DETECTING CITY-DIPOLES IN GREECE BASED ON INTERCITY COMMUTING

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Abstract

According to growth poles theory, the areas lacking critical sizes to develop polycentric structures are restricted to the development of structures of special configuration. In Greece, the development of growth poles is restricted to the emergence of "*urban dipoles*" and "*tripoles*", which are often used in the literature within a not well defined context. Based on a recently introduced method, this paper quantitatively detects functional dipoles in Greece by discriminating zones in the distribution of commuting, the number of daily movements for occupational purposes outside the city of residence. The analysis is implemented at three different levels of geographical scale, the intercity, an adjusted intercity (without the metropolitan regions), and the interregional scale. The analysis detects the functional dipoles per geographical scale and reveals the distance levels where polycentric structures emerge in the setting of commuting in Greece. Overall, this examines the applicability of a new dipoles detection method and paper provides insights into the conceptualization of hierarchy in urban structures, into the context of regional science and regional economics.

Keywords: Growth poles, urban structures, city networks, urban hierarchy, city distribution

JEL classification: R12, R40, R58

1. <u>Introduction</u>

The concept of city, although is easy to comprehend intuitively, is difficult to be defined within a rigorous conceptual framework because of the diverse spatial, economic, cultural, social, ideological, religious, and other characteristics describing each city (O' Sullivan, 2007; Rodrigue et al., 2013; Polyzos, 2015; Delitheou et al., 2019). Such characteristics make the conceptualization of city multivariate and even more complicated within the context of urban and regional research (Liontakis et al., 2010; Ladias et a;., 2011; Lagarias and Sayas, 2018; Napolskikh and Yalyalieva, 2019; Alexiadis, 2020), which enjoys the multidisciplinary contribution of transportation engineers (Christofakis, 2004; Tsiotas, 2020), urban and regional planners (Alexiadis and Ladias, 2011; Tsiotas and Polyzos, 2018), geographers (Ducruet, and Beauguitte, 2014; Anastasiou, 2020), economists (Korres and Tsamadias, 2009; Pougkakioti and Tsamadias, 2020; Rahmi, 2020), environmental scientists (Goula et al., 2015), even statisticians and physicists (Barthelemy, 2011; Marshall, 2018; Tsiotas, 2019). For instance, a city can be defined either according to its geographical coverage (Christofakis, 2004; Polyzos, 2015; UN, 2018), or its location and geomorphology (Sorensen, 2001; Xanthos et al., 2012, 2013; Arvanitidis, 2014; Cepaitiene, 2015), or its major economic functionality (Meijers, 2007, 2008; Duncan et al., 2013), or its population size (de Lavergne and Mollet, 1991; Rastvortseva and Manaeva, 2016; Tsiotas, 2016), or even its role in a transportation network (Mitoula et al., 2013; Rodrigue et al., 2013; Polyzos and Tsiotas, 2020). Therefore, many diverse terms determining cities are available in the literature, such as regional metropolises (Ladias et al., 2011; Duncan et al., 2013; Polyzos and Tsiotas, 2020; Tsiotas et al., 2021), which are central economic actors in their regions; capital cities (Gottman, 1983; Theodoropoulou et al., 2009), which concentrate the majority of administrative and governance functions of a country or region; gateways (Rodrigue et al., 2013; Delitheou, 2021; Tsiotas et al., 2021), which facilitate the entrance to certain economic or administrative functions; medium and small cities (de Lavergne and Mollet, 1991), which are defined within certain population ranges; strategic cities (Soldatos, 1991), which are located at places of strategic and geopolitical importance; satellite cities (Sorensen, 2001), which depend their development on other bigger neighbor cities; rural cities (Xanthos et al., 2012, 2013; Polyzos, 2015), which base their economies on the primary productivity sector; borderline cities (Cepaitiene, 2015), which are located at the country's borders; global cities (Cepaitiene, 2015; Giannakis and Papadas, 2021), which are of great importance in terms of global economic networks, and much more (O' Sullivan, 2007; Polyzos, 2015; Tsiotas et al., 2021).

These multidisciplinary approaches upgrade the level of complexity of urban studies even in those cases where only one city is examined. For instance, in big cities, several activity-spaces emerge at different geographical locations within the city borders, developing thus different functional areas in the city-structure (Goula et al., 2015; UN, 2018; Polyzos, 2015, 2019), such as the city proper (which is the core of the socioeconomic and cultural urban activities), the area of urban agglomeration (where considerable activity is observed due to population density), and the metropolitan area (which is the zone of socioeconomic interaction with the urban centers). In the light of studying the development of urban systems in geographical space, several theories and models have been proposed in the literature (Dacey, 1965; Parr; 1973; King, 1985; Henderson, 1991; Baccini, 1997; Miller et al., 2004; O' Sullivan, 2007), the majority of which built on two fundamental theories (Rodrigue et al., 2013; Polyzos, 2015, 2019), the central place theory, introduced by Christaller and Losch (Dacey, 1965; King, 1985l; Polyzos, 2015, 2019) and the growth-poles theory, introduced by Perroux (Parr; 1973). The first one describes a hierarchical geometric procedure in urban development, where polygonal relations of vertical functional flows emerge between cities of different hierarchy, while the second one suggests a discrete (node-based or network-based) approach of urban development, where horizontal relations and functional flows emerge between cities regardless of their size.

Despite the effectiveness of these major theories (and of their modern derivatives) to describe motifs and pattern-structures in the development of urban systems, all such approaches are restricted to conceptualize centrality and connectivity of urban systems within a disciplinary framework depending on the researchers' background. This can be evident by various terminologies describing urban systems and their structural elements, such as urban networks (Dupuy, 2008), "*réseux des villes*", "*stadtenetze*", and city networks (Smith et al., 2001; Jaglin, 2012), tri-poles (Tsiotas et al., 2021), satellite cities (Sorensen, 2001), bipolar neighborhood (Galster and Booza, 2007) and bipolar cities (Verrest and Jaffe, 2012), urban dipoles and city dipoles (Cerniauskaite et al., 2008; Metaxas, 2009; Zidonis and Jaskunaite, 2013), urban cores and urban centers (Choudhary, 2012; March and Martin, 2012), hubs and gateways (Rodrigue et al., 2013; Tsiotas and Polyzos, 2018), metropolises (Rodrigue et al., 2013), and more, which imply the diverse and multidisciplinary conceptualization of fundamental notions of polycentric development in urban systems. Obviously, the polyphony in this area suggests, on the one hand, a major drive for promoting urban research but, on the other hand, it highlights the demand of integration across the diverse conceptualization of urban structures, in the light of developing a common vocabulary amongst urban science's researchers originating from various disciplines.

An open debate that can be found in academia is the diverse conceptualization of urban or city dipoles (Davis, 2006; Galster and Booza, 2007; Cerniauskaite et al., 2008; Metaxas, 2009; Hudson, 2010; Verrest and Jaffe, 2012; Zidonis and Jaskunaite, 2013; Mallach, 2016). In current literature, an urban dipole suggests a specialization of the growth pole theory (in the case of two cities) and is generally defined by the coexistence of two (usually, but not necessarily, neighbor) cities belonging to a broader urban system, which are developing links that make them seen (or behave) as a couple. Cities composing an urban dipole are supposed to be equivalent in size, to share similar roles in the way they serve their hinterland (Metaxas, 2009), and to develop bonds of synergy or cooperation (Tsiotas et al., 2021). In the Greek literature (Metaxas, 2009; Tsiotas et al., 2021), the urban dipoles that are reported are Larissa–Volos (~144k citizens-120k citizens, with an intermediate distance of 64.1km), in the region (NUTS II) of Thessaly (), Kavala-Xanthi (~54k citizens-56k citizens/ 53.4km), Kavala–Drama (~54k citizens-44k citizens/ 36.8km), and Drama–Xanthi (~44k citizens-56k citizens/ 87.6km), in Eastern Macedonia and Thrace (), Tripoli–Kalamata (~30k citizens–54k citizens/ 82.3km), Patra-Aigio (~205k citizens-26k citizens/ 38.2km), in Peloponnesus (Athanasopoulou et al., 2011; Tsiotas et al., 2021), and Kozani-Ptolemaida (~41k citizens-32k citizens/ 87.6km), in Western Greece (Tsiotas et al., 2021). Further, in Lithuania (Cerniauskaite et al., 2008; Zidonis and Jaskunaite, 2013), the cities Vilnius-Kaunas (~545k citizens-295k citizens/ 103km), which belong to different (NUTS II) regions (LT00A and LT002, respectively), are reported as an urban dipole, while, in the international literature we can find a reference (Davis, 2006) to the cases of Tokyo–Shanghai (~9,270m citizens-24,24m citizens/ 1'780km) and New York-London (8.6m citizens-8.9m citizens/ 5'890km) as "*world city dipoles*".

