector services	
84	Public administration and defence; compulsory social security	
85	Education	
90T96	Arts, entertainment, recreation and other service activities	

Table A5

Groups of industries (fg_i) with fixed interconnectivity within the period 2005-2015, resulted from the interlayer communities' intersection model

Label	Description	Group
01T03	Agriculture, forestry and fishing	fg_1
10T12	Food products, beverages and tobacco	
05T06	Mining and extraction of energy producing products	fg_2
19	Coke and refined petroleum products	
07T08	Mining and quarrying of non-energy producing products	fg_3
16	Wood and of products of wood and cork (except furniture)	
23	Other non-metallic mineral products	
24	Manufacture of basic metals	
25	Fabricated metal products, except machinery and equipment	
27	Electrical equipment	
31T33	Other manufacturing; repair and installation of machinery and equipment	
41T43	Construction	
9	Mining support service activities	fg_4
13T15	Textiles, wearing apparel, leather and related products	fg_5
17T18	Paper products and printing	fg_6
58T60	Publishing, audiovisual and broadcasting activities	
62T63	IT and other information services	
64T66	Financial and insurance activities	
68	Real estate activities	
69T82	Other business sector services	
84	Public administration and defence; compulsory social security	
85	Education	
90T96	Arts, entertainment, recreation and other service activities	
20T21	Chemicals and pharmaceutical products	fg_7
22	Rubber and plastics products	
26	Computer, electronic and optical products	fg_8
28	Machinery and equipment n.e.c.	fg_9
29	Motor vehicles, trailers and semi-trailers	fg_{10}
30	Other transport equipment	fg_{11}
49T53	Transportation and storage	
35T39	Electricity, gas, water supply, sewerage, waste and remediation services	fg_{12}
45T47	Wholesale and retail trade; repair of motor vehicles	fg_{13}
55T56	Accomodation and food services	fg_{14}
61	Telecommunications	fg_{15}
86T88	Human health and social work	fg_{16}

Table A_6

Groups of industries (g_i) with fixed interconnectivity between in the periods [2005-2008]U[2014-2015] and [2009-2013], resulted from the interlayer communities' intersection model

[2005-2008]U[2014-2015]

Label	Description	Group
01T03	*Agriculture, forestry and fishing*[*]	$f_{I}g_{1}$
10T12	*Food products, beverages and tobacco*	
55T56	Accomodation and food services	
05T06	*Mining and extraction of energy producing products*	$f_{I}g_{2}$
19	*Coke and refined petroleum products*	
30	Other transport equipment	
49T53	Transportation and storage	
07T08	*Mining and quarrying of non-energy producing products*	$f_{I}g_{3}$
16	*Wood and of products of wood and cork (except furniture)*	
23	*Other non-metallic mineral products*	
24	*Manufacture of basic metals*	
25	*Fabricated metal products, except machinery and equipment*	
27	*Electrical equipment*	
31T33	*Other manufacturing; repair and installation of machinery and equipment*	
41T43	*Construction*	
9	*Mining support service activities*	$f_{I}g_{4}$
13T15	*Textiles, wearing apparel, leather and related products*	$f_{I}g_{5}$
17T18	*Paper products and printing*	$f_{I}g_{6}$
58T60	*Publishing, audiovisual and broadcasting activities*	
62T63	*IT and other information services*	
64T66	*Financial and insurance activities*	
68	*Real estate activities*	
69T82	*Other business sector services*	
84	*Public administration and defence; compulsory social security*	
85	*Education*	
90T96	*Arts, entertainment, recreation and other service activities*	
20T21	*Chemicals and pharmaceutical products*	$f_{I}g_{7}$
22	*Rubber and plastics products*	
26	Computer, electronic and optical products	$f_{I}g_{8}$
61	Telecommunications	
28	Machinery and equipment n.e.c.	$f_{I}g_{9}$
29	*Motor vehicles, trailers and semi-trailers*	$f_{I}g_{10}$
35T39	*Electricity, gas, water supply, sewerage, waste and remediation services*	$f_{I}g_{11}$
45T47	Wholesale and retail trade; repair of motor vehicles	$f_{I}g_{12}$
86T88	Human health and social work	$f_{I}g_{13}$

[2009-2013]

Label	Description	Group
01T03	*Agriculture, forestry and fishing*	$f_{II}g_{1}$
10T12	*Food products, beverages and tobacco*	
05T06	Mining and extraction of energy producing products	$f_{II}g_{2}$
19	Coke and refined petroleum products	
07T08	*Mining and quarrying of non-energy producing products*	$f_{II}g_{3}$
16	*Wood and of products of wood and cork (except furniture)*	
23	*Other non-metallic mineral products*	
24	*Manufacture of basic metals*	
25	*Fabricated metal products, except machinery and equipment*	
27	*Electrical equipment*	
31T33	*Other manufacturing; repair and installation of machinery and equipment*	
41T43	*Construction*	
28	Machinery and equipment n.e.c.	
9	*Mining support service activities*	$f_{II}g_{4}$
13T15	*Textiles, wearing apparel, leather and related products*	$f_{II}g_{5}$
17T18	*Paper products and printing*	$f_{II}g_{6}$
58T60	*Publishing, audiovisual and broadcasting activities*	
62T63	*IT and other information services*	
64T66	*Financial and insurance activities*	
68	*Real estate activities*	
69T82	*Other business sector services*	
84	*Public administration and defence; compulsory social security*	
85	*Education*	
90T96	*Arts, entertainment, recreation and other service activities*	
61	Telecommunications	
20T21	*Chemicals and pharmaceutical products*	$f_{II}g_{7}$
22	*Rubber and plastics products*	
45T47	Wholesale and retail trade; repair of motor vehicles	
86T88	Human health and social work	
26	Computer, electronic and optical products	$f_{II}g_{8}$
29	*Motor vehicles, trailers and semi-trailers*	$f_{II}g_{9}$
30	Other transport equipment	$f_{II}g_{10}$
49T53	Transportation and storage	
35T39	*Electricity, gas, water supply, sewerage, waste and remediation services*	$f_{II}g_{11}$
55T56	Accomodation and food services	$f_{II}g_{12}$

[*]. Common industries between periods' communities are shown in *italics*