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Exploring the relationship between regional spatial networks and urban economic indicators: the case of Rio Grande do Sul state, Brazil

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Abstract
The spatial structure of cities and regions is becoming more complex, and the socio-spatial interactions that occur in networks of cities seem to play an important role, influencing the economic potential of municipalities. This paper aims to present a methodology that allows analyzing the role of the regional spatial network configuration on the economic performance of the municipalities. The investigation is linked to urban morphology studies, using a systemic and quantitative approach from configurational studies. The network of cities in Rio Grande do Sul is taken as the empirical study. The spatial network model (graph) consists of municipalities (nodes) and highways (connections), allowing the calculation of accessibility and centrality measures. The results of these measures are then related to the economic attributes of the municipalities (GDP and GVA) through a statistical analysis of clusters. The empirical study revealed evidence that a good performance of the municipalities in the configurational network is associated with specific economic indicators: higher GDP, higher values of GVA for industry and services and lower values of agricultural GVA. The conclusions seek to discuss the potential and limitations of the proposed methodology to understand the regional spatial structure.
Keywords: Spatial Networks, Spatial Analysis, Regional Economy, Configurational Models.

Explorando a relação entre redes espaciais na escala regional e indicadores econômicos das cidades: o caso do RS

Resumo
A estrutura espacial de cidades e regiões vem se tornando mais complexa, sendo que as interações sócio-espaciais que ocorrem em redes de cidades parecem ter um papel importante, influenciando o potencial econômico dos municípios. O objetivo deste trabalho é apresentar uma metodologia que permita analisar o papel da configuração da rede

espacial de municípios no seu desempenho econômico. A investigação se insere na área da morfologia urbana, através de um enfoque sistêmico e quantitativo, no campo dos estudos configuracionais urbanos. Toma-se como estudo empírico a rede de cidades no Rio Grande do Sul. O modelo da rede espacial (grafo) é constituído pelos municípios (nós) e pelas rodovias (ligações), sendo calculadas as medidas de acessibilidade e centralidade configuracional. Os resultados destas medidas são então relacionados a atributos econômicos dos municípios (PIB e VAB) através de uma análise estatística de clusters. O estudo empírico revelou evidências de que um bom desempenho dos municípios na rede configuracional está associado a indicadores econômicos específicos: maior PIB, maiores valores de VAB indústria e serviços e menores valores de VAB agropecuária. As conclusões procuram discutir as potencialidades e limitações da abordagem utilizada para a compreensão da estrutura espacial regional.
Palavras–chave: Redes Espaciais, Análise Espacial, Economia Regional, Modelos Configuracionais.

Explorando la relación entre las redes espaciales a escala regional y los indicadores económicos de las ciudades: el caso del estado de Rio Grande do Sul, Brasil

Resumen
La estructura espacial de las ciudades y regiones se está volviendo más compleja, y las interacciones socioespaciales que ocurren en las redes de ciudades parecen jugar un papel importante, influyendo en el potencial económico de los municipios. El objetivo de este trabajo es presentar una metodología que permita analizar el papel de la configuración de la red espacial de municipios en su desempeño económico. La investigación se inserta en el área de la morfología urbana, a través de un enfoque sistémico y cuantitativo, en el campo de los estudios de configuración urbana. La red de ciudades en Rio Grande do Sul se toma como un estudio empírico. El modelo de la red espacial (grafo) consiste en los municipios (nodos) y carreteras (conexiones), y se calculan las medidas de accesibilidad y centralidad configuracional. Los resultados de estas medidas se relacionan con los atributos económicos de los municipios (PIB y VAB) a través del análisis estadístico de *clusters*. El estudio empírico reveló evidencia de que un buen desempeño de los municipios en la red de configuración está asociado con indicadores económicos específicos: mayor PIB, valores más altos de VAB para la industria y los servicios y valores más bajos de VAB agrícola. Las conclusiones buscan discutir el potencial y los límites de la metodología propuesta para comprender la estructura espacial regional.
Palabras clave: Redes espaciales, análisis espacial, economía regional, modelos configuracionales.

1 Introduction

This work examines the regional spatial network configuration and its relationship with urbanization and industrialization processes. The regional network is composed of municipalities of different sizes and economic functions, connected by transport and communication networks. Regional spatial structuring is a dynamic process, usually leading to polarized and unequal regions. From the point of view of the regional economy, sectoral and territorial polarization appears as a natural trend of economic growth in the regions, concentrating income and wealth (SOUZA, 2005, p.108). Agglomeration and de-agglomeration economies play a fundamental role in the concentration and de-concentration of productive activities, engendering dynamic economic landscapes, showing poles of different hierarchies and functions. Literature on regional economy describes such poles (concentrations of economic activities, population, infrastructure, etc.) and also shows how their influence is reduced as distance increases (FUJITA; KRUGMAN; VENABLES, 2002). Geographic space generally appears as a distance (friction), related to transport costs, both for raw materials and finished products.

More recently, the process of regional structuring has been affected by economic globalization, associated with the deregulation of markets and a new international division of labor. New digital communication and transport infrastructures have allowed greater population mobility, generating new socioeconomic interactions and changing production processes, synthesized in the idea of a network society (CASTELLS, 2010). This author notes that, however, such advances in information and communication technologies did not represent the end of cities and the annihilation of geographic distance. Instead, we are witnessing the greatest wave of urbanization in human history (CASTELLS, 2010, p.2738).

Such a global urbanization gives rise to new spatial forms, such as polycentric metropolises, which arise from two interrelated processes: the extended decentralization of large cities and the interconnection of pre-existing cities, which are articulated from new communication capabilities. The formation of these new metropolitan areas may involve several cities, physically separated, but articulated in networks of functions. Such areas tend to cluster around one or more larger cities, spatially separated, presenting an enormous economic strength, from a new functional division of labor. In other words, there is a hierarchical specialization of functions between the different urban centers. The resulting spatial structure is polycentric and hierarchical at the same time.

