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Unraveling latent dimensions of the urban mosaic: A multi-criteria spatial approach to metropolitan transformations

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Abstract

We investigated local-scale urban profiles by analysing the spatial structure of 124 territorial indicators to identify possibly relevant dimensions influencing urban evolution and promoting socioeconomic transformation. To assess patterns and processes of urban expansion, Athens (Greece) was taken as a prototype of metropolitan systems with a diversified morphology and entropic functions. Exploratory spatial data analysis identified six dimensions of urban evolution: population concentration, sprawl, social segregation, income growth, specialization in commerce/retail/logistics and industrial decline. Urban centres were profiled according to the dominant dimension(s). Cluster analysis identified the urban hierarchy in the Athens metropolitan region based on population density, highlighting more subtle gradients associated with settlement morphology, social diversification, local development and economic performance. The proposed methodology stems from the 'factorial ecology' approach, providing a coherent overview of the recent transformations that impact dimensions of urban sustainability.

Keywords

Urban gradient, spatial analysis, contemporary city, sprawl, Europe

Introduction

In recent history, world-wide urbanization processes have produced multiple urban forms having vastly different relationships with some characteristic socioeconomic functions

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associated to population growth, technological change, economic specialization or social disparities (Allen, 1997; Berry, 2005; Brenner and Schmid, 2014; Liu and Seto, 2008). Metropolitan areas have progressively developed a network of multi-directional relationships with the surrounding region, at different spatial scales and including commuting, trade relations, exchange of information and collaboration involving enterprises, social groups, individuals and local institutions (Derudder et al., 2003). These networks usually organize on the basis of the distance from central cities and are sensitive to the size, density and accessibility of sub-centres; place-specific factors have a variable influence (Champion and Hugo, 2004; Markusen and Schrock, 2006; Wyly, 1999).

Economic forces play a major role in shaping land-use and research linking urban morphology with socioeconomic functions has identified some major principles of spatial organization that explain the configuration of metropolitan systems (Guillain et al., 2006). Agglomeration is particularly relevant in shaping processes of urban growth and change, since the benefits deriving from the location factors typical of inner cities reflect the formation and the consolidation of 'agglomeration economies' (Jacobs-Crisioni et al., 2014). Location factors are reflected in the principle of accessibility, influencing the distribution of assets in the urban space via differentiated land price, for example (Couch et al., 2007). Urban growth models have therefore considered the distance from the inner city as the most relevant variable shaping socioeconomic structures (Diappi et al., 1998; Scott et al., 2013; Serra et al., 2014). For example, the central place theory identified a hierarchy of urban levels developing a model for their spatial distribution (Parr, 2014). In this sense, rank–size distribution has been an important tool in the analysis of metropolitan hierarchy across spatial and temporal scales (Xu and Harriss, 2010). The Spatial Cycle Theory in turn provided a (static) interpretation of urban growth (Klaassen et al., 1981), introducing the concepts of 'cycles' and 'transitions' in four distinct phases (urbanization, suburbanization, counter-urbanization, re-urbanization) with defined socioeconomic implications (Cross, 1990; van den Berg et al., 1982).

The most evident transformations in contemporary cities include the production of new economic spaces and the creation of social gradients decoupled from the traditional urban–rural dichotomy, introducing subtle divides within metropolitan regions (Nijkamp and Kourtit, 2013). However, traditional criteria such as physical hierarchy, urban density, linear distances or housing regimes can sometimes lead to simplified, partial, or even misleading interpretations of urban complexity (Page et al., 2001; Portugali, 2000; Pumain, 2005). Instead, competitive advantages based on a mix of inputs, both measurable (e.g. accessibility, population age, land prices, settlement characteristics, topography) and intangible (e.g. social diversification, economic connectedness, workers' skills, environmental quality), correctly reflect the complex dynamics observed in metropolitan regions (Kourtit et al., 2014; Neuman and Hull, 2009; Scott et al., 2013). Econometric approaches have been used to interpret urban expansion, modeling causal interactions between key variables such as regional value added, disposable income, workers' specialization, economic structure, population density and land prices (Chen and Partridge, 2013).

However, other studies (Favaro and Pumain, 2011) have demonstrated that traditional, linear and deterministic approaches overestimate the importance of certain economic factors, providing a biased picture of the overall urbanization process at the regional scale. Different urban dimensions coexist, matching distinct functions to spatial structures (Aguilera-Benavente et al., 2014; Chorianopoulos et al., 2014; Zhang et al., 2013), and urbanization has increasingly been interpreted as a multi-directional and non-linear process (Bura et al., 1996; Cabral et al., 2013; Salvati, 2014) based on the spatially variable relationship between settlement morphology and socioeconomic functions (Couch et al., 2007; Hirt, 2013; Salvati and Gargiulo Morelli, 2014). Going beyond the classical models of urban growth in developed countries, important divergences in the relationship between patterns and processes emerge when reading the spatial structure of a given urban system at the local scale (Cahill and Mulligan, 2003; Grekousis et al., 2013; Massey et al., 1996; Ode and Miller, 2011).

