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GEOGRAPHICAL ANALYSIS OF ROAD NETWORK EFFICIENCY IN THE WILAYA OF SÉTIF: UTILIZING A PRINCIPAL COMPONENT ANALYSIS (PCA) TO REVEAL THE RELATIONSHIP BETWEEN DEMOGRAPHIC INDICATORS AND ACCESSIBILITY OF URBAN CENTERS

Abstract: The study uses a quantitative spatial approach to analyze the relationship between the topological structure of the road network and demographic dynamics in sixty urban centers in the wilaya of Sétif, Algeria, in 2021. This approach involves representing the road network as an undirected graph and calculating five demographic and six topological indicators reflecting accessibility and connectivity. These indicators are then standardized and integrated into a principal component analysis (PCA). The analysis revealed that the variables primarily fall within two composite axes: the functional centrality/accessibility axis, which is closely associated with population size, density, and connectivity; and the population hierarchy and concentration axis. Together, these two axes explained 72.98% of the total variance. At the factorial level (F1–F2), four types of urban centers were identified: dominant centers, medium centers, centers with network centrality exceeding their demographic weight, and weakly integrated peripheries. Population growth was more closely linked to the most network-integrated centers (F1) than to their size or rank in the urban hierarchy (F2). This highlights the lack of a direct correlation between topological accessibility and population hierarchy, despite some overlap between the two. The results show that improving road infrastructure affects both the volume of growth and its internal redistribution among centers according to network integration patterns. The results also confirm that the methodological framework, which integrates

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topological and demographic indicators within PCA, can be applied in other regions to guide investment and reduce spatial imbalances.

Keywords: transportation, road network, accessibility, urban network, population hierarchy, principal component analysis (PCA), Wilaya of Sétif

Introduction

The relationship between the topological structure of road networks and the spatial organization of urban centers is a key issue in transport geography and regional planning. This is because it directly impacts population distribution patterns, investment orientation, and the level of integration between urban and rural areas. In many regions, connectivity and accessibility quality have become key factors in urban network imbalances and the emergence of different types of spatial polarization between dominant and peripheral centers. It raises fundamental questions about the equitable distribution of infrastructure and public services.

Studies examining the relationship between transport and development have shown that the contribution of transport networks to spatial reorganization is still a subject of scientific debate. Some studies suggest that improving transport networks can stimulate growth and reshape the spatial distribution of activities, provided the necessary institutional and planning conditions are in place. This concept is explored in reviews by Banister and Berechman (2001) and Ristić et al. (2013), as well as in the work of Vickerman (2008) and Vickerman et al. (1999) on accessibility and regional development. In contrast, other studies have criticized the idea that infrastructure has an 'automatic structural impact. They argue that attributing complex spatial transformations to a single transport project is overly simplistic and resembles “political myth-making”. This perspective aligns with Offner's (1993) discussion of the “structural effects” of transport projects, a topic that sparked controversy in subsequent French literature. Nevertheless, many of these contributions emphasize the importance of concepts such as connectivity, accessibility, and urban hierarchy in understanding the positioning of centers within networks, as discussed in important works on transport geography and urban systems (Rodrigue, 2020; Offner & Pumain, 1996; Ratkaj et al., 2005).

In the Maghreb and Algerian context, the number of studies explicitly linking road networks and urban network imbalances is limited. One notable exception is Bouzid et al. (2023) study examining the role of the road transport network in supporting development in the wilaya of M'Sila. This study employed a variety of indicators to evaluate road density, accessibility, and development trends over time. However, despite their importance, these studies have mostly addressed the developmental and topological dimensions separately rather than integrating them into a single analysis. The use of a composite statistical framework that combines indicators of size, population density, and topological accessibility at the network level itself is rare, particularly in medium-sized Algerian wilayas such as Sétif. This highlights the need for approaches that focus on this methodological integration when analyzing urban network imbalances.

The wilaya of Sétif, located in the eastern highlands of Algeria, is a prime example of these issues. Between 2008 and 2021, its urban network expanded from 215 to 270 urban centers (+55 centers). Nearly half of the wilaya's population (47.52%) lives in the central strip, where the major urban centers most integrated into the road network are concentrated. More than

57% of the population lives in the main centers compared to rural areas and secondary centers. Analysis of the Ziv database also reveals a significant population surplus in major cities: the city of Sétif has a population of over 395,000, which is more than 116,000 above its theoretical size; meanwhile, the city of El Eulma has a surplus of over 101,000. In contrast, medium and small centers suffer from a clear lack of population density.

These data illustrate the high demand for urban land, resulting in imbalanced urban growth and the emergence of multiple urban issues, including land use imbalances, investment and development concentrated in specific centers, a decline in economic activity in other centers, and inadequate services. In contrast, rural areas suffer from marginalization and limited development opportunities, threatening to exacerbate rural-urban migration and deepen demographic and economic imbalances at the state level. This study selects 60 major urban centers from this vast network of centers for detailed topological analysis.

These data and the urban and spatial imbalances they reflect show that the imbalance in the urban network in the wilaya of Sétif cannot be explained by demographic variables alone. It is also linked to the location of each urban center within the road network and consequently to the relative levels of accessibility between these centers. The research problem is to identify the underlying structures that govern the relationship between the efficiency with which centers are integrated into the road network and the dynamics of their demographic growth. Based on this, the study hypothesizes that population and spatial disparities between urban centers are linked to the topological structure of the road network and the varying accessibility of each center. This hypothesis raises two key questions: To what extent can topological accessibility indicators explain population distribution patterns and imbalances between urban centers in the state? Secondly, how do these indicators, when combined with demographic indicators, contribute to revealing hidden patterns of spatial organization that do not appear in traditional descriptive analyses?

To address this issue, the study uses graph theory to represent the road network in the wilaya of Sétif, calculating a set of topological accessibility indicators alongside five demographic indicators. These two dimensions—topological and demographic-are integrated into a single framework using principal component analysis (PCA), a multivariate statistical method that enables us to move from a binary interpretation of correlations to extracting synthetic axes that reveal underlying structures in the data. This allows us to identify dominant structural axes in space and classify urban centers into homogeneous categories based on size and accessibility. Thus, the study seeks to make dual methodological and practical contributions: firstly, it tests the ability of topological indicators to explain the imbalance of the urban network in a medium-sized Algerian context; secondly, it proposes a synthetic reading to help decision-makers distinguish between different categories of centers and develop more targeted policies to achieve better spatial balance.