The diversity observed in the population size, distance, and regional configuration of the previous cases implies that, in the current literature, the conceptualization of urban dipoles probably builds more on attributes concerning the qualitative aspects (welfare, productivity, occupation opportunities, level of technology, constitution, etc.) of the cities participating to these dipoles rather than on structural characteristics related to space (geography), size, and regional (or urban) configuration. This observation implies that any attempt to define urban dipoles within a structural context (which concerns either the socioeconomic, or size, or geographical features of the cities participating to the pole configurations) is by default indefinable because of the multidimensionality describing cities when are seen as market places. Such indefinability is even supported by the fact that current literature does not succeed to determine even whether the roles of cities within urban dipoles are competitive or cooperative (synergetic). For, instance, the cities of the dipole Larissa-Volos, in the region of Thessaly, Greece, on the one hand, share cooperative roles in attracting non-local enterprises (), while, on the other hand, they compete, for instance, in the development of public university, or hospital, or ministerial infrastructures (Polyzos, 2019). Therefore, in contrast to the physics (Serway, 2004; Griffiths and Schrieter; 2018), where the poles of a magnetic or electrical dipole are by definition heteronymous and cooperative in the development of their electromagnetic fields, in the context of urban science, the concept of urban dipoles appears, first, not well-defined and, secondly, counter-intuitive to its concordant conceptualization (i.e. of the magnetic or electrical dipoles) in physics. Consequently, any attempt to study urban dipoles within a well-defined context should build on their functionality rather than on their structure, where functionality can be easily measurable and convertible to variables, based on the type of the dipole flows. Toward this demand, this paper conceptualizes urban dipoles within the context of commuting flows, which is a functional aspect of daily labor exchange between places, and applies probabilistic and statistical analysis on available empirical data from Greece to define functional commuting urban dipoles within a well-define quantitative context.

In general, commuting is the daily mobility for labor purposes outside the city of residence, it suggests an act of spatial and economic interaction between neighbor regions, and is of great importance for urban and regional research because it develops spatio-socioeconomic structures at different scales such as interurban, regional, and similar (Rodrigue et al., 2013; Polyzos, 2019). This phenomenon has many dimensions, an economic related to transportation-cost (Van Ommeren and Fosgerau, 2009; Tsiotas and Polyzos, 2021) and to the relationship between commuting and productivity (Van Ommeren and Rietveld, 2005), a sociologic related to the psychology of mobility (Koslowsky et al., 1995), a technical related to traffic and accident analysis (Ozbay et al., 2007), a behavioral related to the selection of transportation modes and alternative routing (Murphy, 2009; Liu and Nie, 2011), and others, such as political, technological, etc (Polyzos, 2019). Despite its multivariate nature, commuting sufficiently describes labor interaction between cities, which are seen as labor markets (Rodrigue et al., 2013; Polyzos, 2019), and thus it configures an adequate functional framework for the definition of urban dipoles. Based on the flows intensity, this paper detects significant commuting flows based on a method proposed by Tsiotas et al.

(2021), defining urban dipoles in respect to the significant cases resulted from the analysis. The results are evaluated in accordance with the literature of urban dipoles in Greece and with other empirical findings of the Greek regional economics.

Within the context of the growth poles theory (O' Sullivan, 2007; Polyzos, 2019), this paper studies urban dipoles, which are often overlooked in the literature, building on a dipole detection method introduced by Tsiotas et al. (2021) in the context of network science (Barabasi, 2016). The overall analysis contributes to the demand of integration in the conceptualization of urban structures and promotes interdisciplinary research in urban science amongst researchers originating from various disciplines, by using a common vocabulary and a new method (Tsiotas et al., 2021) for defining and detecting urban dipoles according to a functional attribute.

The remainder of this paper is organized as follows; Section 2 describes an integrated terminology about dipoles in network structures, along with the conceptual and the methodological framework of the study. Section 3 shows the results of the analysis and discusses them within the context of regional and urban science and the relevant Greek literature. Finally, in Section 4, conclusions are given.

2. Methodology and Data

2.1. Functional dipoles: integrating their conceptual framework

An integrated conceptual framework and terminology about dipoles in urban network structures, builds on some elements of network science (Newman, 2010; Brandes et al., 2013; Ducruet and Beauguitte, 2014; Barabasi, 2016: Tsiotas, 2019), which is a newly established discipline emerged by the multidisciplinary study of connectedness. Network science uses the network paradigm to study communication systems and to model network structures to graphs, consisting of sets of nodes (interconnected units) and edges (their connections). Within this framework, geographical systems of socioeconomic interaction can be modeled into spatial networks, which are graphs embedded in the geographical space (Barthelemy, 2011; Tsiotas and Polyzos, 2018). In a network structure $G(V,E)=\{V,E\}$ consisting of a pair-set $\{V,E\}$ of nodes V and links E (Newman, 2010), the elementary expression of network connectivity is by definition an edge (or link) $(u,v)=e_{uv}\in E$, which represents the (either physical or immaterial) connection between two network nodes $u,v\in V$. However, a network edge $e_{uv}\in E$ does not by definition suggest a dipole-structure because it does not include the nodes participating to the connection. Therefore, a definition of a dipole based on network elements builds on a pair-set (Tsiotas et al., 2021):

$$b(u,v)=\left\{\{u,v\in V\},\{(u,v)\in E\}\middle|V,E\in G\right\} \quad (1),$$

consisting of two network nodes $u,v\in V$ along with their connection $(u,v)\in E$. By considering binary connections, the structure $b(u,v)$ can be seen as a "*binary dipole*", to the extent that it represents a (non-polarized) dipole-structure in a connected system (network) free of flaws (wherefrom the term binary stands for). Moreover, for binary directed (polarized) networks, node polarity is defined by the formula:

$$\text{sgn}(u,v)=(-,+) \quad (2),$$

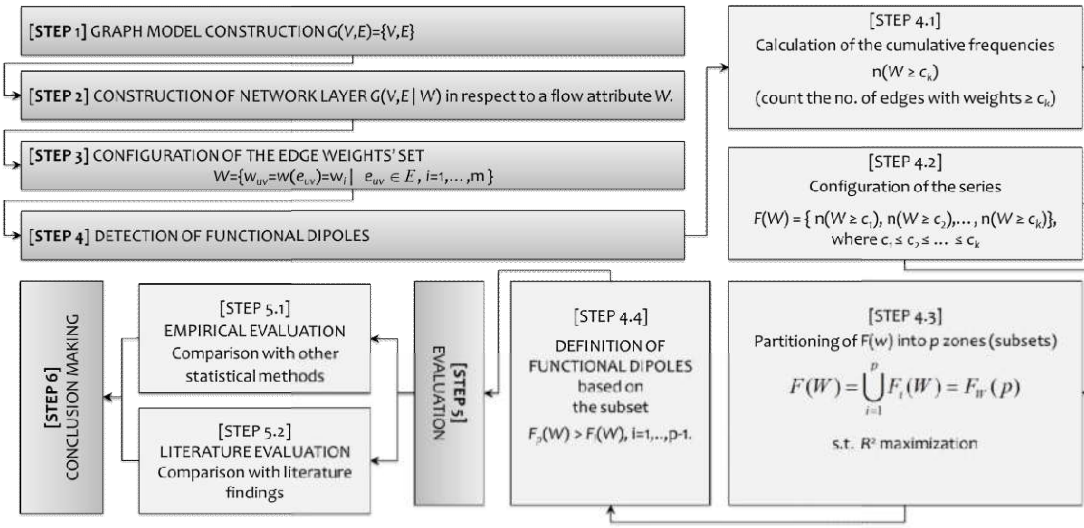
where: sgn(·) is the signum (or sign) function; the first node in edge (u,v) represents the south (negative) pole (sgn(u)=–) in the dipole; and the second node represents the north (positive) pole (sgn(u)=+). The direction of the flow expressed by the edge $(u,v){:}u_{(-)}\rightarrow v_{(+)}$ complies with the marking of outgoing ($u\rightarrow v$:+) and incoming ($u\leftarrow v$:–) flows from node u. Within this context, a polarized binary dipole is defined as as $b(u_{(-)},v_{(+)})$, provided that directed edges $e_{uv}\in E$ exist in the network. For weighted networks, binary dipoles are equipped with weights ($w(u,v)=w_{uv}$) expressing the flow intensity of their edges. Within this context, weighted network structures $b_w(u,v)$ represent "*weighted dipoles*", defined in respect to an attribute W determining edge weights $w_{uv}=W(u,v)$ in the network. In weighted dipoles $b_w(u,v)$ of directed networks, polarity can be defined so that the negative pole (sgn(u)= –) to be assigned to the node satisfying the inequality $w_{uv} - w_{vu} > 0$.

However, in urban networks, not all weighted dipoles develop significant flows to be considered as urban dipoles in the context of urban and regional science. Such specialized structures are called "*functional dipoles*" (in respect to an attribute W), representing weighted dipoles $b_w(u,v)$ of significant flows in the network structure, as expressed by the relation (Tsiotas et al., 2021):

$$b(u,v \mid W)=\{b_W(u,v) \in G(V,E) \mid w_{uv} >> \langle w_{ij} \rangle \} \quad (3),$$

where $i,j \in V$ and $(i,j) \in E$, $\langle w_{ij} \rangle$ is the average edge weight, and $w_{uv} >> \langle w_{ij} \rangle$ is a filtering condition expressing that the edge weight w_{uv} is significantly greater than the average value $\langle w_{ij} \rangle$. According to relation (3), an urban dipole in the context of urban science and growth poles theory (Davis, 2006; Galster and Booza, 2007; Cerniauskaite et al., 2008; Metaxas, 2009; Hudson, 2010; Verrest and Jaffe, 2012; Zidonis and Jaskunaite, 2013; Mallach, 2016; Tsiotas et al., 2021), can be well-defined in terms of network science as a functional dipole $b(u,v \mid W)$ in respect to an attribute W, provided that the filtering condition $w_{uv} >> \langle w_{ij} \rangle$ can be quantitatively defined. In a recent work, Tsiotas et al. (2021) developed a statistical mechanics method to quantitatively defined urban dipoles, as described in the conceptual diagram of Fig.1.

