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Morphometric Indicators for the Definition of New Territorial Units in the Periurban Space: Application to the Metropolitan Area of Valencia (Spain)

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Abstract: New territorial units resulting from urban sprawl processes constitute a major challenge for territorial planning. The aim of this paper is to analyze periurban spaces, focusing on the delimitation and characterization of the urban units arising from urban sprawl processes. The delimitation derives from fractal analysis, where urbanized space is used to detect the limits of the units. The characterization starts with the calculation of eight different indicators, using Geographic Information Systems tools. PCA is used to obtain different dimensions of the urban sprawl phenomenon. Finally, a cluster analysis has been applied to establish a typology of territorial units and facilitate the comparative analysis. The methodology is applied to a case study, the metropolitan area of Valencia. Results show six groups of urbanized spaces, which present different types of urban sprawl structures with different necessities. This applied research can be useful for the spatial planning of the periurban spaces, insofar as it allows the identification of supra-municipal or infra-municipal areas, where it will be possible to improve infrastructures, facilities, or green infrastructure, to empower secondary urban nuclei and to create new inter-municipal cooperation and governance formulas. In addition, the results can constitute a non-administrative territorial basis for the calculation of land occupation indicators that are often used as thresholds for the creation of new residential spaces in regulatory planning documents.

Keywords: urban sprawl; spatial planning; fractal models; morphological units; new territorial units

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1. Introduction

Sprawl areas constitute an increasing part of urban and metropolitan areas. This type of urbanization, characterized by low densities and discontinuity of built space, has a significant social and environmental impact. Negative consequences include increased pollution, decreased accessibility to employment, increased social isolation and segregation, and excessive conversion of farmland and natural spaces to urban uses [1]. Evidence has also been found that it decreases people's satisfaction with livability [2]. This is why the management of such spaces is a major challenge for urban planning, especially when these spaces, as is the case in metropolitan areas, go beyond municipal administrative boundaries, which is the usual framework for planning in Spain. As was noted in [3], the metropolitan reality in the Valencian Region has been present for decades, but local governments show resistance to the cooperation and coordination with other forms of governance that could affect their competences, included the urban planning competences. This may imply not only a lack of coordination of urban strategies, but also competition between administrations to attract investment, which can trigger a negative dynamic for the sustainable use of the territory [4,5]. It can be said that this type of space is an example of the mismatch between the sphere in which economic agents act, and the sphere in which the administration acts, anchored at the local level and, therefore, inadequate to control the dynamics of urbanization [6].

Alternative policies include the reinforcement of the compact city and the strengthening of metropolitan sub-centers, the mixing of functions, the improvement in access to housing, and the articulation of an efficient public transport system. In this sense, territorial policies aimed at articulating the metropolitan region as a polycentric network of cities, each of which is characterized by its physical compactness and the wealth of uses within it, are considered necessary. In [6], four possible strategies for dispersed suburban spaces are identified: selective densification, i.e., taking advantage of typological differences to complete the spaces of dispersed urbanization; typological reformulation, through changes in urban planning regulations that modify the system of open spaces and structuring elements such as volumetrics, heights, and general organization of collective spaces; the enhancement of suburban centrality, through the location of uses that generate urban attractiveness in strategic locations between urbanizations, i.e., creating proximity centrality; and, finally, a comprehensive intervention that considers not only the physical aspect, but also the social, environmental, and cultural aspects, for the social construction of a collective perception of the territory and an urban identity. Other authors point to the need to combine redensification strategies with planning that incorporates urban green infrastructure to avoid the loss of green spaces and contribute to the sustainability of the compact city [7].

However, specific studies have shown that urban sprawl is not a univocal phenomenon, but can take different forms in terms of density and spatial pattern, with different territorial consequences. Specialized literature identifies different dimensions of both the intensity and the spatial pattern of urban sprawl that can be found simultaneously within the same urban space, even if there is a predominant pattern. Therefore, the efficient and effective implementation of these strategies requires an accurate knowledge of the characteristics of the process of suburban sprawl, as well as a temporal monitoring of its evolution in order to evaluate its results. Consequently, it is necessary to use different indicators to measure and characterize urban sprawl. In many cases, studies use the urban or metropolitan set as a scale, defining urban space either by prior administrative delimitations (as in the case of the US metropolitan areas), on the basis of morphological criteria such as the European Metropolitan Urban Areas [8], or—which is generally considered more appropriate—on the basis of functional criteria, usually on the basis of residential residential–work mobility [9–11]. This consideration of the metropolitan whole is very useful for comparing metropolitan areas, but it does not allow the identification of the different spatial patterns that occur within them, preventing the adaptation of planning strategies to the specific characteristics of each space.

When the analysis is applied at the intra-metropolitan scale, the preferred territorial unit of choice is the municipality, which, as the territorial scope of planning, is particularly relevant [12]. However, empirical analyses have shown that within metropolitan areas it is possible to find different processes of urban growth that give rise to distinct urban sprawl patterns, thus requiring the application of specific policies for each case. The municipal division is insufficient to characterize these processes internal to the metropolitan area, since one of the specific characteristics of urban sprawl is that its growth gives rise to large and unconnected areas that can extend over contiguous municipalities, requiring specific planning measures that go beyond the local planning framework. It is therefore considered that the use of municipal administrative boundaries for the calculation of indicators distorts and blurs the characteristics of these intra-metropolitan supra-municipal areas, preventing their characterization, the definition of their problems, and the monitoring of their evolution over time.

To overcome this difficulty, in this article we use a delimitation of territorial units based on fractal methodology, which makes it possible to avoid administrative boundaries, identifying areas of dispersed supra- and infra-municipal urbanization based on the morphology of the area [13]. The fractal methodology makes it possible to identify the spatial limits of an urban pattern from the data itself, without the need to use a prior threshold, making it ideal for identifying the "natural" spatial units defined by the spatial pattern

of the built space itself. The morphological units serve as a basis for the measurement of the different dimensions of urban sprawl, and the elaboration of a typology that allows us to characterize the phenomenon in a specific way, as well as to monitor its intensity and characteristics in the future. It could be used as a guide for the design of specific policies on a supra-municipal scale. The indicators are selected in such a way that they reflect the main dimensions of urban sprawl, are easy to obtain, and allow their application in different geographic and planning contexts.

This methodology is applied in the metropolitan area of Valencia, a Spanish metropolitan area of 1,994,565 inhabitants (792,492 in the central municipality) located on the Mediterranean coast. The area has experienced intense urban sprawl, especially in the period 1990–2013, under the real estate bubble process. From 1987 to 2005, the increase in artificial land in the Valencian region was 76,25%, much higher than the average for Spain (51.87%) and Europe (9.62%) [14].

Our objective is therefore twofold: (1) to identify the most suitable morphological units of analysis to identify urbanization processes, based on fractal methodology; and (2) to perform a morphometric analysis that allows us to characterize these morphological units in terms of the basic dimensions of urban sprawl.

The article is structured as follows: firstly, the study area is presented (Section 2); secondly, the state of the art concerning the processes of dispersion and delimitation of urban areas, as well as the dimensions and indicators, are presented (Section 3). This is followed by the section on materials and methods, which specifies the sources of data used in this work and the methodology to be used (Section 4). Finally, the sections on results, discussions, and conclusions are presented (Sections 5–7).

2. Area of Study

Since the beginning of the 20th century, the Spanish Mediterranean has been characterized by a disproportionate expansion of urbanization processes. As in other countries, in Spain, there have been territorial processes in recent years that have led to a change in the city model. Improvements in communication and transport systems, new residential preferences, and, in some cases, private interests that public policies have been unable or unwilling to control, have led to the spread of suburbanization processes, giving rise to what has been called the "dispersed city" or "diffuse city" [15–17].