From an economic point of view, the socio-spatial interactions that occur in networks of cities seem to play an important role in the economic potential of places (JACOBS, 1969). Taylor, Hoyler, Verbrugger (2010) state that in addition to the hierarchical view of the relationship between the city and its surrounding territory (hinterland), it is necessary to consider intercity relations - broadly horizontal and beyond the hinterland. Due to this network relationship, some cities tend to be the locus of economic expansion, dynamic cities that are fundamental for economic development. In addition, as they are more complex economic units, they tend to be more resilient to crises and adverse changes. Cities never exist alone, they come in assemblages, ordered as networks (TAYLOR; HOYLER; VERBRUGGER, 2010, p.2813).

Cities are centers of population, activities, services, which radiate over their surrounding territory. They are also conceptualized as nodes of a heterogeneous network - of the globalized economy, influenced by external socioeconomic forces. Understanding the regional spatial structure seems to require new methodologies that can simultaneously account for the various aspects involved in this process. In the context of urban configurational studies, the analysis of spatial networks has made it possible to advance the understanding of urban and regional systems. The configurational approach proposes the systemic representation of spaces (cities, regions), based on network descriptions, allowing the identification of a spatial differentiation, that is, a spatial hierarchy that emerges from the regional configuration. Some nodes (cities) will have locational privileges, in terms of relative position and number of connections, generating greater levels of proximity and the ability to intermediate shortest paths in the network. Over time, such locational advantages tend to translate into economic advantages, feeding back the process of spatial differentiation, hierarchy and centrality (BATTY, 2018).

This paper aims at presenting a methodology to analyze the role of the regional network configuration in the economic performance of the municipalities. The network of cities in Rio Grande do Sul is taken as an exploratory empirical study. The specific objectives are: a) to model the network of municipalities in RS as a spatial system (graph), considering the municipalities (nodes) and state highways (connections); b) identify some configurational properties of this system and its components, such as accessibility and centrality; c) discuss the relationship between configurational properties and some economic attributes of municipalities (GDP and GVA) through a statistical analysis of clusters. We question: how does the performance of municipalities in the regional configurational network contribute to understanding their economic performance? As economic performance we will consider the municipalities' comparative results for the selected economic indicators (GDP and GVA).

It is worth noting that numerous factors have the potential to affect the economic performance of a municipality, from historical-cultural aspects, natural site, infrastructure, public incentive policies, among many others. This work will explore a specific factor, which is the performance of the municipality in the configuration of the spatial network on a regional scale.

The paper consists of six sections, in addition to this introduction. First we present the theoretical foundation of the work. Initially, the fundamental relationship between space and economy is discussed, followed by configurational studies and urban spatial networks. The fourth item presents the methodology, selected empirical data and analytical procedures. The fifth item brings the results of the empirical study of Rio Grande do Sul. The last section summarizes the main findings and discusses the strengths and limitations of this approach.

2 Economy and Space

For a long time, economic geography authors have been studying the importance of space in the economy. The geographer Walter Christaller described the hierarchy of the regional landscape in his theory of central place. This theory provides an explanation for the regularities in the spatial distribution of cities, with different sizes and distances from each other, based on the supply of goods and services that, the more specialized, the greater their area of influence and, consequently, the greater the distance between cities. Despite revealing relevant principles of regional spatial structuring, the theory of central place reflects a view of equilibrium and does not inform how the city system would react to changes such as population density or technological innovations, in the means of transport, communication and information (FUJITA; KRUGMAAN; VENABLES, 2002).

In the historical process of urbanization, we observe that the first cities were formed at accessible places in the territory, such as the confluence of rivers, ports, etc. Over time, these locational advantages generate economic advantages of local production and exchange. The so-called agglomeration economies result from the benefits generated by the spatial proximity of companies, which can lower transaction and production costs, inducing more specialized businesses and division of labor.

However, such agglomeration forces of economic activities do not seem to act in isolation. Some authors propose that the equilibrium spatial configuration of economic activities can be seen as the result of a process involving two opposing types of forces, that is, agglomeration (or centripetal) forces and dispersion (or centrifugal) forces (FUJITA; KRUGMAAN; VENABLES, 2002). The agglomeration forces are associated with easy access to inputs, labor and/or the consumer market, being consequences of the size and attractiveness of the consumer and labor market. Dispersion forces (agglomeration diseconomies) are associated with transport costs to supply distant markets, or the immobility of factors that could generate economic growth, or pure external diseconomies, such as congestion, pollution, among others (FUJITA; KRUGMAAN; VENABLES, 2002). There would be a tendency towards the spatial concentration of economic activities in some locations (cities) due to agglomeration economies. However, as the concentration process intensifies, centrifugal forces tend to appear. Such theory suggests an evolutionary process that includes periods of growth, stagnation and redefinition of functions and activities that lead to qualitative changes, opening possibilities for the creation of polycentricism and population movements, such as peripheral growth and dispersion, as well as their contrary, recentralization and densification.

Sixty years ago, Jane Jacobs argued that cities exist primarily to connect people, bring individuals together and serve as a place for exchanging the products of their work, and this, in turn, generates an infinity of networks (JACOBS, 1969). According to the author, networks of cities are fundamental for economic expansion through the mechanism of import substitution. Local production tends to replace what is imported from elsewhere, thus introducing “new work”. Cities grow and expand economically through the introduction of this “new work” creating a more complex division of labor (JACOBS, 1969). This dynamism requires long-distance relationships that go beyond local services, creating opportunities for more complete and complex relationships.

At the end of the 20th century and the beginning of the 21st, this idea of networks, interactions and flows between cities gained prominence, based on the changes brought about by new information and communication technologies. Castells states that the global functions of some areas of certain cities are determined by their connection to global networks of financial transactions, management functions, academic research, technological development, etc. The dynamics of networks is capable of affecting the performance of certain locations, even though there are no specific changes in those locations. Transport and digital communication infrastructures constitute the nervous system of this polycentric metropolis. For places to become nodes of the global network, they need to have a multidimensional connectivity infrastructure: multimodal transport (land, air and sea), telecommunications networks, computer networks, advanced information systems, support services (hotels, entertainment, security, accounting, etc.) required for the node to function.

For Castells, the origin of these agglomerated urbanized regions is the ability to concentrate the production of services, finance, technology, markets and people. Such concentration provides economies of scale, as in past forms of urbanization.

