Modelling Spatial Centrality of Logistics Activities: Study in the Porto Alegre Metropolitan Region, Brazil

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Abstract. Recent transformations in the sphere of production and consumption have created a wide market for the logistics activities. Beyond economic development, such activities can also trigger spatial impacts becoming an urban planning concern. The purpose of this article is: a) to present a methodology for analyzing spatial distribution of logistics activities based on configurational models; b) apply this methodology to the Porto Alegre Metropolitan Region, Brazil. We propose a synthetic measure of the centrality of logistics activities, conceptualized as a hierarchy or locational advantage, and related to access to transportation routes, potential for movement and agglomeration economies. We question: How is this centrality of logistical activities spatially distributed? Is there spatial concentration or decentralization? The regional spatial system is modeled as a network of road segments and we apply Freeman-Krafta Centrality model, weighted by the amount of logistics employees. Empirical data come from RAIS (Annual Census of Social Information), provided by the Ministry of Labor, year 2019. The results show that the proposed methodology is able to identify the spatial distribution of centrality and its irregular pattern over the region. The conclusions point to the relevance of configurational approaches for logistic space studies, as well as potentialities and limits of this methodology.

Keywords: Logistics activities · Spatial centrality · Porto Alegre · Brazil

1 Introduction

Logistics activities include those related to storage, transportation, and product distribution services. Recent transformations in the sphere of production and consumption are restructuring the supply chain and creating a strong market for the logistics sector. The original development foundation of the logistics sector comes from the demand generated by the manufacturing industry [1]. The transfer of logistics functions to other

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companies allows manufacturing industries to focus more on their core activities, seeking efficiency and competitiveness. In the commercial sector, there is also an important transfer of the amount of activities from retailing to logistics sector. According to Coquillat [2], the rapid development of e-commerce tends to eliminate the last link of the supply chain, consisting of the physical spaces of the stores, transferring their functions to other links behind the chain, now absorbed by the logistics sector. The COVID-19 pandemic and the imposition of social distancing tend to further accelerate the transition to trade headed by the logistic sector.

Logistics activities generate economic and spatial development in cities and regions as well as increase jobs and tax revenues; however, such activities can also trigger spatial impacts. Studies are showing that warehouses and distribution centers tend to move away from urban areas towards more suburban and exurban ones, offering lower land prices and good access to highway networks [3]. This sprawling can have negative consequences such as expansion over rural areas, attraction of new residential developments, increasing traffic, pollution, among others, becoming an urban planning concern. Studies in Europe and North America have detected a tendency towards the concentration of the logistics activities at the macro-scale (national, regional) accompanied by a dispersion at smaller scales (intra-regional, metropolitan). In Brazil, there are few studies on this theme, and they focus mainly on the macro scale (country).

The purpose of this article is: a) to present a methodology for analyzing spatial distribution of logistics activities based on configurational models; b) apply this methodology to the Metropolitan Region of Porto Alegre (MRPA), Brazil. We apply a quantitative approach, based on urban network analysis [4]. The intention is to add in the literature by analyzing a case in Brazil, on a metropolitan region scale. This study may be helpful to urban and regional planners providing a better understanding of the spatial relations of logistics activities.

The paper is organized as follows. Section 2 presents a brief review of the location of the logistics activities while also focusing on the configurational approach. Section 3 describes the methodology, empirical data, and the modeling process. Section 4 presents the results and discussion. The last section brings some conclusions, potentials and limitations of the adopted methodology and future research directions.

2 Logistics Activities on Urban and Regional Space

2.1 Location of the Logistics Activities

The problem of the location of activities is of the utmost importance having a significant impact on the operating costs and competitiveness of a business as well as on the price of its goods or services. For logistics enterprises, the transportation of goods is at the core of their business, so accessibility plays a major role in the location decision. Highly accessible areas tend to attract logistics enterprises and employment. Accessibility can be understood as way of overcoming the effect of space (distance, time) in the movement of people and goods, as well as in the exchange of products, services, and information. It is the transport availability that helps to reduce spatial friction on the movement of goods. The location of logistics activities is therefore very sensitive to the quality of the

highway network and the fluidity of traffic; but it fears the bottlenecks that contribute to traffic congestion [5].

The logic for the logistics enterprise's location lies between that of industries and services [6]. Factors bringing logistics locations closer to that of industry are: close links with transport infrastructure, the needs for large amounts of space, and the negative externalities generated. Some factors, on the other hand, bring together the logistics locations to that of services: the close ties with the market demand and the weight of land prices in the location choice. Government policies are also relevant, such as infrastructure provision, zoning, and incentives.