Fig.1. Conceptual diagram of the method used for defining a functional dipole in respect to a flow-attribute W (own elaboration).



In particular, at the first step (Fig.1) of the method, we construct a graph model $G(V,E)=\{V,E\}$ representing a network structure. For a multilayer network (consisting of different layers corresponding to various types of network weights, such as distance, trade flows, labor flows, information flows, capital flows, etc.), we choose in the second step a single flow-attribute W, in which we define functional dipoles. At the third step, we convert the weights matrix of the certain attribute into a vector set $W=\{w_{uv}=w(e_{uv})=w_i \in E \mid i=1,2,\ldots,m\}$, where m is the number of network edges ($m=|E|$). At the fourth step, we define functional dipoles (for attribute W) according to an algorithm developing a partition that fits the best possible parametric curves in each compartment. To do so, we configure first a series of flow thresholds $c_1(W)=c_1 \leq c_2 \leq \ldots \leq c_k$ (k is a natural number sufficiently large to produce a set of frequencies that will be further decomposed into compartments) and then we calculate the cumulative frequencies, according to the relation (Tsiotas et al., 2021):

$$n(W=\{w_i \in E\}_{i=1,2,\ldots,m} \geq c_k) = n(W \geq c_k) \quad (4),$$

expressing the number of edge-weights that are sequentially greater than the values $c_1 \leq c_2 \leq \ldots \leq c_k$. Next, we configure the series of these frequencies, according to the relation (Tsiotas et al., 2021):

$$F(W) = \{n(W \geq c_1), n(W \geq c_2), \ldots, n(W \geq c_k)\} = \{n_1, n_2, \ldots, n_k\}, \quad (5).$$

Therefore, we define a partition $F(W) = \bigcup_{i=1}^{p} F_i(W) = \bigcup_{i=1}^{p} F_i = F_W(p)$ of the set F(W) into p pair-wisely independent ($F_{i=1,\ldots,m}(X) \cap F_{j=1,\ldots,m}(X) = \varnothing$, $i \neq j$) subsets (compartments or zones) $F_i(W)$, which is submitted to the following restrictions:

$$F(W) = \bigcup_{i=1}^{p} F_i(W) = \bigcup_{i=1}^{p} F_i = F_W(p)$$

s.t.

i) $n\left(F_i\left(W\right)\right) \equiv card\left(F_i\left(W\right)\right) >> 3$,

ii) if $f_1(x)$, $f_2(x)$, …, $f_j(x)$ are the best fitting curves than can apply to the compartments of a series $F_W(j)$, we choose the partition $F_W(p)$ that satisfies the criterion $< R^2(f_p(x)) >= \max\left\{< R^2(f_j(x)) >, j \in \mathbf{N}\right\}$, where $R^2(f_j(x))$ is the coefficient of determination of curve $f_j(x)$ and $\langle \cdot \rangle$ is the average operant, (6),

iii) if $F_W(p_1)$ and $F_W(p_2)$ satisfy the above criteria, we chose $p=\min\{p_1,p_2\}$.

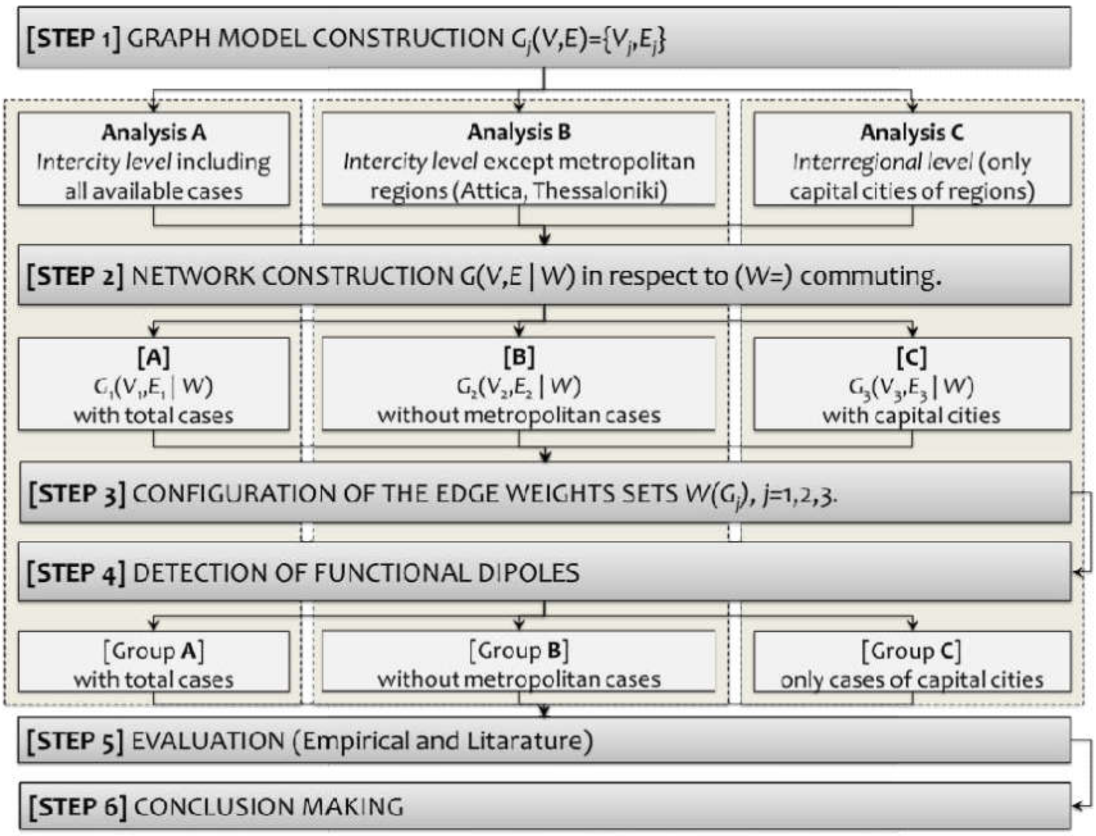
The first restriction (6*i*) describes that the length of each compartment in the partition $F_W(p)$ should be sufficiently large to enjoy a representative curve fitting. The second restriction (6*ii*) interprets that the choice of the number (p) of compartments is made by the partition that provides best fittings, which are described by the highest possible coefficient of determination (R^2). For the purpose of this paper, we consider one type (only power-law) of parametric fittings, although the method (Tsiotas et al., 2021) is open for applying any possible fitting type. Finally, the third restriction (6*iii*) instructs to choose a partition with the smallest possible number of compartments to ensure a low modeling complexity and to avoid over-fittings.

After the configuration of the optimum partition $F_W(p)$, functional dipoles (in respect to attribute W) are included in the last compartment $F_p(W)$ of the partition (Tsiotas et al., 2021). These cases are expected to have significantly higher performance than the other edge-weights, due to the cumulative configuration of the partition $F_W(p)$ in the algorithm. To test this assumption, we first compare the results with outlier detection methods, as boxplot and percentiles (Norusis, 2008; Walpole et al., 2012). In brief, outlier detection through boxplot construction is based on computing the interquartile range IQR=Q_3–Q_1, on which mild outliers are defined as those falling out of the interval [Q_1–1.5·IQR, Q_3+1.5·IQR] and extreme outliers those falling out of the interval [Q_1–3·IQR, Q_3+3·IQR]. On the other hand, "*typical*" percentiles including high outliers are the P_{95} and P_{99} percentiles, which respectively include the 5% and the 1% of the highest values of a distribution. Secondly, we evaluate the results of the analysis with literature findings of functional dipoles.

2.2. Specialization of the methodological framework to the Greek commuting

The dipole detection method (Tsiotas et al., 2021) is further customized to apply in the case of Greece, as it is shown in Fig.2. As it can be observed, it consists of three different parts of the analysis: the first applies to the total dataset (analysis A, at the intercity level, including all available cases); the second one to the non-metropolitan territory (analysis B: at the adjusted intercity level, excluding cases of the metropolitan regions of Attica and Thessaloniki); and the third one to the dataset of capital cities (analysis C: at the interregional level, including only cases between the capital cities of the Greek regions). This multilevel analysis provides a multiple outcome of functional dipoles, at different levels of data resolution (total and non-metropolitan datasets) and geographical scale (total and capital city datasets). The available commuting data are records from the 2011 national census concerning employed persons with residence in the area by place of work, at a local level (LAU 1) (ELSTAT, 2011). The dataset used in the analysis includes 16’526 registrations of commuting flows, which are measured in number of commuters between LAU 1 urban areas. The datasets used for the other two analyses are converted from the total dataset (16’526 cases): (*i*) by omitting cases of non-metropolitan regions resulting to a dataset of 11’675 cases (analysis B) and (*ii*) by retaining 120 cases of commuting flows between capital cities of Greece (analysis C). The series of the flow-thresholds $c_1 \leq c_2 \leq \ldots \leq c_k$ that is used to define the frequency series is the same for all the parts (A, B, and C) of the analysis and consists of the set C_o={0:250, with step 10} ⋃ {260:400, with step 20} ⋃ {400:1200, with step 50} ⋃ {1300:2000, with step 100} ⋃ {2’000:10’000, with step 500} ⋃ {10’000: 13’000, with step 1’000}. Different scales of steps are used to reduce redundant resolution of the series data. This generates a series of cumulative frequencies including 76 cases (as defined in relation 5), to which the analysis is applied.

