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‘Pulsing’ cities and ‘swarming’ metropolises: A simplified, entropy-based approach to long-term urban development

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ABSTRACT

Relocating activities along the fringe, re-designing economic functions, and re-modelling settlement structures across larger regions and broader spatial scales, reflect the inherent shift toward complex metropolitan systems. A refined understanding of urban change requires the adoption of a ‘complex thinking’ that focuses on adaptive behaviour of key agents and local development networks within highly volatile real estate markets. By linking ecology with regional science, our study investigates speed and spatial direction of building activity rates introducing original indicators of urban growth and an exploratory multivariate statistics of the evolving socioeconomic context in the Athens’ region, Greece. Having experienced spatially uncoordinated growth that often resulted in self-organised settlements and socially diversified neighbourhoods, Athens was a paradigmatic example of complex metropolitan systems in Europe. The empirical findings of our study identify non-linear stages of the metropolitan cycle supporting the assumption that long-term urban expansion is a recursive process, with irregular accelerations and decelerations, and a complex relationship between spatial and temporal dimensions. Urban transformations are associated with a broad spectrum of socioeconomic conditions. While playing a variable role over the last century, the most relevant factors in Athens’ growth include population dynamics, urban concentration, and wealth accumulation. Considering such dynamics, spatial planning is required to give adaptive responses to discontinuous socioeconomic development increasingly dependent on territorial aspects and environmental constraints.

1. Introduction

Socio-demographic forces and territorial constraints have driven metropolitan systems toward complex evolutionary paths producing new economic spaces and altering the density gradient of mono-centric cities (Chen and Partridge, 2013; Aguilera-Benavente et al., 2014; Kourtit et al., 2014). Relocating activities along the fringe, re-designing central and peripheral functions, and re-modelling settlement structures across spatial scales, reflect characteristic socioeconomic dynamics (Bura et al., 1996; Punia and Singh, 2012; Zhang et al., 2013; Di Feliciantonio and Salvati, 2015). Multiple (and sometimes contrasting) drivers of growth have moulded increasingly articulated metropolitan regions (Ward, 2003; Champion and Hugo, 2004; Zambon et al., 2017), making the interplay between forms and functions a particularly challenging research task (Neuman and Hull, 2009).

Traditional approaches to the analysis of urban growth have benefited from both theoretical and empirical approaches (e.g. Berry, 2005). A theoretical approach based on economic assumptions and social dynamics has interpreted urban expansion through development models accounting for socio-demographic dynamics and territorial constraints (Chen and Partridge, 2013). An extensive literature focusing on the effects of scale and agglomeration, the influence of accessibility, environmental and cultural amenities, as well as patterns of social inequality reflected in ethnic and class segregation, has characterized the recent evolution of urban studies from strictly economic toward more integrated (socio-demographic and institutional-financial)

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perspectives (Neuman and Hull, 2009; Polyzos et al., 2013; Zhang et al, 2013; Jacobs-Crisioni et al., 2014). Spatial dynamics have been incorporated sometimes into econometric models constructed to verify the proposed assumptions (Scott et al., 2013; Rubiera-Morollón et al., 2015; Salvati et al., 2018).

Deductive, empirical approaches, typical of geography and planning, have introduced a broader vision of urban expansion assumed as a cyclic dynamic that includes different life stages of a city (van den Berg et al., 1982). These stages are understood as sequential growth waves in which population is in equilibrium with economic and environmental resources (Fielding, 1982). For many years, the 'city life cycle' has represented a quantitative approach to the understanding of urban dynamics at various spatial scales (Champion and Hugo, 2004), discriminating urbanization and suburbanization from counter-urbanization and re-urbanization processes (Murcio et al., 2015). These cycles were identified by considering population trends at both central and peripheral locations within a given urban region (Nazarnia et al., 2019). The analysis of individual indicators, e.g. population growth rates, is a widespread tool in this research field (Morelli et al., 2014). Based on the empirical results of such analyses, planning studies have frequently provided an updated interpretation of the regulatory mechanisms of urban growth and local development opportunities deriving from policy stimuli (Salvati, 2016). Identification and characterisation of metropolitan cycles based on population change, however, had controversial aspects involving land-use spatial configurations (Couch et al., 2007), and the underlying (socioeconomic) processes of change (Rontos et al., 2016). These aspects often prevent a complete investigation of the factors driving long-term urban expansion (Gkartzios, 2013; Cuadrado-Ciuraneta et al., 2017; Zambon et al., 2017).

Although economic and geographical approaches have represented an important part of the literature on the long-term evolution of metropolitan systems (e.g. Serra et al., 2014), recent transformations towards morphological complexity and the greater availability of spatially explicit information, justify the development of alternative approaches evaluating urban expansion processes (Portugali, 2000; Pumain, 2005; Punia and Singh, 2012). Involving local communities that exhibit distinctive abilities of growth and change, non-linear evolution of metropolitan systems makes the analysis of urban growth a particularly challenging task for both 'complex thinking' and data-driven approaches (Page et al., 2001; Berkes et al., 2003; Parr, 2014; Fernandez-Vazquez et al., 2014).

A growing literature has defined metropolitan regions as complex socioeconomic systems (Berry, 2005). In this perspective, a refined understanding of long-term urban transformations implies an analytical investigation of new morphological structures and economic functions changing over time and space, taking account of the role of the local background (Kazemzadeh-Zow et al., 2017; Verma and Raghubanshi, 2018; Wolff and Wiechmann, 2018). These dimensions were grounded on the adaptive behaviour of key agents and local networks, the intrinsic development of attractive poles, and rising innovation capacity (Zhang et al., 2006; Singh, 2014; Wang et al., 2020). Their evolution reflects, in most cases, common development patterns that include (rapid) adaptation to change, selection, cooperation, and imitation, reflecting a self-organised – and mostly decentralised – development (Favaro and Pumain, 2011; Patias et al., 2021; Zhao et al., 2022). These patterns – hardly predictable because intimately non-linear – imply the strong influence of external shocks amplifying internal fluctuations (Batty and Longley, 1994; Ferrara et al., 2016; Artmann et al., 2019; D'Amico et al., 2020). The resulting transformations in both forms and functions impact the system's trajectory, consolidating peculiar socioeconomic contexts either at regional and local scales (Chen et al., 2017; Chen and Huang, 2018).

Being involved in path-dependent, historical "lock-in" processes (Bruneau et al., 2003; Folke et al., 2005; Folke et al., 2010), metropolitan systems experience multiple equilibria that emphasize the relation between economic expansion and social transformations (Batty and Longley, 1994; Carpenter et al., 2001; Brand and Jax, 2007). With this perspective in mind, designing interpretative frameworks and data-driven, empirical approaches that investigate the long-term evolution of metropolitan systems is becoming a topical challenge in urban studies (Adger, 2000; Folke, 2006; Harte, 2007). These approaches should be based on dashboards of innovative and multi-disciplinary indicators analysing the diversification (and interpreting the sources of heterogeneity) of recent processes of urban growth (Andersson et al., 2006; Mohajeri et al., 2013; Nazarnia et al., 2019).