The author considers that, currently, the spatial economies of synergy become more important, that is, being in a place that provides a potential interaction with valuable partners creates the possibility of adding value as a result of the innovation generated by this interaction. Synergy economies still require the spatial concentration of interpersonal interaction because, according to the author, face-to-face communication operates with much greater amplitude than digital communication at distance (CASTELLS, 2010, p.2742).

For Batty (2018, p.84) cities must now be looked at as constellations of interactions, communications, relations, flows, and networks, rather as than locations. In the author's view, locations synthesize the interactions between activities that occur across networks. Space can be considered as the integration structure of cities that allows networks - social or physical - to strengthen and develop over time (ZERTUCHE; DAVIS, 2019).

3 Configurational studies and spatial networks

Cities and regions have been considered as complex systems, composed of numerous elements or objects obeying local rules, forming a network where a change, even if small in any of these components, is capable of altering the state of the whole; complex because it is a system of systems, where, depending on the scale at which they are observed, new microsystems are discovered (BATTY, 2018). This new perception makes it possible to study the urban phenomenon through solid scientific approaches and the study of socio-spatial interactions has become the object of several researches. The study of spatial networks makes it possible to evaluate the regional system based on various properties (distance, relative position, number of connections, ability to intermediate paths, etc.) linked to the economic potential of spaces.

Batty (2018) states that to understand cities, we must simplify and abstract, we must dig below the surface of what we see and reveal the foundations of how cities function. Urban configurational studies (HILLIER, 2007; KRAFTA, 2014; VENERANDI et al, 2016) constitute a research area dealing with cities as spatial systems, analyzing their shape and structure in relation to other socioeconomic aspects (movement, uses, income, etc.). It is a quantitative approach, in which cities and regions are represented (modeled) as spatial systems. Such models apply methodologies for disaggregating cities and regions into components (elementary space units, spatial attributes) and their relationships (topological descriptions, adjacencies, connectivity). Graph theory provides the analytical basis for calculating different measures and properties of the spatial network. The models assume the shortest path hypothesis, that is, that the connections between network cells will always be made by the shortest paths.

Configurational studies discuss the potential of spatial configuration and land uses to promote movement (people, vehicles) and, in turn, the influence of movement on the evolution of urban systems. The theory of city as movement economies was developed from the notion of natural movement (HILLIER et al, 1993), showing that, other factors being equal, the flows of movement in different parts of a network of streets are systematically influenced by the spatial configuration of the network itself. The theory of economics of movement

(HILLIER, 2007) proposes a process in which the evolution of the spatial configuration of settlements generates movement patterns leading, trough multiplier effects, to dense patterns of mixed use and intensive development. Specific types of land use, such as commercial and service activities, need to be exposed to movement. Once they appear in a certain place, they help to reinforce this movement, due to their attractive nature. The theory associates these three factors, spatial configuration, movement and land use and how they relate to the formation of centralities. Seen in this way, centrality is clearly a process and not simply a state, a process that contains spatial and functional components. It is present to some degree in every type of urban structure and can evolve over time.

While Hillier's discussion focuses on intra-urban space, this reasoning also applies to regional space. Some nodes (cities), given their relative position, number and distribution of their connections, enjoy advantages of accessibility and centrality in the network of cities, with the potential to influence other aspects such as movement, land use, location of attractive functions, density and socioeconomic interactions. This process feeds back and is cumulative, translating into a heterogeneous network of cities changing over time.

Recent studies have sought to relate the configuration of the regional spatial network with regional hierarchy (CALVETTI, 2016), polycentric urban regions (KRENZ, 2017), the institutionalization of metropolitan regions (UGALDE et al, 2017) or the influence of the regional system on urban forms (COLUSSO, 2015).

Several centrality measures have been developed in order to capture the properties of the spatial system and its constituent elements (LIMA; KRAFTA; RIBEIRO, 2017). Proximity centrality (accessibility) is a measure of the relative distance of a space in the system, it relates to the facilities and difficulties of reaching a certain space and can be defined as the property of a cell being closer to all the others in the network, considering the minimum (or preferential) paths between them (INGRAM, 1971). On the other hand, betweeness centrality is the property of a space falling on the path that connects two others, and its hierarchy is given by the total number of times it appears in the paths that connect all pairs of cells in a system (FREEMAN, 1977). A variation of this measure is the Freeman-Krafta Centrality, introducing the notions of tension and distances: tension reflects the relationship between two cells expressed by the product of their content; the distance refers to the length of the shortest path between each pair of cells, and as distance increases, the centrality of each cell in the path decreases (KRAFTA, 2014).

Concluding this item, we consider the spatial structuring of economic activities as a process of synergy between configuration, movement and land uses (HILLIER, 2007). From some initial locations with accessibility attributes, agglomeration forces tend to spatially concentrate economic activities (industry and services), through a self-reinforcing mechanism. This self-reinforcement involves not only companies attracting other companies (specialized or diversified), but also movement, population, income and infrastructure. In this context, the measure of distance/proximity becomes relevant, as it is associated with the accessibility of each node in the spatial network.

On the other hand, municipalities strategically located and central to the interaction with others are capable of generating centrifugal forces. Factors such as the possibility of reducing transport costs, access to more distant markets, availability of large areas of lower cost, among others, can place these municipalities as new alternatives for locating economic activities. Again, the process of self-reinforcement leads to the concentration of activities at these new points and, at a later time, dispersion forces will act again in the search for new strategic points. Thus, our hypothesis is that the simultaneous attributes of high accessibility and high centrality of municipalities in the spatial network may influence the location of more dynamic economic activities (industry and services).

4 Methodology

This paper develops a spatial analysis on a regional scale, based on the relationship between configurational and economic indicators. The methodology was proposed in three stages, which are presented below.

4.1 Step 01: Configurational indicators

The first step was modeling the spatial system of Rio Grande do Sul state. We adopted a nodal representation, where each city in the state is represented by a point (node) and the highways between the cities represent the connections (links). An advantage of the nodal representation is that it does not present distortions between the real distances and the distances in the equivalent graph.