This has been the case in the metropolitan area of Valencia, where there is currently a large metropolitan area where the suburbanization processes mentioned above can be observed. According to a study on the formation of this metropolitan area and the main means of transport [18], it was the railway network that modeled the expansion of the population and residential location until 1981, while from that time onwards the automobile was the means with the greatest capacity for territorial transformation and location of the population. Taking into account Corine Land Cover data, between 2000 and 2006 almost 46 million m^2 of metropolitan land was transformed into urbanized land, with a clear predominance of low-density models [19–21]. This process has continued until very recently, since, despite the impact of the economic crisis of 2008, the rate of growth of developable land continued to exceed that of urbanized land until 2013, due to the maintenance of the expectations of municipalities, which hoped to recover the pre-crisis rate of construction [22]. Consequently, the growth of built-up space during the period 1991–2015 has been three times higher than population growth, contributing to the reduction in highly productive agricultural space, the fragmentation of the territory, and the conurbation of municipalities [23].

As a result, a space of strong urban continuity has been configured in which it is not easy to identify elements of discontinuity or morphological rupture that allow the definition of the limits of the urban units, with the consequent problems of management and planning. This model of high consumption of resources, linked to mobility by private transport, generates significant negative externalities. As an example, the cost of maintaining the services induced by urban sprawl has been evaluated in the Valencia region to have

increased 20%, although in some municipalities these percentages exceed 40% with respect to the average costs of providing basic services [12].

In response, the Territorial Strategy of the Valencian Community, the framework document for land-use planning in the region, as well as the Territorial Plan for the Metropolitan Area of Valencia (PATEVAL), the main instrument for sub-regional planning, have set, as one of their objectives, defining the areas of low density and remoteness from the compact urban fabrics, as non-sustainable, to be extinguished or restructured. One of the following strategies is established for each of these urban areas [23]: (a) enhancement of elements of urban centrality through the implementation of basic facilities and public and private services; (b) articulation of these spaces with consolidated urban centers; (c) creation of new centralities on the structuring elements of these fabrics, with pieces of higher density and urban intensity; (d) articulation of public transport on these structuring elements; and/or (e) densification of this type of land in the vicinity of access points to the sustainable transport network.

The study area considered is the one defined on the basis of functional criteria by [24]. As recommended by different authors [10–12], the main criterion applied for its delimitation is the existence of residence–work mobility flows, although corrected by some demographic criteria. This area includes 80 municipalities, and totaled 1,994,565 inhabitants in 2022, occupying an area of 2212.57 km^2 (Figure 1).

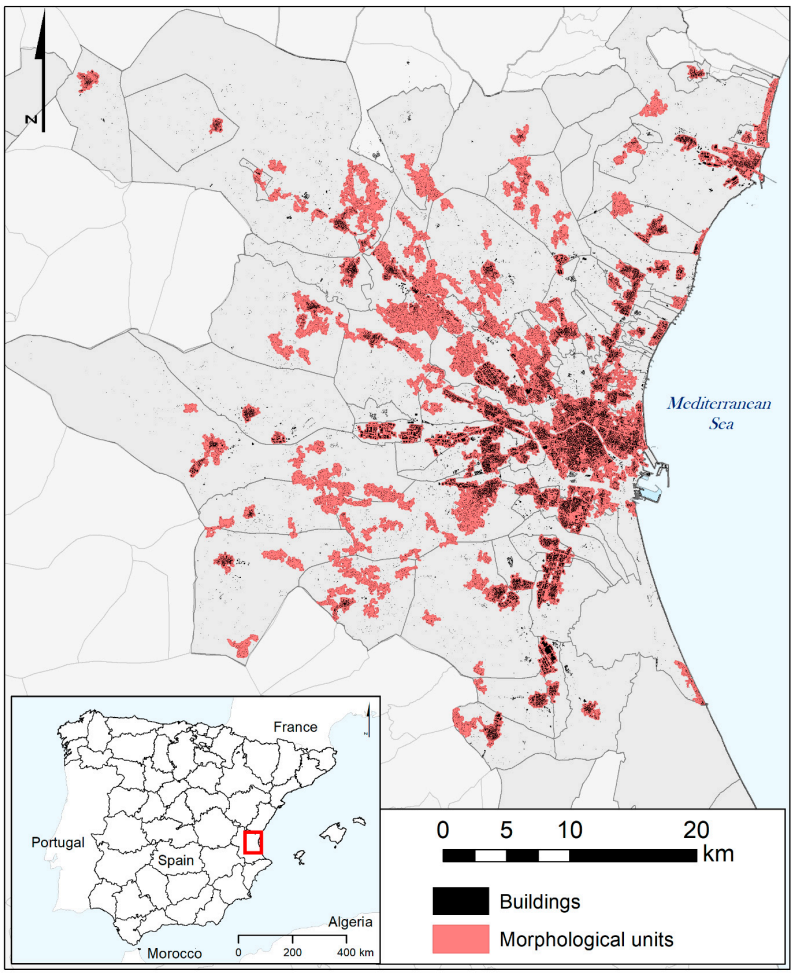


Figure 1. Area of study.

3. State of the Art

3.1. Dispersion Processes and the Delimitation of Urban Areas

The extension of suburbanization processes, and especially those characterized by urban sprawl, in recent years, has become one of the most important issues threatening the sustainability of urban spaces. According to [25], the negative consequences of urban sprawl include loss of agricultural land, reduction in wildlife habitats, increased landscape fragmentation, higher emissions and infrastructure costs for transport, water, and energy, loss of landscapes, and degradation of ecosystems. Therefore, the need to monitor and control urban sprawl has been identified as one of the objectives of spatial planning policies at both national and European levels.

Despite this, the processes of growth of this phenomenon have been maintained, and some of the urban planning policies implemented to improve the quality of cities, such as the planning of green spaces and green corridors, may even have contributed to its increase. The process takes different forms depending on socio-economic environments [26], and is not always linked to urban growth, but can also be found in areas of demographic regression [27]. According to several authors [28,29], urban growth operates according to three main possibilities: infill, edge-expansion, and leapfrog, the latter two being characterized as sprawl. The environmental and socio-economic consequences of these processes are different, as are the planning tools to be used.

Since the 1990s and, in particular, since the beginning of the century, numerous studies have been carried out with the aim of measuring the levels and processes of urban sprawl in the metropolitan areas of different countries, carrying out comparative analyses and typologies and monitoring the phenomenon over time. One of the problems faced by these analyses is the delimitation of the study area, given that the process of urban sprawl itself has contributed to the growing difficulty of delimiting metropolitan spaces, which take the form of a continuum with different levels of demographic and constructive intensity.

Consequently, the delimitation of cities and, in particular, of metropolitan areas, has become a subject of reflection both in academia and at different political-administrative scales [30–34]. In the case of the European Union, the delimitation of harmonized urban spaces has become a relevant issue that has been the subject of successive approaches that have combined criteria of demographic density and size with others derived from population mobility [35–38].

Faced with this problem, different tools and methodological alternatives have been deployed, which can be summarized in two approaches: (1) a functional approach, which is based on the existence of complementary relationships and flows between population centers, with special attention paid to the daily relationships determined by the commuting of the employed population [37,39–41]; and (2) a morphological approach, which uses criteria such as the density of built-up space, the predominant type of land use, or the continuity of the built-up area [42,43]. Often these two perspectives have been combined to define a two-level urban space, a morphological core space, and a functional urban region that constitutes the sphere of everyday relations of the population.

However, these approaches are not without their problems. On the one hand, the delimitation of functional urban spaces faces the scarcity of available sources which, when they exist, lack territorial coverage and continuity (as in the case of mobility surveys) or adequate territorial detail [43]. The morphological approach also presents specific difficulties. The delimitation of the conurbation space requires the application of a distance or time threshold to the built-up space that allows the possibility of interaction, usually through pedestrian routes, to be delimited. This "a priori" threshold is often applied in a homogeneous way in all built-up areas, without taking into account the characteristics of the interstitial space and the population that moves around. Moreover, the application of specific thresholds, adapted to each case study, makes comparisons between urban areas difficult, especially when they belong to countries with different population patterns [44].

To avoid setting an a priori threshold in morphological methods, some authors have proposed alternatives based on statistical analyses of distances between buildings or be-

tween nodes of the road network, identifying a specific threshold [45–50]. One of the most interesting methodological variations is based on the application of fractal models, which uses morphological patterns of built space to detect changes that correspond to formal boundaries in urbanized space, and uses them to detect functional agglomeration and characterize different spaces in multifractal models [51].