Diversified patterns of urban expansion typically manifest at several locations of a given city over multiple temporal resolutions (Cabral et al., 2013; Fan et al., 2019; He and Sheng, 2020). These transformations result in (i) the expansion of urban fabrics and infrastructures, (ii) the emergence (and consolidation) of fringe residential settlements, and (iii) the inherent decline of density gradients (Duvernoy et al., 2018). Studying these patterns contributes to a better understanding of complex mechanisms of urban growth (Hollings, 2001; Holland, 2006; Jacobs-Crisioni et al., 2014; Fistola et al., 2020).

As a pivotal factor affecting metropolitan cycles and long-term urban growth, real estate local markets have been intimately associated with political, institutional, and planning drivers and (differentiated) demographic, cultural, and socioeconomic contexts (van den Berg et al., 1982; Rubiera-Morollón et al., 2015; Zambon and Salvati, 2019), and their volatility contributes to metropolitan complexity (Zhang et al., 2013; Serra et al., 2014; Salvati et al., 2019). With this perspective in mind, building activity rates have been considered an intrinsic property of complex urban systems, and sometimes investigated in relation with the local context (Salvati and Serra, 2016). Being intimately associated with the way settlements expanded over time and space, the notion of 'urban pulse' was recently proposed to interpreting the spatial variability in building activity across multiple temporal resolutions (Miranda et al., 2016). Cities expanded through one or more consecutive 'pulses', intended as isolated or sequential, largely unpredictable events of growth associated with the local context (e.g. Morelli et al., 2014). Moving from the notion of 'life cycle stages' to the 'urban pulse' concept allows a better comprehension of complex mechanisms of metropolitan growth, associated with a pronounced temporal volatility and spatial discontinuity of real estate local markets characteristic of contemporary cities (Dhali et al., 2019).

Spatio-temporal diversification in building activity patterns and the relationship with (rapidly evolving) socioeconomic contexts are key to interpret long-term urbanization processes in the light of 'urban pulses' (Wang et al., 2020). Identification of such events may benefit from a multivariate analysis of building activity rates using entropy indicators and metrics derived from information theory (Deka et al., 2011; Encarnação et al., 2013; Grekousis et al., 2013). The vast ensemble of diversity indexes proposed in the ecological literature provides a significant knowledge in this direction (Crews and Peralvo, 2008; Mohajeri et al., 2013; Liu et al., 2018).

By linking a regional science approach (Losch, 1940) with ecological metrics that explore spatio-temporal complexity in building activity (Van den Bergh and Stagl, 2003), the present study introduces novel indicators of urban growth analyzed through multivariate exploratory data analysis and inferential, non-parametric statistics. In this regard, estimates of building activity from official statistics were assumed to provide a preliminary assessment of urban 'pulses' under sufficiently long time intervals (Zambon et al., 2019). To this aim, our study estimates differential speed and spatial direction of building activity in order to delineate non-linear and discontinuous urban expansion along more than one century in Athens, Greece (Pili et al., 2017). Reflecting the evolution of metropolitan systems in Southern Europe, the Athens' metropolitan region was considered a coherent case to test for the validity of the interpretative framework proposed above (Polyzos et al., 2013; Salvati, 2016; Di Feliciantonio et al., 2018). Based on a long urban tradition, the study area has experienced chaotic, spatially uncoordinated growth since World War II, resulting in self-organised settlements and socially diversified neighbourhoods (Souliotis, 2013; Chorianopoulos et al., 2014; Carlucci et al., 2017). Despite local differentiations, competitiveness and crisis, social segregation and mixed land-use, economic re-polarisation and urban sprawl, are exemplificative dimensions at the base of the increasing complexity of Mediterranean cities (Salvati et al., 2018). Aim of this study is to demonstrate that entropy indicators provide an enhanced knowledge of such complex dynamics.

2. Methodology

2.1. Study area

The investigated area extends more than 3,000 km^2 encompassing Attica, a geographical and administrative region located in Central Greece (Fig. 1). This area coincides with the boundaries of the Athens' Metropolitan Region (AMR) delineated in the Urban Atlas (UA) initiative of the Global Monitoring and Environmental Surveillance (GMES) Land System of the European Environment Agency (2011). The region is primarily steep with a central plateau, the Attica basin, hosting the Greater Athens' area (430 km^2) and including downtown Athens, Piraeus, and their suburbs (Chorianopoulos et al., 2010). One hundred and fifteen municipalities administer the study area, and local communes (including those located in the island of Salamina, nearby Piraeus harbor) are organised into four prefectures: Central Athens (including the historic city and its surroundings), Piraeus (including the old town around the harbour and the surroundings), Western Attica, and Eastern Attica (Rontos et al., 2016). These municipalities formed the sample investigated in the present study.

2.2. Elementary data sources

The present study makes use of homogeneous variables derived from official statistics and covering a long time interval that encompasses more than one century, from the beginning of the 19th century to nowadays. Reflecting the administrative geography of a given region (Jacobs-Crisioni et al., 2014), municipalities were increasingly adopted as the elementary spatial unit of demo-geographic, socioeconomic, and environmental-territorial analysis (Salvati and Serra, 2016). For this reason, they were adopted as the elementary analysis' domain in this study. Municipalities, in Greece as in other countries of Mediterranean Europe, are a representative spatial domain for urban research, since municipal councils are enforced to make decisions on land allocation, building surface and volume, settlement size and spatial configuration, as well as local infrastructures (Chorianopoulos et al., 2010). For each municipality belonging to the study area, the total number of buildings by the age of construction was derived from the Greek National