Quantitative and exploratory procedures have been proposed to characterize urban forms at the metropolitan level (e.g. Tsai, 2005). The spatial distribution of socioeconomic functions and their change over time has also been studied quantitatively, through multivariate spatial analysis (Baumont et al., 2004; Griffith and Wong, 2007; Riguelle et al., 2007). The increasing diversity observed in metropolitan systems' evolution has been read as evidence of urban complexity (Allen, 1997; Anderson et al., 1988; Berry, 1969; Healey, 2006; Holland, 2006; Walloth et al., 2016), to be studied making use of entropy-based approaches (Akkerman, 1992; Batty and Longley, 1994; Derudder et al., 2003) and fractal structures (Batty, 2007; Cabral et al., 2013; Encarnação et al., 2013; Kingsley and Enders, 1975). Attempts to reduce urban complexity through the multivariate analysis of socioeconomic indicators date back to the 1960s and the 1970s, being the main objective of the 'factorial ecology' studies of urban systems (Davies and Murdie, 1991). Factorial analysis could be seen as 'an early data-driven ideographic form of science', and its key contribution was to derive a set of methods that could be applied to illustrate socio-spatial structures (Singleton and Spielman, 2014). Applications based on exploratory statistical techniques have been proposed for the study of the multiple relationships between urban patterns and processes in some exemplificative metropolitan regions, particularly in North America and Europe (Clark et al., 1974; Fielding, 1982; Grekousis and Mountrakis, 2015; Wyly, 1999). The 'factorial ecology' thinking allows the interpretation of apparent and latent patterns of urban growth at different spatial scales (Spielman and Thill, 2008). An important issue at the base of 'factorial ecology' thinking is the flexibility in the selection of relevant variables (or factors) describing the evolution of metropolitan regions (Carey, 1966; Langlois and Kitchen, 2001; Potter and Coshall, 1986).

The 'factorial ecology' perspective has provided an empirical base to study urban fragmentation in the light of economic uncertainty, changing social attitudes and modifications in political rules. Factor analysis has been used to assess specific dimensions of metropolitan systems, including urban hierarchy and specialization (Markusen and Schrock, 2006), crime determinants (Cahill and Mulligan, 2003), urban deprivation (Langlois and Kitchen, 2001), institutional change (Wyly, 1999), socio-spatial differentiation (Davidson and Wyly, 2012; Davies and Murdie, 1991) and social segregation (Le Goix, 2005; Massey et al., 1996).

Some scholars have criticized factorial ecology as an approach able to reveal only a few long-term evolutionary trajectories based on adaptation to change, selection, cooperation or imitation (Berry, 2005), often with a weak theoretical support (Clark et al., 1974). Moreover, technical problems arose in factor applications associated with spatial data (Johnston, 1977) and varying degrees of factors' correlation across different urban areas might explain why factors observed in Western cities were not found elsewhere (Hunter, 1972). Nevertheless, approaches deriving from the 'factorial ecology' thinking, that focus on the intimate (and locally differentiated) relationships between patterns and processes of urban growth, may produce increasingly articulated frameworks for exploring urban dynamics (Fan, 2010; Favaro and Pumain, 2011).

Cities characterized by unbalanced socioeconomic models, governance problems and planning failures are critical examples for the analysis of the interplay between patterns and processes of urban growth (Leontidou, 1990). The Mediterranean region represents a paradigmatic example of how the variety of morphologies, economic structures, socio-spatial contexts and territorial factors shape a kaleidoscopic overview of different urban forms and socioeconomic functional patterns (Salvati and Di Feliciantonio, 2014; Salvati and Gargiulo Morelli, 2014). In this view, urban expansion could be explained by place-specific paths based on the long-established interplay between settlement morphology and socio-spatial structures (Chorianopoulos et al., 2010; Dura-Guimera, 2003; Moliní and Salgado, 2012).

In urban geography, the factorial ecology approach gives value to the mass of statistical information available at progressively disaggregated levels: to reduce the dimensionality of the data, as well as to explore relationships between variables observed in the spatial units, Principal Component Analysis (PCA) is applied (Demšar et al., 2013; see also Marsal-Llacuna et al., 2015 and the references therein). Urban analyses have benefited of PCA to derive latent socioeconomic dimensions linked to, for instance, metropolitan functions in Germany (Growe and Volkmann, 2016), peri-urbanization in Greece (Lafazani and Lagarias, 2016), urban growth models in China (Feng and Liu, 2013) and gentrification and displacement in Hong Kong (Ye et al., 2015).

The present study proposes an approach derived from 'factorial ecology' thinking, supplemented with an exploratory spatial data analysis, to identify relevant socioeconomic dimensions of metropolitan profile and their relationship with urban form in a paradigmatic Mediterranean city, Athens, one of the oldest cities in the western world as well as the capital of a country severely affected by financial upheavals. Our methodology integrates multivariate techniques applied to 124 socioeconomic indicators varying over time and space, revealing in this way the latent interplay between economic, social and environmental factors shaping urban profile. Investigation based on revisited 'factorial ecology' thinking permits the application of socioeconomic indicators at the local scale in support of sustainable development policies, regional planning measures and participative urban design.

Methodology

Study area

We investigated the mainland portion of the administrative region of Attica, Greece, which encompasses the Athens Metropolitan Region (AMR) defined according to the Urban Atlas (UA) nomenclature (European Environment Agency, 2011). The AMR surface area extends nearly 3,000 km^2 and, until 2011, was administered by 114 municipalities (the NUTS-5 level of the European hierarchical classification of territorial units) responding to four prefectures. Despite being considered an arbitrary spatial unit, administrative domains are commonly used in urban studies (Salvati and Carlucci, 2014). In Greece, municipal councils prepare and approve local master plans, release building permits and support central institutions in decisions on settlement size and infrastructures (Chorianopoulos et al., 2010).

The landscape in the AMR is characterized by rugged topography apart from the plateaus occupied by the Athens' urban area (hereafter 'greater Athens') and by Messoghia and Thriasio districts (Supplementary materials, Figure 1). After World War II, this area experienced population growth that resulted in a chaotic and self-organized urban fabric, based on longstanding urban development traditions (Chorianopoulos et al., 2014; Polyzos et al., 2013; Souliotis, 2013). Attica is a heavily urbanized region with population density that increased from nearly 1,500 inhabitants/km^2 in 1951 to more than 4,000 inhabitants/km^2 in 2011. Salvati (2014) identified two phases in Athens' post-war expansion (massive population growth between 1960 and 1990 and a spatially discontinuous increase in the most recent decades). A more detailed look at post-war changes in the AMR socioeconomic context can be found in Salvati et al. (2013).