Literature Review

Although the interactive relationship between transport systems and the spatial organization of communities is now well established in urban geography, from models of central places to analyses of polycentric cities (Christaller, 1968; Batty, 2008), recent reviews in transport geography show that the concept of accessibility now provides a key framework for analyzing this relationship, with various approaches to its application. Geurs and Van Wee (2004) view accessibility measures as integrated indicators for assessing the impact of transport policies and land use on access to activities and opportunities. They also propose an analytical framework for ranking these measures according to different dimensions. Conversely, studies on 'accessibility tools' in planning practice demonstrate that having a wide range of tools does not necessarily lead to their intensive use. Papa and Bertolini (2015) and Chang et al. (2017) reveal that, although many urban transport plans include accessibility in their discourse and objectives, they continue to rely on traditional mobility indicators, such as traffic speed and volume, in their assessments. This reflects a gap between theoretical development and practical application. A third perspective comes from the transport justice movement, which calls for a focus on the distributional dimension of accessibility. This movement argues that accessibility is not merely an indicator of efficiency but also an expression of individuals' and groups' ability to participate in urban opportunities. As Pereira and Fernandes (2017) argue, questions of equity in transport should focus primarily on the distribution of access opportunities rather than on the average overall improvement in networks.

Representing road networks as systems of nodes and links within the framework of graph theory has led to the development of a wide range of topological indicators with which to describe the structure of urban networks. Studies dealing with spatial networks and urban systems show how topological distance measures and shortness indices, along with centrality and degree indices, can be used to determine the location of each node in the network and its degree of integration or marginality (Barthélemy, 2011; Crucitti et al., 2006; Porta et al., 2006). These indices reveal the internal hierarchy of networks and distinguish between central and peripheral nodes and hubs. They also reveal different levels of connectivity within polycentric urban systems. This makes topological analysis a useful tool for studying urban network imbalances and understanding spatial organization patterns.

Several recent studies have emphasized the importance of integrating network characteristics with demographic or social variables in order to understand spatial inequality patterns. Researchers in the fields of spatial justice and urban mobility have employed synthetic statistical methods such as principal component analysis (PCA) to combine network supply indicators with population demand or social group distribution indicators. Examples of this approach can be found in studies examining inequality in access to employment opportunities and services in major cities in Latin America and Europe (Pereira et al., 2017; Boisjoly et al., 2017; Allen & Farber, 2021), large-scale comparative studies also show a systematic correlation between demographic and socioeconomic characteristics, such as population density, income levels, and education, and disparities in access to urban centers and services. Global and regional analyses demonstrate that regions with higher population density or greater economic prosperity generally have better access to cities and essential services, whereas peripheral or poorer regions experience significantly poorer access (Weiss et al., 2018; Sua et al., 2024), in European cities such as Caen in France, principal component analysis was used to integrate indicators of multimodal accessibility (i.e., car, mass transit, and active transport) with population and service distribution. The aim was to explore dimensions of spatial equity in access to urban facilities within the urban territory (Kofi Bonsu, 2025). In the Maghreb and Algerian context, the number of studies explicitly linking the structure of road networks and urban network imbalance remains limited. However, some studies have used an analysis of key components to interpret developmental disparities between Algeria's northeastern wilayas, based on a range of natural, social, and service indicators. This confirms the suitability of the approach for reducing spatial disparities in compositional dimensions at the regional level (Bouziane & Benmissi, 2023). Notable contributions include a study by Bouzid et al. (2023) examining the role of the road transport network in supporting development in the wilaya of

M'Sila. This study employed a set of road density and accessibility indicators to analyze variations between municipalities in terms of time and space. However, despite their importance, most of these studies address the network and development dimensions in parallel rather than integrating them. This study seeks to address this issue by using a single statistical framework that combines indicators of size and population density, as well as indicators of topological accessibility at the network level, in the case of the wilaya of Sétif.

Tools and Methods

Study Area

The wilaya of Sétif is located in the eastern highlands of northern Algeria and includes several key junctions at the intersection of a number of national roads. It comprises 20 districts and 60 municipalities (see Figure 01), covering an area of approximately 6,564 km², and had a population of 2,076,859 according to the 2021 census. It extends between 5.04° and 6.26° east longitude and 34.76° and 36.25° north latitude. The terrain varies, including plains, hills, and highlands, but plains make up around 48% of the area, making the central part of the wilaya a transit and urban attraction area.

The study is based on a significant road network totalling 3,560.65 km in length. This includes 74.8 km of motorways (2.1%), 634.49 km of national roads (17.8%), and 689.18 km of provincial roads (19.4%). In comparison, there are 2,162.18 km of municipal roads (60%). This reflects the wilaya's extensive road infrastructure and the disparities in accessibility between its urban centers (see Figure 02).

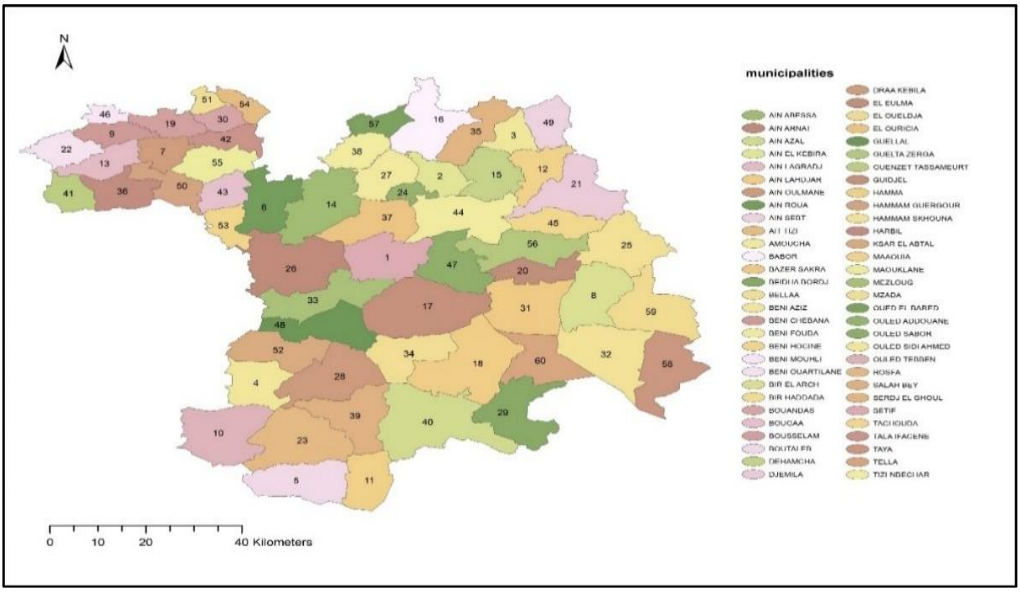

Fig.1. Municipalities of the Wilaya of Sétif (Northern Algeria). Source: Authors, 2024