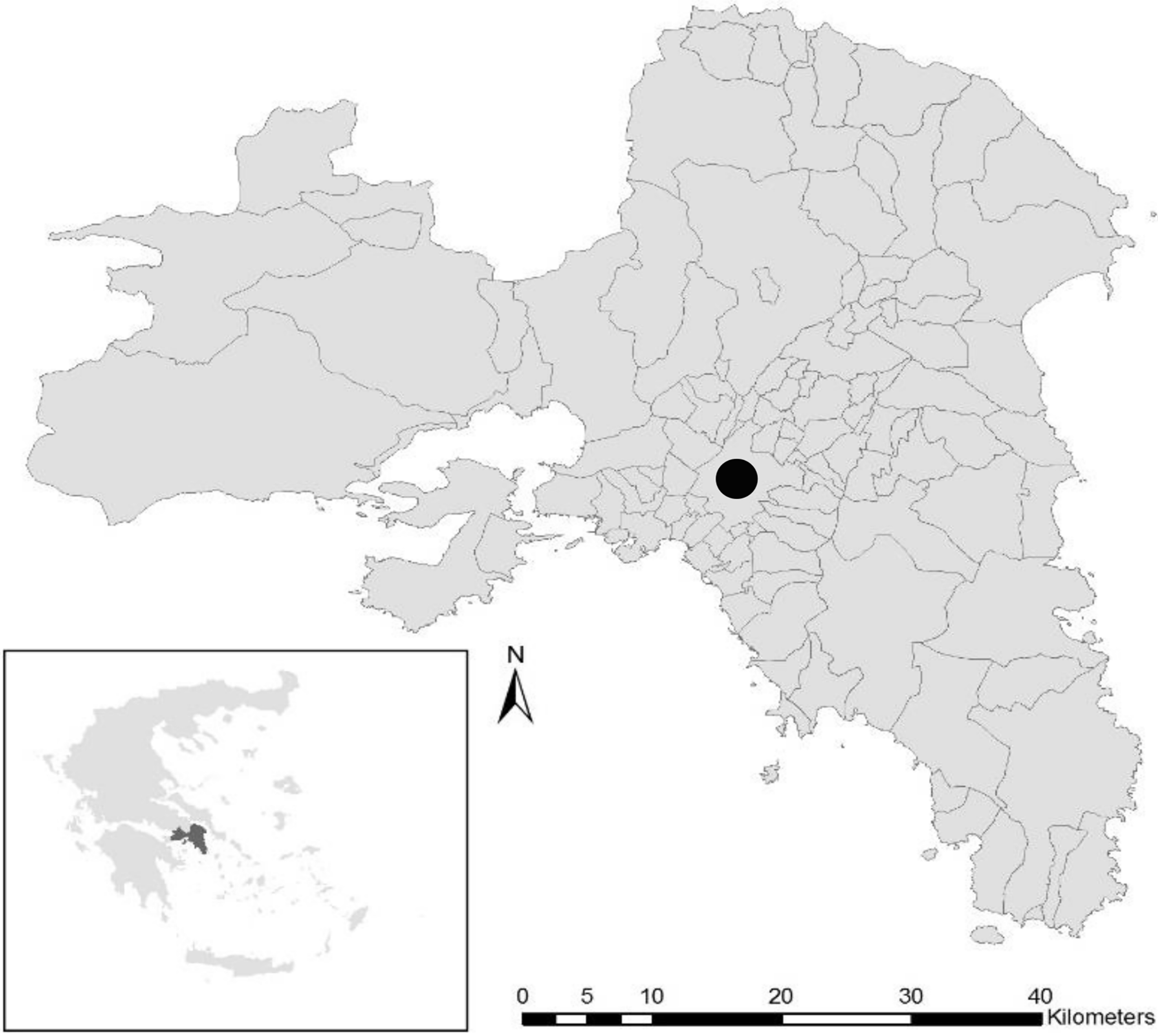

Fig. 1. A map illustrating the boundaries of municipalities in the Athens' metropolitan region (● indicates downtown Athens) and the position of the study area in Greece (insert map).

Statistical Authority (ELSTAT). Data cover 12 time intervals of slightly different length (between the early 1900 s and 1919, 1919–1945, 1946–1960, 1961–1970, 1971–1980, 1981–1985, 1986–1990, 1991–1995, 1996–2000, 2001–2005, 2006–2010, and the early 2010 s, approximately between 2011 and 2013). These figures provide a comparative overview of building trends, identifying basic dimensions of investigation and allowing correlation with the socioeconomic profile of local communities (Di Feliciantonio and Salvati, 2015). The use of widely accepted and homogeneous data sources, such as those derived from official statistics (Di Feliciantonio et al., 2018), allows a comparative investigation of long-term metropolitan trends across regions.

2.3. Data analysis

The present section provides a detailed description of the research design, from data sources to statistical methods implemented to investigate long-term urban growth through the exploratory analysis of building activity rates over more than one century in the study area. First, a specific measure of building activity was implemented by deriving the necessary information from the national census of population and buildings (subsection 2.3.1). Second, a vast set of ecological metrics and statistical indicators was proposed in subsection 2.3.2 and applied to building activity rates with the objective of quantifying apparent and latent dimensions of urban expansion (including – but not limited to – spatial direction and intensity, and the relationship with the background context). Third, the indicators adopted to delineate a socioeconomic profile for each municipality were illustrated in subsection 2.3.3. Forth, the statistical analysis performed to identify different profiles of long-term urban expansion, from homogeneous regimes to isolated 'pulses', is shown in subsection 2.3.4, assessing the intrinsic relationship with local background contexts.

2.3.1. Deriving building activity rates from census data

To assure full comparability across time and space, the number of buildings by municipality (section 2.2) was standardised considering the length of each time interval (years) and the surface area of each spatial domain (km^2), obtaining a representative estimation of intensity and spatial direction of urban expansion (Morelli et al., 2014). In this way, a Standardized (per year and surface area) Building Rate (SBR) was calculated for each municipality *s* as follows:

$$\mathrm{SBR}_{t,s} = \mathrm{B}_{t,s}/(\mathrm{A}_s \bullet \mathrm{Y}_t) \quad (1)$$

where $\mathrm{B}_{t,s}$ is the number of buildings constructed in the time interval *t*, A_s is the surface area of each municipality, and Y_t is the number of years in each *t*. For each municipality, a Total Building Stock (TBS) at the end of the observation period was obtained, cumulating the SBRs observed for each time interval from 1 to *n*, as follows:

$$\mathrm{TBS}_s = \sum\nolimits^{n}_{t=1} \mathrm{SBR}_{t,s} \quad (2)$$

Based on this rationale, urban expansion was assessed diachronically by computing the relative proportion of each SBR in TBS at the level of individual municipalities *s*, regarded as a net Rate of Urban Growth (RUG):

$$\mathrm{RUG}_s = \mathrm{SBR}_{t,s}/\mathrm{TBS}_s \quad (3)$$

for each *t* and *s* in the sample.

This calculation provided a time series of twelve values constituting the statistical distribution of RUG, indicative of urban growth intensity and spatial direction over a sufficiently long time interval in Athens. A specific analysis was designed to extract significant indicators of urban growth, as clarified in the following subsection.

2.3.2. Assessing urban growth from ecological metrics applied to building activity rates

A cross-sectional analysis of RUG across municipalities in the sample (e.g. through maps) provided a thorough investigation of intensity and spatial directions of long-term urban expansion in the study area, discriminating spatially coordinated from uncoordinated development patterns and giving a preliminary assessment of 'urban pulses'. A wide set of indicators was adopted and run on the same dataset to define the intrinsic level of spatial concentration and temporal variability in long-term urban growth (Pili et al., 2017). Ecological metrics analyzing the degree of diversification in the RUG profile over time were assumed as appropriate to explore long-term growth regimes characterized by spatially heterogeneous and irregular accelerations (and decelerations) in building activity (Rontos et al., 2016).