The method defined by [41] for the definition of urban boundaries, which is used in the definition of the morphological units of this paper, is based on the detection of a threshold of change in the morphology of built space, through Minkowski's dilation method for determining fractal dimensions [52,53]. This crucial distance threshold corresponds to a discontinuity along the scales [54], and separates two distinct spatial morphological subsets in fractal terms. In this article we opt for the latter methodology, both to delimit the space of analysis and to identify the morphological units.

3.2. Dimensions and Indicators

Despite the attention received in the literature, there is no generally accepted definition of urban sprawl. Although an accurate definition of urban sprawl is debated, a general consensus is that urban sprawl is characterized by unplanned and uneven pattern of growth, driven by a multitude of processes and leading to inefficient resource utilization [28]. Within this generic term there are multiple dimensions with different territorial effects and requiring different types of policies. Different authors have pointed out that this generic term contains different dimensions that have different territorial effects and require different types of policies.

Ref. [9] points out that there are different models of urban sprawl, defined by the combination of eight dimensions, which can be present in different degrees and combinations in different urban areas, or parts of the same urban area. They define a series of indices for each of these dimensions to classify different types of sprawl and calculate a synthetic index, which they use to show negative externalities and appropriate policies. Dimensions can also be used to monitor over time and measure the effects of such policies. These dimensions are as follows:

- Density is defined by the number of dwellings per Ha of developable land.
- Continuity is the degree to which developable land has been built over urban densities in an uninterrupted manner ("leapfrog development" according to [55]).
- Concentration measures the degree to which urban development is disproportionately located on relatively little of the total urban area.
- Clustering is the degree to which growth has been grouped to minimize the total amount of developable land occupied by residential uses.
- Centrality is the degree to which urban development is located close to the CBD of the urban area.
- Nuclearity is the extent to which an urban area is defined by a mononuclear (as opposed to polynuclear) pattern of development.
- Mix of uses is the degree to which two different land uses exist in the same area.
- Proximity is the degree to which a particular type of use or pair of uses are close to each other.

Each of these dimensions has specific negative effects. Thus, sparse clustering creates large impervious surfaces that contribute to flooding and erosion, as well as increasing travel distances between residences and jobs. A polynuclear pattern may reduce commuting costs, but increases other costs, such as land values in the vicinity of major employment nodes. On the other hand, the separation of different land uses increases commuting time and distance to work, leading to traffic congestion and an increase in trip length and travel time.

The literature review in [56] identifies four types of indicators: growth rates, density indicators, spatial geometry indicators, and accessibility indicators. In terms of growth rates, urban sprawl is defined as population growth in the suburban area greater than that experienced by the central area, or as the ratio between the rate of growth of built-up space

and the rate of population growth in a given area ("Sprawl Index" or "Sprawl Quotient"). The most commonly used density indicators are those that relate the volume of residential units or the number of residents to the surface area. In the case of accessibility measures, there are indicators related to the length and fractal dimension of roads, household travel times, some ecological measures such as the Mean Proximity Index (MPI), and others used in gravity transport models.

The most numerous indicators, however, and the ones that have been most closely related to the different dimensions of urban growth, are indicators of spatial geometry, derived from ecological research [28] or fractal geometry [55,57–60]. Among the latter we highlight the work of [61]. These authors analyzed the spatial pattern of built space in the Wallonia region of Belgium using fractal indices, and showed that the subarea partitioning of the region based on fractal indices was identified with an outcome of the history of urbanization. The indices used proved to be useful for characterizing and understanding built landscapes, as well as for modeling and planning urban realities.

According to [56], spatial geometry indicators measure two main characteristics of the urban landscape: configuration, which refers to the geometry of built space, i.e., measures that quantify the level of dispersion and fragmentation of the urban landscape, of which the most commonly used are measures of "leapfrog" or continuity; and composition, which identifies the level of heterogeneity of uses within the area, as the pattern of urban sprawl is identified with a more homogeneous and segregated land use. In this case, the most common measure is the percentage of different land uses, which quantifies the level of heterogeneity.

Ref. [62] simplifies the proposal of [9], and synthesizes it into three specific dimensions, which they relate to different types of territorial impact: density, pattern, and surface area.

- Low density puts pressure on the economic efficiency of technical infrastructure and increases transport demand and car dependency. Public transport is less effective and less cost efficient, infrastructures have higher development costs, and the needs of energy consumption are also higher (heating). There are negative health effects due to a lower level of physical activity, as residents walk less and suffer more from obesity and chronic diseases.
- A pattern characterized by an irregular, discontinuous form, with a highly fragmented mosaic of different land uses, has as its main negative consequences the loss of efficiency of urban services such as road infrastructure or sewage systems, longer commutes, and the fragmentation of the landscape, with the consequent separation and isolation of habitat areas and natural or semi-natural ecosystems.
- Finally, changes in the land uses affect the natural or agricultural land, which transform into built-up areas. Impermeable land has complex effects on ecological systems and the scarcity of open space, the loss or degradation of quality agricultural land, increased pollution, and the contribution to the urban heat island, and negative impacts on aquatic systems.

Ref. [11] points to the existence of seven conceptually distinct dimensions, some of which coincide with those mentioned by the previous authors:

- Density, i.e., the degree to which urban space has been intensively developed, as measured by the number of dwellings or jobs per floor area.
- Continuity: The degree to which built space has been developed without interruption throughout the urban area.
- Concentration: The degree to which housing and jobs are disproportionately located in a small area of urban space.
- Centrality: The extent to which housing and jobs are located near the center of the urban area.
- Proximity: The degree to which dwellings or jobs are close to each other in the urban area.

- Mixed use: The degree to which housing and employment are located in the same area throughout the urban area.
- Nuclearity: The degree to which jobs are disproportionately located in the center of the urban area, as opposed to a multicentric model.

These authors point to correlations between health and density, car ownership, and public transport use; density and centrality; traffic congestion and density; continuity and centrality; and racial segregation and job continuity, density, and compactness.

Moreover, other authors have related spatial patterns and the cost of municipal public services, identifying the expenditure items most affected by overspending and relating them to different indicators of spatial dispersion dimensions of concentration, centrality, and local proximity between land uses [1,12,26]. The results indicate that the effects on the local economy depend on the dispersion dimension considered, suggesting that the spatial configuration of cities affects local finances in different ways.

Therefore, it is concluded that the use of different indicators that are relevant to different dimensions of sprawl is important, if we consider, as [11] do, that different empirical analyses have indicated that different dimensions are empirically independent, and have different predictive powers with different phenomena of interest. This multidimensional view has important implications for planning and policy design, as the achievement of specific objectives necessitates the alteration of specific aspects of land use. Generic anti-sprawl policies may produce different metropolitan impacts depending on the type of existing land use pattern [11,63].

However, when conducting an empirical analysis, it is essential to make a selection of indicators since some of the indicators used for landscape metrics provide redundant information, as they are highly correlated with each other, or confusing results when applied to urban environments [64,65]. In this regard, it should be noted that the analysis conducted by [11] on 257 US metropolitan areas, using 14 different indicators, identified four uncorrelated dimensions associated respectively with (1) the intensity of residential and non-residential use; (2) compactness, i.e., the degree to which development is concentrated; (3) the mix of residential and non-residential land uses; and (4) the dominance of the center, i.e., the degree to which jobs and population are distributed according to a monocentric pattern.

4. Materials and Methods

4.1. Data Sources

The basic information used in this article comes from the cadastral cartography in shape format available at the Spanish Cadastre Office (https://www.sedecatastro.gob.es/ (accessed on 7 February 2019)), more specifically from the layers corresponding to the "Urban Sub-parcels" representing the built volumes within a parcel (CONSTRU files). Urban and rural buildings are included. The polygons corresponding to the buildings are selected, eliminating non-built spaces such as plots or unbuilt land, as well as other urban uses not corresponding to buildings (gardens, roads, ports, etc.). The above steps have been carried out using an iterative model developed using the Esri ArcGis Model Builder tool. The information analyzed corresponds to the cadastral situation on 7 February 2019.