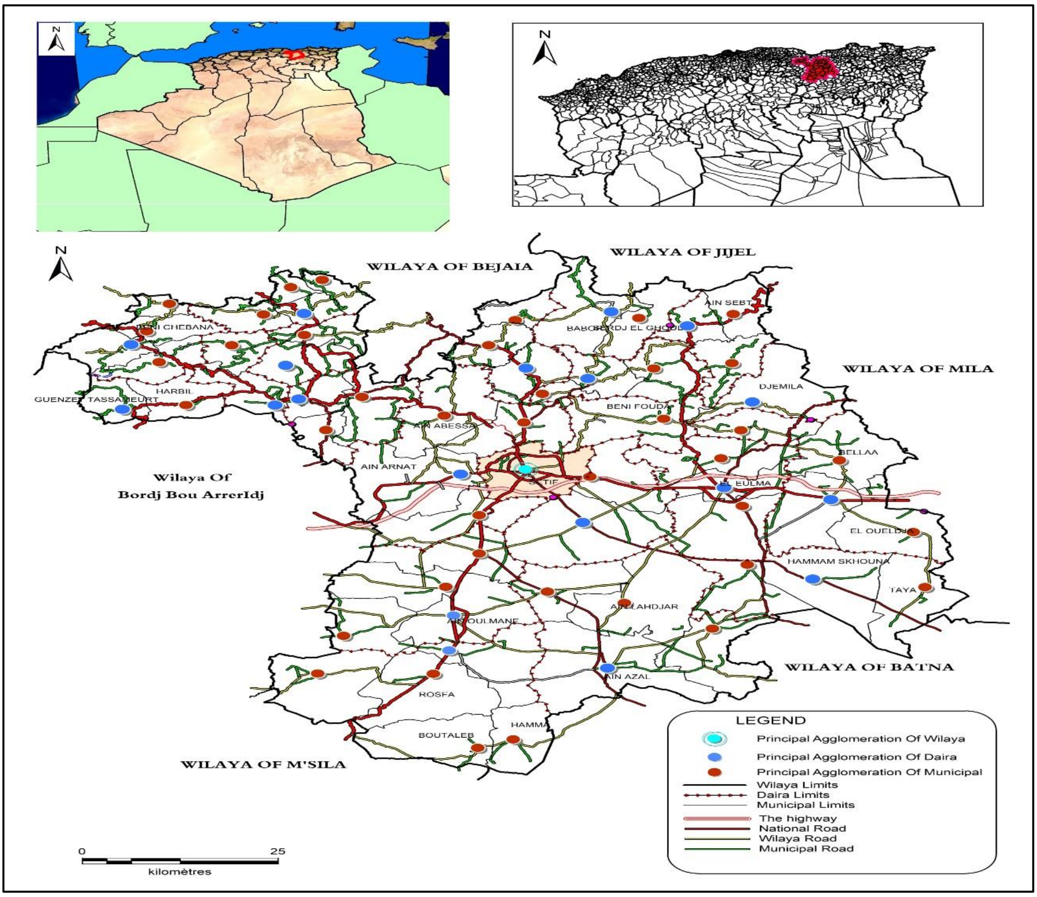

Fig. 2. Road network of the Wilaya of Sétif. Source: Authors, 2024

Methodology

This study takes a quantitative-spatial approach to analyze the relationship between the topological structure of the road network and the demographic changes in urban centers in the wilaya of Sétif in 2021. The methodological approach consists of four main steps:

Representing the road network at the provincial level as a graph, where urban centers are represented as nodes and connecting roads as edges.

Calculating six topological accessibility and network integration indicators, along with five selected demographic indicators, for each center.

Standardizing and aggregating these indicators within a single framework using principal component analysis (PCA) to reduce them to a limited number of synthetic dimensions.

Interpreting these dimensions, classifying urban centers into homogeneous categories, and mapping spatial imbalance patterns at the state level.

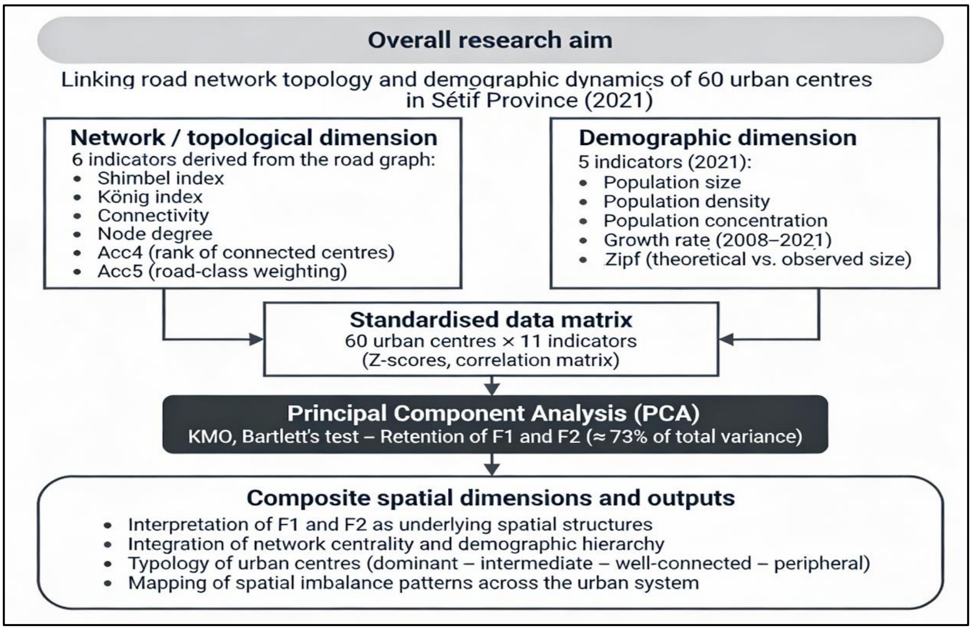

Fig. 3. The general methodological framework of the study. Source: Authors, 2025

Data and Variables

Demographic Indicators

This study uses five demographic indicators to measure the size and dynamism of urban centers in 2021. 'Population' (Pop) represents the total number of inhabitants in each urban center, while 'population density' (Den) is calculated by dividing the number of inhabitants by the municipal area of the center in question. The concentration/dispersion indicator expresses the proportion of the population living in the main center compared to the municipality's total population, enabling the distinction between municipalities with a clear urban core and those with a dispersed fabric. The population growth rate for the period 2008–2021 (Gr_08/21) measures medium-term population growth dynamics. Finally, the difference between the theoretical and actual sizes according to Zipf's rule indicates the population surplus or deficit of each center relative to the city size hierarchy model.

Topological Indicators of the Road Network

a) Road Network Modelling as an Undirected Graph

The road network in the wilaya of Setif for 2021 is represented in an undirected graph, in which the urban centers studied are represented as nodes and the roads connecting them as edges, in accordance with the classic approach to spatial network analysis in transport geography (Barthélemy, 2011; Porta et al., 2006; Crucitti et al., 2006), the study used 60 urban centers as spatial units for analysis, representing the main urban centers at the state level, while the edges represented the various national, state, and municipal road sections that provide direct connections between these centers. Each edge was assigned a specific description, including the length of the section (in kilometers) and the classification of the road (national, wilaya, or municipal), as was done in previous studies on road networks in the Algerian context (Bouzid et al., 2023).