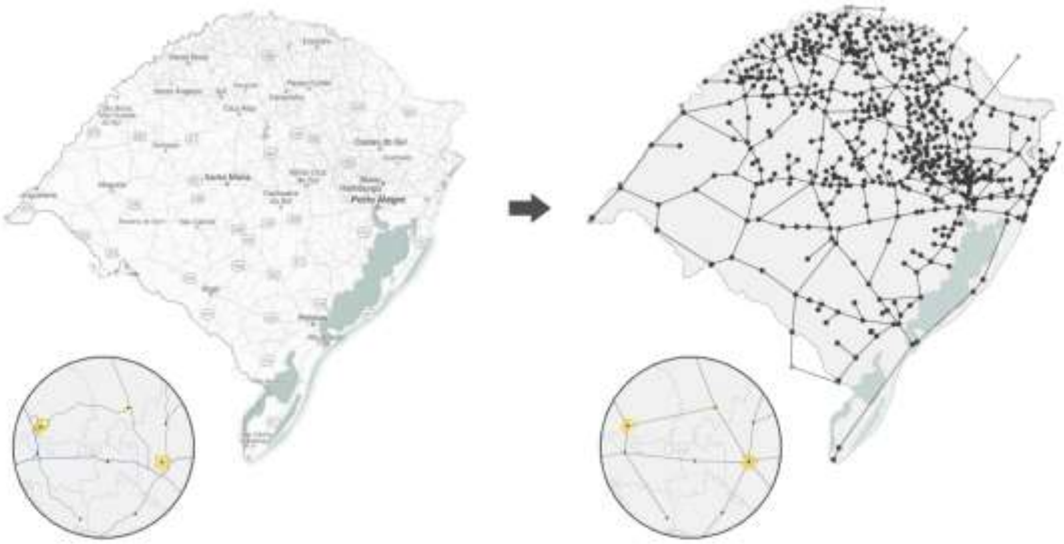
The model was elaborated in the software QGis v3.10 (QGIS, 2020) using the following files as a basis: a) shapefile containing the road network of Rio Grande do Sul state, obtained from IBGE, year 2015 (IBGE, 2015a) which includes the division of the RS territory into 497 municipalities; b) shapefile of urbanized areas of Rio Grande do Sul state obtained from IBGE, year 2015 (IBGE, 2015b) with urbanized areas of municipalities, this shapefile is only available for cities with more than 100 thousand inhabitants; c) road network of the Autonomous Department of Highways of RS (DAER) in 2015 (RIO, 2015), this map is not available in shapefile format, so it was only used to confirm connections between cities; d) satellite images from Google Earth and Open Street Maps, used for conferences and adjustments to the spatial representation.

We used the file of the urbanized areas (IBGE, 2015b), to generate centroids of each municipality through the "Polygon Centroids" tool (QGIS, 2020). Some municipalities had more than one spot, and through the analysis of Google Earth satellite images, the municipal seat was identified (larger, denser, presence of the City Hall, City Council, etc.). The municipalities that did not have the urban area vectorization in the IBGE shapefile received an approximation using Google Earth images. A shapefile was created containing each of the 497 municipalities in the state; each one was represented by a point (node).

Using the DAER road network map (RS, 2015) and based on satellite images, a second shapefile was developed with the connections between the cities. We used a straight line connecting the points that correspond to the cities; all the paved federal and state highways were represented. It should be clarified that: a) some municipalities have more than one access of this type, generating more inter-municipal connections; b) a few municipalities do not have accesses of this type. In these cases, connections through paved municipal roads were allowed, and in the absence of these, unpaved municipal roads were considered. This strategy was used to prevent any municipality from being disconnected from the network. Another particularity of this model is that when representing the highways, some nodes were generated that represent road junction points, where the highways cross or bifurcate to give access to some municipality. Such nodes compose the system graph, but do not receive the attributes of cities.

We must highlight that, when modeling only a part of a wider spatial system, elements and events that occur beyond the boundaries of the model are excluded. As algorithms are fundamentally relational, such an omission can affect the results (GIL, 2016). In the case of RS, this edge effect is naturally minimized by the presence of the coast to the east and the Uruguay River to the west, which limits connections to a few cities with border bridges. We sought to include the immediate connections between the municipalities on the RS border with municipalities in Uruguay, Argentina and the state of Santa Catarina. Figure 1 presents the resulting graph.

Figure 1 - Municipalities of RS (left) and nodal representation of the network graph (right). In detail, the nodes positioned at the centroids of urbanized areas.



Source: authors

After finishing the spatial representation, the Graph Analysis of Urban Systems - GAUS software (KRAFTA; DALCIN, 2020) was used to calculate the spatial measures. The distances were geometrically processed (geodesic) in order to maintain the real distance between cities, which is relevant when it comes to this state scale. Accessibility and Freeman-Krafta Centrality measures were calculated. The GAUS software adds the measures values for each node to the attribute table. Using the layer “Municipal road network of RS”, and the tool “Join attributes by location”, the data of “Municipality Name” and “Municipality Code” were added to the nodes. The road junctions were manually identified and these fields were deleted from the table, thus generating 497 nodes that have the attributes of “City code” and “Municipality name” and 111 empty nodes, which do not have these attributes.

In order to create clusters of these nodes, we used the QGis plug-in “Attribute based clustering”. The attributes considered for creating the clusters were the Accessibility and Freeman-Krafta Centrality values. The K-means clustering method was used, which is based on the concept of similarity, that is, the main idea is to find similar items according to their attributes. It is possible to choose the number of clusters and we used the Elbow Method to define this optimal number. This method consists of analyzing the sum of the squared distances of a value in relation to the centroid of the closest cluster, verifying how close the value is to its peers. This verification simulates the various possibilities of clusters (in this case, 'k' from 1 to 50) and calculates the sum of the distances for each of the cases, thus generating a graph of distance per 'k' (number of clusters).

As the number of clusters increases, up to the point where there is one cluster per value, the sum of the distances tends to zero. The optimal number of clusters would then be the value of 'k' where the curve starts to change behavior, the "elbow" point. However, sometimes this point is not easily visible and there are algorithms within the Python environment that help in this reading. Following the described method, we defined seven clusters for analyzing our results.

4.2 Step 2: Economic Indicators

This work sought to relate configurational attributes to economic attributes of the municipalities, here analyzed through the Gross Domestic Product (GDP). The value of GDP is the main measure of the total size of an economy, and can be obtained by adding the values of Gross Value Added (GVA) of each sector of the economy in a region (agriculture, industry and services) plus taxes (PESSOA, 2017).