Data and variables

A dataset with 124 variables was compiled with the aim to explore the (apparent or latent) urban dimensions characterizing the study area (Supplementary Materials, Table 1). Variables were classified into nine domains (land-use (23 indicators), land imperviousness and regional planning (25 indicators), topography and environment (11 indicators), economic structure (22 indicators), urban settlements (14 indicators), income and wealth (8 indicators), social composition of working population (10 indicators), demography (11 indicators)). Variables were derived from the most recent official statistics produced by the Hellenic National Statistical Authority (hereafter ELSTAT) from the national census of Population, Households and Buildings, or other national or supra-national institutions at the level of municipalities. For a few variables, mid-2000 or late-2000s data were considered due to the lack of updatable and reliable estimates for more recent time periods. Based on the availability of a restricted number of variables along a sufficiently long time interval, a total of 18 variables distributed in all selected analysis domains were calculated for two time points (early-1960s and early-2010s) to identify possible changes in the AMR. Variables were selected according to the indications provided in previous studies (Salvati and Carlucci, 2014; Salvati and Di Feliciantonio, 2014; Salvati and Serra, 2016).

Land-use municipal data were derived from the Athens UA map (scale 1: 10,000), a Copernicus-Land initiative on behalf of the European Environment Agency. The profile of land imperviousness was derived from the pan-European soil sealing map (100 m spatial resolution) produced by the European Environment Agency (2011) using 2006 data. Average per-capita disposable income figures were derived from recent statistics disseminated by the Hellenic Ministry of Finance and by Prodromidis (2014). Social composition variables were based on census data on working population, according to the European Socio-Economic Classification's nomenclature for nine socioeconomic categories (Salvati and Di Feliciantonio, 2014). Distance variables were measured using the centre of gravity of each municipality and quantifying the distance to a fixed reference place. We chose four urban centres (Athens, Piraeus, Maroussi and Markopoulo Messoghias) to test different spatial organization models (Salvati and Serra, 2016). Taken together, the selected variables provide a multidimensional assessment of urban changes over a sufficiently long time period (Salvati, 2014).

Statistical analysis

To identify dimensions of the urban mosaic at the local scale, we implemented a framework structured into three analytical steps: (i) PCA to identify urban dimensions, (ii) spatial autocorrelation analysis based on global and local Moran's indexes with the aim to assess the spatial structure of each urban dimension, (iii) hierarchical clustering to profile municipalities based on similarity in the dimensions identified by PCA.

Identifying urban dimensions with a PCA. According to the rationale described in the introduction, PCA is a statistical methodology widely used to explore and summarize the multivariate relationship between variables within a large set of data, reducing information redundancy and producing a limited number of independent and meaningful axes that can be interpreted on the basis of their correlation with the input variables. In this study, we applied a PCA based on the correlation matrix of the data set composed of the 124 indicators described in 'Data and variables' section. Due to the high number of input variables, we analysed all the components with eigenvalue >3. Plots of component loadings and maps of component scores were used to identify variables and municipalities, respectively, forming distinct dimensions of the urban socioeconomic context.

Identifying the spatial structure of urban dimensions with Moran's autocorrelation analysis. We used Moran's indexes of spatial autocorrelation to explore the structure of each socioeconomic dimension previously identified ('Identifying urban dimensions with a PCA' section). To assess the space horizon within which autocorrelation effects may occur, the global Moran's index was calculated at eight distance ranges (5, 10, 15, 20, 25, 30, 35 and 40 km), producing z-scores and significance levels for spatial autocorrelation at $p < 0.05$. Minimum and maximum distance ranges were respectively selected according to the average municipal size and the total surface area of Attica region. Taking into account multiple distances allowed us to estimate the extent to which interactions between spatial units occur (Patacchini, 2008). While global Moran's index reflects the dominant autocorrelation regime at the regional scale (De Dominicis et al., 2013), local spatial autocorrelation statistics provide disaggregated estimates allowing assessment of the dependency relationship across space (Ali et al., 2007). Positive values of the local Moran's index (z-score) identify spatial clustering of similar values (high or low), whereas negative values indicate spatial clustering of dissimilar values between an area and its neighbours. We classified spatial units (municipalities) in four groups according to a Moran scatterplot (Salvati and Carlucci, 2014): (i) units with a significantly high value surrounded by units with significantly high values (hereafter HH), (ii) significantly high value surrounded by significantly low values (HL), (iii) significantly low value surrounded by significantly high values (LH), and (iv) significantly low value surrounded by significantly low values (LL). Significant z-scores were tested at $p < 0.05$. Units classified as HH and LL indicate spatial clustering of similar values; units classified as HL and LH reflect spatial clustering of dissimilar values. Classification of municipalities in the four groups described above was illustrated through maps for all the studied dimensions identified by the selected principal components ('Identifying urban dimensions with a PCA' section).

