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Size and spatial and functional structure of aggregate daily mobility networks in functional urban areas: Integrating adjacent spaces at several scales

Severino Escolano-Utrilla [a,*], Carlos López-Escolano [a,*], José Antonio Salvador-Oliván [b]

[a] Department of Geography and Territorial Planning, University of Zaragoza, Calle Pedro Cerbuna 12, 50009 Zaragoza, Spain
[b] Department of Documentation Science and History of Science, University of Zaragoza, Calle Pedro Cerbuna 12, 50009 Zaragoza, Spain

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ABSTRACT

People's daily movements, as aggregated in spatial units, shape mobility flows that can be modelled by geospatial networks. The structure of these networks both reflects and influences how cities are lived in, perceived and planned. In this study, location tracking data from mobile phones were used to investigate the functional and spatial structures of daily mobility networks and how these networks change as they grow in size. A case study was performed on 81 Spanish functional Urban Areas (FUAs). The results of this study show that the friction of the space and the average length of the aggregate daily mobility are constant and do not depend on the area and demographic size of the FUAs. The average length of the aggregate daily mobility is associated with the increase in complexity that occurs as mobility networks grow, which is reflected in an increase in the number of levels of interaction and the proportion of local flows that integrate adjacent spaces across different scales. The method used provides quantitative indicators that reveal the similarities and differences of daily mobility, as well as the interactions that occur in FUAs according to their size. This information is very useful in urban and mobility planning.

1. Introduction

Complexity and *mobility* are archetypal and interrelated properties of cities. Knowledge of these properties is essential to understand the evolution of and changes in urban spaces. Cities are characterized by multiple mobile entities, including objects, matter, energy, information, capital and living beings. The daily mobility of people is a high relevant social behaviour because it integrates the effects of various social practices –such as work, school, shopping, housing, leisure and other activities– with territorial factors and personal preferences (Jirón, 2009; Sheller & Urry, 2006; Urry, 2007). These factors together strongly shape the ways in which a city is perceived and lived in (Brickman, 2021; Fortunati & Taipale, 2017; Luille & di Virglio, 2021; Miralles-Guasch & Cebollada, 2009; Salazar, 2021).

The daily journeys of people, grouped into spatial units, form complex networks of geographical nature. The configuration of these networks is more influenced by the friction of space than the networks of other flows and is related to territorial accessibility and the decisions of individuals. For these reasons, urban daily mobility, especially spatial patterns, plays a fundamental role in the organization of contemporary urban life (Jirón & Imilán, 2018, p. 19) and is a key element in urban planning (Bertaud, 2004; Bertolini, 2012), especially regarding infrastructure, provision of services and the shaping of urban sustainability policies (Barbosa-Filho et al., 2017; Jacobs, 1961; Lyons, 2018; Vega-Pindado, 1970).

Research on daily mobility has revealed valuable insights into the topological, spatial, and functional characteristics of these networks of human interaction. In particular, this has highlighted the effects of distance (as expressed in terms of separation between locations, travel cost or the effort expended in travelling) and other factors on people's mobility. However, difficulties persist in the representation, analysis and conceptualization of urban mobility (Batty, 2018). There is no complete understanding of several issues, as the morphology and structure of aggregate urban mobility networks or of how networks connect places into larger territories at various scales. In metropolitan spaces it is needed a better and coordinated transport and land-use planning, which would lead to a reduction of travel and transport needs, enhancing connectivity between urban, peri-urban and rural

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* Corresponding authors.
E-mail addresses: severino@unizar.es (S. Escolano-Utrilla), cle@unizar.es (C. López-Escolano), jaso@unizar.es (J.A. Salvador-Oliván).

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areas, key issues to foster sustainable urban and mobility models in the context of the energy transition and climate adaption (United Nations, 2017). This challenge becomes especially important in the planning of European metropolitan spaces such as functional urban areas, going beyond the classic administrative borders (European Commission, 2019).

This paper investigates changes in the topological, spatial, and functional properties of everyday mobility networks and their size increases in functional urban areas with very diverse sociodemographic characteristics. The aim of this study is to address, from a geographical perspective, questions such as the following: What are the differences and similarities among daily mobility networks of cities of different sizes? How are different spaces in cities reflected in aggregate mobility networks? Are there universal models for the daily mobility networks of cities converge that do not depend on the functional structure and distribution of the city population? The study uses data from the aggregate daily mobility networks of 81 Functional Urban Areas (FUAs) in Spain that are analysed with concepts and methods situated at the intersection of spatial analysis and network analysis (Adams et al., 2012; Barthélemy, 2011, 2022). This study goes beyond the case studies where a single city or metropolitan area is analysed (Gadziński, 2018; Ming Yip et al., 2016), as well as other that include more cities but in a still limited number (Lee et al., 2018) or mobilities between cities tracked by mobile phone data (Marada et al., 2023) since it allows the identification and representation of the structure of mobility patterns in diverse functional urban areas. In this context, the urban spaces analysed respond to a wide diversity in their sociodemographic, geographical and functional characteristics, which allows providing an interesting study approach for the better understanding of daily mobility behaviours covering different urban contexts.

The approach of this work differs from previous ones on the subject in two aspects: i) the topological, weighted and spatial structure of the aggregate network of everyday mobility is analysed, ii) these structures are differentiated according to the size of the FUAs. The results can be used in other international contexts at in-country level and, additionally, to support cross-country benchmarking studies. For example, the method could be useful for the design of urban and metropolitan mobility policies in the energy transition and climate adaption, among other examples as the Urban Agenda for the European Union intends for functional urban areas (European Commission, 2019).

2. Literature review

Urban mobility has long been studied using both qualitative and quantitative methods (Barbosa-Filho et al., 2017). This field has been enriched by the use of new-fangled approaches and data, especially those generated by the application of novel information technologies to the observation and management of people's movements (Cao et al., 2021). Urban mobility is intrinsically dynamic, and its social and spatial patterns have been becoming increasingly complex, especially in large metropolitan areas (García-Palomares, 2008; Gutiérrez & García-Palomares, 2007).

Studies carried out on spatial networks of the aggregate daily mobility in cities have revealed empirical regularities and become the subjects of theoretical debate. Particular attention has been paid to how mobility flows depend on the distance of trips (corresponding to the duration or cost). A certain degree of convergence has been found in the shape of the distributions of these distances in space and in time, showing that effect of the distance on reducing mobility flows. This effect of spatial friction (distance-decay) on the mobility has mainly been estimated using exponential and potential models (Barbosa-Filho et al., 2017; Barthélemy, 2011). The volume of inputs and outputs of mobility flows of the spatial units used in these studies was calculated for individual locations by using the opportunities, distance (Euclidean or as measured by the transport network) to other locations and other complementary variables as modelled by gravity, intervening opportunities and radiation models (Barbosa-Filho et al., 2017). Other investigations have revealed the heterogeneity of mobility flows (both individual and aggregate) that are associated with socioeconomic variables and the urban structure (Yang et al., 2019), the income level (Carra et al., 2016) or the centrality of the origin (regardless of whether the origin is a *hotspot*) and destination nodes of flows (Louail et al., 2015).

Studies on transport and land use have shown that variations in the spatial patterns of daily mobility are related to properties of the urban structure and shape, such as land use patterns, the spatial distribution of the residential density, the location of employment centres and the size of cities (Bertaud, 2004; le Néchet, 2012; Rodrigue, 2020).

In general, the morphology of spatial networks of the aggregate daily mobility reflects the cost imposed by the geographic space on the formation of long-distance connections. However, the morphology and structure of mobility networks have not been investigated to the same extent as daily mobility networks and the changes in these networks with increasing size of cities, a crucial challenge in urban and mobility planning.

3. Modelling the daily urban mobility as a spatial network: context, theoretical framework and research questions

3.1. *The daily mobility in the context of cities*

Daily mobility patterns in cities evolve within the context of urban transformation. In general, there has been a notable increase in the physical and demographic dimensions of large cities and metropolitan areas since the end of the 20th century that has occurred in conjunction with transformations in the sociodemographic, spatial and functional structures of these cities, each with their own intensity and rhythm. Other components of the very widespread process of urban expansion with different degrees and forms of polycentrism include the gentrification of urban centres; the social, functional and morphological diversification of peripheral areas; the fragmentation of social and physical space; and the improvement in transportation networks. This trend has been verified for central and peripheral spaces (Angel et al., 2016; McMillen & Smith, 2003) and is strongly manifested in North America (Muller, 1986) but is somewhat more subdued in Europe and Latin American countries (Escolano-Utrilla et al., 2015; Romein et al., 2009).

Mobility is the product of multiple transformations and factors in the urban expansion process (García-Palomares, 2008). One of the most notable transformations in cities is the great expansion and dispersion of peripheral spaces, which has increased distances between places on the periphery of cities (Gutiérrez & García-Palomares, 2007) and between these places and city centres. The emergence of new centralities and employment opportunities in peripheral areas has reduced daily travel to urban centres but has driven an increase in travel from central to peripheral spaces. Additionally, the modes and means of daily mobility in cities have been diversified, and different factors affect people's decisions to move. Notable factors include the cost of travel (Giuliano & Small, 1993), housing, land use and sociodemographic trends and characteristics of the population (Antipova et al., 2011; Cervero, 1989). In summary, the spatial patterns of urban daily mobility have evolved towards more complex shapes and structures, in accordance with the underlying social processes and urban forms.