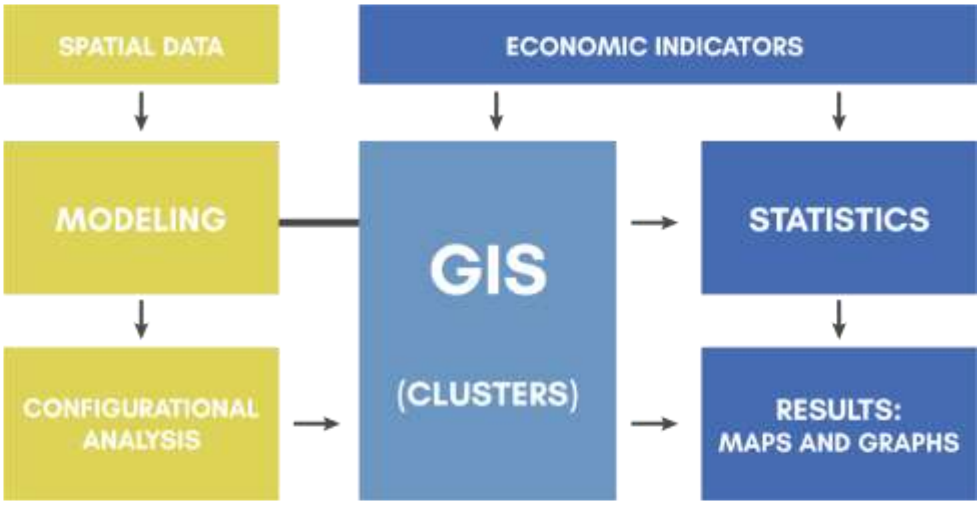
GVA Services includes trade, transport, education, communication, professional and scientific activities, health and public administration. The Agricultural GVA includes agriculture and livestock; the Industry VAB refers to industrial production. In this work, values of GVA and GDP come from the Fundação de Economia e Estatística (FEE-RS), year 2015 (PESSOA, 2017).

In the GIS environment, using the “Join Layers” tool, the GDP and GVA were allocated as node attributes using the “City Code” as a connector. Therefore, only the municipalities received these attributes, the empty nodes (road junctions) had no values.

4.3 Step 3: Analysis of the relationship between the proposed indicators through a statistical analysis

The last methodological step analyzes of the relationships between the configurational performance of the municipalities and their economic attributes (GDP and GVA). Using the Minitab statistical software (MINITAB, 2020), bivariate correlations were first generated between the configurational measures in separate (Accessibility and Freeman-Krafta Centrality) and the economic indicators. As a second analysis, graphs were generated using the seven clusters generated with the combination of the two measures. The idea is to verify the percentage of GDP and GVA that each cluster captures from the total of the state. In this statistical step, only the 497 nodes of the municipalities were considered. Figure 2 summarizes the steps of the proposed methodology.

Figure 2 – Research methodological steps



Source: authors

5 Empirical study: Rio Grande do Sul spatial network

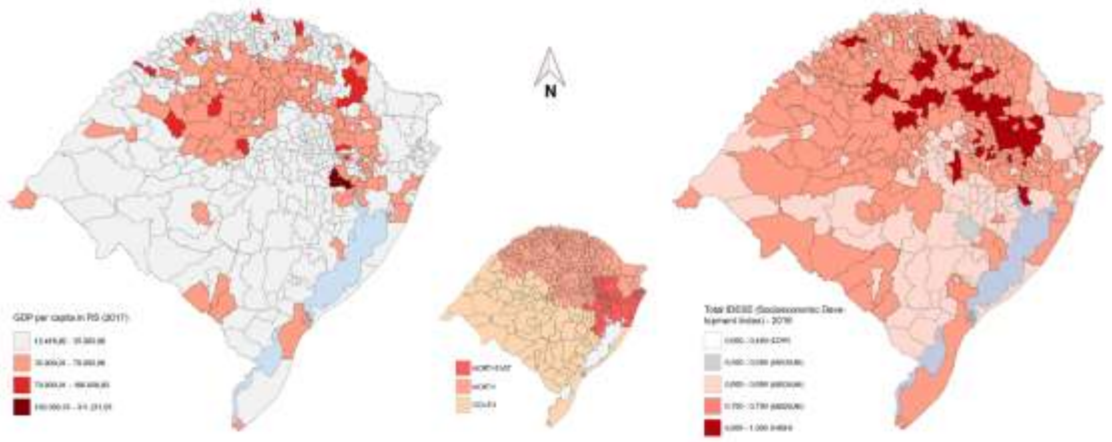
5.1 Brief contextualization of the regional structure of RS

Rio Grande do Sul has an estimated population of 11,422,973 inhabitants, ranking 5th in population and 4th highest per capita income among Brazilian states (IBGE, 2017). The state has strong regional inequalities in terms of socioeconomic development, and three distinct macro-regions can be identified: north, northeast and south (ALONSO, 2006). The southern region of RS has larger properties, livestock and rice farming, and low population density. The northern region is predominantly agrarian, characterized by small and medium-sized properties, where initially diversified production gave way to mechanized wheat and soybean crops, concentrating the land. The northeast region is characterized by the presence of several industrial sectors, small properties, in addition to large urban concentrations and high population density. The last two regions constitute the northern half of the state.

Such socioeconomic disparities between the southern and the northern half of RS have their origins in the historical process of the territory occupation. The southern half was influenced by Portuguese colonization, based on the agricultural sector and large monoculture plantations. The northern half was forged through Italian and German immigration, in diversified production on small properties and greater population density (SHULZ; KÜHN, 2020).

Alonso (2006, p.104) shows that the participation of the southern region in the industrial GDP of RS was 34.57% in 1939, and in the following decades it experienced a persistent process of relative deindustrialization, reaching the mark of 9.6% in 2001. According to the author, this shows that the industrial park that was formed in this part of the state (beef, rice and wool processing) never gave it the status of an industrialized region. On the other hand, the other macro-regions (north and northeast) were the main beneficiaries of the industrial expansion that took place in the state. The northeast region has been leading industrial production from 1939 (47.57%) to 2001 (70.35%) and the northern region has maintained relative stability in this indicator (17.85% in 1939 and 20.05% in 2001). Figure 3 illustrates regional inequalities, through the indicators of GDP per capita and the Total Socioeconomic Development Index (IDESE).