Profiling local-scale socioeconomic dimensions with hierarchical clustering. Cluster analysis, a common exploratory technique for statistical data analysis, is usually applied to urban realities to identify meaningful classification when dealing with socio-spatial differentiation (see, for instance, Matthews and Parker, 2013; Vicino et al., 2013; Wei and Knox, 2015). Hierarchical clustering is a particular method of cluster analysis aimed at defining a hierarchy of units based on homogeneous groups. This methodology, often run on results specifically obtained from a PCA (see 'Identifying urban dimensions with a PCA' section), usually refers to agglomerative or divisive approaches based on fixed linkage distances to derive a dissimilarity matrix among observations. In our case, we ran a hierarchical clustering with Euclidean distances and Ward's agglomeration rule on the matrix formed by the scores of each principal component extracted for the municipalities within the study area. The final objective of the analysis is to identify groups of municipalities characterized by a single urban dimension (as evidences by PCA) or multiple dimensions, possibly separating strictly urban municipalities with a characteristic socioeconomic profile from peri-urban municipalities with a more mixed profile.

Results

Identifying latent urban dimensions with a PCA

The PCA run on the data matrix composed of 124 socioeconomic and territorial variables extracted six components with absolute eigenvalue >3, explaining nearly 56% of the total variance. Components were interpreted by assessing loadings for each studied variable (Supplementary Materials, Table 2) and scores for each municipality (Figure 1). In the following paragraphs we illustrate the profile of the components extracted using specific labels: 'urban centrality', 'sprawl', 'social diversification', 'settlement compactness', 'industrial concentration' and 'urban shrinkage'. Components with higher explanatory power can be easily ascribed to well-identifiable socioeconomic forces, while the last components paint a somewhat 'blurred' – and partly overlapping – picture. However, just these 'shaded' dimensions, each of them revealing different nuances of the productive structure of the study area, could better catch latent, place-specific factors reflecting local-scale interplay between settlement morphology and socioeconomic functions.

Urban centrality. Component 1 (hereafter PC1) accounted for 23.1% of the total matrix variance and represents a gradient of 'urban centrality' in the study area (as indicated in the first panel of Figure 1). The highest number of variables (64 out of 124) was associated (positively or negatively) with this component. PC1 illustrates the classical spatial outcomes of a mono-centric growth model, typically observed in post-war Athens. Thus, PC1 is positively associated with continuous and discontinuous dense urban fabric, population density, diversification in the use of urban land, soil sealing intensity and diversification, density and diversity of economic activities, compactness indicators such as density and vertical profile of buildings, diversity in settlement types, multiple usage buildings, the presence of an urban master plan enforced in law, participation rate to the job market, percent share of intermediate working classes, diversity in working class composition and population growth in the post-war period (1951–1961). Conversely, PC1 appears to be negatively associated with percent class area of buildable land and cropland, mean elevation, distance from the main urban centres (Athens, Piraeus, Maroussi, Markopoulo Messoghias), per-capita built-up area, one-dwelling buildings, residential buildings, sparse urban nuclei, self-contained settlements, municipal size, percent share of construction enterprises and hotels/restaurants, percent share of higher as well as some lower-level working classes. Component scores are systematically higher in greater Athens municipalities than in surrounding areas, possibly indicating the persistence of a mono-centric spatial organization.

Urban sprawl. Component 2 (hereafter PC2) accounted for 15.7% of the total variance and reflect the spatial outcomes of (more or less recent) sprawl processes in Athens. A relatively high number of variables (39) is associated (positively or negatively) with this component. PC2 was positively associated with: percent class area of residential, low-density urban land-use and of land with moderate sealed soils (between 1% and 45% imperviousness), per-capita disposable income, upper-level working class, residential buildings, percent share of real estate and financial service enterprises, population from abroad, and especially from other European countries. Accordingly, PC2 was negatively associated with percent class area of compact, continuous and dense settlements, land with sealed soils >80% imperviousness, percent share of manufacturing and, more generally, industrial activities, commerce enterprises, lower-level working classes, multiple-usage buildings and the share of population living in the same municipality since at least five years. The spatial distribution