More specifically, the statistical distribution of RUG at the level of individual municipalities was assessed over time using 19 indicators based on (i) an empirical philosophy quantifying relevant moments of RUG statistical distribution (Aguilera-Benavente et al., 2014), and (ii) an extensive analysis of other metrics derived from ecology and grounded on diversity science and information theory (Salvati, 2014). While providing an informative overview of long-term metropolitan growth in Athens, indicators included in this approach were, in some cases, similar and partly redundant, justifying the use of a multivariate exploratory approach that extracts non-redundant information relevant to policy and planning for sustainable urban development (Salvati and Serra, 2016), contributing to identification of urban expansion regimes.

Concerning point (i), a set of 13 metrics (i.e. 7 descriptive statistics of RUG and 6 correlation coefficients with reference quantities) were computed considering data for the whole study period at each elementary analysis' domain (i.e. municipalities). Descriptive statistics include indexes of central tendency (Median), dispersion (Coefficient of Variation, maximum RUG value), form (asymmetry, kurtosis, median-to-mean ratio), and a standard indicator assessing the period with the highest RUG over the investigated time series (Pili et al., 2017). Correlation statistics include six coefficients estimating intensity and sign of the pair-wise relationship between RUG time series at each municipality and the aggregated RUG time series at (i) regional scale (Attica) and (ii) national scale (Greece). This analysis compared Pearson parametric coefficient with Spearman and Kendall non-parametric coefficients (Salvati et al., 2018). These coefficients were selected to identify both linear (Pearson) and non-linear (Spearman) pair-wise correlations between target variables. Significance was tested at $p < 0.05$ after Bonferroni's correction for multiple comparisons under the null hypothesis of uncorrelated variables (Salvati, 2016). Similar (significant) Pearson and Spearman (or Kendall) coefficients indicate a linear correlation between target variables. Significant Spearman (or Kendall) coefficients with a non-significant Pearson coefficient indicate a non-linear correlation between target variables (Duvernoy et al., 2018). Assuming a specific building activity profile for each municipality of the study area, these indicators provide a refined evaluation of the intimate characteristics of urban expansion, evidencing synchronic (or diachronic) mechanisms of growth over one century (Salvati, 2016), and thus posing the base for identification of urban 'pulses'.

Concerning point (ii), the statistical distribution of RUG over time (t) and across municipalities (s) was considered the input of 6 well-known metrics derived from information theory and ecological science (Salvati, 2014) that estimate the degree of diversification in building activity rates representative of different urban expansion regimes, as follows:

(a) Simpson index (S) estimating the dominance pattern in a statistical distribution. The index ranges from 0 (all RUG are equally intense) to 1 (RUG at a given time dominates the time series) and was calculated as:

$$\mathrm{S} = 1\text{-}\sum\nolimits_i (\mathrm{RUG}_i)^2 \quad (4)$$

(b) Shannon index (H'), ranging from 0 to infinity and evaluating diversification in building activity rates, as follows:

$$H' = -\sum_i (RUG_i)\ln(RUG_i) \quad (5)$$

(c) Buzas and Gibson's index (E) quantifying entropy (E) in a statistical distribution as:

$$E = e^{H'}/T \quad (6)$$

where H' is Shannon index and T is the number of time intervals with non-null building expansion.

(d) Brillouin's index (B), another measure of diversity in building activity rates calculated as:

$$B = (\ln(T!) - \sum_i \ln(RUG_i!))/T \quad (7)$$

(e) Menhinick's richness index (M), providing a gross estimation of heterogeneity in a statistical distribution of RUG:

$$M = T/\sqrt{N} \quad (8)$$

(f) Equitability (namely Pielou's evenness) index, computed as the Shannon diversity index (H') divided by the logarithm of T, the number of time intervals with non-null building expansion.

A thorough analysis of diversification in building activity rates at the municipal scale based on such metrics provides additional information to identify urban pulses characteristic of long-term Athens' development.

2.3.3. *Contextual indicators*

A total of 24 variables were chosen to profile the socioeconomic context of municipalities in the Athens' metropolitan region. These variables were derived from official statistics produced by ELSTAT and referring to diachronic census waves. Variables include population growth over time (percent annual rate of change, 1951–1961, …, 2001–2011), population density at the exact census dates between 1940 and 2011 (inhabitants/km^2), average elevation (meters at the sea level), distances (km) from Athens, Piraeus, Maroussi (Olympic Stadium), and Markopoulo Messoghias ('El. Venizelos' International Airport), a Soil Quality Index, municipal size (km^2), as well as three dummies classifying municipalities in 'urban' or 'rural', 'wealthy' or 'economically disadvantaged', 'coastal' or 'inland' type. These variables provide a multidimensional assessment of local contexts undergoing urban change over a sufficiently long time period, being regarded as proxies of system's complexity and transitions along its development path (Serra et al., 2014; Salvati and Serra, 2016; Di Feliciantonio et al., 2018). The four urban centres mentioned above were selected to test different spatial organisation models (Di Feliciantonio and Salvati, 2015): (i) a strictly mono-centric structure centred on downtown Athens; (ii) a model based on the gravitation around Piraeus (industry, transport and logistics); (iii) a model based on the gravitation around the 'Olympic municipalities' North-east of Athens representing the new Central Business District of the city; and (iv) a suburbanisation model based on the gravitation around Messoghia district, which represents the most evident sprawling area in Attica (Couch et al., 2007; Chorianopoulos et al., 2010; Pili et al., 2017). Distance variables were measured using spatial functions such as the 'centroid' command provided by ArcGIS (ESRI Inc., Redwoods, USA) that identifies a central place for each municipality and measures the distance to a fixed reference place (Morelli et al., 2014). Wealthy and economically disadvantaged neighbourhoods were identified considering an average per-capita disposable income estimated in 2008 (before the economic crisis) and derived from statistics disseminated by Hellenic Ministry of Finance (Di Feliciantonio et al., 2018).

2.3.4. *Statistical analysis*

Assuming complex metropolitan systems as shaped by a continuous interplay of (partly redundant) elements, the analytical strategy proposed here contributes to a long-term assessment of urban growth in such contexts. More specifically, the 19 metrics illustrated above contributed to the empirical definition of the dominant model of urban expansion for each spatial domain (i.e. municipality) of the study area. Three representative examples of the possible range of models were illustrated in Fig. 2 – from homogeneous, continuous urban growth (left) to sequential accelerations/decelerations determining sequential – while possibly irregular – 'beats' (middle), and to a sudden concentration of building activity within a given time reflective of one 'pulse' that explains the large part of metropolitan expansion (right).