Figure 3 - GDP per capita and Total IDESE with an indication of the division into three macro-regions (based on Alonso, 2006)



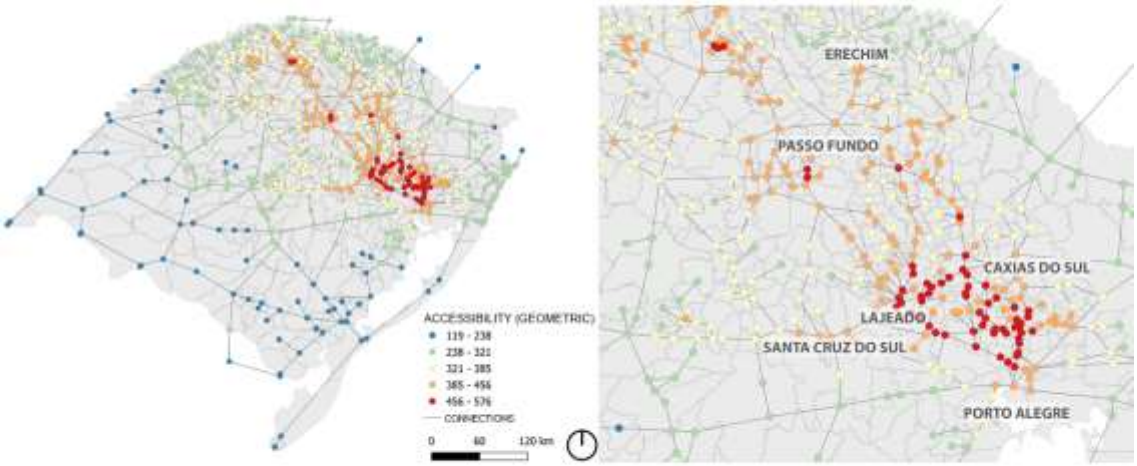
Source: authors based in RS 2020a e RS, 2020b.

The North and Northeast macro-regions have in general higher GDP per capita and are classified with high IDESE values. It is clear that RS presents a very heterogeneous and hierarchical network in economic and social terms, leading us to explore the relationships between the configuration of the spatial network and the other attributes of the cities.

4.2 Results and discussion

As mentioned, the methodology proposed in this work initially involved the modeling of the network of municipalities in RS and the calculation of configurational measures of accessibility and centrality of the spatial network, whose results are shown in Figures 4 and 5.

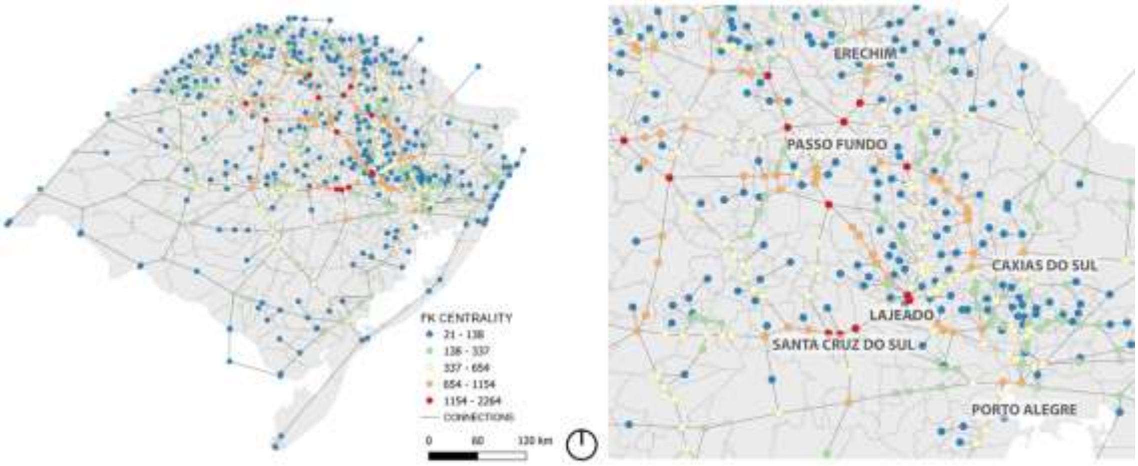
Figure 4 - Cities by accessibility classes in the RS network.



Source: authors

Accessibility refers to the ease of accessing a place; to the property of being closer to all others or more distant (more segregated in the system). The results highlight the RS northeast and also the northwest region, from the Metropolitan Region of Porto Alegre (MRPA) up to Lajeado. This group of cities enjoys an advantage of proximity in the network, favored by the relative position and density of existing road connections. On the other hand, centrality (Figure 5) reveals the relative importance of municipalities in the routes (shortest paths connecting the spatial system), being associated with trough-movement. Again in the RS northeast some axes that connect important cities stand out, such as BR 386 (towards Lajeado and Carazinho), BR 453 (Lajeado towards Caxias do Sul), BR 470 (Bento Gonçalves towards Passo Fundo). It is interesting to note that 162 municipalities resulted in zero centrality, meaning that they have a single access and are not the path to any other.

Figure 5 - Cities by classes of Freeman-Krafta centrality in the RS network.



Source: authors

Table 1 presents an analysis of bivariate correlations between economic indicators and configurational measures.