3.2. *Modelling the aggregate daily urban mobility as a sociospatial network*

The daily mobility of cities is constituted by trips people make from their homes to places of activity (work, study, leisure and appointments) and back. These trips can have one or more purposes, and one person's choice of places of residence or work influences other people's choices in a variety of ways. This interaction between agents and places is the basis for modelling daily mobility as a network of nodes and links. Individual displacements are aggregated into spatial units. The network nodes are designated as the centroids of these units, and the links (or edges) of the units represent the direction and volume of people flows between the nodes. Thus, the nodes, links and their attributes constitute the direct and weighted features of a daily mobility network.

The nodes and the edges of a spatial network are located in geographical space, such that the cost of forming connections among nodes (in terms of time, resources, psychological factors and effort) depends on the friction of space (Adams et al., 2012; Barbosa-Filho et al., 2017; Barthélemy, 2022). The constraints imposed by the geographical space in which spatial networks exist also affect the network topology, which is characterized by an excessive number of local connections relative to the number of long-distance connections. The principle of spatial autocorrelation of geographical phenomena, stated in the well-known "first law of geography" that "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970, p. 236), maintains that short-distance connections are more abundant than less frequent long-distance connections. Short-distance mobility between a residence and nearby (generally adjacent) locations is the most frequent type of mobility and is characterized by dense, continuous and fairly regular networks. At the other extreme, long-distance travel is less frequent and is characterized by looser and discontinuous networks. Short-distance mobility flows are stronger than long-distance mobility flows. Consequently, spatial networks are characterized by their topology and the geographic locations of the nodes and edges (and their attributes).

Granovetter's hypothesis of the *strength of weak ties* for social networks (Granovetter, 1973) is that networks with abundant strong edges have strong local cohesion but weak global cohesion and that, in contrast, networks with frequent weak connections (weak edges) have relatively strong global cohesion and weak local cohesion. The strength of an edge is represented by the volume of the origin-destination flow. The magnitude of the origin-destination flow volume is distributed approximately continuously between the lowest and highest value. The first law of geography can be combined with Granovetter's hypothesis to explain the distributions of distances and the spatial and functional organization of aggregate networks of the daily mobility: strong edges overlap and converge in strongly cohesive local spaces, whereas longer and weaker edges enable the creation of more expansive connections to remote spaces.

In the context of everyday mobility networks, it follows from both theories that as flows between two spatial areas increase, neighbouring areas are more likely to have mutual flows as well, resulting in local clusters. Conversely, flows between very distant areas tend to be less frequent and less voluminous (weak ties). However, these flows unite the urban space as a whole, especially the labour market, allowing the urban space to function as a unit,

3.3. Research questions

The objective of this study was to determine the functional and spatial organization of daily mobility networks and how the network structure changes with increasing size. The following questions needed to be answered to achieve this objective: a) does the spatial distribution, magnitude and direction of trip lengths vary with the network size?; b) what is the structure of the connectivity of networks of different sizes, that is, how do flows of different lengths and magnitudes combine at different places? and c) in mobility networks of different sizes, how do clusters (or communities) at different levels (local, intermediate and global) emerge from connections of different intensities between places?

These three questions are relevant in being related to significant properties of the organization and dynamics of daily mobility networks, as well as to the sustainability, efficiency and social aspects of cities. We used the daily mobility networks of 81 Spanish FUAs as a case study. The networks were classified by demographic size into three groups.

Within the aforementioned context and theory, and as some research has shown, the city size is a variable that influences daily mobility patterns (Bertaud, 2004; le Néchet, 2012; Rodrigue, 2020). An increase in the average distance travelled is not accompanied by a proportional increase in the time spent travelling, which indicates there may be a "fixed budget" (for energy, time, cost and effort) for investment in daily mobility (Levinson & Wu, 2005). Based on these facts, we hypothesized that daily mobility networks become increasingly complex with growth, that is, adjacent spaces assemble at functional and spatial levels with different degrees of local and global connectivity. This strategy makes it possible to maintain the connectivity of an entire urban space without a significant increase in the average length of the mobility flows. However, real networks, even those with similar sizes, exhibit varying degrees of complexity depending on various geographical (population, area, density, etc.) and socioeconomic factors (transport modes, income level, etc.).

Therefore, the per capita length of the daily mobility is expected to be similar for FUAs of different sizes, and the variation in the magnitude of this length from the average value should be highest for the smallest FUAs. The spatial distribution of the population, population density, surface area and other factors have a larger influence on FUAs with small populations than on those with large populations.

The two main contributions of this study to the field are empirical and methodological in nature. First, spatial analysis and geosocial network modelling were combined to characterize the structure of daily mobility networks at *meso* and macro scales for application to spatial attributes. In particular, data on the location, magnitude and direction of mobility flows were used. Second, the formation process of residential mobility networks and changes in the network structure with size were determined in this study and were not investigated in detail in previous studies.

4. Materials and methods

4.1. Data and spatial units

The basic mobility data used in this study express the number of people who travel daily from their homes to other places. These data are grouped into spatial units. Each unit is called an "INE mobility cell" and is the minimum spatial unit of information available for urban areas in Spain, that serves as a case study. Spanish cities have not been immune to the aforementioned changes. There is growing spatial dispersion of the urban fabric and population (Azcárate Luxána et al., 2010; de Miguel González, 2001) and a tendency towards fragmentation of locations and activities of the population (Gil-Alonso et al., 2020; Olazabal & Bellet, 2019). This dispersion and fragmentation are related to changes in spatial patterns of daily mobility (Gutiérrez & García-Palomares, 2007; Gutiérrez-Puebla & García-Palomares, 2005), among other factors.

The study period is one week of normal mobility (November 18 to 21, 2019). This information was prepared and published by the *Instituto Nacional de Estadística* (Spanish Statistical Office) (INE, n.d.). Information on mobility was derived from the registry of location changes of a sample representing 78.7 % of mobile phones in Spain.

Each mobility cell must contain >5000 registered inhabitants. A municipality that contains between 5000 and 50,000 inhabitants constitutes a mobility area. If a municipality has <5000 inhabitants, the inhabitants within that province are grouped into cells containing between 5000 and 50,000 inhabitants. Cities with >50,000 inhabitants are disaggregated into neighbourhoods or districts containing >5000 inhabitants. A total of 3214 mobility cells were delimited in 2019 (Instituto Nacional de Estadística, 2020). One mobile phone is assigned to the residence cell that was occupied for the longest time between 22:00 and 06:00 h over the four observation days. The obtained information is contrasted with 60-day historical data. The destination mobility area is where the terminal was located for at least 4 h from 10:00 to 18:00 h for two of the four observation days. Destination areas also include residences. The destination area cannot be identified for all cases using the aforementioned methods. The published flows are those of 25 people or more.

The proposed method and units retain the daily mobility at a relatively fine resolution (mainly for travel to work or study) but do not retain the long-distance mobility, intraurban flows or *micromobility*. We use mobile phone movements as a general proxy for daily mobility (Calabrese et al., 2013; González et al., 2008).

FUAs are urban entities within a city of generally >100,000 inhabitants and adjacent municipalities in which >15 % of the workforce travels to the main city (EUROSTAT, n.d.). This study was performed on 81 FUAs delimited by EUROSTAT for Spain and the corresponding centres (*core*) (EUROSTAT, n.d.). The *centre* and the *remainder of the territory* of an FUA (henceforth referred to as the periphery) constituted the spatial units used to determine the direction of mobility flows. A mobility cell was assigned to an FUA if the centroid of the cell was located within the FUA boundary. A mobility cell for which the centroid lay outside the boundary of an FUA but part of the cell surface area intersected with the FUA boundary was manually added to the FUA. This procedure was used to identify 1803 mobility cells in the territories of Spanish FUAs. As functional units, FUAs are suitable for the study of daily mobility. The 81 FUAs were grouped by demographic size into three categories: large FUAs (containing between 500,000 and 7 million inhabitants; 13 FUAs), medium-sized FUAs (containing between 100,000 and 500,000 inhabitants; 48 FUAs) and small FUAs (containing between 59,000 and 100,000 inhabitants; 20 FUAs).

In addition to the total population and mobility data, the following socioeconomic data were obtained: personal income; activity rate; median age of the population; proportion of travel by car, on foot and by public transport and the average duration of travel in the FUA. The aforementioned information was obtained for 2019, except for some movement variable values that were obtained for 2011 (INE). The average distance to the central business district (CBD) of the main city of each FUA was used as a measure of the spatial dispersion of the FUA population.

The daily mobility, as measured by the described method, is higher in the FUAs than in the rest of Spain, that is eight out of ten of the investigated trips originate from or terminate in an FUA. The proportion of the national total of trips associated with FUAs is higher than that associated with the population or the surface area and shows the remarkable complexity and density of interactions in urban spaces (Table 1; Fig. 1).