Cadastral cartography is a source of a fiscal nature that identifies all existing buildings in Spain, and provides highly accurate digital cartographic bases. The great advantage of its use, as opposed to the use of satellite images as is usual in this type of work, is that it is very precise spatial information, without establishing a minimum polygon surface for its inclusion, so that all buildings are represented. It is also very useful because it is a constantly updated database, due to its fiscal purpose. As limitations, it is emphasized that it requires knowledge of the database to perform adequate data cleansing of constructive elements, as detailed in [13].

The population data used are from the 2011 Spanish population census, specifically, from the 1 km^2 population grids published by the Spanish national statistics institute. These grids allow us to approach the territory in a much more precise way than with the

census section level data published by this organization. This is why the 2011 data were used, since for the current 2021 census the grid data have not yet been published.

Finally, municipal planning data, obtained in our case from the Valencian Cartographic Institute, have been used to distinguish between residential, industrial, and commercial areas. This differentiation has served to add information to the primary data source of the cadastre and to be able to add population to the residential areas, as detailed later in the methodology.

4.2. Delimitation of Morphological Units

The morphological units we use as a basis for our morphometric analysis are those resulting from the application of the methodology designed by [44] to the 2019 digital cadastral mapping of the municipalities included in the metropolitan area of Valencia, the first results of which were published in [13]. The most relevant aspect of this procedure is that it allows to identify, from the spatial pattern itself, a distance threshold that allows us to delimit and map significant groupings of built spaces of different sizes, which in this article we call urban morphological units. In [13], the point of maximum curvature of the dilation curve was identified, which is the one that reveals a major spatial discontinuity along the scales. The corresponding distance threshold separates two distinct morphological spatial subgroups in fractal terms. The maximum curvature value obtained (−0.354907) is very close to 0; this means that the differences between the morphological patterns of the urban space and its periurban and rural environment are not high, and there is no clear cutoff, which is consistent with what we know about this space. This point of maximum curvature allows us to identify the distance threshold beyond which the distances between buildings no longer exhibit the same fractal behavior (90.0264 m).

This distance threshold was applied to the elements of the built space, which made it possible to identify the significant morphological units. The resulting layer consists of 360,008 polygons of built-up spaces, totaling a built-up area of 524.64 km^2. For the purposes of this analysis, we have selected the morphological units larger than 50 hectares, which we consider to be the most relevant for planning purposes.

4.3. Morphometric Analysis

There are two opposing trends in the development of landscape metrics: (1) the differentiation of indices to distinguish more precisely between specific aspects of landscape structure; and (2) the concentration to select a few metrics that represent highly correlated groups of measures [66]. In this paper we opt for the latter, taking into account that only a limited number of indicators can be reported in monitoring systems.

The selection of indicators was made taking into account the following criteria:

- To collect information on the main dimensions of urban sprawl identified by the literature, namely density, pattern, centrality, and mix of uses, avoiding redundant information that may be provided by a very large battery of indicators, which hinders comparability, interpretation, and meaningful conclusions [28,64].
- Within each of these dimensions, indicators are selected that are considered appropriate to characterize the delimited intra-metropolitan territorial units. Thus, global indicators of metropolitan structure are not applied, as they are not considered appropriate for the present analysis, which focuses on the comparability of intra-metropolitan spaces, and not between MAs.
- Finally, and with the aim of making them an instrument applicable in different contexts and useful for planners, indicators are selected that are based on easily accessible information, identifiable by the planner and interested agents, because of their relative accessibility and because they are directly associated with planning problems and instruments.

In this sense, this work has not used indicators based on fractal methodology, which has been applied exclusively in the phase of delimitation of territorial units.

Taking into account four significant dimensions of urban sprawl (density, pattern, centrality and mix of uses), eight representative indicators are selected:

- Density: Density indicators are the most widely used in the literature and are considered indispensable in the investigation of urban sprawl. Positive values of this factor are associated with high values of net density, which describes the capacities of urban settlements to sustain more population within less dispersed urban areas.
    1. The first density indicator (Dens1) is obtained according to [62,67] taking into account the percentage of developed land per total area. Developed land is considered as the "footprint" of the built-up space, which is obtained from cadastral databases, while the total area is that corresponding to the morphological unit.

$$\text{Dens 1} = (\text{Developed land})/(\text{Morphological Unit Area})$$

    2. The second density indicator (Dens2) refers to net building density as defined by [68]. In this case, built-up volumes are taken instead of the built-up surfaces of the previous indicator. The volume is obtained by multiplying the built-up areas by the heights of the buildings.

$$\text{Dens 2} = (\text{Built volumes})/(\text{Morphological Unit Area})$$

    3. The third density indicator (Dens3) takes into account the population within built-up land [62]. The population within each morphological unit has been estimated from the information provided by the National Institute of Statistics for the 1 km^2 side grid of the 2011 Population Census. The calculation has taken into account only the residential polygons from the urban planning and the volume of urbanized areas. The population is distributed over the volume of built-up residential space.

$$\text{Dens 3} = (\text{Population of morphological unit})/(\text{Built volumes})$$

- Pattern: Among the different indicators of the pattern, those related to the continuity and compactness of the urbanized space, as well as the proximity to other urbanized spaces, have been selected as the most relevant. The shape index (Comp1) measures the level of deviation of an urban area from the ideal compact form of a circle. These urban forms are more difficult to supply with urban services (e.g., public transport) than compact areas. The openness index or contiguity (Cont1) reflects the integration of the morphological unit into the existing infrastructure.
    4. Compactness ratio (Comp1) provides a compactness measure to compare the area of a shape (A) with the area of the smallest circle that circumscribes the shape (Ac) [69]. It shows the irregularity of the areas.

$$\text{Comp 1} = A/Ac$$

    5. Continuity (Cont1) is derived from the openness index [62]. It is obtained as the percentage of non-urban land in a 1 km buffer from each unit. It allows measurement of the level of integration of new urban areas into the existing urban mix.

$$\text{Cont 1} = (\text{Non-urban land in the buffer})/(\text{Buffer's area}) \times 100$$

- Centrality: The degree to which the urban development is located close to the CBD of the urban area. Due to the importance of the municipal level in the planning and management of infrastructures, the distance to the head or heads of the municipalities over which the morphological unit extends has also been considered.

6. The first centrality indicator used (Centr1) is calculated from the distance from the centroid of each morphological unit to the CBD of the area, located in Valencia City Council [68].
7. The second centrality indicator (Centr2) is obtained from the distance from each morphological unit to the municipal capitals in which it is included. The morphological unit may be within a single municipality or several municipalities, in which case the average distance to the corresponding municipal centers is obtained.

- Mix of uses: The proximity of non-residential uses minimizes travel and improves the quality of life of the population.
  8. The mix of uses indicator (Mix1) is calculated as the percentage of uses other than residential within the morphological unit [56]. In this case we add up all the areas corresponding to industrial, commercial, and tertiary uses.

4.4. Typology of Spaces

Once the corresponding indicators have been obtained for each morphological unit, we undertake a first analysis to check if there are common factors underlying groups of variables that are associated, applying a principal component analysis (PCA). This is a widely used methodology for the classification and analysis of the internal structure of urban areas, although in order to be useful the quantitative result must be interpreted with a detailed knowledge of the territory and the processes that affect it. In the present case, a factor analysis using PCA was applied to the 8 indicators that were selected according to the theoretical framework. The statistical treatment was carried out using IBM SPSS Statistics version 26©. The analysis yielded significant results according to Bartlett's test (significance level of less than 0.001) and the Kaiser–Meyer–Olkin index (KMO equal to 0.637). To facilitate the interpretation of the results, the matrix was rotated using the VARIMAX method.

Once the main components were identified, a cluster analysis was applied to these components to establish a typology of territorial units to facilitate comparative analysis. Cluster methods are heuristic methods that are designed to create homogeneous groups of cases or entities and allow for the development of a typology or classification. The strategy of cluster analysis is to look for a data structure that is not readily apparent through visual inspection [70]. To generate the clusters, the squared Euclidean distance and a hierarchical agglomerative process are used as an index of dissimilarity, which allows the internal structure of the data to be explored more easily [71]. This method starts from as many groups as there are cases to be studied, and successively groups the cases with the lowest dissimilarity values. The complete linkage method is used as an aggregation method, which tends to form relatively compact clusters composed of highly similar cases, thus facilitating the detection of significant groups.