The intrinsic redundancy of the indicators' ensemble presented in sub-section 2.3.2 was removed using (i) multivariate statistics that decompose input data matrices into non-redundant analysis' dimensions, whose relationship with background territorial indicators (sub-section 2.3.3) was further studied *via* (ii) non-parametric correlation analysis. More specifically, (i) a Principal Component Analysis (PCA) was run on the rectangular matrix (12●115) of RUG values by time interval (columns) and municipality (rows). PCA is an exploratory approach selecting few independent dimensions (and the most associated variables) from a given data set, identifying structural changes in building activity over time (Zambon et al., 2019) and latent urbanisation trends in the study area. Since a correlation matrix was used as the input matrix of the PCA, each input variable contributes with unitary variance to the overall matrix variance (Recanatesi et al., 2016). While not based on hypothesis testing, selection of significant components was based on eigenvalue threshold: components with eigenvalue >1 were retained and analysed further (Karamesouti et al., 2015).

PCA results were analysed with the final aim at summarising the spatio-temporal patterns underlying building activity rates, allowing identification of specific profiles characteristic of long-term urban expansion. Such profiles distinguish homogeneous and continuous growth from a regime made up of irregular beats and a unique 'pulse' explaining the large part of settlement growth over the study period. In this perspective, component loadings were used to delineate distinctive temporal regimes of urban development (Zambon et al., 2017). Local-scale regimes of urban expansion identified above were finally correlated with the specific territorial and socioeconomic profile at the same spatial scale (municipalities) by analyzing the relationship between municipal scores of the selected Principal Components (see above) and the 24 background indicators illustrated in sub-section 2.3.4. Non-parametric Spearman rank coefficients were used to identify socioeconomic profiles with influence on urban development regimes, investigating pair-wise correlations between component scores and background indicators. Spearman correlation analysis reveals both linear and non-linear relationships, testing for significance at $p < 0.05$ after Bonferroni's correction for multiple comparisons (Duvernoy et al., 2018).

3. Results

3.1. *Descriptive statistics*

Building activity in Athens has mainly been differentiated over the study period as far as intensity and spatial direction are concerned (Fig. 3). Settlement expansion was more intense during the 1970 s and the 1980 s. In more than 3 municipalities out of 10, the highest building rate was recorded between 1981 and 1985; in almost 2 municipalities out of 10, the maximum rate was observed between 1971 and 1980. The same indicator showed a rapid decline since 1991, with a moderate recovery between 2001 and 2005 (coinciding with the 2004 Olympics) and a more evident reduction in the subsequent time intervals coinciding with the economic crisis. A map of the time intervals with the highest building rate indicates a substantial centre-periphery gradient coherent with a pure mono-centric model.

Representative examples of the 'centre-periphery' gradient mentioned above were illustrated in Fig. 4, evidencing specific patterns

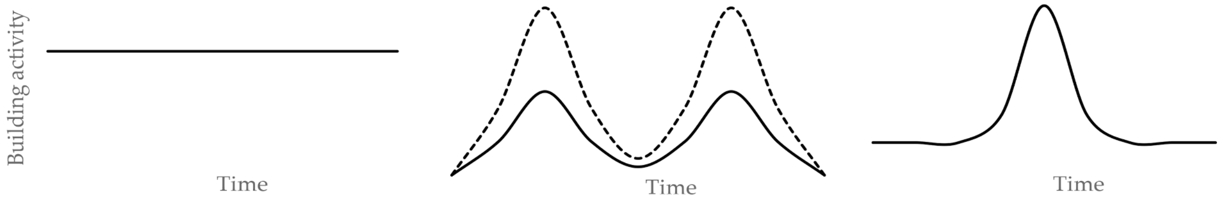

Fig. 2. Selected profiles of long-term urban cycles based on building activity (left: homogeneous and continuous urban growth; middle: 'pulsing' waves of urban growth with sequential accelerations and deceleraations at different intensities (continuous and dashed lines); right: massive urban expansion with building activity concentrated in a given time).

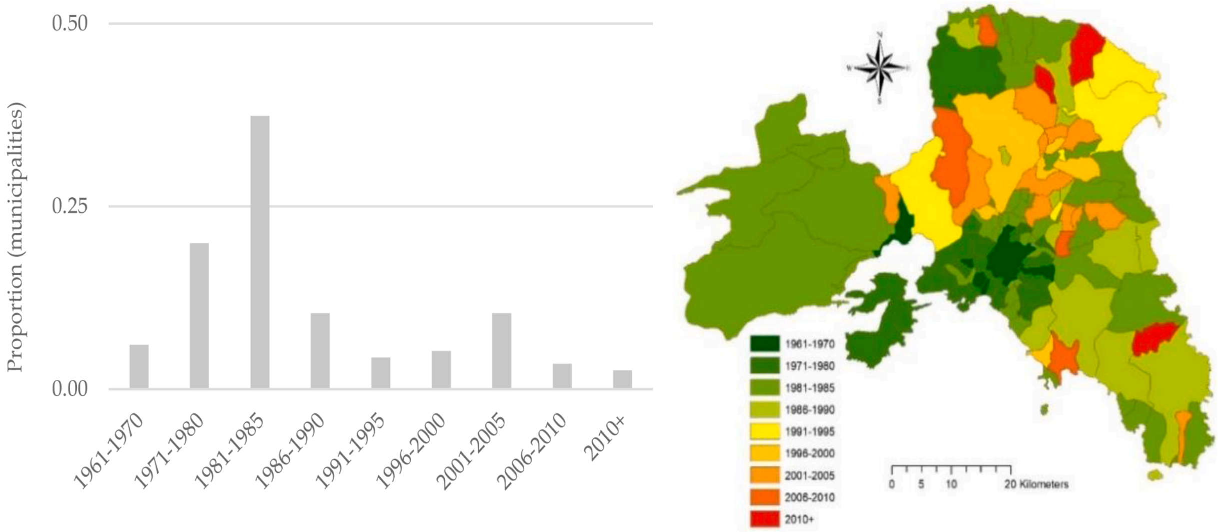

Fig. 3. Municipalities with the highest concentration of building activity in the Athens' metropolitan region over the study period (left: relative proportion in the sample; right: spatial distribution), by time interval (no municipalities with the maximum concentration of building activity were observed before 1960).

at six locations in the Athens' metropolitan region. Compared with aggregate data referring to the Attica region and Greece as a whole, diversification in long-term urban growth at selected municipalities was particularly evident when considering individual profiles of building activity over time.

The spatial distribution of a small set of indicators profiling long-term urban expansion was illustrated in Fig. 5. These indicators were selected to represent three basic dimensions of the urban cycle: (i) serial homogeneity, (ii) temporal volatility, and (iii) spatial concentration. Pielou Evenness ratio (J) was taken as a representative index of the level of serial homogeneity in building activity as the result of long term urban expansion. In Athens, J values showed a heterogeneous distribution across municipalities, with no apparent relationship with essential geographical gradients (e.g. elevation, distance from the sea coast, distance from downtown Athens). Suburban municipalities of Attica have displayed, on average, the highest values (>0.9) of the Pielou J index. However, high values of the index were also observed in industrial municipalities, e.g. Piraeus district.