4.2. Analytical procedures

To achieve the study objectives, these data were processed in three phases: a) sociospatial mobility networks were constructed for each FUA, b) several spatial and topological properties of the connectivity of mobility networks were analysed, and c) a random forest regression analysis was performed to correlate the mean distance of the flows of each FUA with various geographic and socioeconomic factors.

Table 1

General magnitude of the daily mobility in functional urban areas, 2019.

General magnitude	Spain	FUA	FUA/Spain (%)
Total population (people) (000)	47,026	33,185	70.6
Surface area (km^2) (000)	505	130	25.8
INE mobility cells	3,214	1,803	56.1
Municipalities	8,198	3,027	36.9
Number of people staying in a residence cell (000)	19,297	12,105	62.7
Total daily mobility between INE cells (000)	13,747	10,967	79.8
Number of cells with a positive incoming–outgoing balance	1,133	693	61.2
Number of cells with a negative incoming–outgoing balance	2,083	1,110	53.3

Source: INE pilot study on mobility based on mobile phone positioning. Compiled by the authors.

First, the flow data were used to construct a matrix of the origin-destination flows among the 1803 mobility cells. The network nodes represented the mobility cells, and the location (the centroids of the sections) and edges of the cells represented the direction from the origin to the destination and the magnitude of the mobility between nodes. The obtained data were used to build 81 mobility networks (direct and weighted), that is, one network per FUA.

To address the first question, the magnitude, length, and direction of mobility flows have been analysed.

The trip length is a key variable for modelling human mobility and most frequently expressed as a Euclidean distance (Barbosa-Filho et al., 2017). In this study, the mobility flow length was estimated as the Euclidean distance between the centroids (nodes) of different mobility cells. A potential function was used to vary the distribution of the mobility flow with the distance. The volume and direction of the mobility flows between the centre and periphery of the city were determined. The relationship between the length and flux of the mobility fluxes was fitted by a power-law function, the scale-free characteristics of which facilitated comparison of interaction networks of different sizes:

$$\mathrm{P} = \mathrm{d}^{-\beta}$$

$$\mathrm{Ln}(\mathrm{P}) = -\beta \bullet ln(\mathrm{d})$$

where P is the cumulative distribution of mobility flows, and β is the coefficient of distance decay (indicating the influence of the distance on the volume of flows between places).

The range of displacement from a place at a given distance was described using the magnitude of the *radius of gyration of a place* (RGP, which is analogous to the radius of gyration of an individual), which was calculated as follows:

$$\mathrm{RGP}_{\mathrm{i}} = \sqrt{\Sigma d^2{}_{ij} {}^{*}\mathrm{f}_{ij} / \Sigma f_{ij}}$$

where RGP_i is the radius of gyration of a place I, d_{ij} the Euclidean distance between the places i and j, and f_{ij} is the flow between the places i and j.

To answer the second question, it is necessary to determine the mode of connection for each node with other nodes on local and global. The networks were analysed using a few topological global and local descriptors and the flow length. The density was used as the only global indicator to express the ratio of the number of network edges to the number of potential edges.

The *degree* value was used as the local descriptor of each node and represented the total number of incoming and outgoing connections for the node. The *weighted degree* was used as the measure of the volume of the flows for each connection. The degree-based node distribution was used as an indicator of the network structure.

We used the *average neighbourhood connectivity* of a node, which is defined as the average connectivity of all the nearest neighbours of a node n (Maslov & Sneppen, 2002) and calculated as follows:

$$C_N(k) = \Sigma_q qP(q/k)$$

where $P(q/k)$ is the conditional probability that a link belonging to a node with a connectivity k points to a node with a connectivity q. The distribution of $C_{(k)}$ over k is a measure of the *assortativity* when $C_{(k)}$ is an increasing (positive) function and of the *disassortativity* when $C_{(k)}$ is a decreasing (negative) function. The assortativity is the propensity of nodes of a certain degree to connect with nodes of a similar degree (*hubs* connect to *hubs*), and the disassortativity is the tendency of low-degree nodes to connect with high-degree nodes (Barrat et al., 2004).

To complete the third question has been used the *Infomap* node clustering algorithm to identify functional groups (clusters, modules or communities), thereby revealing the network structure considering the

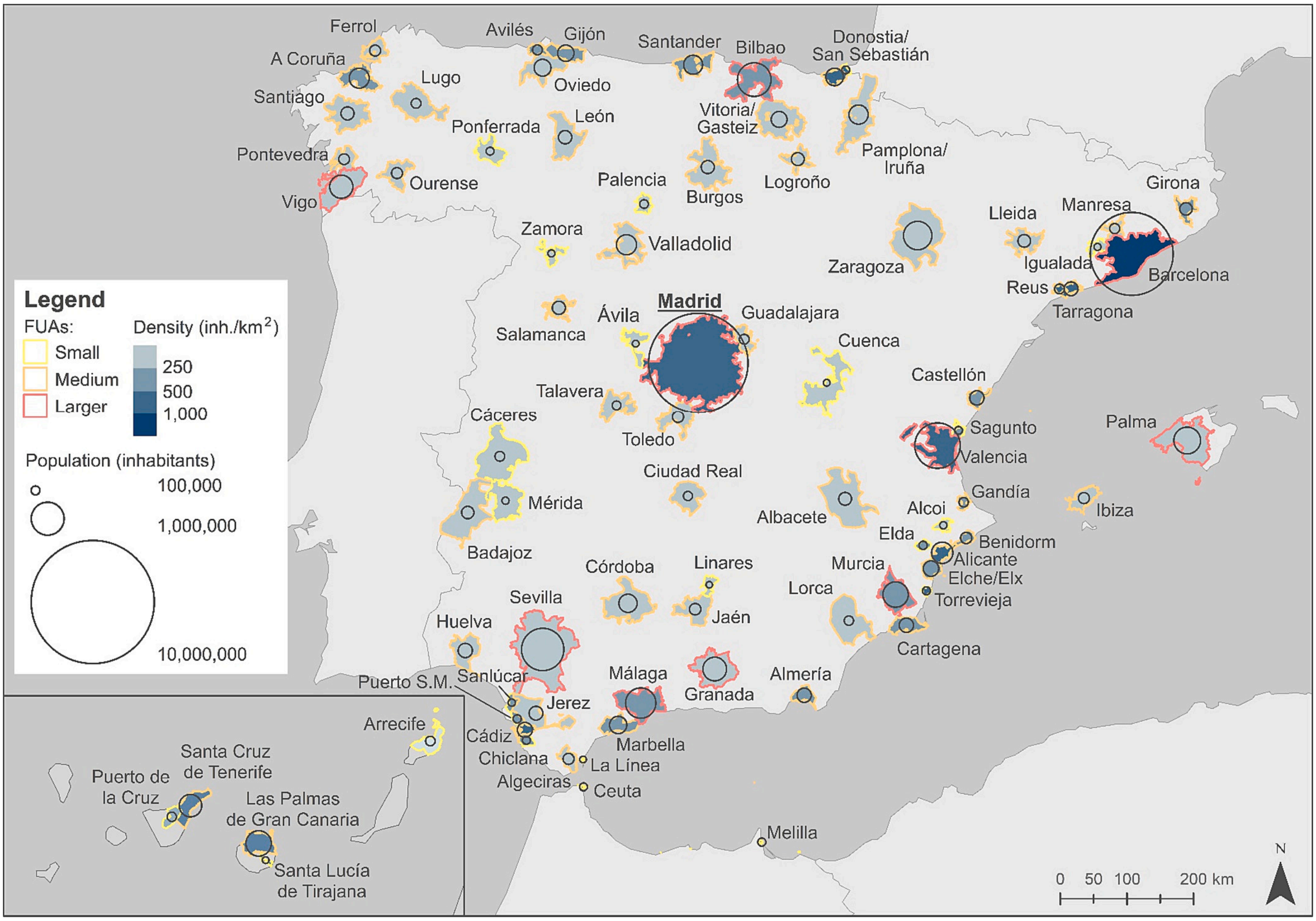


Fig. 1. Location, population density, population size and levels of FUAs.
Source: INE pilot study on mobility based on mobile phone positioning. Prepared by the authors.

hierarchical flows represented by connections (Rosvall et al., 2009). This method can be applied to *directed networks* and networks with weighted connections (mobility flows), can detect nested levels and the membership of nodes to various clusters and identify clusters of various configurations. Therefore, this method was highly suitable for application in this study considering the characteristics of the networks investigated. The algorithm version implemented in the *Community Detection* module (Singhal et al., 2020) of the software *Cytoscape 3.9* was used (Shannon et al., 2003). The parameter Markov time ($0 < \text{mt} < 1$) scales link flow to change the cost of moving between modules. A high value has been applied to this parameter (0.95) to hinder the formation of many small modules.