5. Results

5.1. Morphological Units

In the study area, 360,008 morphological units of built spaces of different sizes were identified, with a total built surface area of 524.64 km^2, accounting for 23.7% of the surface area of the metropolitan area. However, as can be seen in Table 1, almost half of these occupy less than 1 Ha, as they are made up of small groupings of buildings. At the other extreme, we find extensive dispersed areas, which extend over several municipalities, constituting an important land-use planning problem.

For the purposes of this analysis, the 131 morphological units larger than 50 hectares were selected, which account for 56.2% of the built-up space in the metropolitan area, and which are the most relevant for planning purposes. Some of these areas are mixed land uses, containing both residential and industrial, commercial, and service areas, although 17 of them correspond to exclusively industrial areas, and therefore they do not have a resident population. The analysis of the resident population in the 131 morphological areas

shows that they contained 88.78% of the total metropolitan area, according to the estimate made on the basis of the 2011 Census. Figure 2 shows the number of morphological units by size, while Figure 3 shows the number of morphological units according to their resident population.

Table 1. Characteristics of morphological units.

Size (Ha.)	Number of Cluster		Surface (km^2)		
	Number	%	km^2	%	% of M.A.
<1	5120	49.08	42	7.95	1.88
1 to 5	4392	42.00	87	16.53	3.92
5 to 10	434	4.16	30	5.67	1.34
10 to 20	225	2.16	31	5.95	1.41
20 to 50	129	1.24	40	7.68	1.82
50 to 100	59	0.57	41	7.85	1.86
100 to 200	36	0.35	48	9.14	2.17
200 to 500	24	0.23	72	13.71	3.25
500 to 1000	8	0.08	53	10.16	2.41
>1000	4	0.04	81	15.36	3.64
Total	10,431	100.00	525	100.00	23.71

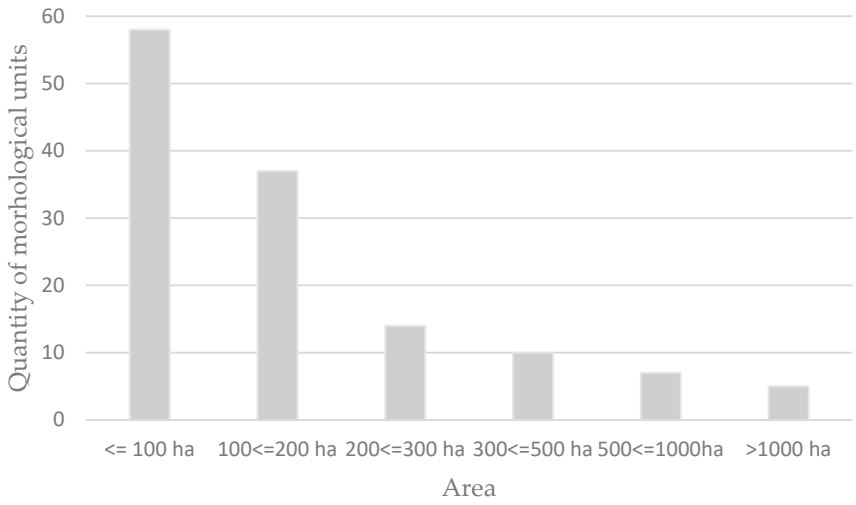


Figure 2. Morphological units according to area.

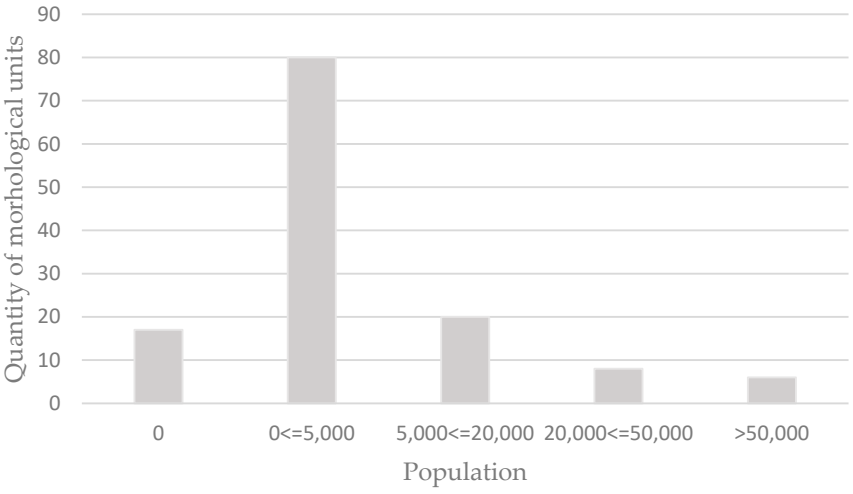


Figure 3. Morphological units according to population.

5.2. Morphometric Characterisation

As described in the methodology, eight indicators corresponding to different dimensions of urban sprawl were calculated for each of the morphological units. Table 2 shows a summary of the results in our study area.

Table 2. Summary of the application of the indicators.

Frequency	Mean	Std	Max	Min
DENS_1	18.06	13.04	57.01	3.63
DENS_2	46.26	43.88	250.92	4.91
DENS_3	115.49	112.22	558.60	0
COMP_1	0.37	0.11	0.63	0.10
CONT_1	77.19	10.80	93.53	39.69
CENTR_1	18,717.10	7792.20	48,412.5	1189.97
CENTR_2	3655.21	2974.60	21,399.20	19.84
MIX_1	13.03	20.43	100	0

As shown in Table 3, some of these indicators are highly correlated. In particular, a high correlation is observed between the density indicators (Dens 1, Dens 2, and Dens 3). In contrast, the indicators of compactness, continuity, and mix of uses are poorly correlated with each other, indicating the existence of different components of urban sprawl that are not necessarily associated with each other.

Table 3. Correlation matrix.

	Dens1	Dens2	Dens3	Comp1	Cont1	Centr1	Centr2	Mix1
Dens1	1	0.866 **	0.393 **	0.206 *	−0.359 **	−0.285 **	−0.213 **	0.6 **
Dens2	0.866 **	1	0.717 **	0.110	−0.484 **	−0.385 **	−0.295 **	0.361 **
Dens3	0.393 **	0.717 **	1	−0.006	−0.461 **	−0.343 **	−0.294 **	−0.164 **
Comp1	0.206 *	0.110	−0.006	1	−0.010	0.079	−0.062	0.167
Cont1	−0.359 **	−0.484 **	−0.461 **	−0.010	1	0.556 **	0.873 **	−0.121 *
Centr1	−0.285 **	−0.385 **	−0.343 **	0.079	0.556 **	1	0.511 **	−0.167 **
Centr2	−0.213 *	−0.295 **	−0.294 **	−0.062	0.873 **	0.511 **	1	−0.076
Mix1	0.6 **	0.361 **	−0.164 **	0.167	−0.121 *	−0.167 **	−0.076	1

** Significant at 0.05. * Significant at 0.10.

The principal component analysis allows for the identification of the main dimensions of urban sprawl that are not related to each other. The first three principal components with an eigenvalue greater than 1, which account for 77.376% of the explained variance, were retained. The rotated saturation matrix (Table 4) has allowed us to identify each of the components with one of the components of urban sprawl: pattern, density, and mix of uses. Thus, the first component, which accounts for 29.577% of the variance, is associated with the continuity (Cont1) and distance (Dist1 and Dist2) indicator. The second component, which accounts for an additional 27.575%, is related with the density indicators (Dens1, Dens2, and Dens3). Finally, the third component (20.224%) is associated with the percentage of non-residential uses (Mix1) and the compactness index (Comp1).

Table 4. Rotated component matrix.