Fig.2. The computational algorithm for detecting urban dipoles of commuting in Greece.

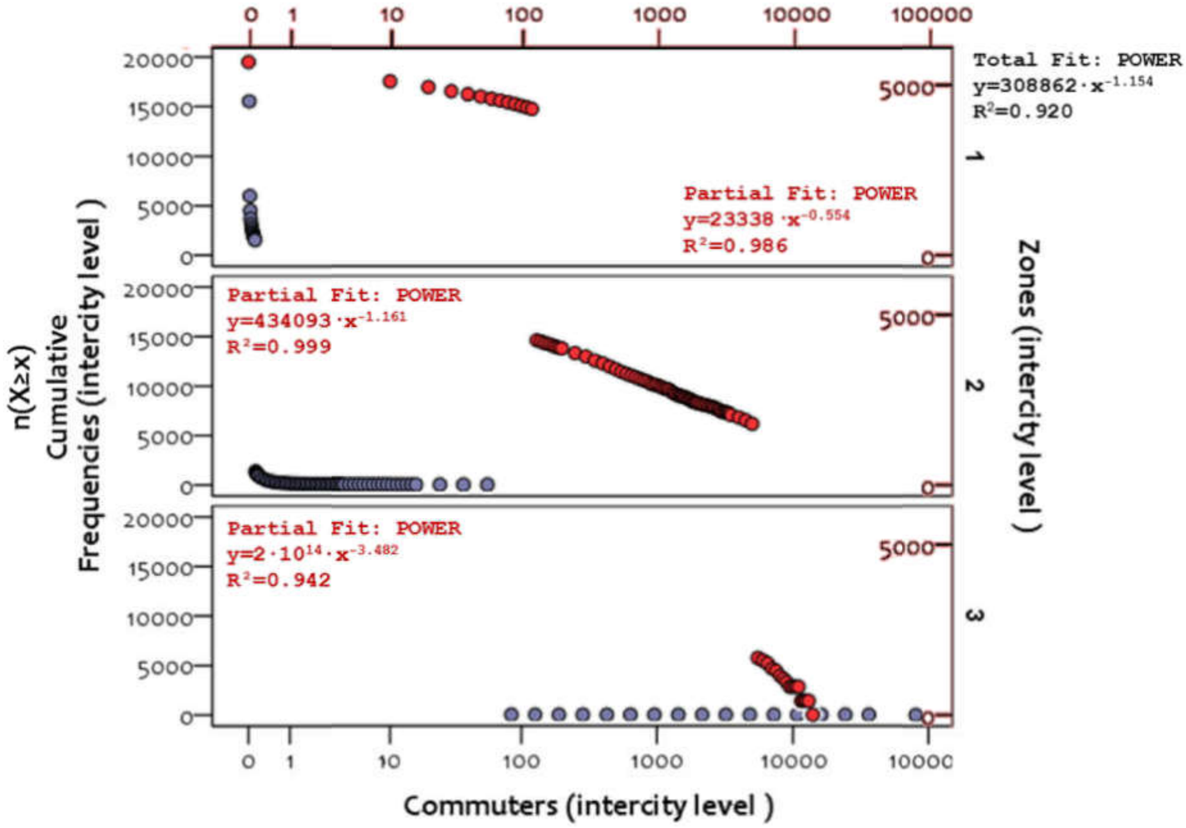


3. Results and Discussion

3.1. Analysis at the intercity level

The first part of the analysis is implemented on the total dataset including 16’526 cases. The results are shown in Fig.3, where it can be observed that the series of cumulative frequencies is divided into 3 compartments (zones). The first two compartments are described by patterns of power-law decay, where: (*i*) the first one has an exponent smaller (in absolute terms) than one (y=23’338·$x^{-0.554}$, R^2=0.986), expressing a smooth decay; (*ii*) the second one is described by a heavier decay with an absolutely exponent greater than one (y=434’093·x–1.161, R^2=0.999); whereas (*iii*) the third one is described by a pattern of exponential decay (y=150.17·exp{–4·10^{-04}·x}, R^2=0.958). All fittings are of high determination, describing at least 95.8% of the variability of the data. The first fitting zone includes 91.41% of commuting flows, the second one 8.49% of cases, and the third zone includes 16 cases (high flows).

Fig.3. Scatter plot with the distribution of the Greek intercity cumulative commuting flows (dataset A), divided into three compartments (zones): two of power-law and one of exponential decay (left: metric scale; right: log scale).



Among these 3 fitting zones (compartments) (Fig.3), the compartment of exponential decay (y=150.17·exp{–4·10^{-04}·x}, R^2=0.958) includes functional intercity dipoles of commuting. The dipoles included in this zone are shown in Table 1, along with additional information (commuting flows, percentiles, city population, and intermediate distance). As it can be observed, at this geographical scale, functional dipoles are Greek cities belonging to the two metropolitan regions of Attica and Thessaloniki, have population over 59'000 people, are distant within a range of 3-16km (with an average of 9.68km), and have flows of 5'730-13'037 (with an average of 8'030) commuters. In comparison with their percentile ranking, these 16 functional dipoles are "*extraordinary*" extreme outliers. In particular, the dipole Kalamaria-Thessaloniki belongs to the 100% percentile (P_{100}), whereas all the others to the 99.9% percentile ($P_{99.9}$), which are not typical outlier classes of percentile assessment. In terms of boxplot outlier detection, the mild outliers are defined by the complement (cases that do not belong to) of the interval [0,61] and the extreme outliers are defined by the complement of the interval [0,97] (both measured in number of commuters). This yields 2'509 mild outliers (15.89% of the total cases) and 1'809 extreme outliers (10.89% of the total cases), illustrating that neither the boxplot consideration succeeds to highlight the intercity functional dipoles within a realistic context.

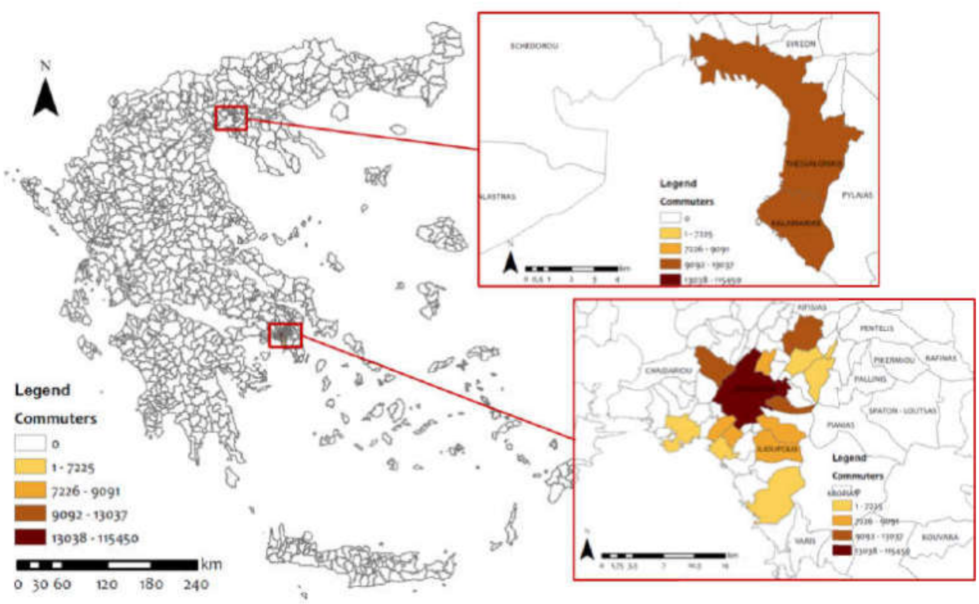
Table 1. The Greek cities configuring functional dipoles according to the first part of the analysis (A: intercity level).

Rank	Origin	Destination	Commuters (people)	Percentile	Distance (km/min.)	Origin Population (people)	Destination Population (people)
1	Kalamaria (Thessaloniki)*	Thessaloniki	13’037	P_{100}	8 (21)**	91’518	325’182
2	Peristeri (Attica)	Athens (Attica)	11’378		8 (18)	139’981	664’046
3	Zografou (Attica)	Athens	11’113		7 (20)	71’026	664’046
4	Kallithea (Attica)	Athens	9’091		3 (13)	100’641	664’046
5	Nea Smyrni (Attica)	Athens	8’529		5 (15)	73’076	664’046
6	Galatsi (Attica)	Athens	8’097		10 (22)	59’345	664’046
7	Vyronas (Attica)	Athens	7’848		5 (19)	61’308	664’046
8	Helioupoli (Attica)	Athens	7’664		9 (20)	78’153	664’046
9	Halandri (Attica)	Athens	7’225		12 (23)	74’192	664’046
10	Agia Paraskevi (Attica)	Athens	6’988	$P_{99.9}$	14 (24)	59’704	664’046
11	Helion (Attica)	Athens	6’696		10 (20)	84’793	664’046
12	Marousi (Attica)	Athens	6’616		16 (21)	72’333	664’046
13	Piraeus (Attica)	Athens	6’440		9 (19)	163’688	664’046
14	Athens (Attica)	Marousi	6’059		16 (21)	664’046	72’333
15	Glyfada (Attica)	Athens	5’976		15 (26)	87’305	664’046
16	Palaio Faliro (Attica)	Athens	5’730		8 (15)	64’021	664’046

*. Names inside parentheses refer to the city regions
**. Numbers in parentheses refer to time-distance measured in minutes.