Table 1 - Statistical correlations between configurational and economic indicators

Spatial Indicator	Economic Indicator	Spearman Correlation	Confidence Interval
Accessibility	GDP	0,101	0,013 ; 0,188
Accessibility	Services GVA	0,090	0,002 ; 0,177
Accessibility	Industry GVA	0,243	0,157 ; 0,325
Accessibility	Agricultural GVA	-0,262	-0,343 ; -0,177
FK Centrality	GDP	**0,438**	0,361 ; 0,510
FK Centrality	Services GVA	**0,455**	0,379 ; 0,526
FK Centrality	Industry GVA	0,408	0,328 ; 0,481
FK Centrality	Agricultural GVA	0,289	0,204 ; 0,369

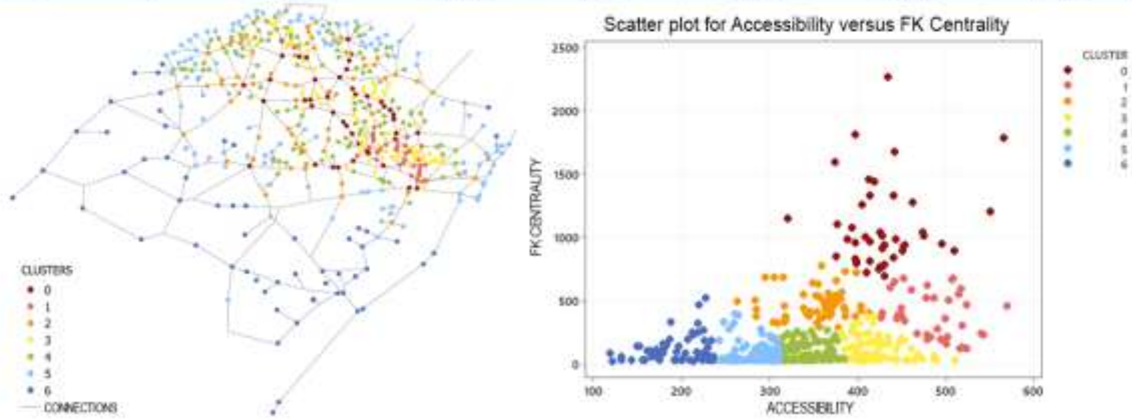
Source: authors

The correlations were all significant; and zero value is not included in the confidence intervals, demonstrating a statistical correlation between the configurational measures and the economic attributes. The highest correlations were found between Centrality FK and Services GVA (0.455) and Centrality FK and GDP (0.438), being positive moderate correlations. As expected, the correlation between Accessibility and Agricultural GVA was negative, which means that the higher Accessibility values, the lower the Agricultural GVA values. Agricultural activities do not follow the pattern of agglomeration and accessibility of industrial and service activities. The road network at southern RS is more rarefied, with fewer road connections and large distances between its urban centers, thus reducing its accessibility values. The GDP, which includes the total wealth produced by the municipalities, had a stronger correlation with FK Centrality (0.438) than with Accessibility (0.101), evidencing the role of the strategic location of municipalities.

In order to test our hypothesis, a second analysis was performed considering that both configurational measures, simultaneously, are related to the presence of industrial and service economic activities. For this, seven clusters of municipalities were identified, using the values of accessibility and FK centrality as attributes for the grouping. Figure 6 presents the table with the seven clusters, informing the number of municipalities, the minimum, maximum and average Accessibility and FK Centrality of each of the groups, identified by colors. Below is the map of RS with the identification of the location of the municipalities in each cluster by color. On the right, the scatter plot, where the "y" axis presents the FK Centrality values, and the "x" axis the Accessibility values, also identifying each cluster by color.

Figure 6 – Table, map and graph with the identification of seven clusters of municipalities in RS according to the Accessibility and Freeman-Krafta Centrality

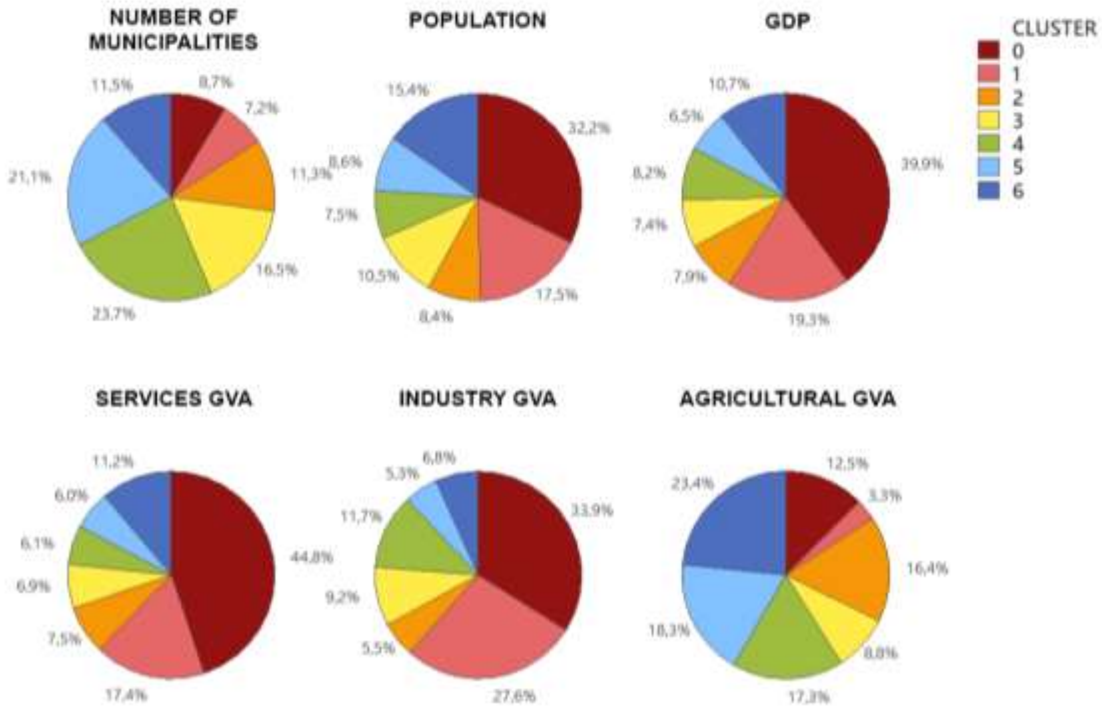
CLUSTER	NUMBER OF MUNICIPALITIES	MIN. ACCESSIB.	MAX. ACCESSIB.	AVG. ACCESSIB.	MIN. FK	MAX. FK	AVG. FK
0	43	319,67	564,95	428,44	697,00	2264,37	1087,53
1	36	425,85	568,83	486,05	121,63	676,94	392,07
2	56	262,07	412,33	350,67	289,12	780,05	474,41
3	82	379,71	509,95	419,41	29,37	382,54	119,60
4	118	312,66	383,21	344,07	33,20	269,70	92,27
5	105	237,73	311,56	281,07	27,84	394,02	85,35
6	57	119,05	235,89	195,14	28,26	522,04	116,26



Source: authors

Figure 6 shows that cluster zero (dark red) brings together the municipalities with the highest accessibility values and FK centrality simultaneously, followed by cluster one (pink), also with high accessibility values. Clusters number four (green), five (light blue) and six (dark blue) are the ones with the lowest values of centrality and accessibility simultaneously. The other clusters identify groups with different compositions for the measurement values. A comparison of these clusters with the economic indicators is presented in Figure 7.