Variable	Component		
	1	2	3
Dens1	−0.155	0.713	0.614
Dens2	−0.247	0.905	0.293
Dens3	−0.260	0.857	−0.304
Comp1	0.023	−0.010	0.517
Cont1	0.902	−0.275	−0.029
Centr1	0.713	−0.238	−0.038
Centr2	0.939	−0.047	−0.033
Mix1	−0.090	0.096	0.890

As can be seen in Figures 4–6, these three components present different spatial patterns, not necessarily associated with a center–periphery model. The first component, associated with indicators of continuity and distance, presents an axial pattern, articulated by the main road axes. The second component, associated with density indicators, adopts a vaguely decreasing pattern with distance from the metropolitan center. Finally, the third component, associated with the mix of uses indicator and the compactness index, presents an agglomerate pattern, corresponding mainly to the location of industrial, commercial, and service areas located in the first metropolitan ring.

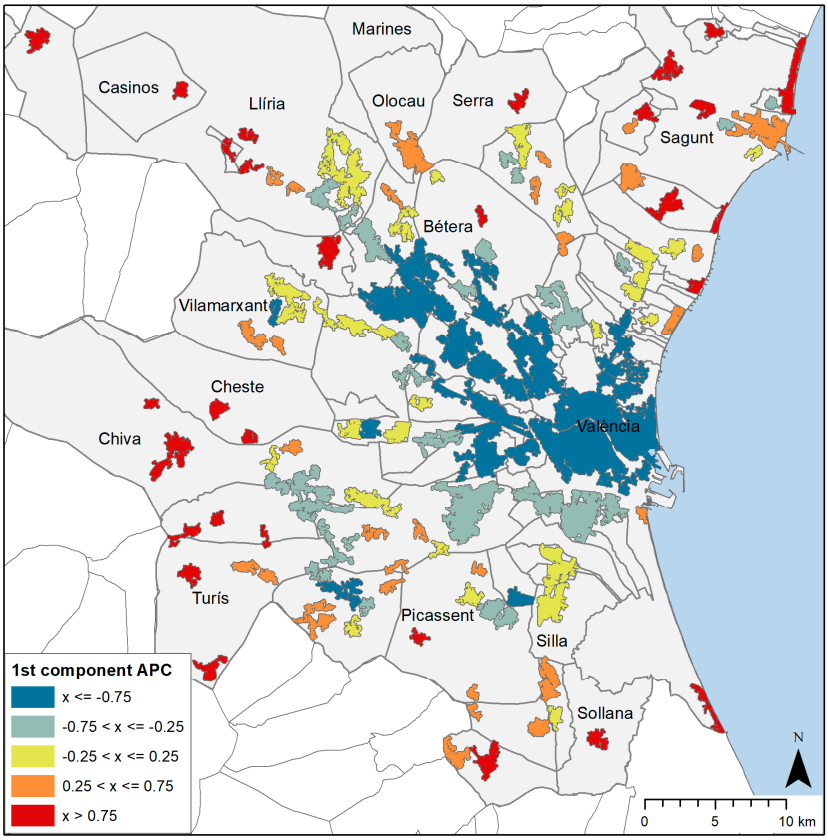


Figure 4. Component 1.

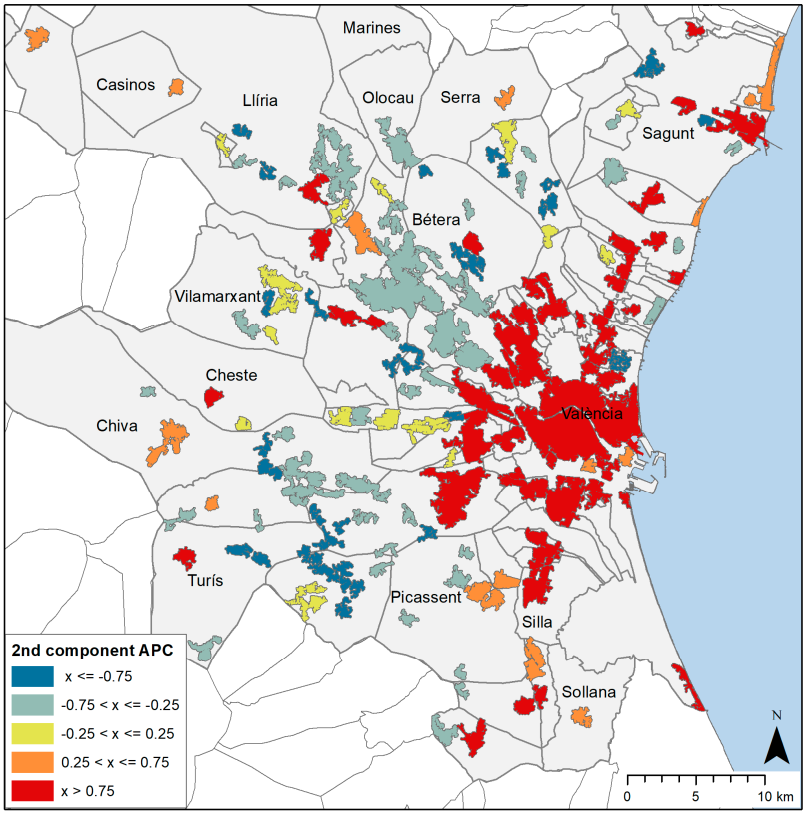


Figure 5. Component 2.

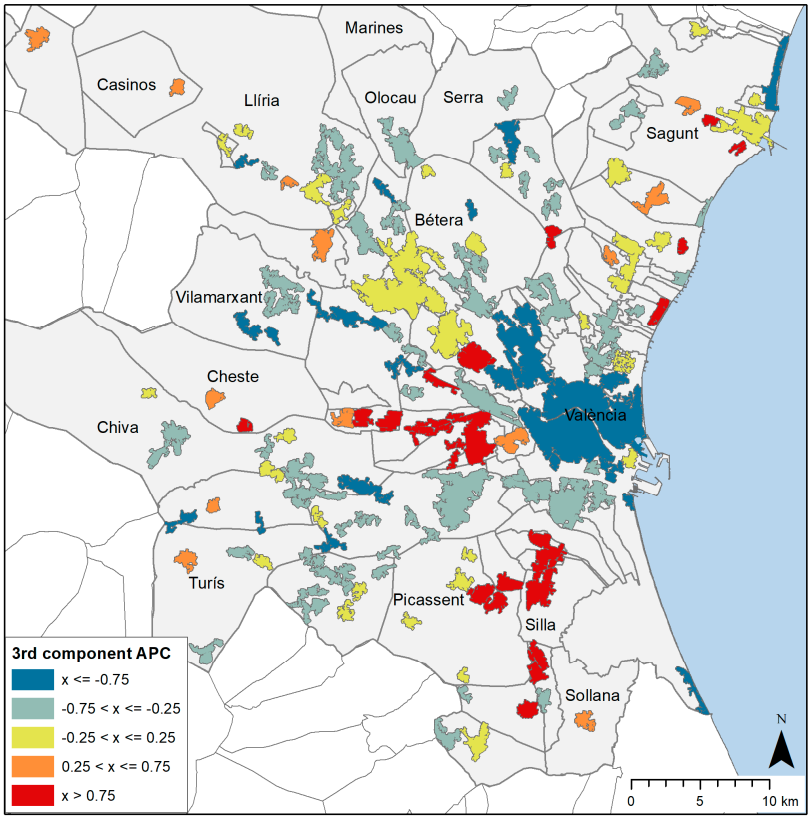


Figure 6. Component 3.

5.3. Typology

As explained in the methodological section, based on these three components, a cluster analysis has been applied to define six groups of urbanized spaces, which present different types of urban sprawl structures.

1. Compact city: Identifies the central core of the metropolitan area. It is made up of four large contiguous spaces characterized by high values for component 2, i.e., a high level of building and population density, and low values for components 1 and 3, i.e., a high degree of continuity and a low percentage of non-residential uses, although with a higher-than-average weight of tertiary use and less industrial use.

2. Suburban discontinuous areas: These consists of a series of areas (27 cases) of a certain size and demographic volume with high density indices and low discontinuity indices, with a mix of industrial, residential, and tertiary uses. They are located in the first metropolitan ring, arranged along road axes, and present percentages of tertiary and industrial land above the average.