The location of the functional dipoles of Table 1 is shown in the map of Fig.4, where it can be observed that all dipoles, except Thessaloniki-Kalamaria (which belongs to the prefecture of Thessaloniki), are included in the Attica (capital of Greece) prefecture. In terms of the growth poles theory (O’ Sullivan, 2007; Christofakis and Papadaskalopoulos, 2011; Polyzos, 2019), this observation highlights the central role of the city of Athens in the commuting functionality of the Attica prefecture, developing a pattern of a hub-and-spoke (star-like) topology, where Athens is the commuting hub enjoying 15 connections. The effect of the spatial proximity is evident to the configuration of the Attica’s cluster of dipoles, since all nodes participating in this star-like structure range within a distance of 3-16km, with an average of 9.8km. This outcome complies with the neighborhood criterion of polycentricism in the literature (Parr, 2003; Meijers, 2007, 2008), according to which polycentric areas consist of neighbor but discrete interacting urban cores.

Fig.4. Map of the functional dipoles of the first part of the analysis (A: intercity level metropolitan regions).

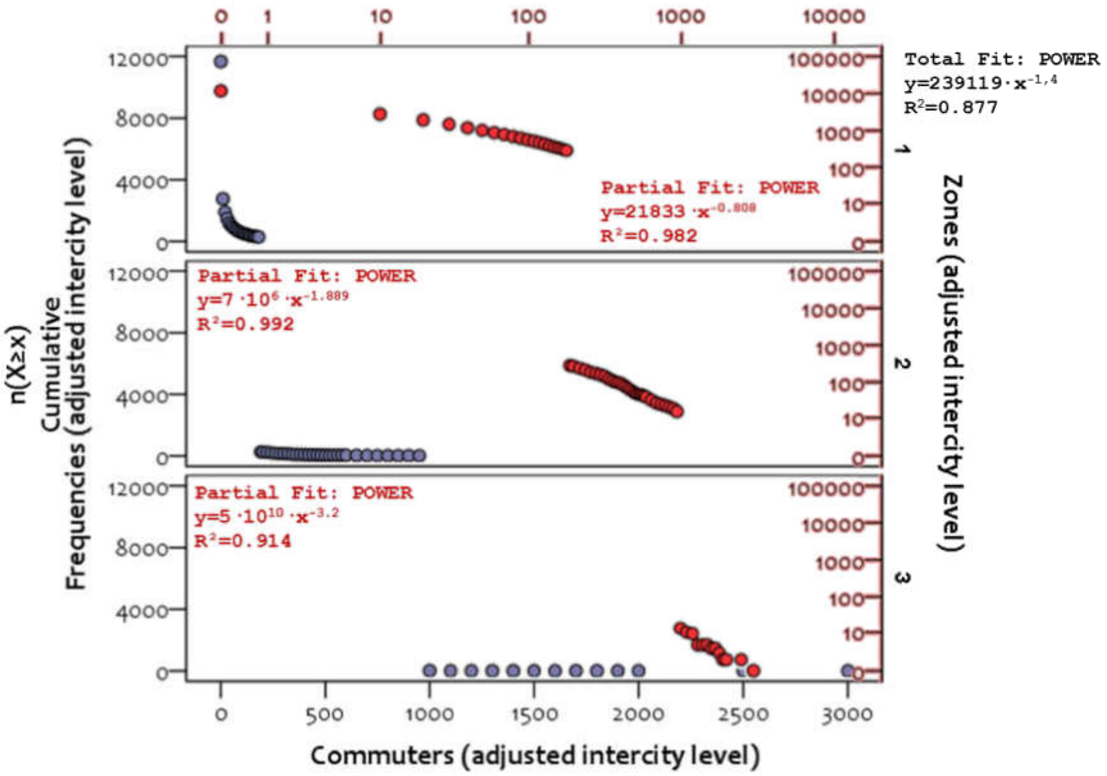


Finally, this part of the analysis highlights the gravitational drives in the configuration of the commuting functionality in Greece. In particular, the cities participating in the star-like cluster of dipoles in Attica have 1’404’867 people population, which corresponds to the 13% of the country total. On the other hand, the population of the cities participating in the commuting dipole of Thessaloniki is 416’700 people, corresponding to the 4% of the country total. The commuting distances are also very short, with an average time-distance less than 30min (Google Maps, 2021). Overall, the functional dipoles of commuting that were detected in this part of the analysis have a population share of 17% of the country total. This outcome first complies with the literature about the gravity configuration of commuting (Van Ommeren and Rietveld, 2005; Liu et al., 2012; Rodrigue et al., 2013; Polyzos, 2019) and secondly highlights the effectiveness of the method in detecting functional dipoles within a realistic context.

3.2. Analysis at the adjusted intercity level

The second part of the analysis is implemented to the dataset without metropolitan regions, including 11’675 cases. The results are shown in Fig.5, where we can also observe 3 compartments in the frequency series, all of which are described by patterns of power-law decay. All fittings are also of high determination, describing from 91.4-99.2% of the data variability. The first fitting zone includes the 97.58% of commuting flows, the second one the 2.29% of cases, whereas the third zone includes 14 cases. The power-law exponents of these curves are successively increasing (in absolute terms), where: (*i*) the first is smaller than one (y=21’833$\cdot x^{-0.808}$, R^2=0.982), expressing a smooth decay; (*ii*) the second one is near the value two ($y=7\cdot 10^6\cdot x$–1.889, R^2=0.9917); and (*iii*) the third one is greater than three ($y=5\cdot 10^{10}\cdot x^{-3.2}$, R^2=0.914). In terms of scale-freeness, which a property related to hierarchical structures in networks (Barabasi, 2016; Tsiotas, 2019), power-law exponents within the typical range $2<\gamma<3$ are related with good structures of network hierarchy. Within this context, we can loosely claim that the last two zones of the frequency series are privileged to have structural benefits of hierarchy, although the third one ($y=5\cdot 10^{10}\cdot x^{-3.2}$, R^2=0.914) includes the functional intercity dipoles of commuting in the adjusted case (excluding the metropolitan regions).

Fig.5. Scatter plot with the distribution of the Greek intercity cumulative commuting flows (dataset B: without the metropolitan regions), divided into three compartments (zones) of power-law decay (left: metric; right: log scale).



The dipoles included in the final (third) compartment are shown in Table 2, and are Greek cities that belong to regions of the whole Greek territory, have population between 1’115-167’446 people, are distant within a range of 2-34km (with an average of 12.14km), and have a flow of 1’000-2’785 (with an average of 1’408) commuters. In comparison with their percentile ranking, these 14 functional dipoles are extraordinary extreme outliers, because the dipole Nea Ionia (Magnessia)–Volos (Magnessia) belongs to the 100% percentile (P_{100}), whereas all the other dipoles belong to the 99.9% ($P_{99.9}$) and 99.9% ($P_{99.8}$) percentile. In terms of boxplot outlier detection, the mild outliers of the second dataset distribution are defined by the complement of the interval [0,20], and the extreme outliers are defined by the complement of the interval [0,30] (both measured in number of commuters). This yields 1’915 in number mild outliers (16.4% of the total cases) and 1’474 extreme outliers (12.63% of the total cases), illustrating that neither the boxplot consideration succeeds to highlight the intercity functional dipoles within a realistic context.

Table 2. The Greek cities configuring functional dipoles according to the second part of the analysis (B: adjusted intercity level, without metropolitan regions).