High or very high values of Pielou J index delineated socioeconomic contexts where urban expansion has occurred homogeneously and progressively over time, without accelerations (or decelerations) of the building activity typical of the initial phases of the cycle (e.g. as observed during sequential phases of urbanisation and suburbanisation). On the contrary, municipalities with very low J values (<0.8) concentrated in rural and marginal areas, especially in Northern Attica. These municipalities were characterised by intense 'pulses', following long periods of stability. The municipalities that have assumed intermediate values of the J index were basically located in the Greater Athens' area and include urban and suburban contexts with an economic structure oriented towards traditional and advanced services. In those areas, urban expansion proceeded through accelerations and decelerations in building activity rates that resulted in a radio-centric growth of residential settlements.

The intrinsic volatility of building activity over time was assessed considering the Coefficient of Variation (CV) in municipal SBRs. This indicator quantifies variability in building activity, reflecting accelerations and decelerations of the cycle. An accentuated variability was observed in rural and peripheral municipalities of Attica. Municipalities characterised by a lower CV were instead concentrated in fringe districts at intermediate distances from Athens. Finally, urban municipalities in Greater Athens assumed intermediate CV values and reflected heterogeneous mechanisms of settlement expansion, characteristic of several metropolises of the Mediterranean basin. Finally, a third indicator (Max) outlines the spatial distribution of short-term 'pulses' of settlement expansion, identifying municipalities where most of the building activity is concentrated in a specific time interval. From this point of view, it can be observed how, in some rural and marginal municipalities, more than 30% of building activity concentrated in a given time interval. Less concentrated building activity was observed in fringe municipalities, where settlements expanded progressively and additively.

3.2. Multivariate analysis

A Principal Component Analysis was run on a data matrix constituted of 19 indicators (see subsection 2.3.4) assessing long-term urban expansion in Athens. We extracted three significant components accounting for a cumulated variance >92%. The analysis summarises multidimensional patterns for each urban dimension considered in this study and the variables contributing the most to such trends (Table 1). Component 1 extracted 47% of the overall variance in the data matrix,

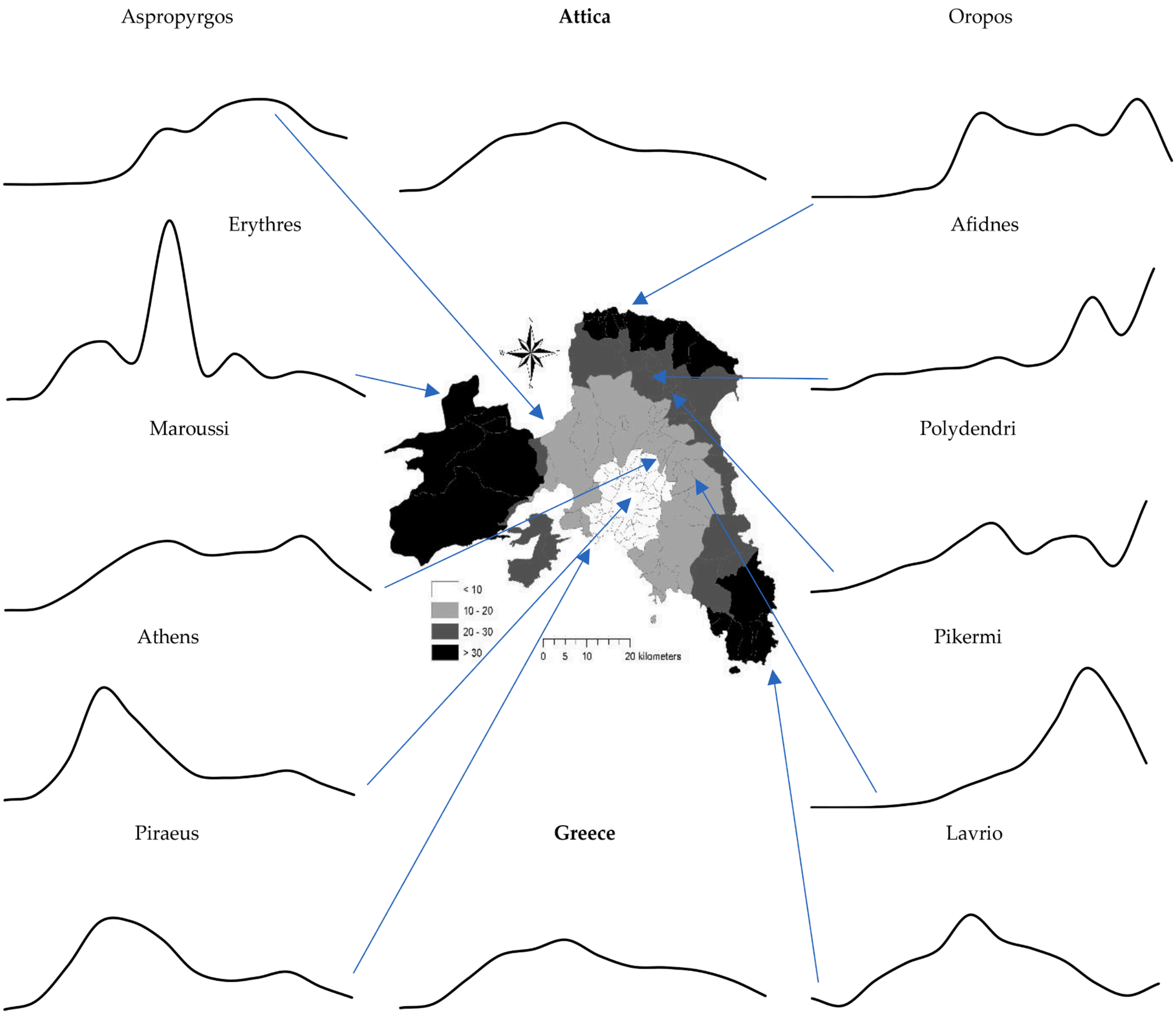

Fig. 4. Diversification in long-term urban expansion (individual profiles based on building activity by time interval) of selected municipalities in the study area, as well as in Attica region and in Greece (the central map illustrates the average distance of municipalities from downtown Athens, km; all graphs of building activity over time were set on the same X-Y scale and therefore are fully comparable).