3. Supra-municipal residential areas: This type of area (39 cases) is characterized by very low density values and a low level of discontinuity, as well as a certain presence of tertiary uses, but no industrial activity. They are relatively large areas resulting from the coalescence of residential developments in the second metropolitan ring.

4. Low-density, highly discontinuous residential areas: This is the group with the highest number of cases (52). They have below-average density levels, a very high degree of discontinuity, and little or no non-residential uses. These areas are generally small and sparsely populated, with a preferably peripheral location in the metropolitan area, and relatively far from the municipal capital.

5–6. Industrial areas: These groups include dispersed industrial and commercial areas, with minimum population density values, and maximum values for the percentage of non-residential uses, especially industrial. The difference between groups 5 and 6 is established in terms of the degree of continuity and the distance to the metropolitan center. While group 5 (three cases) groups industrial areas closer to the central urban core, and therefore with a high degree of continuity, group 6 (six cases) identifies areas of much smaller extension with a more peripheral location and a high degree of discontinuity.

Figure 7 and Table 5 present the main characteristics and location of the identified groups.

Table 5. Characteristics of the groups identified: average value of the group's indicators.

Variable		Group						
		1	**2**	**3**	**4**	**5**	**6**	**Total**
Nº Cases		4	27	39	52	3	6	131
Total Area (km^2)		54.22	93.16	74.33	68.43	4.56	5.62	300.33
Total Population		919.587	632.157	73.843	145,026	0	75	1,770,688
Nº Municipalities		12	81	67	76	6	8	250
Average Value	FACTOR 1	−2.46	−0.38	−0.54	0.87	−1.95	0.29	0
	FACTOR 2	2.36	0.92	−0.83	0.04	−0.63	−0.38	0
	FACTOR 3	−1.07	0.37	−0.35	−0.32	1.95	3.13	0
	Dens_1	29.19	32.84	8.45	13.83	38.15	33.27	18.06
	Dens_2	158.56	89.84	16.15	34.03	68.19	65.97	46.26
	Dens_3	495.50	187.18	62.10	109.05	0.00	0.18	115.49
	Comp_1	0.3460	0.3648	0.3655	0.3519	0.3907	0.4713	0.3648
	Cont_2	46.40	70.57	74.01	85.85	60.05	81.82	77.20
	Centr_1	3494.99	13,489.41	18,045.59	23,689.01	9147.91	18,449.23	18,717.10
	Centr_2	2716.61	2477.28	4443.52	3825.13	2462.38	3581.37	3655.21
	Mix_1	5.07	20.53	1.45	3.79	52.47	91.89	11.73
	Industrial and Commercial	4.01	20.03	0.76	3.57	52.47	91.76	11.30
	Tertiary	1.06	0.50	0.69	0.22	0.00	0.13	0.43
	No municipalities	3.00	3.00	1.72	1.46	2.00	1.33	1.91

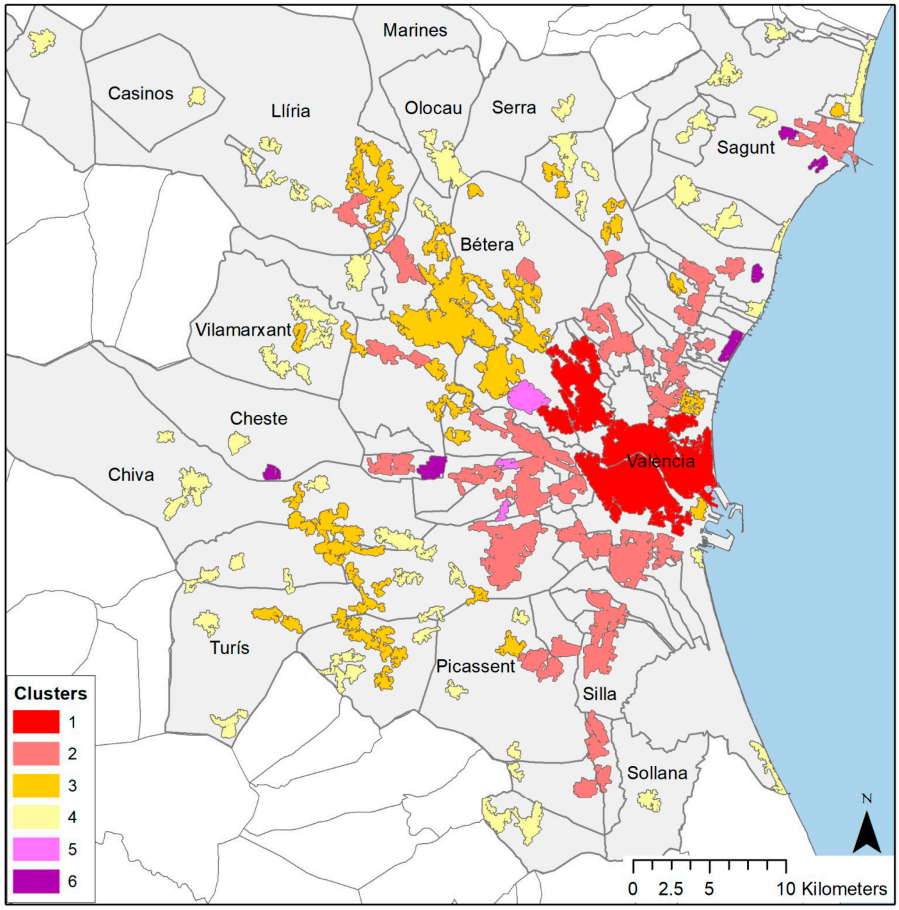


Figure 7. Typology of morphological units according to urban sprawl indicators.

6. Discussion

The technique of delimitating urbanized spaces based on fractal methodology allows the identification of morphological units that can be analyzed from the point of view of their urban sprawl characteristics. The results obtained are considered to be relevant, especially on three levels.

The first is related to the identification of intra-metropolitan morphological units. It should be noted that the area is characterized by a high degree of urban dispersion, with 131 discontinuous morphological units of more than 50 hectares having been identified on the basis of the existing breaks in the fractal pattern of the footprint of built space. Most of these correspond to mixed spaces with a predominance of residential uses, although there are also several areas, some of a certain extension, of an exclusively industrial, commercial, or tertiary nature.

The identification of these morphological units has allowed the focus of analysis to be lowered to the intra-metropolitan scale, also escaping the local administrative boundaries which, although relevant for planning purposes, prevents the joint analysis of spaces that go far beyond these limits. The number of municipalities over which the morphological areas extend are shown in Table 6. Thus, of the areas analyzed, 47% extend over more than one municipality, and 21% over three or more, which poses a major problem for the coordination of planning policies. Leaving aside the central metropolitan core, the cases included in group 2 are particularly striking, where we find discontinuous suburban areas that extend over up to 10 municipalities, which makes it necessary to abandon the municipal perspective in order to find joint planning solutions. To the multiple administrative dependence of these areas, in some cases the discontinuity and/or distance from the main population centers are added, which generates higher planning and infrastructure manage-

ment costs, as well as greater mobility in the event of excessive residential specialization resulting in a deficit of jobs and/or services and facilities.

Table 6. Number of municipalities over which the morphological areas extend.

Nº Municipalities	Group						
	1	**2**	**3**	**4**	**5**	**6**	**TOTAL**
1	2	6	22	34	1	4	69
2		9	10	13	1	2	35
3		3	5	4	1		13
4	1	5	1	1			8
5		2					2
6	1		1				2
8		1					1
10		1					1
Total	4	27	39	52	3	6	131

The existence of different territorial models and processes in metropolitan spaces is an aspect that has been pointed out by different authors and that is overlooked in studies that analyze metropolitan areas as a unit. On the other hand, municipal-based analyses such as those carried out by [12], although they provide, as a positive element, the possibility of relating the characteristics of the territorial model with municipal management, do not allow us to identify these supra-municipal agglomeration processes that require specific planning interventions based on the cooperation of local administrations. This supra-municipal intra-metropolitan perspective is not contemplated in most of the published works, so we consider that this work constitutes a contribution in this sense.