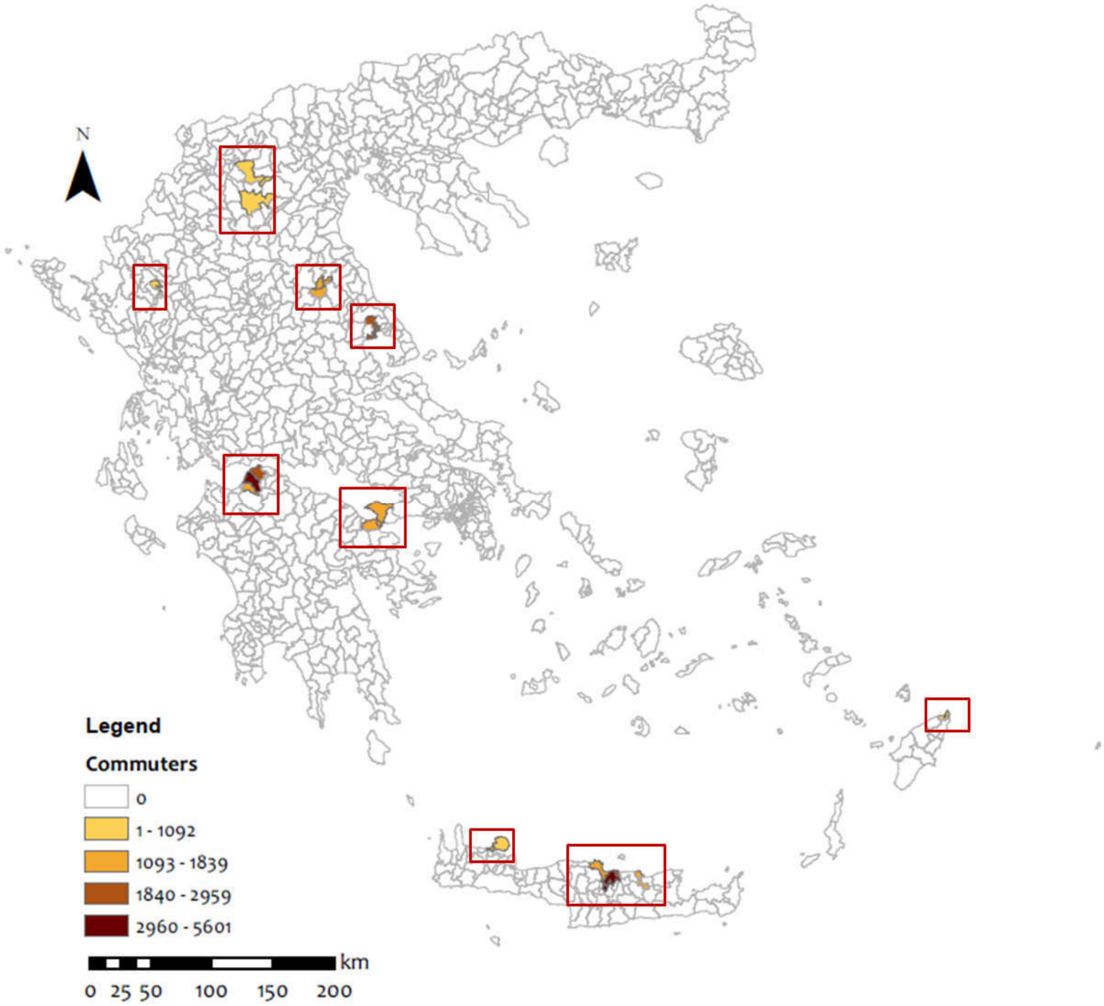
Rank	Origin	Destination	Commuters (people)	Percentile	Distance (km/min.)	Origin Population (people)	Destination Population (people)
1	Nea Ionia (Magnessia)*	Volos (Magnessia)	2’785	P_{100}	2 (8)**	33’578	86’046
2	Gazi (Herakleion)	Herakleion	1’839	$P_{99.9}$	24 (5)	14’640	140’730
3	Patra (Achaia)	Rio (Achaia)	1’767		9 (18)	167’446	5’252
4	Messatida (Achaia)	Patra (Achaia)	1’585		14 (27)	13’852	167’446
5	Korinthos	Loutraki (Korinthos)	1’296		20 (16)	30’176	11’564
6	Giannouli (Larissa)	Larissa	1’285		6 (9)	7’847	144’651
7	Nea Alikarnassos (Herakleion)	Herakleion	1’261		2 (5)	12’925	140’730
8	Herakleion	Nea Alikarnassos (Herakleion)	1’259		2 (5)	140’730	12’925
9	Herakleion	Hersonissos (Herakleion)	1’242		25 (22)	140’730	1’115
10	Rio (Achaia)	Patra (Achaia)	1’192		9 (18)	5’252	167’446
11	Ialyssos (Dodekanessa)	Rhodes (Dodekanessa)	1’092		7 (12)	11’331	50’636
12	Anatoli (Ioannina)	Ioannina	1’084		4 (11)	5’815	65’574
13	Kozani	Ptolemaida (Kozani)	1’020	$P_{99.8}$	34 (29)	41’066	32’127
14	Akrotiri (Chania)	Chania	1’000		12 (24)	13’100	108’642

*. Names inside parenthesis refer to the city regions

**. Numbers in parentheses refer to time-distance measured in minutes.

The location of the functional dipoles of Table 2 is shown in the map of Fig.6, where it can be observed that the spatial distribution of these dipoles is extended throughout the Greek periphery. In particular, 6 out of 14 dipoles belong to the region of Crete, one to the region of Dodecanese, 3 out of 14 to the region of Peloponnese, and the other 4 to the mainland Greece. These dipoles have considerably high commuting flows (≥1’000 commuters) in comparison with the other cases of the distribution (which belong to the $P_{99.8}$ percentile and over), but considerably (over 5.5 times) lower from the commuting flows of the dipoles extracted from the previous analysis (A: including the metropolitan regions). This observation supports the previous discussion about the gravitational configuration of commuting (Van Ommeren and Rietveld, 2005; Liu et al., 2012; Rodrigue et al., 2013; Polyzos, 2019). As far as the spatial distribution is concerned, we can observe in Fig.6 that the spatial arrangement of the functional dipoles configures an “*S-pattern*”, oriented toward the west part of Greece but is mainly fitted to the east coastal and Aegean Sea forehead of the country. This arrangement complies with the *S*-pattern ruling the developmental dynamics of the country (Polyzos, 2015, 2019; Tsiotas et al., 2021), which is mainly coordinated along the major highway road network axis, at the east coastal forehead of Greece (where transportation infrastructures, constriction, and economic activity is more intense in comparison with the other country). Next, the regions of Crete and Dodecanese, in which the half of the functional dipoles of Table 2 are included, also concern cases of significant regional development in Greece. In particular, the insular region of Crete is a considerably attractive tourism destination with a significant share in the tourism product of the region of Aegean Island and generally of the country (Tsiotas, 2017; Polyzos, 2019; Tsiotas et al., 2020; Delitheou et al., 2021). The cities of Chania and Herakleion are within the top populated countries of Greece (Xanthos et al., 2012, 2013; Tsiotas, 2016; Polyzos, 2019), therefore enjoying economies of scale. The island of Rhodes is also a considerable tourism destination of the Dodecanese region, suggesting a core of many economic activities at the south Aegean Sea (Polyzos, 2019).

Fig.6. Map of the functional dipoles extracted according to the second part of the analysis (B: intercity level without metropolitan regions).



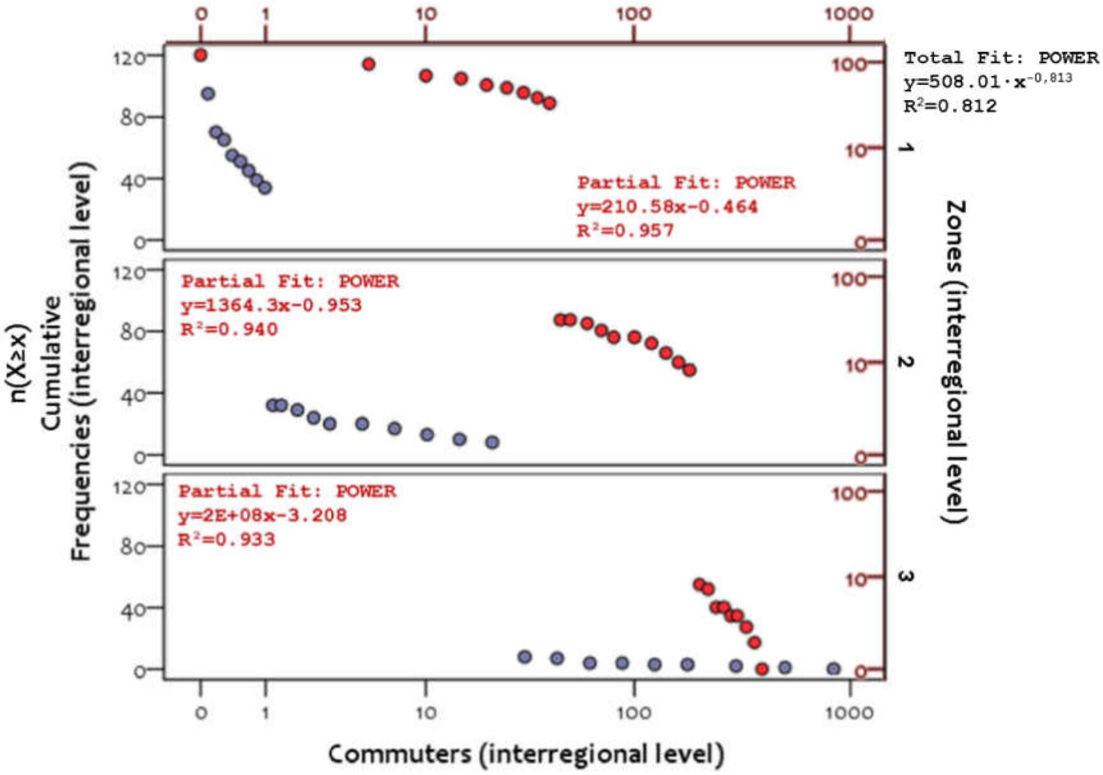
Finally, this part of the analysis also highlights the effect of the spatial proximity to the configuration of the dipoles included in Table 2, since all nodes in these dipole structures are distant within a range of 2-34km, with an average of 12.14km. As is evident, commuting distances are (also in this case) very short, with an average time-distance less than 30min (Google Maps, 2021). In gravitational terms, the cities participating in the functional dipoles of this analysis have a total population of 998’113 people, which refers almost to the 10% of the country’s population. This results also supports the gravity configuration of commuting (Van Ommeren and Rietveld, 2005; Liu et al., 2012; Rodrigue et al., 2013; Polyzos, 2019) and accredits the effectiveness of the method.