The external-internal index (EI_i) was used as a normalized indicator of the cohesion of a module. This index is the ratio of the mobility between the cells of the same cluster (internal connections: I) and the mobility between cells that are not part of the same module (external connections: E). The EI_i can be generalized to incorporate weights (mobility flows: *w*) of connections:

$$\text{EI}_\text{i} = (\text{E}_\text{w} - \text{I}_\text{w})/(\text{E}_\text{w} + \text{I}_\text{w})$$

The EI_i index varies between -1 and 1, where a value of -1 indicates that all connections are internal (is an isolated group), a value of 1 indicates that all the edges are external, and a value of 0 indicates an equal number of internal and external edges (or equal internal and external flows).

Finally, a random forest regression of several geographical factors of each FUA was applied against the average distance of the daily mobility, where this distance was considered a variable resulting from adjustment processes that was to minimize the cost, time or effort expended in making daily trips.

Note that the type of data used in this study underestimate the daily mobility. In addition to possible technical and sampling errors, the method used does not retain displacements by multiple cells, movements for which stays in cells other than the home are less than 4 h in length, flows involving fewer than 25 people and internal mobility within individual cells. Thus, a medium-resolution image of the daily mobility structure is produced that is very useful for investigating the territorial aspects and planning of the daily mobility.

ArcGIS Pro (ESRI) software was used to perform mapping of spatial data. A topological analysis of the networks was carried out using *Cytoscape* (Shannon et al., 2003), and the random regression forest analysis was carried out using *Orange* (Demsar et al., 2013).

5. Results

5.1. Properties of aggregate mobility flows: length, strength and direction

For the spatial units used in this study, the average length of travel is 9.5 km (8.2 km and 15.3 km for the centres and peripheries of the FUAs, respectively). However, travel varies considerably among FUAs (between 2.2 and 35.1 km), mainly due to the different transport modes used and differences in the surface areas of the FUAs (Table 2).

The behaviour of the daily mobility, as measured by the length of journeys, exhibits two structural characteristics in relation to the demographic size of the FUAs.

Table 2
Average length (km) of mobility flows for FUAs.

FUA size	Core	Periphery	Average	Minimum	Maximum
Large	7.4	15.5	10.2	6.8	13.4
Medium	8.8	15.9	11.6	6.4	29.5
Small (excluding	9.4	19.8	11.0	2.5	10.8
three outliers)	(7.5)	(12.7)	(8.1)	(23.7)	(44.1)
All FUAs	**8.2**	**15.3**	**10.71**		

Source: INE Pilot study on mobility based on mobile phone positioning. Compiled by the authors.

First, the average length of the displacements is approximately constant, regardless of the population volume of an FUA. The variability in the displacement length is most pronounced for the small FUAs and decreases and eventually stabilizes as the FUA population increases (Fig. 2).

Second, the most important characteristic of the flow distribution with the length is a long tail: 46 %, 38 % and 39 % of the large, medium and small FUAs have lengths below 5 km, respectively. By comparison, a larger proportion of flows have lengths below 10 km (70 %, 63 % and 75 % for large, medium and small FUAs, respectively), that is, only a small proportion of the flows have large lengths. The decay-distance parameter β is determined from a linear fit of the log-log distribution: $\beta = -1.914$, -1.965 and -1.843 (-2.065 without outliers) for large, medium and small FUAs, respectively (the corresponding R-square values are 0.88, 0.91 and 0.84; Fig. 3). These parameter values are similar to those obtained by Yang et al. (2019) for Shenzhen (China) based on individual trip data ($\beta = -1.853$), smaller than that ($\beta = -1.60$) obtained for other compact cities, such as Harbin (China) (Gao et al., 2013), and larger than those of other cities, such as Singapore ($\beta = -2.5$) (Kang et al., 2013). These differences in β depend on the resolution of the spatial units used and reflect the difference in characteristics of urban spaces and modes of mobility.

The balance and direction of the mobility were analysed considering two spatial units for the origin and destination of trips: the *centre* and the remainder of the FUA, i.e., the *periphery*. There were two notable and interrelated aspects of the global values of the balance and direction of mobility: the inhabitants of the centre had a higher mobility than those living at the periphery, especially for the large FUAs, indicating the importance of the centre as the main destination of flows (Table 3).

There are clear spatial patterns in the distributions of the absolute and relative intensities of the mobility for the large FUAs: centre-periphery patterns are generally observed but there are no continuous peaks in the central and peripheral areas. Thus, the ratio between the number of people arriving in and leaving each mobility area is higher in the centres than in the peripheral areas, except for certain areas with high concentrations of jobs (hubs; Fig. 4).

The composition of the flows based on their origin and destination in centres or peripheries is mainly related to the size, shape and location of the FUAs and can be categorized into three groups. The first group is formed by FUAs with centralized structures for which urban areas have pronounced functional monocentrism, such as Zaragoza, Malaga, Granada, Vitoria-Gasteiz and other cities in the peninsular centre and coastal areas. The second group is composed of large FUAs (such as Madrid, Barcelona, Valencia, Seville and Bilbao) and other smaller FUAs, for which the most highly weighted mobilities originate and end in FUA centres and the second most highly weighted mobilities originate and end in peripheral areas. This group reflects the considerable expansion of suburban spaces and the decentralization of activities. Finally, the third group exhibits a balanced mobility profile that is typical of a relatively small FUA located mainly in the peninsular centre (Fig. 4).

The daily mobility flows between the FUAs and neighbouring territories are also important. Approximately 315,000 people are directed from FUAs to other (generally adjacent) mobility areas (corresponding to 3.5 % of the total FUA mobility), and 395,000 people arrive from other areas to FUAs. These exchanges are especially intense (between 10,000 and 20,000 people) for the FUAs of Barcelona, Valencia and Murcia.

5.2. *Topological and spatial properties of daily mobility networks*

Mobility networks are constituted by daily movements between places of origin and a destination. The morphology, functional and spatial organization of these networks express the levels and modes of territorial deployment of the daily mobility. The values of the global descriptors of the mobility networks (the number of nodes and edges and the proportion of connections) reflect differences between groups of FUAs that are related to the FUA demographic size and other factors (Table 4). The connectivity values of the mobility networks of the FUAs were used to characterize the topological and spatial organization of the connectivity, as detailed below.

First, the mobility networks of the largest FUAs are larger than those of the medium and small FUAs, as expected. However, compared to the

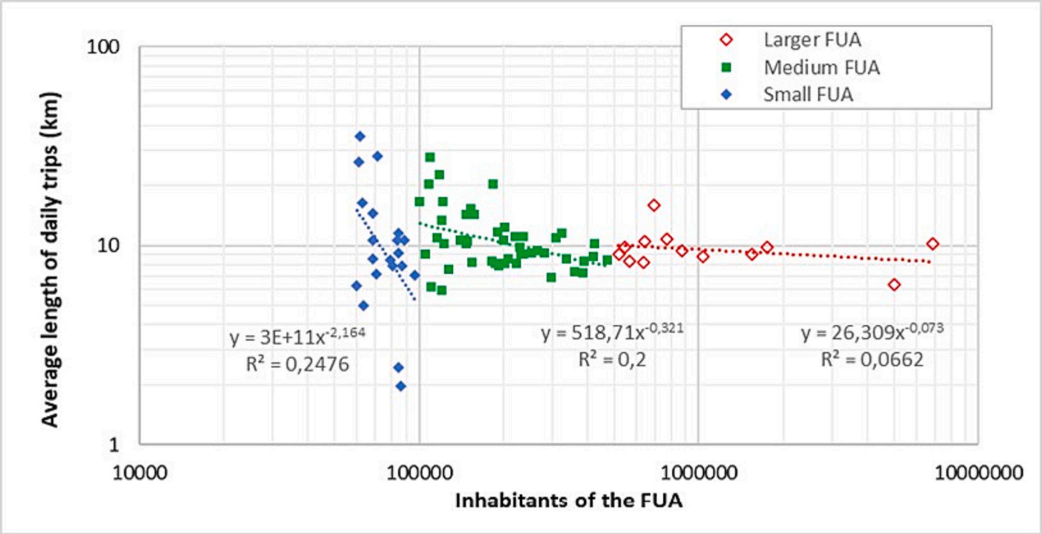


Fig. 2. Relationship between the average length of the daily mobility and the FUA demographic size.
Source: Prepared by the authors.