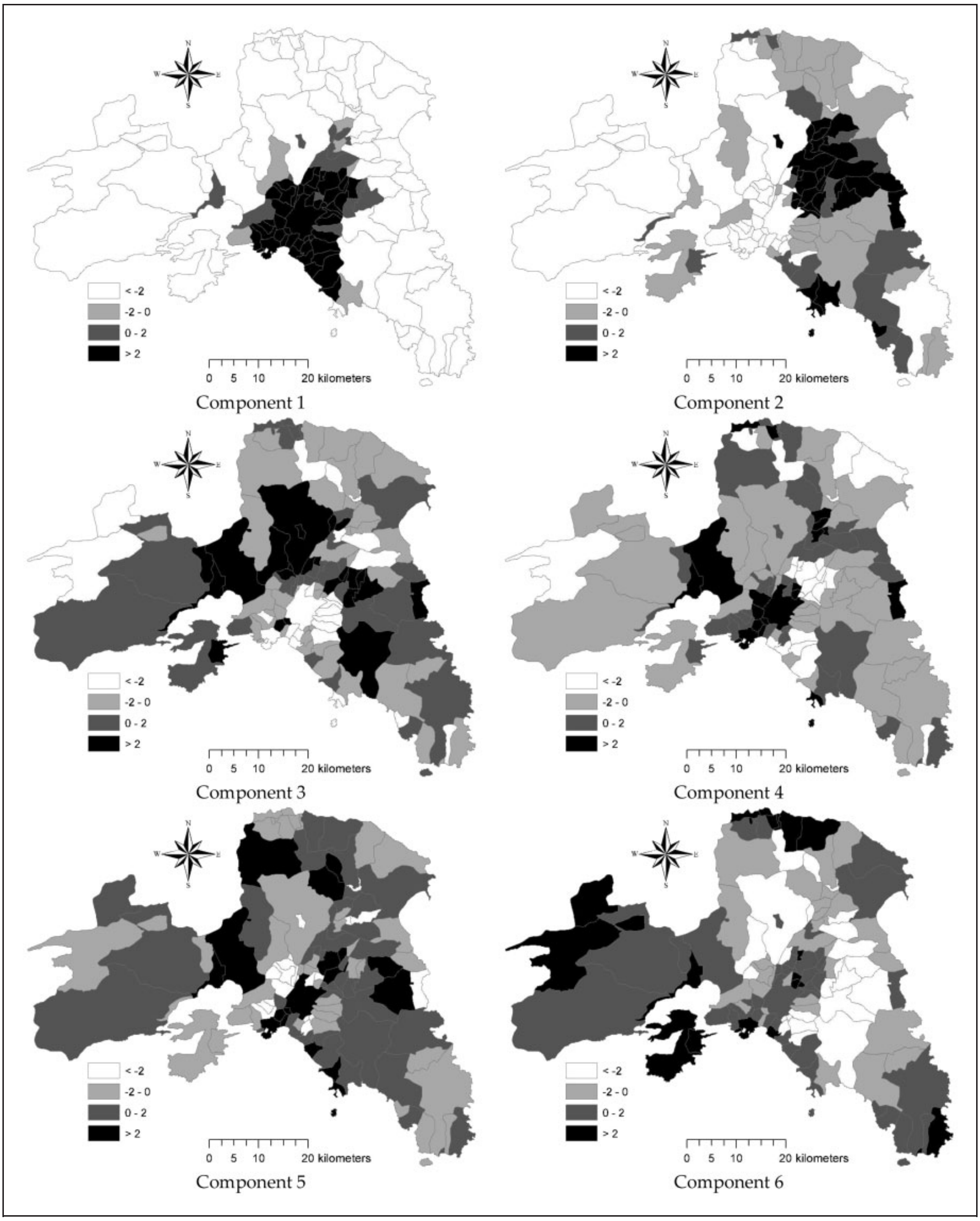

Figure 1. Principal component analysis results: component scores for each municipality of the study area.

of component scores indicates a concentration of municipalities with the highest component scores in the eastern side of greater Athens and especially in the Messoghia district.

Social diversification. Component 3, accounting for 5.8% of the total variance, reflects a gradient of social diversification in Athens, highlighting industrial concentration and the distribution of (low-skilled) workers around the central city. Twelve variables were associated (positively or negatively) to this component. The following variables were positively associated: percent class area of industrial settlements and abandoned areas (currently with no use), percent share of industrial activities and lower working class, population growth rate in the most recent decade (2001–2011), birth rate and percentage of one-dwelling buildings in the years of economic expansion. The following variables were negatively associated: diversification in working class composition (Pielou's evenness index), elderly index, vertical profile of buildings and soil quality index. Areas with the highest score on component 3 – typically dominated by industrial settlements – are situated along the peri-urban Athens' ring (Koropi, Messoghia) and especially in the western side of Attica department (Acharnes, Thriasio, Salamina) and include one municipality in greater Athens (Aghios Ioannis Rendis).

Settlement compactness. Component 4 (hereafter PC4), accounted for 4.9% of the total variance, and illustrates a gradient of settlement compactness from western to eastern Athens' urban area, coupled with mixed socio-demographic characteristics. Fourteen variables were associated (positively or negatively) to this component. Positive loadings to PC4 were observed for the percent growth rate of per-capita declared income (2008–2011), productive (industrial, commercial, public, military) use of land, class area of discontinuous medium- and low-density settlements and land with extremely high (96–100%) imperviousness rate, in turn associated to small neighbouring areas with low imperviousness rate (1–15%). Negative loadings were observed for the percent class area of discontinuous high-density settlements, land with intermediate sealing rate (51–65% imperviousness), and the percent share of native Greeks in total resident population. The spatial distribution of municipalities with the highest scores to component 4 is mixed, with sparse clusters in the central and western part of greater Athens and in Thriasio plain.

Industrial concentration. Component 5 accounted for 3.5% of the total variance and depicts a gradient from residential to productive use of land highlighting industrial concentration and local specialization in service activities. Only 4 variables were associated to this component; a positive association was found with the percent share of industrial and commercial settlements and the percentage of buildings with industrial, commerce and service use. Negative loadings were observed for the percent share of residential buildings. The map of component scores illustrates some sparse urban municipalities with high density of commercial activities. Inner Athens, Piraeus and Maroussi, the coastal municipalities south of Athens (especially Alimos and Voula) and some fringe municipalities north and east of Athens (Avlon, Kapandriti, Pikermi) showed the highest component scores. Municipalities in Thriasio plain (especially Aspropyrgos) had high scores for component 5 because of local specialization in retail and logistics activities.

Urban shrinkage. Component 6 accounted for 3.4% of the total variance and represents a centre-periphery gradient showing some characteristic signs of urban shrinking: population ageing and negative rate of growth, high distance from the economically-dynamic suburban centres of Maroussi and Markopoulo Messoghias, as well as negative association with job market participation, industrial presence and diversification of the economic structure (Pielou's evenness index). The spatial distribution of component scores identifies a substantial divide between demographically growing and economically dynamic suburban municipalities (especially in Messoghia district) and marginal areas south-east (Lavrio), north (Oropos) and west/south-west (Vilia, Salamina) of Athens. These areas featured industrial decline (Lavrio and, partly, Oropos and Salamina) and poor accessibility (Vilia) in a framework of population ageing, tourism decline and weak diversification of the local productive base.