Figure 7 - Clusters of municipalities and their performance in the economic indicators.



Source: authors

These results would allow a detailed discussion of different empirical situations in RS, which is beyond the scope of this work. Here we will focus on just a few relevant relationships arising from the proposed method. As mentioned, cluster zero (dark red) identifies the group of municipalities with the highest values of Accessibility and FK Centrality. It can be seen that this cluster includes only 43 municipalities (8.7% of the total), but concentrates 32.2% of the population, 40% of the GDP, 44.8% of the Services GVA and almost 34% of the Industry GVA of RS. This cluster shows the best configurational performance and is composed, in addition to Porto Alegre, of the northeast municipalities, around the BR-386 (Lajeado, Estrela, Carazinho, Passo Fundo, Erechim) and some municipalities in the high elevation region (Bento Gonçalves and Garibaldi). Outside this northeast axis, we found Santa Maria, in the central region, Santa Cruz do Sul and Venâncio Aires, in the Vales region and some municipalities further north (Ijuí, Panambi and Cruz Alta).

When clusters zero and one are analyzed together (the latter with high accessibility values and medium FK Centrality values), it can be seen that these 79 municipalities (15.9% of the total) cover almost half of the population of RS (49.7%), almost 60% of GDP, 62.2% of Services GVA, 61.5% of Industry GVA. In the case of agricultural GVA, almost 60% of its added value is in the three clusters with the worst performance in accessibility and centrality (4, 5 and 6).

From this empirical analysis it is also possible to identify the presence of endogenous factors to the regional structuring process, that is, the mutual influence between industrialization, population growth and improvement of infrastructure, indicators that reinforce each other and tend to grow together.

6 Final remarks

This paper presented a methodology to analyze the role of the spatial network of municipalities' configuration on their economic performance. The exploratory empirical application in the RS network indicated that the simultaneous attributes of high accessibility and high centrality of municipalities in the spatial network are associated with the presence of more dynamic economic activities (industry and services). We found the relevance of the northeast macro-region of RS, as already identified in the 1990s by Alonso (2006) as the most dynamic and industrialized. The northeast region presented a high spatial hierarchy, in terms of accessibility and configurational centrality. These results confirm our hypothesis, even if preliminarily; however, further studies are needed to deepen this understanding.

Processes of regional industrialization and urbanization are complex, dependent on several factors. In this work, we focused on a specific aspect, that is, the performance of municipalities in the regional spatial network. Our empirical case indicates the dependence of the initial conditions and the history of the regions. In the case of RS, the initial occupation, the type of land property, natural resources and population seem to characterize the structure of the urban network until these days, as north-south dichotomy.

Also noteworthy are the regional inequalities associated to industrialization processes. From the point of view of regional economic planning, public policies seek to maximize the effects of more dynamic industrial activities. For Souza (2005, p.108), in practice, public investments tend to focus on infrastructure and directly productive activities in certain regions, creating or reinforcing existing poles. Thus, growth has been spatially uneven, causing strong inter-regional migrations, and the impoverishment of peripheral regions. According to the author, the challenge of obtaining a less polarized growth would involve the development of urban networks, linked to the main centers by means of transport and communication channels, favoring contacts between polarized companies, located in smaller centers, with others in the larger centers. This highlights the importance of the urban spatial network in economic processes and regional development policies. Planning actions require an in-depth knowledge of this socio-spatial network and its relationship with industrialization processes, underlining the importance of studies such as the one presented here.

In the sequence, we include some considerations about our methodology. The proposed method allowed for a disaggregated analysis of the performance of each municipality in the spatial network, enabling a deeper study of the spatial constraints to the location of economic activities and identifying its strengths and weaknesses. A virtue of the proposed methodology is the possibility of generating alternative scenarios, for example, simulating the building of a new highway, evaluating impacts in terms of losses and gains in accessibility and centrality. In addition to physical networks (roads) there is the possibility of including other types of functional networks in the modeling, such as public transportation or internet, as layers in the model. The possibility of representing these other types of functional flows (physical and remote) between municipalities allows the analysis of regional systems as multi-layer networks of socio-spatial interaction, exploring the combination of physical, functional, operative, economic, cultural elements, etc.

Another model exploration is to weight the municipalities based on some attributes, such as population, number of industrial jobs, retail establishments, educational institutions, among others. In this way, specific models can be generated to analyze different aspects of the network. Working with directed graphs (origins and destinations) it is also possible to simulate the interactions between complementary activities (universities x young population; jobs x working age population, etc.), giving greater realism to the model. To calibrate the model, it is also possible to introduce impedances in the connections (roads), in order to represent restrictions on road capacity, resulting from the width of the lanes, paving, etc. Such possibilities were not tested in this work, but remain as possibilities for future studies.

In this work, the regional spatial structure was analyzed in a specific time frame, even knowing that this process is dynamic and evolutionary. Future studies can develop evolutionary analysis, relying on time series data, which could help to identify transformation trends.

About empirical data, we privileged open data, such as those from IBGE and FEE-RS and available technologies, such as QGIS and OpenStreetMap. As for the calculation of configurational measures, we used GAUS (KRAFTA; DALCIN, 2020), a software developed within research scope, available for non-commercial uses. Several other similar software are available, such as Numerópolis (KRAFTA; SPRITZER, 2018), UNA – Urban Network Analysis (SEVTSUK, 2017), DephtmapX (VAROUDIS, 2020), UrbanMetrics (POLIDORI et al, 2016).

In conclusion, systemic and quantitative methodologies, such as the one presented here, play an important role in revealing the spatial structure of cities and regions.

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