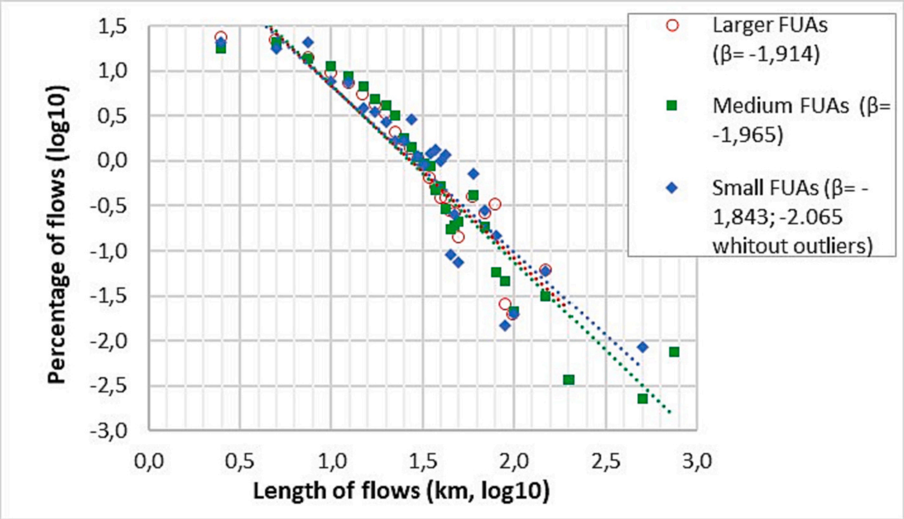


Fig. 3. Flow distribution with the length for FUAs, 2019.
Source: Prepared by the authors.

Table 3
Direction of the daily mobility between the centre and periphery of the FUAs.

FUA size	Number of inhabitants (000)			Direction of flows (%) (C: centre, P: periphery)			
	Total	Centre	Periphery	C to C	C to P	P to C	P to P
Large	21,464	16,591	4,873	78.4	5.6	8.1	8.0
Medium	10,209	7,402	2,807	67.2	11.3	14.3	7.2
Small	1,512	1,350	1,62	81.7	9.7	6.6	1.9
All FUAs	**33,185**	**25,343**	**7,842**	**75.2**	**7.4**	**9.9**	**7.5**

Source: INE Pilot study on mobility based on mobile phone positioning. Compiled by the authors.

medium and small FUAs, the largest FUAs are denser and have a proportionally larger number of connections (Table 4).

Second, the proportion of nodes with many connections is very low. The degree distribution decreases rapidly from 30 to 40 connections (Fig. 5a) as the number of incoming edges decreases. The outgoing links have a different distribution, which remains almost flat as the number of incoming edges increases up to 30–40 edges and then decreases slowly. The nodes with the most connections are found in the centres and urban peripheries.

Third, as the number of incoming edges (in-degree) to a place (node) increase, there is an exponential decrease in the average mobility flow. The distributions of all the FUAs groups are similar: the highest flows have very similar average values up to an in-degree threshold of the nodes and then decrease quickly (Fig. 5b).

Fourth, places have predominantly short RGPs. All groups of FUAs have similar RGP distributions: the most frequent RGP is the 5–10 km interval, corresponding to >35 % of all the RGPs, and the cumulative frequency of up to 10 km exceeds 80 % of all the RGPs. In addition, the average RGP for the large and medium FUAs decreases as new edges are added to a node up to a threshold, that is, nodes with many edges connect with other more distant nodes (Fig. 5c).

Finally, the mobility networks of each group of FUAs exhibit a slight tendency overall towards assortativity, that is, nodes with many connections connect with other nodes with many connections (corresponding to *hub-to-hub* connections). However, the connectivity of the networks of the largest FUAs can be fitted by a positive composite function up to a value k (number of neighbours) and then decreases (Fig. 5d).

Taken together, the properties mentioned above describe a continuous mobility network that is neither random nor hierarchical and has a fairly uniform density. Reciprocal connections in the network form preferentially among adjacent or nearby areas, where the highest flows often occur between neighbouring areas and fewer and weaker connections occur between places that are far from each other.

5.3. Functional modules of networks: assembling adjacent territories across scales

The composition of networks for modules or functional communities is one of the most outstanding aspects of how such complex networks function. Clusters of mobility areas emerge over an entire network that have mutual flows with considerably higher mutual intensities than those in other mobility areas. These clusters reflect how mobility networks delineate the spaces of FUAs at nested levels of different scales (Table 5; Fig. 6).

Global structures (Level 0) generally correspond to isolated FUAs that form a single area in which strong cohesion makes it impossible to identify clusters or modules. This phenomenon is observed for 15 small FUAs and one large FUA (Granada).

Clusters can be differentiated in large FUAs or territories formed by several adjacent or very close FUAs: in FUAs with *transition global-local* structures, only one level of clusters can be distinguished, whereas in FUAs with *complex global-local* structures, clusters collapse at Levels 2 and 3. These *transition global-local* structures are made up of small or medium-sized FUAs that are adjacent to or very close to each other, such as the coastal FUAs of Galicia, Asturias, the Canary Islands and in the inner Spanish mainland. Valencia is the only large FUA that forms this type of structure with nearby smaller FUAs. *Complex global-local* structures emerge for large FUAs (such as Zaragoza) or in macro-areas formed by the agglomeration of FUAs of different sizes, that is, several FUAs around Madrid, Barcelona, Seville, cities in the Basque Country, Palma de Mallorca and the FUAs around Alicante and Murcia (Fig. 6).

The identified clusters are characterized in terms of the mobility between modules and shape. The EI index indicates that practically half of the mobility flows of the Level 1 and 3 clusters occur within the spaces of the FUAs. By comparison, the intercluster mobility is more relevant for Level 2 *complex global-local structures*. Movements between clusters belonging to different FUAs are observed at all levels, because these FUAs are adjacent, very close or well-connected by high-speed rail networks or plane routes (Madrid and Seville; Madrid and Ciudad Real; Barcelona and Palma de Mallorca; Zaragoza and Tarragona; Arrecife and Santa Cruz de Tenerife, etc.). All the territories of the mobility clusters are made up of continuous and nonfragmented spaces, with irregular

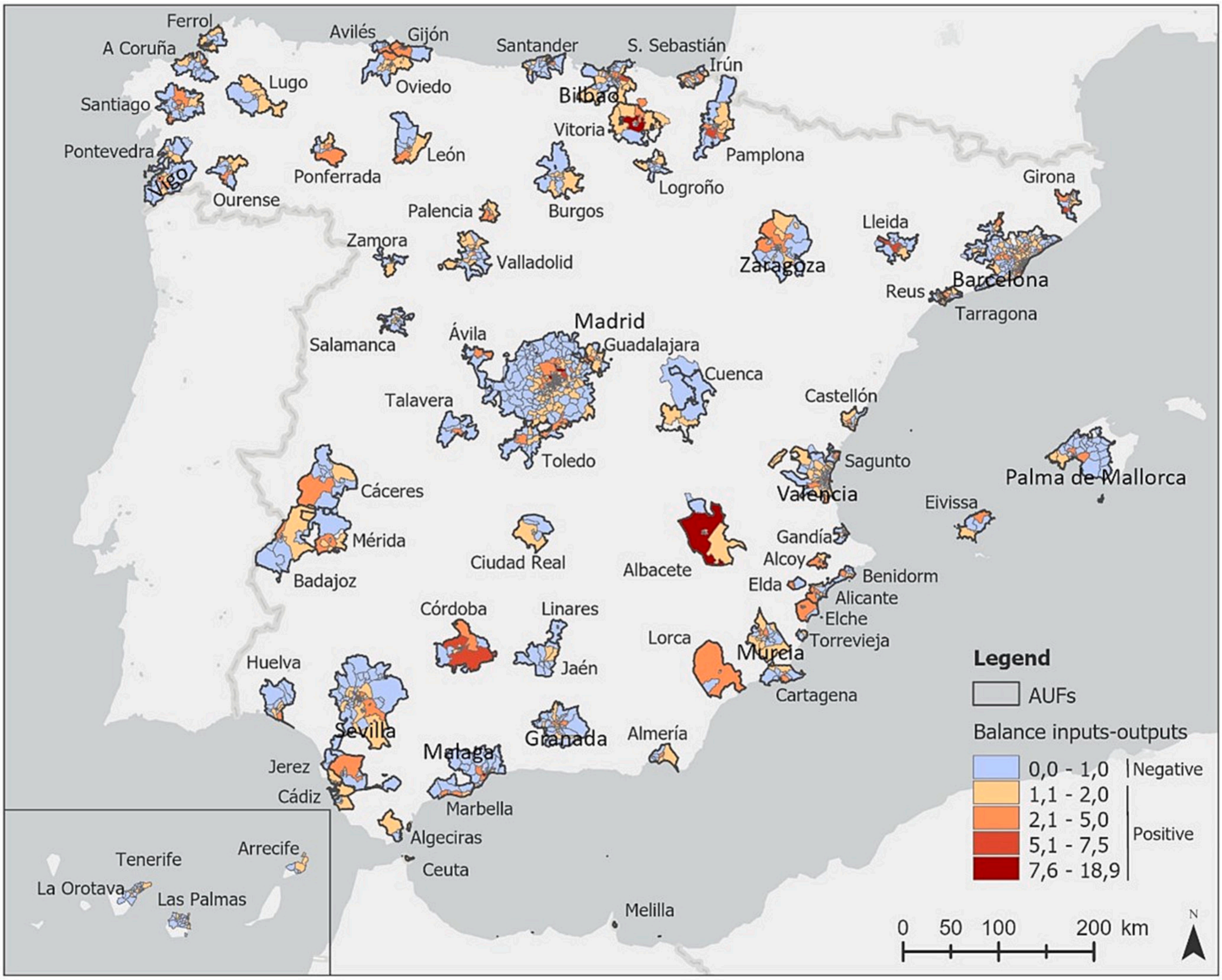


Fig. 4. Relationship between the number of people arriving in and leaving mobility areas.
Source: INE Pilot study on mobility based on mobile phone positioning. Prepared by the authors.