Identifying the spatial structure of socioeconomic dimensions with Moran's autocorrelation analysis

Global Moran's indexes of spatial autocorrelation were run separately for each urban dimension identified in 'Identifying latent urban dimensions with a PCA' section by computation on component scores at the municipal scale (Supplementary Materials, Table 3). A significant ($p < 0.05$) structure of spatial autocorrelation was identified for each urban dimension. Taken together, urban dimensions with the highest spatial autocorrelation (as measured by the global Moran's z-score) were associated to components 1 (urban centrality), 2 (sprawl) and 4 (settlement compactness). The lowest spatial autocorrelation regime was observed for component 5 (industrial concentration). For each component, the highest global Moran's z-score was observed at different distance bands, possibly indicating distinct spatial processes for each urban dimension. The highest global Moran's z-score was observed at 20 km distance for component 1, 15 km for component 2, 10 km for component 3, 5 km for components 4 and 5, 25 km for component 6. Narrow-scale autocorrelation regimes (indicating relevant disparities at the urban level) were observed for the dimensions of settlement compactness and industrial concentration; intermediate-scale autocorrelation regimes were observed for sprawl and urban centrality; broad-scale autocorrelation regimes (indicating intense regional disparities in the respective urban dimension) were observed for social diversification and urban shrinkage.

The local Moran's index of spatial autocorrelation (Figure 2) provides a comprehensive analysis of the distribution regime of each urban dimension. According to the classification of municipalities based on the Moran's scatterplot, component 1 shows a typical urban–rural divide, distinguishing inner city municipalities (HH) from peripheral areas (LL) and identifying an intermediate urban fringe (HL and LH) between HH and LL municipalities. Component 2 displays a spatial pattern associated to the north-eastern fringe of Athens (HH), where sprawled settlements are mainly concentrated, contrasting with the LL cluster of municipalities in the compact fringe south-west of Athens. Component 3 contrasts deprived industrial areas north-west of Athens (HH) with wealthy municipalities in central Athens and along the eastern fringe (LL). Component 4 identifies a latent gradient of short-term income growth in municipalities in the western fringe of Athens (HH) and those located in the eastern fringe (LL). Component 5 highlights the opposition between municipalities with an economic structure based on industry and commerce (HH) and those with specialization on tourism and other service activities (LL) typically observed at the urban scale. Component 6 depicts an industrial gradient with declining activities in marginal areas west of Athens (HH) and performing activities in the municipalities located in the eastern fringe of Athens (LL). These findings corroborate PCA results illustrated in section 'Identifying latent urban dimensions with a PCA'.

Profiling local-scale urban dimensions with hierarchical clustering

Results of hierarchical clustering applied on rows (municipalities) of the principal component score matrix are illustrated in Figure 3. The dendrogram separates municipalities not specialized in any urban dimension from municipalities well characterized along one or two dimension(s) and from municipalities with a profile characterized by multiple urban dimensions. These municipalities are preferentially