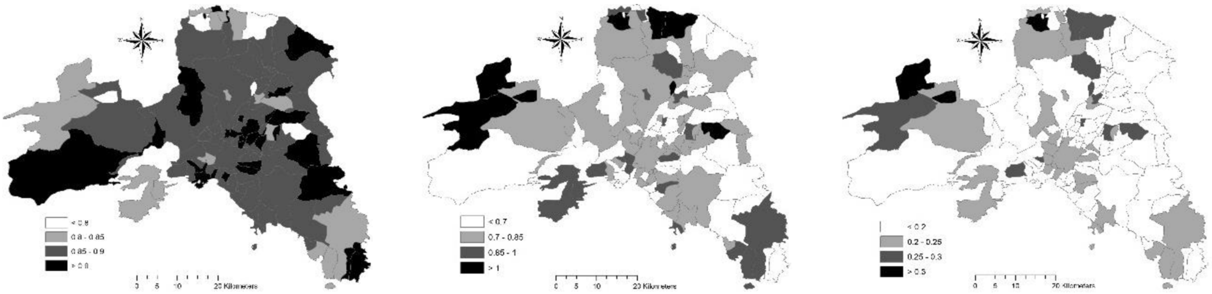

Fig. 5. Spatial distribution of selected indicators of urban expansion (left: Pielou evenness index (J), middle: Coefficient of variation in building activity (CV), right: the highest SBR value.

being associated negatively with a vast ensemble of metrics delineating variability and asymmetry in the statistical distribution of building rates over time. The fact that positive loadings to Component 1 were assigned to indexes of distributional symmetry and homogeneity (such as the median building rate and the ratio of median-to-mean building rate) indicates that discriminating homogeneous (i.e. continuous over time) from heterogeneous (i.e. displaying more or less regular accelerations and decelerations) mechanisms of urban expansion is the most relevant dimension emerging from PCA. In this perspective, indicators delineating diversification and evenness in building rates were positively associated with Component 1. A specific socioeconomic profile was associated with this component, including (i) municipalities with the highest population growth rate in the most recent decade of investigation (2001–2011), (ii) above-average wealthy neighbourhoods, and (iii) areas surrounding the Messoghia plain (Markopoulo), a suburban district experiencing massive sprawl in the last decades. These results seem to be counterintuitive, since they indicate how suburban locations are associated with a continuous, relatively homogeneous process of

Table 1

Variable loadings (per cent share of population by age class in total population) to selected principal components (see also Fig. 2); only loadings > |0.5| were reported; Italics indicates supplementary variables.

Indicator	Component loadings			Variable	Corr. with contextual variables		
	PC 1	PC 2	PC 3		PC 1	PC 2	PC 3
Median	0.86			*Population density (1940)*		*0.74*	
Maximum	−0.93			*Population density (1951)*		*0.74*	
Coeff.Variation	−0.96			*Population density (1961)*		*0.73*	
Asymmetry	−0.89			*Population density (1971)*		*0.72*	
Kurtosis	−0.65		0.48	*Population density (1981)*		*0.70*	
Median-to-mean	0.87			*Population density (1991)*		*0.66*	
Decade(Maximum)		−0.86		*Population density (2001)*		*0.63*	
Pearson-Attica		0.98		*Population density (2011)*		*0.61*	
Pearson-Greece		0.98		*Urban municipalities*		*0.63*	
Spearman-Attica		0.98		*Econom.disadvant.municip.*	*−0.25*		
Spearman-Greece		0.98		*Average elevation*		*−0.47*	
Kendall-Attica		0.98		*Distance from Athens*		*−0.58*	
Kendall-Greece		0.98		*Distance from Piraeus*		*−0.68*	
Simpson index				*Distance from Markopoulo M.*	*−0.25*		*0.27*
Shannon index	0.85			*Population growth (1951–61)*			*−0.37*
Evenness index	0.91			*Population growth (1961–71)*			*−0.41*
Brillouin index	0.91			*Population growth (1971–81)*		*−0.39*	*−0.35*
Menhinick index			0.83	*Population growth (1981–91)n growth (1981–91)*		*−0.78*	
Equitability index	0.94			*Population growth (1991–01)*		*−0.71*	
Expl.Var.(%)	**46.6**	**36.8**	**7.7**	*Population growth (2001–11)*	*0.35*	*−0.57*	

* non significant variables (Municipal size, Proximity to the sea coast, Soil quality index).

urban expansion along one century, being less associated with intense dynamics possibly reflective of one (or more) ‘urban pulses’.

Component 2 accounted for 37% of the total variance and was positively associated with the correlation coefficients (referred to all metrics tested here) between long-term building rates at each municipality and the respective rate at both regional and national scales. A negative loading was recorded for the decade with the highest building rate observed over the investigated period, suggesting that Component 2 is oriented along a time gradient from earlier decades (negative scores) to recent years (positive scores). Component scores were correlated positively with population density and negatively with mean elevation, distance from Athens and Piraeus, and population growth since 1971. All in all, these results suggest how Component 2 reflects the density gradient consolidated over time in Athens. Component 3 explained 8% of the total variance and was associated positively with kurtosis and Menhinick diversity index, indicating the dominance of ‘pulse’ waves of growth instead of a regular, continuous expansion of settlements. This component associated negatively with population growth between 1951 and 1981 (corresponding with continuous urbanisation all over the study area) and positively with the distance from Messoghia (Eastern Attica), indicating how rapid, unanticipated, and short accelerations in the urban expansion were primarily observed in *peri*-urban and rural districts of Northern and Western Attica.

4. Discussion

With cities acting as inherently dynamic systems, urban growth is intended as a multidimensional process of change that involves multiple socioeconomic dimensions (Fielding, 1982; Scott et al., 2013; Rubiera-Morollón et al., 2015). Approaches identifying metropolitan regions as complex systems that consist of multiple dimensions shaping non-linear mechanisms of urban growth, have exerted a particular interest in regional science (Kingsley and Enders, 1975; Walker et al., 2004; Walker et al., 2006). Our study integrates knowledge and methodologies of ecological science with exploratory approaches typical of economic and social disciplines. To provide a refined assessment of long-term urban growth, novel indicators and a multivariate statistical analysis documenting the latent relationship with the evolving local contexts were used (Crews and Peralvo, 2008). This rationale provides a systemic interpretation of temporal complexity and spatial variability characteristic of long-term urban expansion (Kallis and Norgaard, 2010). The metrics adopted in this study – derived from information theory (Karamesouti et al., 2015) and, more generally, from diversity science (Kelly et al., 2015) – allow a comparative analysis of individual stages of urban expansion. The resulting evidence outlines the importance of building activity rates when assessing intensity and spatial direction of urban expansion (Salvati et al., 2019), suggesting how rigid and sequential interpretations of metropolitan cycles can be inappropriate in some contexts (Zachary and Dobson, 2021). On the contrary, we used a data-driven, step-by-step analysis to understand the latent diversification in urbanisation processes and the underlying socioeconomic forces (Recanatesi et al., 2016). Simplified approaches, freely available indicators, and intuitive statistical techniques analysing local-scale, long-term regimes of urban growth over more than one century give a novel contribution to regional science (Salvati, 2014). Our procedure is adaptable to different and multifaceted socioeconomic contexts, since it consider a widely available information set enriched with new variables and analysis’ dimensions that provide a refined interpretation of urban growth and change (Pumain, 2005).