Table 4
General absolute size of daily mobility networks of FUAs.

Descriptor	All FUAs	Large FUAs	Medium FUAs	Small FUAs
Number of nodes	1,803	900	533	370
Number of edges	47,915	37,216	9,521	1,178
Density* (%)	1.5	4.6	3.3	0.9
Number of people/edges	693	577	1,072	1,283
Number of inhabitants (000)	33,184	21,464	10,209	1,511
Surface area (km^2): total	76,681	30,385	39,752	6,544
Minimum	20.9	847.9	203.7	20.9
Maximum	13,589.3	13,589.3	790.9	931.1

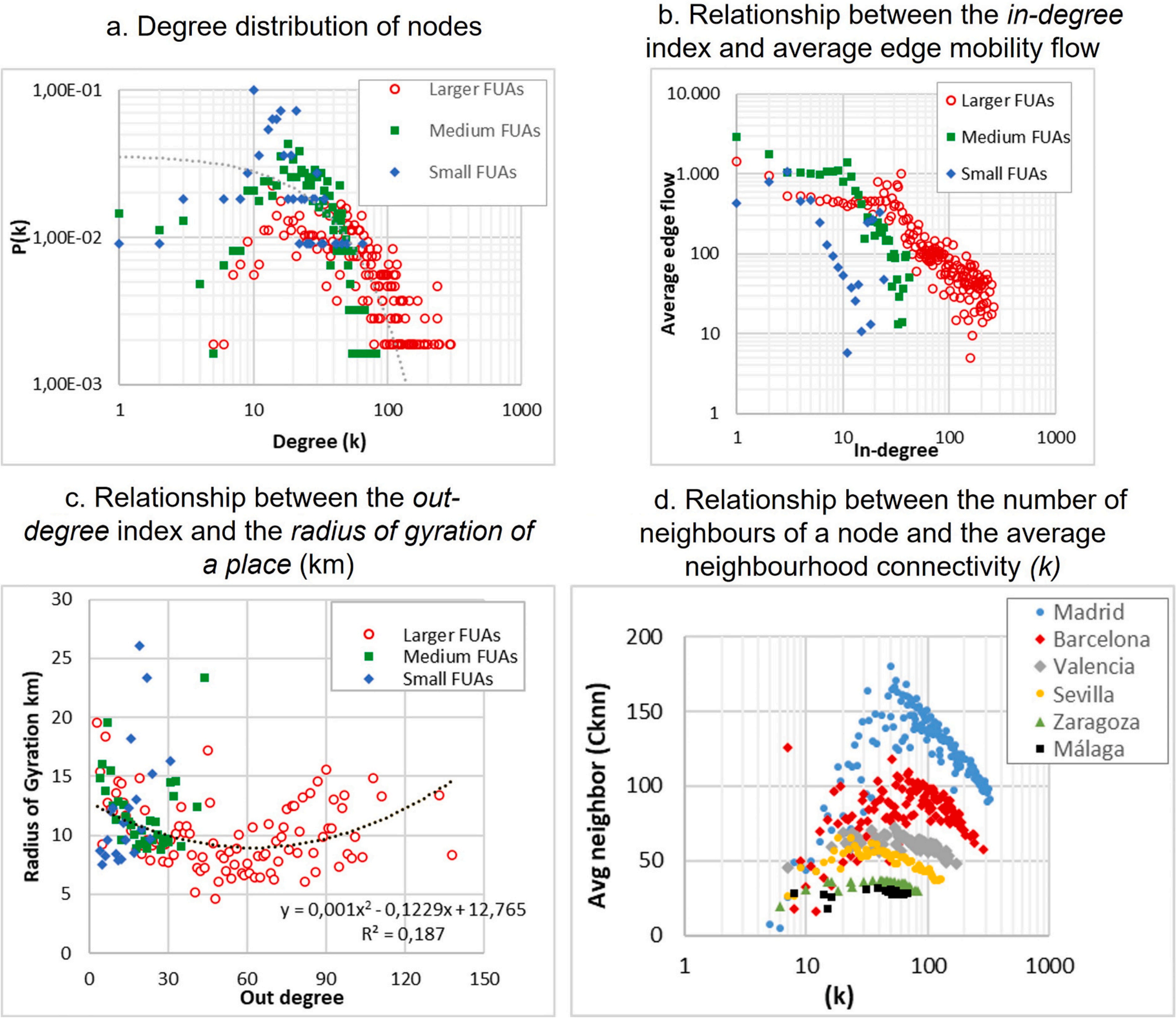
Density: Number of edges/number of edges required to connect a node with all other nodes (nodes*nodes-1).
Source: INE Pilot study on mobility based on mobile phone positioning. Compiled by the authors.

shapes that sometimes lengthen following the configuration of the main infrastructure and transport services (for example, Paseo de la Castellana in Madrid and other peripheral routes in the macroareas of Madrid, Barcelona and Valencia). The spatial continuity of these clusters reflects the weight of geographical factors, such as the distance and travel time (Fig. 7).

5.4. *The importance of sociogeographical factors in the configuration of daily mobility networks*

The absolute size of daily mobility networks and the connectivity patterns of the network nodes are influenced by the geographical and socioeconomic characteristics of the FUA space. To explore some of these relationships, a random forest regression analysis was performed using various parameters of the mobility networks as dependent variables and social and geographic factors as independent variables. The results are summarized below (Table 6).

- Multiple geographic and socioeconomic variables influence the absolute and relative sizes of daily mobility networks and the network connectivity, where the corresponding influence trends vary across FUAs.
- The absolute size of a network, as measured by the number of edges or connections, depends primarily on the total population of an FUA, especially for small FUAs. As the FUA population increases, new nodes are added proportionally, whereas the number of absolute connections grows almost exponentially because each new node allows for more connections. The absolute size of a network is also related to the proportion of trips made on public transport and the average duration of travel to work mainly for the largest FUAs, such as Barcelona, Valencia, Seville and Zaragoza.



a. Degree distribution of nodes

b. Relationship between the *in-degree* index and average edge mobility flow

c. Relationship between the *out-degree* index and the *radius of gyration of a place* (km)

d. Relationship between the number of neighbours of a node and the average neighbourhood connectivity *(k)*

Fig. 5. From left to right and from upper to lower. A) Degree distribution of nodes. B) Relationship between the *in-degree* index and average edge mobility flow. C) Relationship between the *out-degree* index and the *radius of gyration of a place* (km). D) Relationship between the number of neighbours of a node and the average neighbourhood connectivity (*k*).
Source: Prepared by the authors.

Table 5
Clusters and structure of daily mobility networks of Spanish FUAs.

Type of structure of mobility network cluster level	Number of clusters	Number of FUAs	Number of inhabitants (000)	EI index (%) < −0.7	EI index (%) > 0.2
Global					
0	32	16	2,799	100.0	
Transition global-local					
1	71	30	8,875	49.3	2.8
Complex global-local					
2	76	14	8,173	30.3	7.6
3	10	21	13,338	50.0	10.0
All FUAs	**189**	**81**	**33,185**		

Source: INE Pilot study on mobility based on mobile phone positioning. Compiled by the authors.

- In general, the FUA demographic size influences the values of all the indexes, positively for the node connectivity and negatively for the network density. The FUA demographic size has a moderate impact (which can be positive or negative) on the average length of the mobility flows. The population density is the variable with the greatest influence on the average length of mobility flows: this influence is positive for FUAs with low densities and irregular shapes (Cáceres, Mérida, Lorca and Cuenca) and negative for large FUAs (Barcelona) or very small FUAs (Ceuta, Melilla and La Línea). Modes of travel are also significantly associated with the network morphology: the higher the proportion of travel via public transportation is, the greater the number of edges, average edge flow size and number of edges per node (connectivity). A similar relationship is observed between the connectivity and time spent at the workplace. The effect of the central flow ratio on the average flow per edge is generally moderate but highly positive for small FUAs in which central movements predominate. Finally, the income level has a moderate effect on the mobility length: the higher the income level is, the lower the mobility length is.

Other sociodemographic variables, such as the activity rate, median age of the population and proportion of travel by car, are not significantly correlated with any size or shape variable and the general characteristics of the mobility networks at the scales of both the FUA and mobility area.