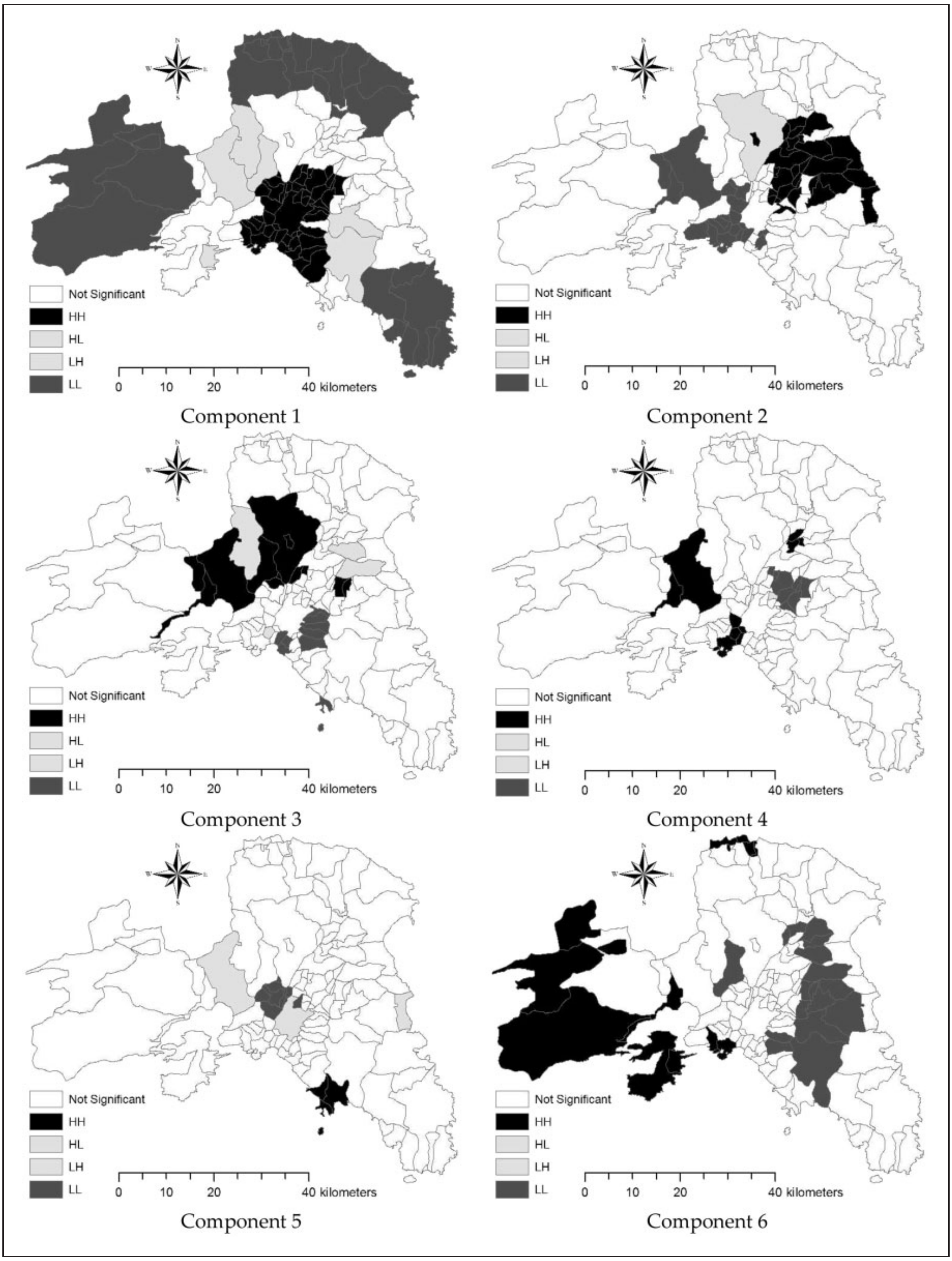

Figure 2. Spatial trends in Moran's local spatial autocorrelation index run on the individual score of the six principal components for each municipality of the study area (High-high: HH, High-low: HL, Low-high: LH, Low-low: LL; see 'Identifying the spatial structure of urban dimensions with Moran's autocorrelation analysis' section for technical details).

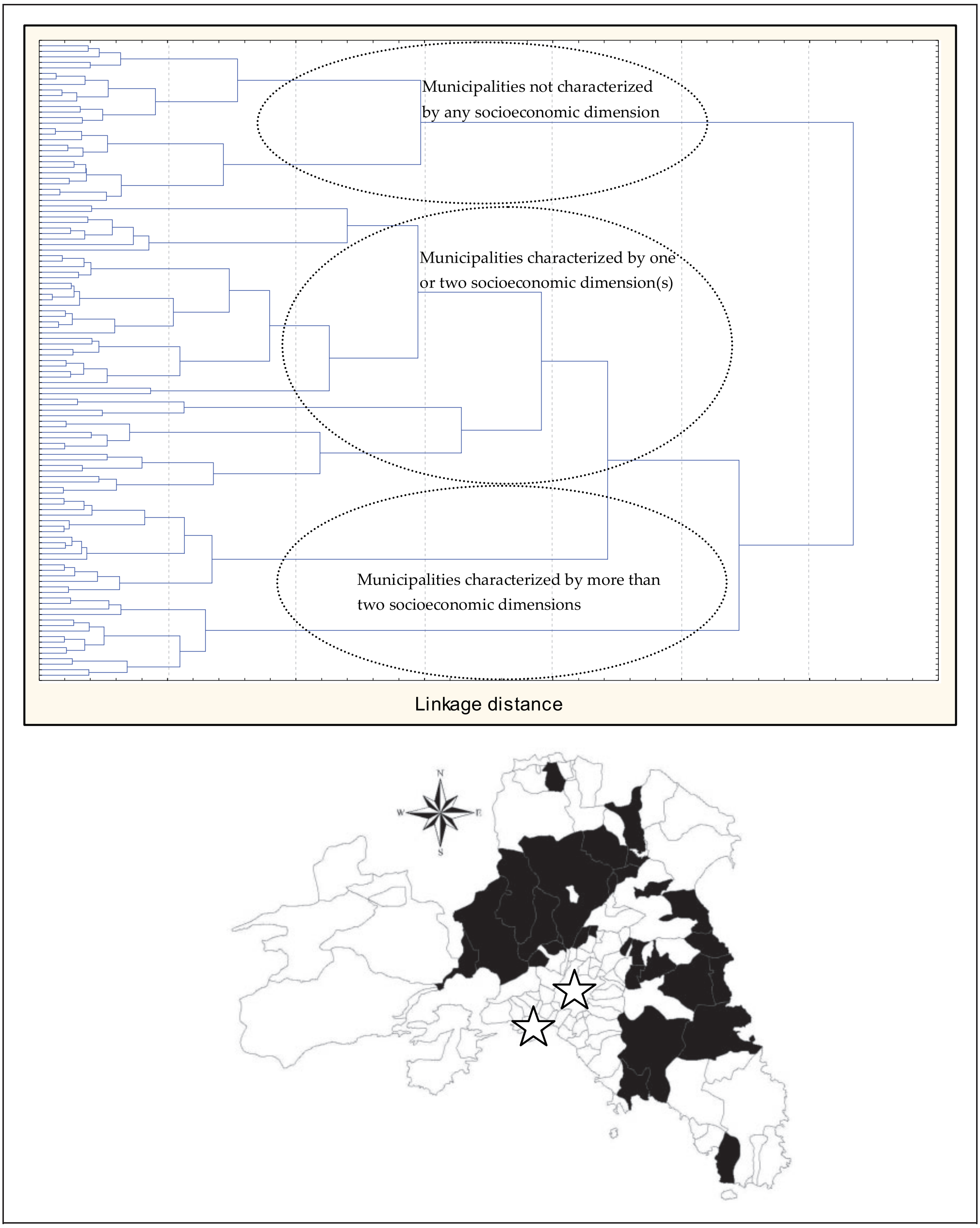

Figure 3. Hierarchical clustering (Euclidean distances with Ward's agglomeration rule) run on principal component scores representing municipalities in the study area; upper panel: a dendrogram illustrating similarities among municipalities, lower panel: a map identifying with black color the municipalities characterized by more than two socioeconomic dimensions (stars indicate Athens and Piraeus municipalities).

situated along the Athens' fringe and are characterized by a mixed socioeconomic profile typical of peri-urban districts under rapid transformations.