Based on this representation, two basic matrices were constructed for topological analysis: the connectivity/adjacency matrix, which indicates whether or not there is a direct link between each pair of centers, and the Shimbel shortest-path matrix, which records the shortest path connecting each pair of nodes within the network in terms of the number of edges or path length. These two matrices provide the computational basis for deriving topological distance indices (e.g., the Shimbel and König index), connectivity indices, and node degree, as well as weighted accessibility indices that incorporate the rank of connected centers and the classification of the roads connecting them.

b) Network Topological and Accessibility Indicator

The position of urban centers within the road network in the wilaya of Sétif is analyzed using six topological indicators extracted from a graphical representation of the network, where centers are represented as nodes and connecting roads as edges. The Shimbel index measures the sum of the shortest topological distances between each center and the others in the network. Low values indicate centers that are closer and more integrated in terms of network distance (Shimbel, 1951; Raham, 2001). The König index expresses the maximum topological distance between two centers and is used to capture the degree of marginality or distance from the edges of the network (Gleyze, 2001). The general centrality/connectivity index measures each node's position within the network by linking the number of actual links to the level of possible connectivity. This allows a distinction to be made between centers located at the heart of the network and those that are less integrated within its structure.

These network distance-based indicators are complemented by connectivity-related measures. The node degree indicator expresses the number of adjacent nodes that are directly connected to each node in the graph, whether at intersections, secondary urban centers within the municipality, or neighboring urban centers. This is a simple indicator of local connectivity density, where high values reflect a greater number of direct connections in the vicinity of the node (Crucitti et al., 2006; Porta et al., 2006).

The accessibility index based on the rank of centers (Acc4) incorporates information about the status of connected centers. It assigns higher weights to links directed towards centers of greater size or demographic importance, thereby reflecting the benefit that centers receive from their connections to higher-ranked centers in the urban hierarchy. In contrast, the connecting road classification index (Acc5) focuses on the characteristics of the links themselves, weighting them according to their classification (national, provincial, or municipal). This means that the index value increases in centers primarily connected to higher-class roads, reflecting a better level of integration into the structural network (Bouzid et al., 2023).

In all cases, low values for the topological distance indices (Shimbel and König) indicate better accessibility. Conversely, high values for the node degree and weighted accessibility indices (Acc4 and Acc5) reflect a higher level of connectivity and integration into the road network. These indicators can be grouped into three main categories: topological distance indicators (Shimbel and König); connectivity/centrality indicators, including node degree and some general centrality measures; and weighted accessibility measures (Acc4 and Acc5).

Principal Component Analysis and Analytical Strategy

Principal component analysis (PCA) was employed to transition from interpreting demographic and topological indicators separately to a single synthetic framework that condenses information into a limited number of spatial dimensions. The analysis was based on a data matrix comprising 60 urban centers and 11 indicators (five demographic and six topographical), with all variables standardized using z-scores to ensure comparability between indicators with different units and ranks. The analysis was performed on the correlation matrix using XLSTAT 2019 software, and the suitability of the data was verified using the Kaiser–Meyer–Olkin (KMO) measure (0.794), indicating a good level of sample adequacy. Bartlett's test of sphericity ($\chi^2 = 756.345$, $df = 55$, $p < 0.0001$) confirmed that the correlation matrix differed significantly from the unity matrix, rendering it suitable for factor analysis (Jolliffe, 2002). Based on Kaiser's criterion (eigenvalues >1) and the scree plot, two main components (F1 and F2) were retained, explaining 72.98% of the total variance and reducing the multidimensional structure of the indicators to only two composite levels without significant loss of information.

At the analytical level, F1 and F2 were interpreted as two composite spatial dimensions, combining characteristics of size and demographic growth and degree of network integration and topological accessibility, respectively. This was based on the correlation coefficients between the original variables and their loadings on each axis. The 60 urban centers were then projected onto the (F1, F2) plane and categorized according to their population size and their level of integration into the road network (dominant, Regional, connected, or marginal centers). These results were then represented on thematic maps showing the distribution of categories in the provincial area. This allowed patterns of imbalance in the urban network to be detected and areas requiring priority planning intervention in terms of improving connectivity or supporting urban development to be identified.

Results and Discussion

Eigenvalues

In principal component analysis (PCA), eigenvalues are an indicator of the amount of variance explained by each component. According to the Kaiser criterion, components with eigenvalues greater than one are considered statistically significant. In this study, the first and second principal components were found to explain 72.982% of the total variance, reflecting an adequate representation of the original data with only two levels. is illustrated by the data in Table 01 and the scree plot in Figure 04, both of which were extracted from the analysis of the PCA results.

Table 1. Principal Component Analysis: Eigenvalues and Explained Variance

Component	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
Eigen value	5.542	2.486	1.079	0.768	0.518	0.282	0.130	0.078	0.052	0.039	0.028
Variance (%)	50.380	22.602	9.805	6.984	4.708	2.561	1.177	0.706	0.471	0.350	0.255
Cumulative (%)	50.380	**72.982**	82.787	89.771	94.479	97.040	98.217	98.923	99.395	99.745	100.000

Note. N = [60]. Components with eigenvalues > 1.0 were retained according to Kaiser criterion. The first two components explain 72.982% of total variance

Source: Authors, 2024.

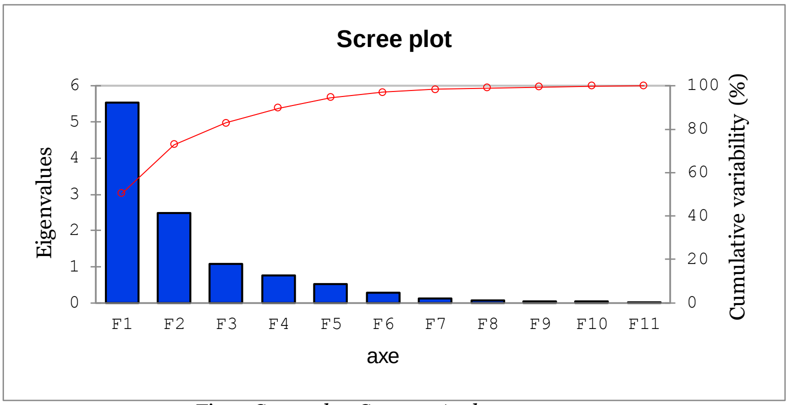

Fig.4. Scree plot. Source: Authors, 2024

Correlation matrix (Pearson (n))

As shown in Table 02, the correlation matrix analysis reveals strong positive relationships between various topological indicators related to accessibility, including the Shimbel index, the König index, the connectivity index (CI), the connectivity node, and the connection road. Demographic indicators, such as population, population density, growth rate (2008/2021), population concentration, and Zipf's index, also show positive correlations with each other, reflecting internal consistency within each group of indicators.

In contrast, the results revealed a strong negative correlation between Connectivity (CI) and Node Degree, indicating that high Connectivity (CI) is associated with low Node Degree. The relationship between Connectivity (CI) and most demographic indicators was generally negative, reflecting an inverse relationship between accessibility and population density, as well as manifestations of population concentration.