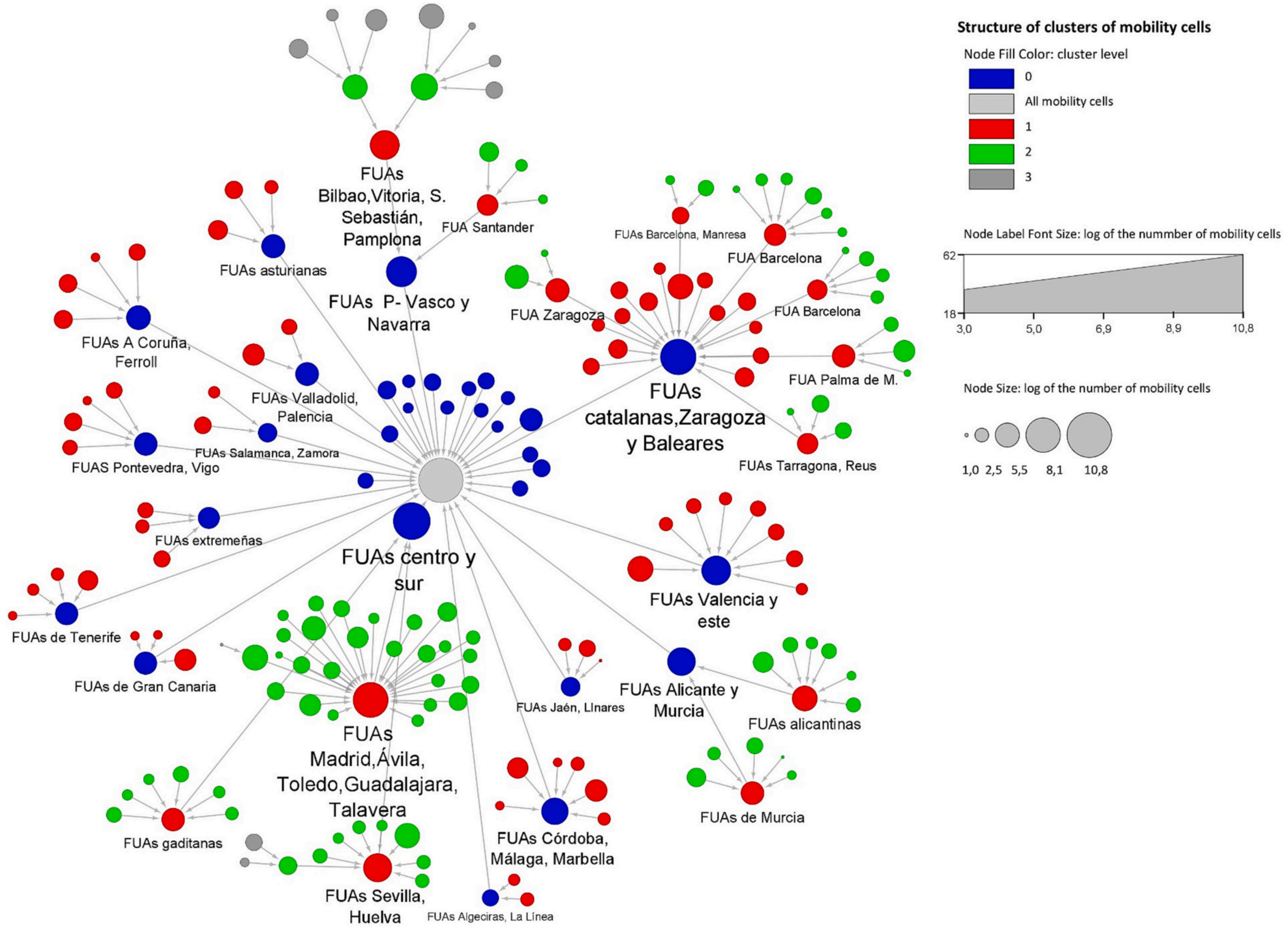


Fig. 6. Structure of clusters of mobility cells.
Source: Prepared by the authors.

6. Discussion

The results show that mobility networks can be used to model the spatial and functional characteristics of the daily mobility in Spanish FUAs, as a sociospatial practice. From a functional and spatial perspective, the topological and spatial configuration of these networks is related to the sociogeographical characteristics of the FUAs (the population, population density, modes of travel, income level, etc.) in a nonstationary but heterogeneous manner. This work provides a novelty regarding the method in its purpose since we use it to compare structures according to FUA sizes. The main processes and patterns that characterize the structure and growth of these networks are highlighted below.

6.1. The emergence and growth of daily mobility networks

The parameters that describe the structure of mobility networks indicate that the behaviour of mobility agents is the main process that determines the network configuration. The behaviour of mobility agents is represented by the total population, which tends to minimize the friction of the FUA space (in terms of the distance, cost or effort). This process is common to all FUAs and generates a mobility pattern formed by highly intense reciprocal movements between adjacent and nearby places, as well as other looser and weaker links with more distant places that are located mainly in the FUA centres and certain peripheral areas. Mobility networks grow by replication of this pattern with some adaptations in new peripheral suburban development. This general process develops against a changing matrix of geographical, socioeconomic, cultural and urban factors, infrastructures and services that condition the patterns of daily mobility networks.

The differences in the average length of mobility between urban centres and peripheries grow with the FUA demographic size. Commuters residing in the centres travel approximately half the distance as those residing in the peripheries, especially for large FUAs. However, residents in the peripheries make similar journeys, regardless of the FUA size. In the FUA centres, the compactness of the urban fabric and existence of multiple employment opportunities result in the generation of dense networks composed of short- and medium-length connections (the mobility cell with the largest number of connections corresponds to the Complutense University of Madrid in the centre of the city). We speculate that frequent travel on foot and by public transport generates local spaces with strongly cohesive mobilities and forms conditioned by collective transport services. Additionally, distance has a preferential valuation over opportunities: the results show that the model of closest opportunities is followed (Carra et al., 2016).

Compared to the FUA centres, in the FUA peripheral areas, the connections are usually longer, and the networks are less dense, although some flows are considerable. Notably, strong *attractors* that act as hubs, such as industrial parks, large facilities and commercial and services centres, are located at the peripheries of cities. Based on the spatial units used in this study, the following areas are identified as mobility destination centres: industrial parks in the peripheral areas of all FUAs; facilities such as universities, especially on campuses in

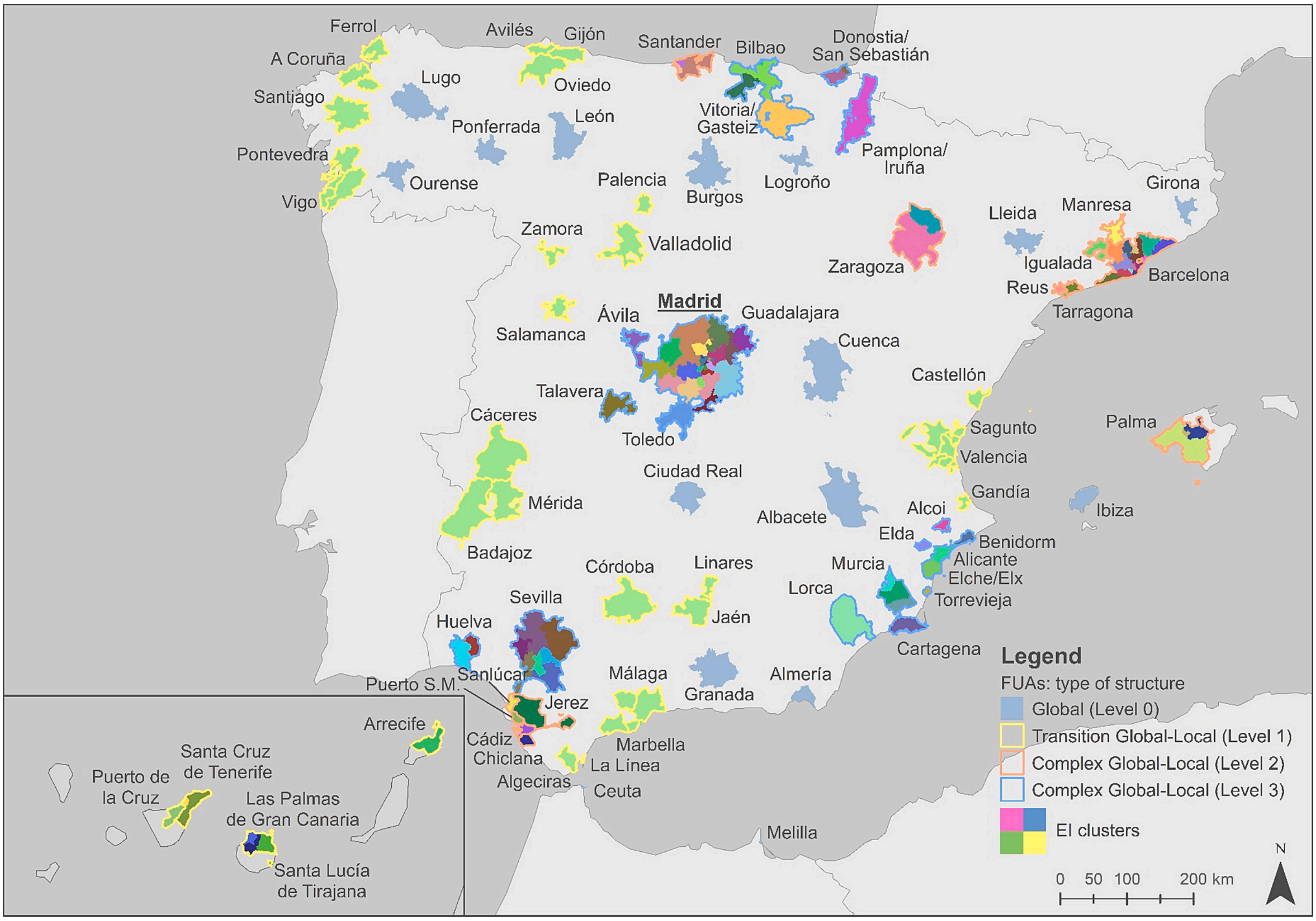


Fig. 7. Clusters of daily mobility in Spanish FUAs.
Source: INE Pilot study on mobility based on mobile phone positioning Prepared by the authors.