Going beyond traditional urban–rural divides, trends over time in building activity highlight the complex geography of Athens’ expansion and recognises spatial heterogeneity as an intrinsic feature of long-term metropolitan development in the study area (Pili et al., 2017), in line with the empirical evidence of earlier studies (Chorianopoulos et al., 2010, 2014; Rontos et al., 2016). The empirical results of the statistical analysis (e.g. Fig. 3) illustrate the multiplicity of urban growth regimes on a local scale (Di Feliciantonio and Salvati, 2015). Regular construction patterns in some municipalities were intermixed with irregular temporal progressions in the rate of building activity (Salvati and Serra, 2016). At the aggregate (regional) level, a strong acceleration of building activity was observed between 1981 and 1985 (Salvati, 2016). This coincided with the economic growth following the restoration of democracy in Greece after the colonels’ regime and it was mostly driven by socialist government policies boosting urban development – partly covered with public debt (Morelli et al., 2014).

On a local scale, a variety of spatio-temporal growth regimes were observed (Fig. 4). Central locations (e.g. Athens) showed an irregular trend, with one or two ‘pulses’ that explain a major part of the total growth. For example, the pulse observed in downtown Athens in the 1960 s, following the baby boom and the positive impact of agglomeration factors, consolidated hyper-dense settlements (nearly 20,000 inhabitants/km^2) and led to spillover mechanisms in the surrounding municipalities since the early 1970 s. This coincided with the transition from compact urbanization to suburbanization, with population moving towards less congested locations along the sea coast (Salvati and Serra, 2016). In this sense, fringe municipalities have shown the most regular trend over time, acting as a sink of population spillover from central nuclei (Athens and Piraeus) and consolidating semi-dense fabrics (Pili et al., 2017). Maroussi and Aspropyrgos are representative examples of this trend (Di Feliciantonio et al., 2018). More peripheral suburban municipalities, such as Afidnes and Polydendri, exhibit particularly irregular patterns over time, with a multiplicity of beats not fully coupled. This processes led to a moderate sprawl that consolidated low-density and mostly sparse settlements around original (compact and rural) nuclei (Rontos et al., 2016). Such dynamics derive from the action of multiple growth factors, related e.g. to the slow (but continuous) spillover of population and economic activities from central areas (Chorianopoulos et al., 2010) thanks to unrested infrastructural development (e.g. motorways, and suburban railways realized between the early 1990 s and the late 2000 s). Finally, a single pulse concentrating most of the urban growth in the last century was observed in some rural municipalities, consolidating small but compact settlement nuclei (Di Feliciantonio and Salvati, 2015). Erythres, a rural center located on the border with the Boeotian region, is an example of such municipalities. More latent dynamics – not entirely attributable to the demographic and economic growth of central areas – have been influenced long-term urban development in such locations, shaping metropolitan morphology toward semi-dense and moderately dispersed settlements (Pili et al., 2017), an intrinsic characteristic of contemporary Attica (Chorianopoulos et al., 2014) mostly derived from the legacy of past urban cycles since World War II. Based on these changes, the traditionally compact and vertical morphology of Athens was progressively moving toward horizontal growth and a more dispersed settlement model (Zambon et al., 2017). Sequential pulses consolidated both compact and hyper-dense settlements in central location and semi-dense and spatially discontinuous settlements in more peripheral locations (Zambon and Salvati, 2019).

Taken together, the results of our study support the assumption that metropolitan transformations are associated with a broad spectrum of socioeconomic conditions (Souliotis, 2013). While playing a variable role over the last century, indicators characterising the evolution of Athens' region include population growth rates, demographic density, and socioeconomic characteristics (Chorianopoulos et al., 2014). Population dynamics, business concentration and wealth accumulation have contributed to this transition thanks to, e.g. the inherent polarisation of residential settlements in high-density and low-density areas (Di Feliciantonio et al., 2018).

On the base of the empirical results of this study and literature evidence, analysing socioeconomic profiles of municipalities suggest how spatial heterogeneity in building activity may reflect the dynamic interplay of different socioeconomic classes (Duvernoy et al., 2018). Infrastructural development fueled by internal (public and private) investments and European funds, changes in the economic base alimenting the shift from manufacturing to advanced services, immigration, and deregulated planning were additional factors of change (Di Feliciantonio and Salvati, 2015). In this regard, a diachronic analysis of urban cycles, correlating building activity and settlement characteristics with demographic conditions, socioeconomic forces, and place-specific territorial aspects, sheds light on the most recent metropolitan transformations in Southern Europe (Salvati, 2016). By overcoming the supposed homogeneity in the housing markets of contemporary Mediterranean cities, the results of our study corroborate the idea of distinct development paths based on a regional-based sequence of metropolitan cycles (Morelli et al., 2014).

Based on these premises, long-term urban expansion is interpreted as a recursive process, with irregular accelerations and decelerations, and a non-linear relationship between spatial and temporal dimensions (Gowdy, 1994). The growing unpredictability of future development paths reflects the heterogeneity and inherent complexity of modern metropolitan systems (Klaassen et al., 1981). Spatial planning should imperatively consider these dynamics, giving adaptive responses to increasingly fragmented social phenomena, progressively decoupled from economic growth (Zambon et al., 2017). As financial and building cycles are often synchronised, a better knowledge of spatial determinants and timing of the former cycle at regional (and local) scale may provide relevant information on the latter (Zambon and Salvati, 2019). The importance of investigating these cycles lies in the holistic understanding of complex systems' dynamics (Portugali, 2000). As demonstrated in our study, results of a quantitative analysis of the relationship between building cycles and urban changes contribute to design local developmental policies oriented toward sustainability (Rontos et al., 2016). Further research on the latent relationship between spatial planning and building cycles is necessary to orient urban expansion toward environmental sustainability, social equity, and economic competitiveness.

5. Conclusions

Novel indicators – moving from exploratory analysis of population dynamics to an explicit investigation of changes over time in building activity rates and settlement characteristics – and multivariate statistical approaches contribute to a spatio-temporal analysis of urban cycles and the associated socioeconomic structure. In this perspective, a permanent assessment of metropolitan transformations is challenging for both research and policy since it associates the intrisic complexity in urban form to economic functions and social dynamics at the same spatial scale. Mediterranean cities characterised by unbalanced socioeconomic models, governance failures, and planning ineffectiveness are therefore considered as representative examples of complex metropolitan systems. This study documents how a diachronic analysis of local-scale indicators from freely available, official statistics is meaningful when debating on the future evolution of urban regions. A spatially explicit analysis of long-term regimes of urban growth may finally inform strategies stimulating a faster recovery of metropolitan systems from external shocks. A stronger integration between socioeconomic indicators is essential to achieve a comparative outlook of urban dynamics under volatile economic cycles in countries with characteristic social transformations and an evident volatility in real estate local markets.

CRediT authorship contribution statement

Samaneh Sadat Nickayin: Writing – review & editing. **Leonardo Bianchini:** Data curation. **Gianluca Egidi:** Formal analysis. **Sirio Cividino:** Software. **Kostas Rontos:** Resources. **Luca Salvati:** Writing – original draft

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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