Table 2. Pearson Correlation Matrix between Topological and Demographic Variables

Variable	1	2	3	4	5	6	7	8	9	10	11
1. Shimbel index	1										
2. König index	.946	1									
3. Connectivity (CI)	.620	.503	1								
4. Node Degree	-.628	-.573	-.602	1							
5. Connectivity Node	.612	.502	.922	-.557	1						
6. Connection Road	.617	.516	.937	-.564	.841	1					
7. Zipf's Index	-.208	-.235	-.166	.567	-.182	-.144	1				
8. Population density	-.299	-.304	-.257	.665	-.234	-.223	.939	1			
9. Growth Rate	-.525	-.530	-.302	.419	-.293	-.321	.319	.372	1		
10. Population Concentration	-.131	-.158	-.062	.302	.0045	-.147	.362	.484	.323	1	
11. Population	-.355	-.371	-.265	.647	-.247	-.247	.902	.937	.463	.467	1

Source: Authors, 2024

Analysis of the interrelationship between indicators according to the correlation matrix

The analysis of the correlation matrix shows that there are two main groups of related indicators. The first group is about how accessible things are, while the second group is about demographic factors. The first group is related to topological characteristics of accessibility, while the second group relates to demographic variables. The correlation analysis reveals two main groups of interrelated indicators. The first group is related to topological accessibility characteristics, and the second group relates to demographic variables. However, there are some points of intersection between the two groups, indicating limited functional overlap between the spatial and demographic dimensions of the study area.

a) Demographic indicators:

These indicators exhibit a strong internal correlation, especially between population size, population density, and Zipf's index. This reflects a coherent demographic structure in terms of size and spatial distribution. In contrast, the growth rate from 2008 to 2021 shows a weaker correlation with the other indicators. This may indicate a different dynamic for this indicator, linked to circumstantial shifts or temporal demographic cycles. These results align with previous studies on the intricate relationships between demographic indicators and urban growth and population shifts in both normal and exceptional contexts (Bettencourt et al., 2010; Verbavatz & Barthelemy, 2020; Steck, 2012; Buresch et al., 2024; Wirawan & Januraga, 2021; Fay et al., 2022).

b) Topological Indicators of Accessibility:

This group is characterized by strong internal consistency among the Shimbel index, the König index, the connectivity index (CI), the connectivity node, and the connection road indicators. This indicates that they consistently measure accessibility. This finding aligns with Rajeh et al.'s (2021) study, which revealed that topological accessibility measures tend to be positively correlated with one another, regardless of network size.

c) Internal Functional Differentiation:

Within its group, Connectivity showed functional differentiation, registering a stronger correlation with the Connectivity Node and Connection Road indices than with the Shimbel and König indicators. This suggests that connectivity measures a different dimension of central accessibility. This differentiation aligns with observations by Meghanathan (2015) and Schoenfeld and Pfeffer (2021), who distinguished between topological proximity and link quantity within networks. The Connectivity Node and Connection Road indicators also showed a high correlation ($r = 0.841$), reflecting consistency in their characterization of the network's connectivity structure. Studies have confirmed the effectiveness of these indicators in analyzing network structure and identifying spatial accessibility characteristics, supporting these results (Rubulotta et al., 2013).

d) The Node Degree indicator exhibited independent behavior:

This indicator exhibited behavior that differed from the rest of its group. It showed an inverse correlation with the other topological indicators while showing a positive correlation with the demographic indicators. This finding supports recent research indicating that the relationship between the Node Degree indicator and closeness centrality is not necessarily linear but rather influenced by network structure and link distribution (Evans & Chen, 2021). Table 03 illustrates the interconnection analysis of indicators according to the correlation matrix (Oldham et al., 2018).

Table 3. Relationship between topological indicators of accessibility and demographic indicators

Type of relationship	Strength	Average correlation coefficient	Theoretical significance	Notable examples
Topological and demographic indicators of accessibility	Moderately negative	r ∈ [-0.530, -0.131]	Areas with high topological centrality tend to be less densely populated.	Shimbel index with population (-0.355), König index with population (-0.371) Shimbel Index with Growth Rate (-0.525) König index with Growth Rate (-0.530)
Node Degree and Demographic Indicators	Strongly positive	r ∈ [0.302, 0.665]	Conversely, areas with higher local clustering tend to be more densely populated.	Node Degree with Population (0.647), Population density (0.665)

Source: Authors, 2024

The analysis of the interrelationship between indicators, according to the correlation matrix in Table 2, shows a negative relationship between topological accessibility indicators and demographic indicators. The node degree indicator is the exception, consistent with many studies that have reached the same conclusion (Spankulova et al., 2024; X. Li et al., 2025). Furthermore, this relationship's type or direction is consistent with recent theories assuming that the topological structure of urban or social networks evolves independently of population distribution, often reflecting historical, geographical, or planning factors (Altaweel et al., 2021; Daniels & Mulley, 2012).

The positive correlation between node degree and demographic indicators aligns with spatial organization theories (Y. Li et al., 2024), which propose that population clusters develop more interconnected local networks. This may reflect a pattern of urban development in which dense local networks form in densely populated areas. Recent studies indicate that areas with higher population density often have local sub-networks with a high degree of connectivity. This means that each node (area or spatial unit) connects to a larger number of neighbors than nodes in less densely populated areas (Cao et al., 2022; Zeng et al., 2023).

The results revealed two distinct spatial organization patterns. The first pattern is the central pattern, which encompasses areas with high accessibility, low local agglomeration of urban centers, and low population density. The second pattern, the clustered pattern, is evident in areas with limited accessibility, dense agglomeration of urban centers, and high population density. The node degree index is a key explanatory variable because it links the topological structure to demographic characteristics. This reflects the index's pivotal role in explaining spatial organization and understanding the topological structure's relative independence.

The inverse relationship between connectivity index (CI) and population density shows that the development of the topological structure of the road network is partially independent of population distribution. These results of distinguishing between different spatial organization patterns when analyzing the relationship between the topological structure of a network and the demographic characteristics of urban centers in the wilaya of Sétif.

Correlations between variables and factors

The results of the principal component analysis (PCA) in Table 4 and Figure 5 confirm that the spatial system of the wilaya of Sétif is governed by two main dimensions (F1 and F2), which together explain 72.98% of the total variance. This high level of explanation lends strong statistical reliability to the geographical conclusions drawn and enables an accurate interpretation of the nature of the extracted axes.