peripheral areas (those in Madrid, Palma, Alicante, Huelva, Cáceres and Pamplona-Iruña) and large centres of commerce, recreation and services. The dispersion of facilities and services in urban peripheries is a shared feature in contemporary urban spaces on a global scale. The creation of new attractions in peripheral areas has increased flows between these areas and decreased the distance travelled by the inhabitants of these areas. However, these advantages are eliminated to some extent by new movements from other urban spaces, as in the case of Zaragoza. Undoubtedly, these attractor centres provide services closer to those living in peripheral areas than the centres, but the strong cohesion between these attractors and the rest of the urban space makes it impossible to identify clusters of mobility areas in medium and small FUAs (Fig. 7).

6.2. Functional modules integrated by adjacent spaces

As the size of FUAs grows, the FUA structure increases in complexity, whereby the average lengths of mobility flows become similar and independent of the FUA size. The main mechanism that enables networks in the FUA peripheries to grow without increasing the average length of the mobility flows consists of the creation of multiple nested functional levels of mobility that are composed of continuous and strongly cohesive mobility spaces (clusters or modules). Several mobility cells are assigned to two or more adjacent modules, in both the centres and peripheries of FUAs that are very close to each other, for example, Bilbao and Santander, as well as Galician FUAs and other FUAs on the Mediterranean coast.

In the smallest FUAs (especially those with a large population dispersion, such as Cuenca and Santa Lucía de Tirajana), functional modules are not differentiated and the flows have a strong random component (Fig. 7), which increases the average mobility length. In large FUAs or adjacent FUAs that function as a unit, the flows are organized according to a monopolycentric model and the movements are simultaneous, radial, lateral in the peripheries and random (Bertaud, 2004). These models suggest that people adopt strategies to reduce their travel distance to places of work, study, leisure and other activities. For example, people may change residences (individuals with higher average incomes reside closer to their destinations than those with lower average incomes) or public transportation routes and may change their employment and study locations to be closer to their residences. The internal flows of individual modules have larger volumes in *global-local transition* structures than in *complex global-local* structures (Table 5). These findings for Spanish cities are consistent with those found for other geographical contexts based on mobile phone data. People with low incomes travel larger distances on average than those with high incomes, as has been found for Latin American cities (Moya-Gómez et al., 2021) and Singapore (Xu et al., 2018). In this sense, the evidence found in the analysed context also coincides with others such as Hong Kong, where people from poor neighbourhoods tend to move to poor districts while richer people move to richer ones, therefore the pole may be mobile but interaction with other income groups may be limited (Ming Yip et al., 2016). However, there are some exceptions to this trend, such as in North American cities where spatial segregation of economic activities and residential areas results in long travel distances (Xu et al., 2018). These findings help in the planning of cohesive urban spaces that avoid segregation (United Nations, 2017).

Table 6
Relationship between the properties of FUAs mobility networks and geographic and socioeconomic factors.

Network property (Y)	R^2 for large FUAs Three most important variables	R^2 for medium FUAs Three most important variables	R^2 for small FUAs Three most important variables
Number of edges (absolute network size)	0.57 POB, DCBD and TF	0.32 POP, PD and RCF	−0.17 POP, PI and PD
Density (relative size)	0.45 TPT, TTW and PI	0,37 RCF, DCBD and POP	−0.22 POP, PD and PI
Connectivity (average number of edges per node)	0.28 PD, POP and TTW	0.46 POP, TTW and PD	−0.13 POP, DCBD and PD
Average size of edge flow	0.19 POP, TC and TTW	−0.32 RCF, PI and TPT	0.11 RCF, POP and PD
Average length of mobility flows	−0.53 TF, TC and TTW	0.11 PD, POP and RCF	0.54 PD, DCBD and POP
Independent variables (X)	Total population of the FUAs (POP); population density of the FUAs (PD); average distance of the population to the central business district (km) (DCBD); ratio of central flows (centre-to-centre, centre-to-periphery and periphery-to-centre) to the total number of trips (RCF); average personal income per year (€) (PI): proportion of travel on foot (TF), by public transport (TPT) and by car (TC) and average duration of travel to work (minutes; TTW)		

Density: Number of edges/number of edges required to connect a node with all other nodes (nodes*nodes-1).
Source: INE Pilot study on mobility based on mobile phone positioning. Compiled by the authors.

The procedure applied in this study enabled the identification of modules of different FUAs (that were sometimes far from each other) connected by significant mobility flows. A preliminary analysis enabled the assessment of the role of large-volume transport infrastructure, in particular, high-speed rail, which is reshaping some Spanish metropolitan spaces (Garmendia Antín et al., 2011; Ureña, 2005).

Finally, the results for the distance and direction of mobility obtained in this study are not directly comparable to the results of other studies based on different spatial units but are consistent with those obtained by Gutiérrez and García-Palomares (2007): that is, centres remain important as origins and destinations, but as peripheral areas develop, mobility between peripheral sectors has been increasing, whereas the average flow length has not increased significantly. The relationships between the flow length and the origin and destination of flows in urban centres or peripheries and the demographic size determined in this study also agree with those obtained by Louail et al. (2015).

7. Conclusions

In this study, we analysed networks of daily mobility flows for Spanish FUAs. These networks were constructed by aggregating movements estimated from changes in mobile phone locations into medium-resolution spatial units. The findings of this study confirm already known general aspects of human mobility, such as the distance-decay property, and reveal new aspects of the functional and spatial configuration of mobility networks. The specific contributions of the research to the topic studied are the following:

1. Weighted and spatial topological connectivity are related.
2. The weights and distance of the flows show a long-tailed distribution: there is a large heterogeneity, more pronounced in the larger FUAs. The probability distribution of the flows fits a power-law distribution, which means that the everyday mobility network follows a scale-free behaviour.
3. Larger FUAs have more complex networks, with functional modules in all cases spatially continuous. In this sense, a counterintuitive fact has been verified: the average length of the aggregate daily mobility is constant, regardless of the FUA size. All the identified functional modules are spatially continuous, which demonstrates the strength of the spatial autocorrelation of the daily mobility. Likewise, all the mobilities are not completely contained in any of the identified modules. These result imply that a) no FUA is made up of functional units that are self-sufficient in terms of the mobility, that is, in all cases, the entire urban space consists of a unit of residence, activity locations and the mobility; b) optimization of the mobility, which is understood as a reduction in the aggregate length of mobility flows, is only possible by increasing the internal flow of each module, through decreasing the distances among the locations of residences, jobs and other activities.
4. Variations in size and structure, as well as other characteristics of daily mobility, are related to demographic, socioeconomic and spatial factors. The configuration, shape and development of mobility networks, emerges from the aggregate and autonomous decisions of people to optimize the friction of the FUA space (in terms of the distance, time and cost of travel). Therefore, the total population, spatial distribution of residences and locations of places of activity govern the size and structure of mobility networks. In addition to this basic principle of social practice, the configuration of mobility networks is affected by other socioeconomic dimensions, such as transport modes, transit services, income levels and individual perceptions and preferences. In this sense, other international research has shown similar results, although this work has included a significantly greater number of urban areas with different characteristics.

The aforementioned process generates mobility networks characterized by good local connections, in accordance with the *first law of geography*, and weaker global connections established through the longest flows, as maintained by the *strength-of-weak-ties hypothesis* and the *first law of geography*. Mobility networks grow via replication of this pattern, which also implies an increase in the network complexity. As networks grow, new functional modules are formed that operate at different scales and levels.

5. The obtained results verify that, within the limitations of this study, the data used and analyses performed provide a reasonable picture of the daily mobility. The method used provides quantitative indicators that reveal the similarities and differences of daily mobility, as well as the interactions that occur in the FUAs according to their size.

Finally, to deepen our understanding of this fundamental means of human interactions in cities, the relationship between the shape of mobility networks and the socioeconomic status of the residents of mobility areas should be investigated further. Specifically, the morphology of mobility networks for residents in mobility areas with different income levels should be compared, and the spatial location of nodes with the highest attraction in the main FUAs should be analysed.

Declaration of interests

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.

CRediT authorship contribution statement

Severino Escolano-Utrilla: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing, Project administration, Software. **Carlos López-Escolano:** Conceptualization, Investigation, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **José Antonio Salvador-Oliván:** Data curation, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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