3.3. Analysis at the interregional level

The third part of the analysis is implemented to the dataset of interregional connections, including 120 cases of commuting flows between the capital cities of the Greek regions. The results of the analysis are shown in Fig.7, where we can also observe 3 compartments in frequency series. The first one describes a pattern of logarithmic decay ($y=-27.81\cdot \ln x+138.39$, $R^2=0.9875$), whereas the other two describe patterns of exponential decay. All fittings are also of high determination, describing from at least 94.9% of the data variability. The exponent coefficients of the exponential curves are almost equal, namely 0.01

(absolutely) for the second one (y=51.019·e$^{-0.01x}$, R^2=0.9794) and 0.012 (absolutely) for the third curve (y=86.509e$^{-0.012x}$, R^2=0.949), implying that substantial differences in the slope of these curves are due to the term coefficients, where this of the third fitting curve is almost 70% greater than of the second one. In terms of coverage, the first fitting zone includes the 73.33% of commuting flows, the second one the 20% of cases, whereas the third zone includes 8 cases of high flows. The third fitting curve (y=86.509e$^{-0.012x}$, R^2=0.949) is also the candidate of including functional interregional commuting dipoles.

Fig.7. Scatter plot showing the distribution of the Greek interregional cumulative commuting flows (dataset C) that is divided into three compartments (zones), one of logarithmic and two of exponential decay (left: metric; right: log scale).



The dipoles that are included in the final (third) zone are shown in Table 3, where it can be observed that Greek cities composing these dipoles belong to regions of the mainland Greek territory. This result is due to the modeling restriction of considering in this analysis only flows between capital cities, where inter-island or coastal-island commuting flows were by default negligible at the interregional level. Also, the functional dipoles of this analysis have population between 80’419-3’828’434 people, are distant within a range of 50-80km (with an average of 64.13km), and involve 207-372 commuters (with an average of 275 commuters). In comparison with their percentile ranking, these 8 functional dipoles belong to the 93% percentile (P93) and above, which is a broader outlier zone, in comparison with the P95 (which counts 5 cases) and the P99 (which counts just one case) values. This consideration illustrates the potential of the method to discriminate cases with more structural (e.g. the frequency pattern) than numeric (percentage) criteria. In terms of boxplot outlier detection, the mild outliers are defined by the complement of the interval [0, 112] and the extreme outliers are defined by the complement of the interval [0, 169] (both measured in number of commuters). This yields 19 mild outlier values (15.83% of the total cases) and 10 extreme outlier values (8.3% of the total cases), which are greater (although near) in number than the cases resulted by the method.

Table 3. The Greek cities configuring functional dipoles according to the third part of the analysis (C: interregional level).

Rank	Origin	Destination	Commuters (people)	Percentile	Distance (km/min.)	Origin Population (people)	Destination Population (people)
1	Thessaloniki	Kilkis	372	P_{100}	50 (58)**	1.110.551	80.419
2	Katerini (Pieria)*	Thessaloniki	345	P_{98}	75 (49)	126.698	1.110.551
3	Chalkida (Euvoia)	Athens	324	P_{97}	80 (56)	210.815	3.828.434
4	Kavala	Xanthi	268		56 (63)	124.917	111.222
5	Kilkis	Thessaloniki	232	P_{96}	50 (58)	80.419	1.110.551
6	Thessaloniki	Polygiros (Chalkidiki)	230	P_{95}	70 (59)	1.110.551	105.908
7	Volos (Magnessia)	Larissa	222	P_{94}	60 (47)	190.010	284.325
8	Veroia (Hemathia)	Thessaloniki	207	P_{93}	72 (57)	140.611	1.110.551

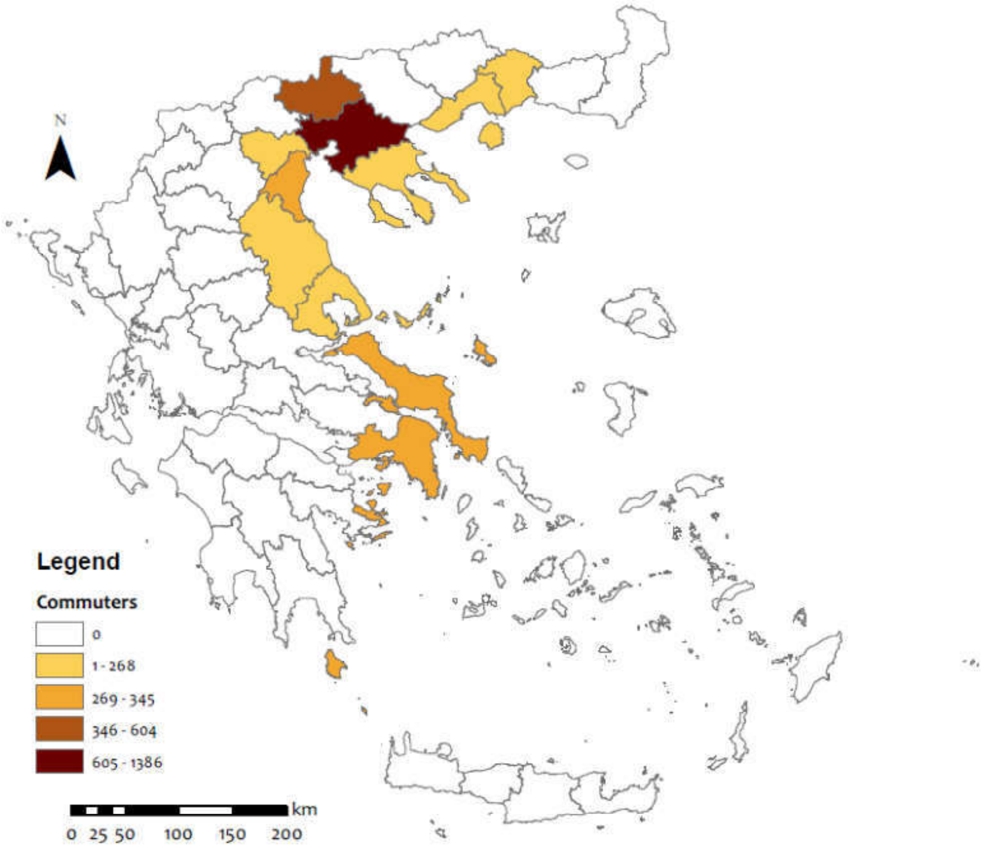
*. Names inside parenthesis refer to the city regions

**. Numbers in parentheses refer to time-distance measured in minutes.

The location of the functional dipoles resulted by this analysis is shown in Fig.8, where it can be observed that the spatial distribution of these dipoles is extended throughout the periphery of the mainland Greece. These dipoles do not have considerably high commuting flows (<400 commuters), compared to the cases of the other parts of the analysis, a fact which supports the previous discussion about the gravitational configuration of commuting (Van Ommeren and Rietveld, 2005; Liu et al., 2012; Rodrigue et al., 2013; Polyzos, 2019). As far as the spatial distribution is concerned, we can observe that (also in this interregional case) the spatial arrangement of the functional dipoles configures an "*S*" pattern, which is oriented toward the east coastal and Aegean Sea foreheads of the Greece. This pattern complies with the developmental dynamics of the country (Polyzos, 2015, 2019; Tsiotas et al., 2021), as it was previously discussed. In terms of spatial proximity, the distance range of the functional dipoles at this (interregional) level is almost 6 times, on average, greater (50-80km) than the cases of the previous two geographical levels. Also, the volume of commuting flows at the interregional level is almost 18 times, on average, decreased comparatively to the previous cases, verifying the gravitation configuration of the commuting phenomenon (Van Ommeren and Rietveld, 2005; Liu et al., 2012; Rodrigue et al., 2013; Polyzos, 2019).

Further, among these 8 functional dipoles of Table 3, the half (4 out of 8) of them belong to the region of Thessaloniki and one to the Attica region, referring together to the 62.5% of the total cases. This observation supports the importance of the metropolitan regions in the configuration of commuting flows in Greece and the gravitational configuration of the phenomenon. In this part of the analysis, we can also observe that the distances where the functional dipoles of commuting emerge are relatively short (50-80km) and the time-distances are on average below 60min (Google Maps, 2021), a fact which also highlights the importance of proximity in the configuration of the commuting phenomenon (Rodrigue et al., 2013; Polyzos, 2019). Finally, in this part of the analysis, we can observe that the region of Thessaloniki and their neighborhood regions configure a polycentric pattern of commuting poles, with a star-like (hub-and-spoke) structure having a hub at the city of Thessaloniki. A similar structure was also detected at the intercity level (first part of the analysis) for the case of Attica region. This result also verifies the gravity configuration of commuting in Greece, outlining that the metropolitan regions of the country are the only sufficing to configure polycentric structures of commuting. In particular, Athens (with a population of almost 4m people) develops a polycentric functional pattern of commuting within its region (at the intercity level), whereas Thessaloniki (with a population over 1m people) does so at the interregional level (a between regions structure).