Table 4. Correlations between variables and factors

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
Shimbel index	**-0,791**	**0,347**	-0,395	0,173	0,201	0,064	0,011	-0,019	-0,091	0,119	0,028
König number	**-0,746**	**0,259**	-0,494	0,209	0,233	0,123	-0,007	0,030	0,070	-0,109	-0,020
Connectivity (CI)	**-0,756**	**0,526**	0,319	-0,143	-0,062	0,026	-0,021	-0,039	-0,087	-0,085	0,092
Node Degree	**0,856**	**0,074**	-0,095	-0,082	-0,164	0,467	-0,004	-0,012	-0,031	0,000	-0,003
Connectivity Node	**-0,723**	**0,534**	0,317	-0,004	-0,118	0,075	0,258	0,003	0,055	0,027	-0,040
Connection Road	**-0,740**	**0,513**	0,245	-0,249	-0,029	0,065	-0,233	0,042	0,046	0,042	-0,057
Zipf's Index	**0,631**	**0,672**	-0,228	-0,211	0,049	-0,121	0,011	-0,170	-0,042	-0,025	-0,067
Population density	**0,718**	**0,642**	-0,185	-0,090	-0,019	-0,045	-0,010	-0,009	0,133	0,039	0,093
Growth Rate2008/2021	**0,612**	**0,081**	0,525	0,108	0,569	0,086	0,003	-0,022	0,010	0,004	0,002
Population Concentration	**0,380**	**0,481**	0,193	0,729	-0,221	-0,037	-0,076	-0,016	-0,011	-0,005	-0,013
Population	**0,743**	**0,606**	-0,089	-0,103	0,052	-0,090	0,043	0,209	-0,074	-0,017	-0,017

Source: Authors, 2024

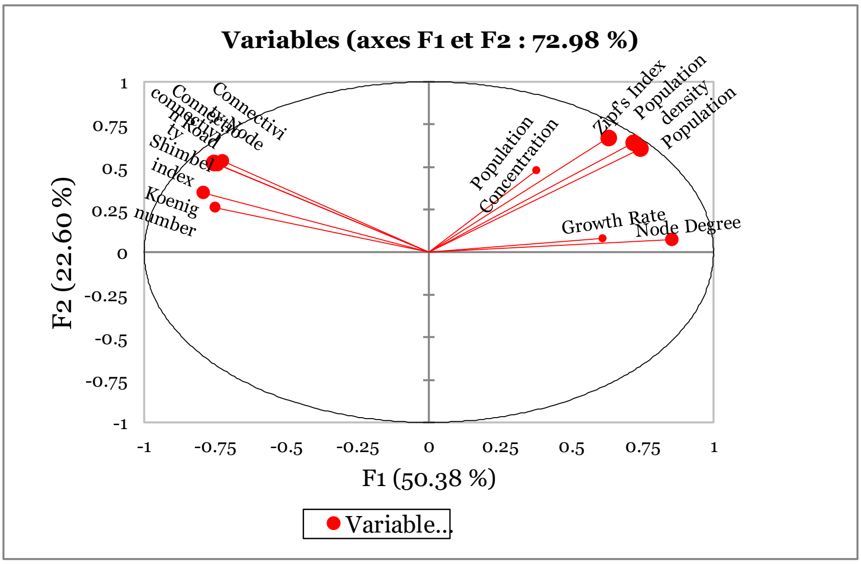

Fig. 5. Correlations between variables and factors (F1.F2). Source: Authors, 2024

- **First axis (F1):** Functional centrality/accessibility (explaining 50.38% of the variance)

This axis represents the wilaya of Sétif's fundamental geographical contrast. The positive pole of the axis is strongly correlated with node degree, population, and population density, reflecting relatively large urban centers with dense direct connections and high integration into the road network (such as Sétif and El Eulma). In contrast, the negative pole is strongly associated with topological distance indicators such as the Shimbel index (r = -0.791) and the König number (r = -0.746). This reflects centers that are more distant from the rest of the network in terms of topological distance and are less integrated into the road network and less attractive in terms of population density.

This finding aligns with the results of studies on urban networks in various contexts, which have shown that population density and activity tend to concentrate in the most topologically integrated nodes, creating a strong urban center in contrast to less connected peripheral areas. These poses increasing challenges to network efficiency in advanced stages of urban growth (Altaweel et al., 2021; Barthelemy & Flammini, 2008; Rui, 2013; Rotaru et al., 2024; Z. Li et al., 2015).

- **The second axis (F2)**: is related to hierarchy and population concentration, (explaining 22.60% of the variance)

This axis essentially captures the population distribution structure within each municipality. The positive pole of the axis is associated with high values for Zipf's index (Zipf's Index, r = +0.672), population density (Population density, r = +0.642), and total population (Population, r = +0.606), which characterizes units where a large proportion of the population is concentrated in a dominant urban center compared to secondary centers within the same municipal territory. In other words, there is a clear hierarchical structure to the organization of the population. In contrast, the negative pole corresponds to units with a less hierarchical structure, where the population is more evenly distributed between centers and residential patterns are less subject to a clear urban hierarchy.

Although F2 is primarily population-based, it is also moderately correlated with some accessibility indicators within the network. For example, the correlation with Connectivity Node is r=+0.534 and with Connection Road is r=+0.513. This indicates that units with a more hierarchical and concentrated population structure tend to play a relatively structured role as connection points in the road network. This is evident in their location in the node structure and the passage of important links through them. However, this network dimension does not reach the decisiveness level of the first axis (F1) in explaining degrees of integration and peripheral isolation.

Plotting the population growth rate variable in the principal component space reveals an important result: it has a moderately positive correlation with the first axis (F1) (r = +0.612), but a very weak correlation with the second axis (F2) (r = +0.081). This indicates that growth dynamics in the wilaya of Sétif are primarily influenced by the integration of centers into the road network and their urban characteristics (the positive aspect of the urban centrality axis F1), rather than the hierarchy or absolute size of centers, as captured by the second axis. In other words, population growth is not limited to the largest cities but also includes medium-sized centers that benefit from a favorable location and good accessibility within the network.

This result reveals a correlation between topological accessibility and demographic dynamics: centers located in network hubs with denser connections are the most attractive for population growth. This conclusion aligns with literature on compact urbanism and network-efficient cities, which suggests that combining high population density with efficient transport infrastructure can enhance network efficiency and reduce land consumption. However, this concentration must be managed within appropriate planning frameworks (Barthelemy & Flammini, 2008; Pont et al., 2021; Rui, 2013; Shrivastava, 2009). However, this literature also warns that, if not accompanied by land use regulation and improved spatial equity in access to services, concentrating growth in a limited number of central nodes may produce new forms of spatial inequality rather than reducing it.

The analysis confirms that the geographical pattern of the wilaya of Sétif clearly favors a centralized model. The highest population growth values are concentrated in centers located on the positive pole of the urban centrality axis (F1), while some peripheral centers remain poorly integrated into the network and are demographically marginal. This indicates a "response gap" between population growth dynamics and infrastructure development and road connectivity, as pressure on networks and urban spaces in central centers is increasing faster than network rehabilitation in marginal areas. These findings therefore highlight the need for proactive planning strategies that prioritize developing areas with high network integration. These strategies should incorporate spatial equity approaches into the distribution of road investments and urban services, ensuring a more balanced path of spatial development.