The application of the methodology developed by [50] makes it possible to identify these supra-municipal spaces from the discontinuities of the spatial pattern of urbanized space, using a digital cartographic base available in most countries, which can be completed in countries that do not have it from collaborative mapping such as Open Street Map, and with greater detail and simpler treatment than satellite images, an alternative source for the study of urban sprawl.

The second key issue is the indicators of urban sprawl. In our case, we have selected eight indicators, corresponding to the main components of this phenomenon identified in the literature: density, pattern, centrality, and mix of uses. In this respect, it is worth noting the low level of correlation between most of the indicators and the distance to the metropolitan center (Centr1), which points to the existence of a complex spatial pattern far removed from the center–periphery scheme.

Correlation analysis between the indicators has shown that the three density indicators are positively related to each other, while they are also related to compactness. On the other hand, the indicators of continuity and mix of uses are poorly correlated with the previous indicators and with each other, indicating, as mentioned above, the existence of different components of urban sprawl that are not associated with each other.

Principal component analysis has identified three distinct dimensions of urban sprawl, associated respectively with the dimensions of density, continuity, and mix of uses. These three dimensions show distinct spatial patterns resulting from complex metropolitan growth processes.

Although the number of indicators selected is significantly lower than those used in other estimates, these results coincide with those obtained by other authors. Thus, [72], using 14 indicators for U.S. MAs, obtained four components related to (1) intensity: the intensity of residential and nonresidential land use overall; (2) compactness: the degree to which development is concentrated and more intensively developed near the historical core compared to the periphery; (3) mixing: the degree to which residential and nonresidential uses are integrated at a fine scale; and (4) core-dominance: the degree to which jobs are distributed in a monocentric pattern. Leaving aside the latter, which makes sense only

at the scale of the metropolitan whole, the results are consistent with ours. Ref. [56], in their analysis of Israeli cities, also identified three dimensions of sprawl, which they call density, scatter (or fragmentation), and mix of land uses. Finally, analysis of American cities [65], although less comparable to the present analysis since it included dynamic variables, also identified the components of density (which the authors called urban) and pattern. Therefore, we can conclude that the selection of indicators has been appropriate, and that the use of a smaller number of indicators has not prevented us from finding the right dimensions for the dimensions of the urban density component.

The third issue to highlight is the typology of cases obtained, which has allowed us to characterize different intra-metropolitan urban sprawl processes, which result in different problems and therefore require specific policies.

The first case is the central metropolitan agglomeration, included in group 1, which is characterized by high building and population densities, high continuity, and a mix of uses.

On the other hand, axial growth processes generate suburban areas of relatively high density, with a low level of discontinuity and a mixture of residential, industrial, and tertiary uses (group 2). In these cases, the main planning problems lie in the absence of supra-municipal planning to organize the area as a whole, dealing with the scarcity of open spaces, the environmental impact, and the coordination of facilities and infrastructures. In this context, the low level of compactness of these areas is an added problem for the planning and management of infrastructures.

In addition, type 3 areas, which are the product of urban residential dispersion in the intermediate area, have as their main problem the remoteness from the central nuclei of the municipalities, aggravated by their low levels of population density. As noted above, low density puts pressure on the economic efficiency of technical infrastructures and increases the demand for transport, increases car dependency, and leads to less efficient public transport and higher infrastructure development costs, especially in cases where the distance to the municipal center is often significant.

These problems are aggravated in type 4 areas, very numerous in our case, which, in addition to low density, have a high level of discontinuity and little or no presence of uses other than residential. The fragmentation of the urban mosaic has as its main negative consequences the loss of efficiency of urban services, longer distances to travel, and the fragmentation of the landscape, with the consequent separation and isolation of habitat areas and natural or semi-natural ecosystems. In these cases, measures such as the promotion of elements of urban centrality through the implementation of basic facilities and public and private services, and the articulation of these spaces with the consolidated urban centers, are particularly recommendable.

Finally, discontinuous industrial zones (type 5 and 6) require specific management strategies related to sustainable mobility of workers, especially in the case of those located at a greater distance from residential areas and the metropolitan center. In these cases, the separation of different land uses increases commuting time and distance to work, leading to traffic congestion, increased journey length, and increased travel time.

Previous studies have detected a similar complex typology at the metropolitan scale. Thus, ref. [65] identified four groups of cities, differentiated not only by intensity, but also by urban sprawl typologies: (1) deconcentrated and dense areas developed intensively and continuously; (2) leapfrog areas, with low density and discontinuous development, in low-density pockets; (3) compact areas with developments close to the central core but moderate density and contiguity; and (4) dispersed areas, with developments far from the center without secondary concentrations. On the other hand, this typology of cases is common to other urban growth processes, such as those detected in the south of France by [73], who, typified new urban growth developments in the following categories: “clustered infill urban densification”, “scattered infill urban densification”, “low-density edge-expansion”, “compact edge-expansion”, “low-density scattered urban development”, and “leapfrog urban development”, thus showing that new residential buildings are not contributing to

urban sprawl and development in a similar fashion, which generates a complex landscape with different planning implications.

In all cases, the authors' conclusion is that the diversity of cases and the lack of homogeneous characteristics in relation to urban sprawl make it inappropriate to consider sprawl as a measurable phenomenon on a unidimensional scale. Metropolitan areas manifest spatial patterns resulting from a combination of four different combinations of urban sprawl, which leads to the need to develop specific policies according to the concrete characteristics of the urban sprawl process in each section of the metropolitan area.

To conclude, we point out some limitations of this study. In relation to data sources, it should be noted that in this study we did not have detailed information on the location of employment, so it was not possible to calculate employment density indicators or to draw conclusions on the dispersion processes of economic activities. Another limitation is related to methodology. We used a fractal approach exclusively for the delimitation of morphological units, but the indicators and the mathematical methods used, as principal component analysis and cluster analysis rely on the concept of characteristic scale [74,75]. In works such as [50,68,76], indicators based on fractal methodology, such as the fractional dimension, have been used in some cases together with other non-fractal indicators in the characterization of urban spaces. It is considered that fractal indicators can be relevant when comparing different urban areas between them, but they do not seem to provide special information in the context of the comparison of morphological units within an urban area. In addition, we have to keep in mind that the purpose of this analysis is for planning necessities and that, as [28] (p. 738) states, "*While developing new tools and metrics, one should remember that the end users of these metrics are the city administrators and planners who are not essentially a scientist. Therefore, the tools and metrics should be simple, less demanding (in terms of data and computation), reliable, and robust*". In this applied research, it was decided to use a methodology that could be understandable and replicable for urban planners.

7. Conclusions

The technique of delimitation of urbanized spaces based on fractal methodology makes it possible to identify morphological units of intra-metropolitan built spaces that can be analyzed from the point of view of their urban sprawl characteristics and, therefore, to identify their specific characteristics for the purpose of designing targeted policies that can be developed on a supra-municipal scale.

The necessary information base, i.e., vector mapping of built space at a detailed scale, is homogeneous at the national scale, and has become widespread in most countries, which facilitates comparative analysis. The availability of online collaborative cartography such as Open Street Map can compensate for the lack of this information in other geographical contexts.

The results obtained point to the fact that it is not necessary to develop a complex system of indicators for policy design, but that it is necessary to analyze the combinations of the dimensions of density, structure, and mix of uses that characterize the different types of urban sprawl and that require specific policies. The complex typology of urban sprawl spaces resulting from the combination of these dimensions points to the need for systematic analyses of the relationship of these dimensions with the intensity and types of territorial problems in order to adapt territorial policies. Beyond the existence of a metropolitan policy, the results underline the importance of inter-municipal cooperation.

Future lines of work include the incorporation of a dynamic perspective that will make it possible to follow the evolution of the processes, knowing the role of geographical and other factors in the intensification of sprawl. Another potential expansion is the extension of the case studies to other MAs in order to contrast the suitability of the instruments applied. To address one of the noted limitations, in further work it would be convenient to test indicators derived from fractal geometry in order to have a gallery of indicators that are not scale-dependent and that could identify the structural characteristics of the urban sprawl process in a comparable way. It would also be especially useful to examine the

deepening of the relationship between the dimensions and typologies of urban sprawl and the management problems they generate, as well as the most appropriate management instruments for each case.

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