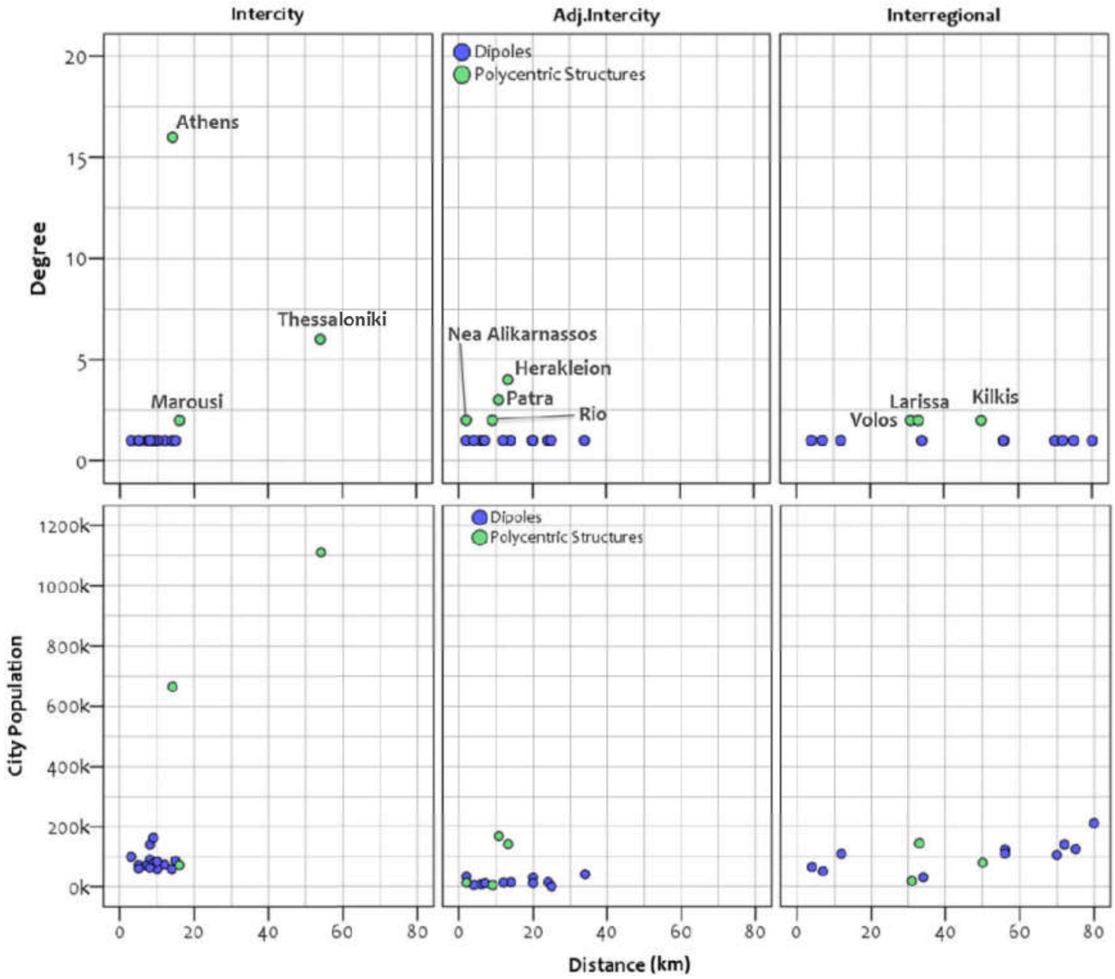
Fig.8. Map of the functional dipoles according to the third part of the analysis (C: interregional level).



3.4. Further analysis

After the detection of the functional dipoles, at the three levels of geographical resolution, we apply a further analysis on the dipoles' dataset consisting of the collection of cases included in Tables 1, 2, and 3. The analysis builds on correlation plots between (*i*) kilometric distance and polycentric structure degree and (*ii*) kilometric distance and city population, distinguishing cases (cities) of dipole structures (node degree =1) and higher order (node degree >1) polycentric structures. The analysis aims to reveal patterns of polycentric configuration in the urban functional dipoles detected for the cases of Greek commuting. To perform the analysis, we define the variable of degree as the number of dipole connections in which each city participates. The results of the analysis are shown in Fig.9, organized into windows of geographical scale (intercity, adjusted intercity, and interregional) and groups of polycentric structure (dipoles, polycentric structures). In terms of degree, we can observe that polycentric structures of commuting in Greece emerge at geographical distances between 2-55km, and particularly between: 15-55km, at the intercity level; 2-15km, at the adjusted (without metropolitan cases) intercity level; and 31-50km, at the interregional level. These kilometric ranges are the same with those shown in the case of distance-population correlation. The concordant intervals in the emergence of dipoles range between: 2-15km, at the intercity level; 2-35km, at the adjusted (without metropolitan cases) intercity level; and 2-80km, at the interregional level. Under a combined consideration, we can observe that (*i*) at the intercity level, polycentric structures emerge at longer distances than dipoles, (*ii*) at the adjusted intercity level, they emerge at shorter distances than dipoles, and (*i*) at the interregional level, they emerge at middle distances than dipoles. As far as intercity and adjusted intercity levels are concerned, we can observe that the effect of the capital cities of Athens and Thessaloniki shifts the polycentric structures' configuration at longer distances, under a gravitational rule. Overall, this approach provides insights into the dynamics describing the spatial emergence of polycentric structures, addressing avenues of further research for further empirical evaluation.

Fig.9. Scatter plots of the (Distance, Degree) and (Distance, City Population) correlations, constructed for the collective cases of functional city dipoles resulted from the analysis.



4. Conclusions

Within the context of the growth poles theory, the areas that lack the critical sizes to develop polycentric structures of socioeconomic functionality (structures composed by core cities and several independent smaller urban units that socioeconomically interact and influence each other) are restricted to the development of special or limited structures proportionally to their characteristic sizes. In the case of Greece (as well as of other countries with similar population and economic sizes), the growth poles development is restricted to the development of urban networks of special structures described by small participation of cities. In the literature, this restriction has led to the emergence of the specialized terms "*urban dipoles*" and "*tripoles*", which are often used within a not well defined and comprehensive context. Aiming to promote the empirical research of urban dipoles, this paper applies a recently introduced method detecting functional dipoles (in respect to an attribute), based on statistical mechanics. The method was applied to data of the Greek commuting and was implemented at three different levels of geographical scale, including intercity, adjusted intercity (without the metropolitan regions of Attica and Thessaloniki), and interregional connections. The first part of the analysis revealed 16 functional dipoles of commuting, including cities with population 1'100-168'000 people, distance within a range of 3-16km (and below 30min time-distance, on average), and flows of 5'700-13'100 commuters. The second part resulted to 14 functional dipoles of commuting, including cities with population 59'000-665'000 people, distance within a range of 2-34km (and below 30min time-distance, on average), and flows of 1'000-2'800 commuters. The third part revealed 8 functional dipoles of commuting, including cities with population 80'000-3'830'000 people, distance within a range of 50-80km (and below 60min time-distance, on average), and flows of 200-400 commuters. In comparison with their percentile ranking, the functional dipoles that were detected at the first two parts of the analysis (at the intercity level) were exceptionally extreme outliers belonging to the 99.8% percentile ($P_{99.8}$) and above. In these cases, the boxplot outlier analysis yielded thousands of mild and extreme outlier values, illustrating that neither the percentile or boxplot consideration succeeded to highlight the intercity functional dipoles within a realistic context. On the other hand, at the third part of the analysis (at the interregional level), the functional dipoles regarded outliers belonging to the 93% percentile (P_{93}) and above, but were less in number than those emerged by the boxplot outlier analysis. This outcome highlighted the flexibility of the applied method to be adaptable in geographical scale. The intercity analysis revealed dipoles belonging to the two metropolitan regions of Attica and Thessaloniki, where a polycentric structure of a hub-and-spoke (star-like) topology emerged in Attica. The adjusted intercity analysis (without metropolitan regions) revealed dipoles belonging to regions of the whole Greek territory, whereas the analysis at the interregional level resulted to dipoles belonging to regions of the mainland Greek territory, in which a polycentric structure of a hub-and-spoke (star-like) topology emerged in the region of Thessaloniki and their neighborhood regions (with Thessaloniki serving as a hub). In all parts of the analysis, the effect of the spatial proximity were evident to the configuration of the dipoles, where all nodes participating in these structures were considerably near in kilometric and time-distance, a result which complied with the neighborhood criterion of polycentricism in the literature. The analysis also highlighted the gravitational drives in the configuration of the commuting functionality in Greece, where the most populated cities of the country participated in the dipole configurations that covered about 20-60% of the total population. In terms of location, the spatial distribution of the detected functional dipoles illustrated an *S*-pattern configuration, which is the one ruling the developmental dynamics of the country due to its geomorphological, infrastructure, and socioeconomic features. Finally, the analysis revealed the importance of the metropolitan regions of Attica and Thessaloniki in the configuration of commuting, which were only that sufficed to configure polycentric structures, the first at the intercity and the second one at the interregional level. Overall, this paper contributed to the demand of integration in the conceptualization of urban structures, it developed a common vocabulary, and applied a new method for defining and detecting urban dipoles based on a functional attribute, further highlighting its utility.

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