The positioning of urban centers, alongside demographic and topological indicators, at the factorial level (F1–F2)

Figure 06 shows the two-dimensional biplot resulting from the principal component analysis (PCA). The topological indicators related to accessibility and the demographic indicators are represented in red, and the urban centers are represented in blue in the space defined by the F1 and F2 dimensions (See Figure 06).

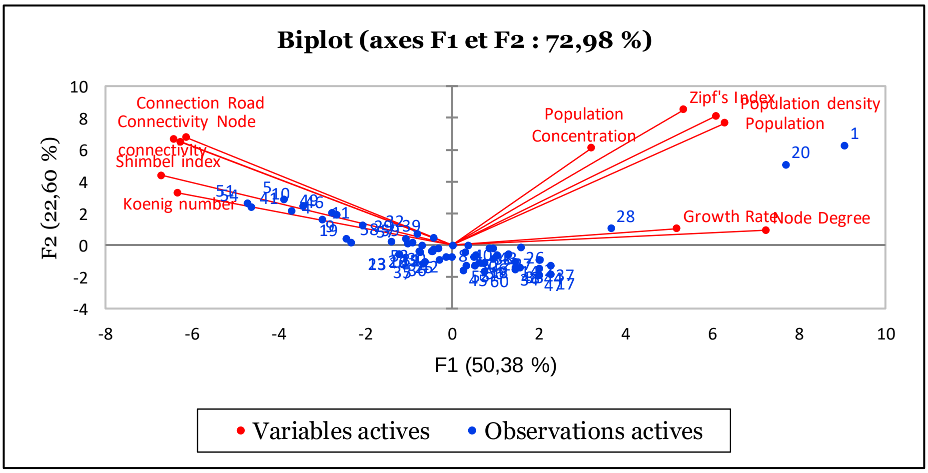

Fig. 6. Representation of Urban Centers and Indicators on the Factorial Plan F1 and F2
Source: Authors, 2024

Applying principal component analysis (PCA) to the topological and demographic indicators of 60 centers in the wilaya of Sétif enabled accurate spatial classification, explaining around

73% of the total data variance across two main axes: the first axis (F1) representing functional centrality/accessibility, and the second axis (F2) representing population hierarchy and concentration. Based on the axis reference (origin point 0, 0), this classification reflects four distinct spatial patterns, as shown in Table 5 and Figure 07. These patterns represent different stages of interaction between road infrastructure and demographic dynamics.

Table 5. Spatial characteristics of urban centers in municipalities extracted from PCA

Group	Centres	Share	Key characteristics	Developmental orientation	Spatial pattern
1 (F1>0, F2>0) Dominant centers	1, 20, 28	5%	High centrality; high population hierarchy	Dominant primary urban centres	Improving the internal efficiency of the network
2 (F1>0, F2<0) Regional centers	2, 17, 44, 47, 33, 34, 37, 14, 26, 27, 48, 24, 6, 43, 18, 38, 60, 56, 52, 21, 50, 3, 55, 40, 45, 8	43.3%	High functional centrality; medium population hierarchy	Intermediate and regional centres	Guiding spatial diffusion: investing in services (F2) to strengthen the hierarchy and transform these centres into integrated urban poles
3 (F1<0, F2>0) Connected centers	51, 54, 5, 41, 10, 4, 49, 46, 9, 19, 11, 58, 29, 57, 59, 32, 39	28.3%	High network efficiency; low functional centrality	Rural clusters with a structural role	Removing structural isolation: increasing direct connectivity (node degree) to turn them into growth centres
4 (F1<0, F2<0) Marginal centers	7, 23, 13, 35, 36, 22, 31, 16, 25, 42, 15, 12, 30, 53	23.3%	Low centrality; low population hierarchy	Marginalised rural clusters (dual weakness)	Comprehensive intervention: integrated plans to raise F1 and F2 to break the marginalisation cycle

Source: Authors, 2024.

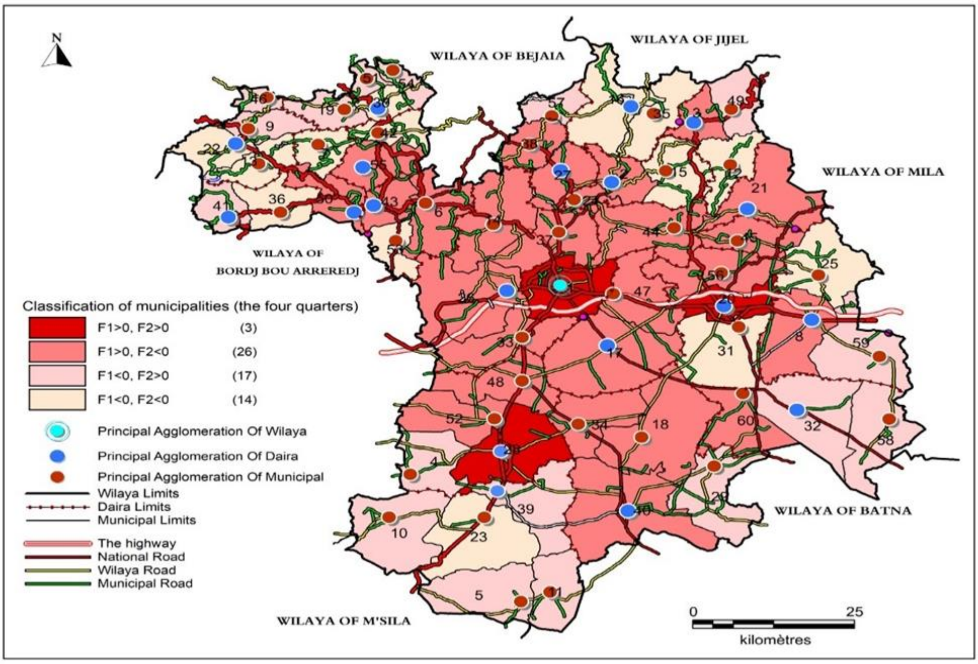

Fig. 7. The urban centers of municipalities, according to their positioning in the factorial space.
Source: Authors, 2024

- **The first group: (F1>0, F2>0) dominant centers**

This quarter is home to centers that achieve positive synergy between topological centrality and population hierarchy. The distinctive locations of the centers in Sétif and El Eulma suggest the presence of a bipolar system dominating the wilaya, alongside the center in Aïn El M'hadem, which is the third most dominant. The strong correlation between F1 and node degree, and between F2 and population density, confirms that these areas are vital meeting points for the network, facilitating the aggregation of populations and activities. However, the distance of these poles from the network efficiency vectors (Shimbel Index and König index) suggests a structural paradox: absolute dominance in centrality can result in decreased internal mobility efficiency, a phenomenon commonly observed in densely populated urban centers.