Discussion

Non-linear dynamics in urban systems are commonly influenced by path-dependent direct factors and latent causes linking city form and functions (Hirt, 2013; Salvati et al., 2013; Scott et al., 2013). According to the dimensions cited above, more articulated visions of evolving metropolitan regions can better address the intimate, dynamic relationship between urban patterns and processes at the base of urban actual configuration (Couch et al., 2007). The relationships between form and functions in metropolitan regions require multidisciplinary approaches that consider spatial connections on a regional scale together with the finer grain that characterizes the urban landscape (Portugali, 2000).

In this line of thinking, 'factorial ecology' appears still useful to identify self-organized development paths at the base of patterns of urban expansion (Derudder et al., 2003; Markusen and Schrock, 2006; Vicino et al., 2007). While not related directly to theoretical background assumptions taken from the economic theory, the strength of the 'factorial ecology' approach lies in the analysis of urban multiple dimensions, integrating socioeconomic and territorial factors in an empirical scheme without any a-priori hierarchy. The novelty of this study lies in the use of simplified approaches, freely available indicators and exploratory spatial techniques for the analysis of metropolitan growth along a relatively long time period. The 'factorial ecology' approach has been integrated in this study with a spatial autocorrelation analysis to identify spatial clustering separately for each dimension identified by PCA. The exploratory spatial data analysis adopted here allows for a comprehensive investigation of the main contextual factors at the base of non-linear paths of urban expansion (Salvati et al., 2013).

In this view, municipalities and urban districts are considered a relevant spatial scale of analysis because they are homogeneous partitions from institutional, socio-demographic, economic and statistical points of view. Multivariate techniques allow exploring different hypotheses in the analysis of factors promoting growth and change at the local scale, trying to simulate spatio-temporal complexity in urban systems (Le Goix, 2005; Salvati et al., 2013; Vicino et al., 2007). For example, an analysis of the highest scoring tracts on the relevant principal components extracted demonstrates the way in which some socioeconomic dimensions have relatively high incidences in shaping defined urban profiles, thereby identifying the particular characteristics of local centres. Latent socioeconomic factors contribute to determine specific spatial patterns at the local scale. Our results especially outline how the interplay of socioeconomic processes at the base of recent urban expansion reflects the inherent shift from strictly mono-centric spatial configurations (typical of the decades immediately following World War II) to more scattered models (Gkartios, 2013), also suggesting how urban areas are not homogenous units, in turn displaying a great variability that may or may not be associated with distance from the mono-centric core. Non-linear relationships between central cities and the surrounding areas under intense – but sometimes unpredictable – suburbanization patterns characterize these models of spatial organization of urban spaces (Parr, 2014). Such expansion modes are common to other Mediterranean cities (Salvati, 2014).

Many variables proved relevant in characterizing the overall evolution of the Athens metropolitan system. Urban expansion was primarily driven by migration inflow, second-home suburbanization and infrastructure development stimulated by the 2004 Olympics (Chorianopoulos et al., 2010; Grekousis et al., 2013; Polyzos et al., 2013). Empirical evidences confirm an urban evolution based on the coexistence of various factors determining economic expansion and socio-demographic transformations, in turn reflected in sprawled settlements and a spatial re-organization of economic activities (Leontidou, 1990; Moliní and Salgado, 2012; Salvati and Gargiulo Morelli, 2014), as clearly reflected in the geographical gradients identified by PCA. Peri-urban municipalities show a higher diversity in economic structure and socio-spatial patterns than strictly urban and rural areas. Inner-city municipalities display less diversified local contexts. In our analysis, basic characteristics of local units (e.g. population density, distance from the inner city, per-capita disposable income) seem to play a minor role than stochastic processes, possibly consolidated by planning deregulation and chaotic suburbanization patterns (Salvati and Carlucci, 2014). In this direction, the use of variables assessing spatio-temporal trends in building permits at a very local scale may provide confirmation of the main patterns of urban growth and metropolitan restructuring in rapidly expanding cities (e.g. Hirt, 2013).

Highly diversified socio-spatial structures are a distinctive trait of southern European cities (Salvati, 2014). However, while grounded in the Mediterranean socioeconomic context, our results contribute to a broader perspective. Policy implications of this study are especially interesting for metropolitan systems characterized by subsequent cycles of expansion and stagnation that result in economic polarization and social inequalities. Analysis of local-scale form-function relationships provides relevant information for innovative policies of urban sustainability (Hirt, 2013). Fine-tuning an analysis of ecologically compatible and economically productive morphologies and competitive urban functions with a spatially balanced socio-demographic structure is a particularly desirable policy outcome (Diappi et al., 1998). Multi-scale developmental policies, together with participation planning (Scott et al., 2013), are potentially effective responses to the increased complexity of metropolitan systems, whose growth is progressively decoupled from classical models and more closely linked to rapidly changing economic factors and increasingly mixed social contexts (Bura et al., 1996). Monitoring changes in urban form and functions through integrated exploratory and interpretative analysis centred on socioeconomic indicators will provide the necessary information base for such actions.

Conclusions

Designing interpretive frameworks and empirical models to improve understanding of the evolution of metropolitan systems is a challenging issue in urban studies. Integrating multiple perspectives and approaches contributes to a comprehensive interpretation of recent transformations in urban forms and socioeconomic spaces at the local scale. Empirical frameworks based on exploratory spatial data analysis can provide a satisfactory outline of socioeconomic dynamics at the base of the relationship between patterns and processes of urban growth. Understanding multiple dimensions of urban reality is definitely a key issue when proposing strategies of urban recovery in light of post-crisis strategies for metropolitan development. How the recent crisis has shaped the interplay between forms and functions is an intriguing issue that deserves further investigation. Future development trends could produce a more detailed picture of urban heterogeneity at the local scale, justifying original, multi-scale approaches to the interpretation of both apparent and latent consequences of post-crisis socioeconomic processes.

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