Studies indicate that large urban centers with high population density and advanced infrastructure are considered the heart of the urban network. These centers combine high accessibility, economic growth factors, and distinctive demographic indicators, making them key drivers of growth and attracting populations and economic activities (X. Li & Neal, 2023). The literature also emphasizes the importance of these centers in supporting economic growth and providing an environment conducive to innovation, resulting from the accumulation of human resources and infrastructure integration (Schmutz-Bloch & Sidibé, 2024).

- **The second group: (F1>0, F2<0) Regional centers**

This quarter represents urban sprawl, where centers acquire high topological centrality on the positive F1 axis, as indicated by high node degree and growth rate. However, they have not yet reached the level of population hierarchy on the negative F2 axis. Examples of such centers include Boukaa, Ouerissa, Ain Abassa, Amoucha, Jamila, and Ain Arnat. These centers are the preferred destinations for the modern population and urban growth.

These finding confirms that road infrastructure is the main driver of growth in these areas, as improved accessibility attracts residents even before urban services have been fully developed. This pattern poses a challenge for planners, who must direct investment towards improving services (F2) to ensure that growth does not remain random sprawl but rather transforms into sustainable urban development.

These results align with previous studies that emphasize the importance of enhancing regional connectivity and investing in integrated infrastructure as pivotal elements in the transformation of medium-sized urban centers into effective drivers of development within the state's urban network (Levinson, 2012; Pont et al., 2021; Connectivity and City Clusters, 2018).

- **The third group: (F1<0, F2>0) Connected Centers**

This quarter is characterized by a striking structural contradiction: a decrease in topological centrality on the negative F1 axis is offset by the maintenance of a medium population hierarchy on the positive F2 axis. The centers of Geunzet, Ouled Taban, Boutaleb, Ait Tizi, and Ouled Si Ahmed are located in areas of high network efficiency, strongly correlated with the Shimbel Index and König index. This strategic geographical location reduces the total distance to reach the other centers.

This contradiction suggests that, although these areas play a structural role in the regional road network, they suffer from functional isolation due to poor direct connectivity and a low node degree. This pattern suggests latent development potential: increased topological centrality (through projects to break isolation) could rapidly transform these areas into growth poles, given their existing population and infrastructure.

These findings are consistent with previous studies indicating that rural or semi-urban areas with good connectivity to more developed centers play a strategic role in regional development. However, this requires improved infrastructure and enhanced connectivity to ensure sustainability and spatial equity. Such connectivity is also crucial for improving living standards and reducing poverty in these areas (Baye, 2025; Pont et al., 2021; Yi et al., 2017).

❖ **Group four: (F1<0, F2<0) marginal centers**

This quarter comprises 14 centers representing areas of structural weakness that fall below the regional average in terms of topographical centrality and population hierarchy. Centers such as Babur, Harbil, Sarj al-Ghul, al-Rasa, al-Dahmasha, and Balaa suffer from double isolation: poor direct connectivity and a low node degree limit their attractiveness, resulting in a decline in population and growth rates.

This pattern confirms the existence of a vicious circle of marginalization: weak infrastructure leads to demographic decline, which reduces the justification for investment in infrastructure. To break this cycle, these areas require comprehensive and simultaneous development interventions targeting both road infrastructure to increase F1 and the provision of basic services to increase F2.

Studies show that these areas often suffer from a severe lack of basic services, such as transportation, electricity, water, and healthcare. This has a negative effect on economic and social development, leading to high rates of poverty and migration to more developed areas. Researchers also emphasize that a lack of investment in infrastructure and communication networks contributes to the deterioration of human capital, a decline in the quality of education, and fewer job opportunities, thereby deepening the cycle of marginalization and social exclusion (Saaida & Saaidah, 2023).

PCA analysis shows that the spatial system in the wilaya of Sétif is imbalanced and is strongly influenced by the interaction between the road infrastructure and population dynamics.

The results also confirm that the wilaya's spatial system is polycentric and imbalanced. Understanding these distinct spatial patterns is fundamental to adopting differentiated spatial policies, whereby development interventions must target the specific characteristics of each spatial system to ensure more equitable and efficient regional development.

Conclusion

This study reveals that the urban center network in the wilaya of Sétif exhibits a high level of structural complexity and typological diversity. This complexity cannot be adequately explained by the 'center-periphery' dichotomy alone. Combining correlation analysis with principal component analysis (PCA), based on integrating topological road network indicators with demographic and population dynamics indicators, has enabled a quantitative synthesis to be constructed that highlights the interaction between infrastructure and population concentration within the provincial urban system.

The results of the correlation analysis revealed two significant patterns. The first pattern showed strong positive relationships between direct connectivity indicators and network complexity (particularly node degree), as well as demographic indicators. This confirms that road network density and interconnectivity are fundamental structural factors in explaining urban attractiveness and population concentration. In contrast, the second pattern showed a moderate negative correlation between distance-based network efficiency indicators (Shimbel and König) and population growth rates. This indicates that higher topological efficiency is not necessarily associated with higher growth dynamics. It also reflects a partial shift in the drivers of expansion towards areas that are less networked or that are governed by different urban and investment considerations.

At the compositional level, principal component analysis revealed that the variables could be organized into two explanatory dimensions, which together accounted for approximately 72.98% of the total variance. The first dimension embodies functional centrality and accessibility (F1) and is strongly linked to population mass, density, and connectivity. The second dimension reflects population hierarchy and demographic concentration (F2), as evidenced by its correlation with the Zipf index and concentration indices. This structure highlights a partial disconnect between network centrality and population hierarchy, suggesting that centers may occupy a structured functional position within the network without being at the top of the population hierarchy, and vice versa.

Projecting urban centers at the factorial level (F1, F2) has made it possible to distinguish four main spatial-functional patterns. These are dominant centers combining strong network integration and high demographic weight; centers with advanced functional growth within the population hierarchy; structural peripheries with promising network positioning but insufficient urban bases; and finally, marginal centers suffering from dual weaknesses in terms of accessibility and population size. This classification reflects an imbalanced urban system in which growth trajectories coincide with patterns of fragility and spatial isolation.

From a scientific perspective, the study contributes to the development of a synthetic methodological framework for understanding the complex relationships between road network topology and demographic dynamics. It highlights the importance of moving from analyzing individual indicators to using multivariate approaches that can reveal the underlying dimensions of spatial organization. The results also confirm that the relationship between infrastructure and demographic change is nonlinear and multilevel, necessitating more comprehensive explanatory models in spatial research.

At the applied level, the results indicate the necessity of adopting differential spatial policies based on the structural characteristics of each type of urban center. Dominant centers need to improve the efficiency of their internal networks and manage congestion; while emerging functional centers require growth to be guided by investment in services to enhance their sustainability. In contrast, structural peripheries can be upgraded by improving direct connectivity, and marginal centers require integrated interventions that address weak connectivity, population, and service bases simultaneously.

In conclusion, this study paves the way for future research, such as longitudinal studies incorporating additional socio-economic and environmental variables. This will enhance the role of multivariate statistical analysis in supporting rational planning decisions and consolidating the principles of regional equity and sustainability in transport and spatial development policies.

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