The presence of several of these factors in a region promotes the concentration of logistics activities. Spatial concentration is favored by agglomeration economies related to labor market (specialized labor), inputs sharing (combining transport flows, reducing transportation costs) and knowledge spillovers (cooperation between enterprises). This polarization of logistics facilities towards large urban regions at the relative expense of smaller areas has been noted in several world regions [6]. In the case of Brazil, Catapan and Luna [7] identified concentrations of logistics activities in some southern and southeastern states of the country. In the capitals of these states, which are large consumption centers, there is a greater concentration of logistics activities, aimed at serving the consumer market. Concentrations of logistics activities associated with industrial activities were also identified. In these cases, factors related to the availability of transport infrastructure (highways, multimodal terminals, and ports) and the supply of production factors (specialized labor, government incentives) are preponderant.

On a smaller scale, 'sprawling' patterns have been identified for logistics firms in some urban regions. In a study in North America, Woudsma et al. [3] find that warehouses and distribution centers are sprawling within the core urban area of Toronto and also the exurban area, offering lower land prices and good access to highway networks. However, negative consequences of this sprawl are additional truck-miles traveled and subsequent emissions and congestion, causing concern among city managers.

The driving forces of logistics activities spatial evolution can be seen as centripetal (agglomeration) and centrifugal (dispersion) provided by land price, market demand, traffic accessibility, agglomeration advantages and government policies [8]. These forces act at different spatial scales and may change over time.

2.2 Logistic Space and Urban Configuration

An interesting way to understand logistic space is considering it as a spatial system composed of logistics enterprises, logistics nodes and logistics infrastructure [1]. In general terms, a system can be conceived as a set of interrelated components, where changes in one element may affect the entire system [9]. Studies of the urban form as a spatial system – network analyses - have been developed in geographic studies since the 1960's [10]. More recently, the availability of the necessary tools and data have spread network analysis for urban and regional studies.

Configurational studies were first developed by Hillier and Hanson [11] applying network analysis to urban planning and design, known as Space Syntax analysis. They

propose a relationship between the hierarchy of the street grid and other urban features as pedestrian movement, land uses, density, land prices, and so on. Several others approaches to graph analysis of street network have emerged since then [12–14].

Porta et al. [12] present a set of centrality indices for network analysis, being the main ones: closeness (relative distances), betweenness (importance in the shortest paths) and straightness (efficiency in the nodes communication). Each centrality captures a different aspect of one place as "being central" in geographic space. The authors find good correlations between densities of retail and service activities and betweenness centrality in studies in Bologna and Barcelona.

Broadly speaking, betweenness centrality is the property of a node (space) being along the shortest path that connects two other nodes, and their hierarchy is given by the total number of times this node appears in the paths connecting all pairs of a system [15]. Krafta [14] proposes an adaptation of betweenness centrality, named Freeman-Krafta Centrality, introducing the notions of tension and distance: the tension reflects the relationship between two nodes expressed by the product of its contents; the distance refers to the extension of the shortest path between each pair of nodes. The tension generated by each pair of nodes will be "dissipated", in other words, it will be distributed among all nodes that are part of the shortest paths. The method is capable of capturing the spatial differentiation resulting from the extension of paths. Freeman-Krafta (FK) centrality for a node k is defined as a three-step calculation (Eqs. 1, 2 and 3).

$$\text{Tension} : t_{ij} = a_i a_j \tag{1}$$

$$\text{Dissipation} : t_{ij}(k) = \frac{a_i a_j}{d} \tag{2}$$

$$\text{Centrality} : C(k) = \sum_{i,j}^{n} t_{ij}\,(k) \tag{3}$$

Where tij is the tension between two nodes i and j, ai and aj are the attributes respectively in i and j, tij(k) is the portion of tension between i and j attributed to k, where k is a node belonging to the shortest path(s) between i and j, d is the number of nodes in the shortest path. Finally, C(k) is the centrality of k given after the computation of all possible pairs of the system.

When compared to the original Freeman model, the FK centrality acquires new variables (activities and interaction between them) and new features (potential tension and extension of shortest paths). The model captures the essence of location advantages in urban or regional areas, and its values should be reflected in the intensity of movement (pedestrians, vehicles) and land uses, for example, densities of services benefiting from that movement. As can be inferred, the model contains both vectors of agglomeration and dispersion [14]. The agglomeration presents itself in the form of attractiveness of the more central locations in the system; dispersion is underlying the accumulation of activities, tensions and flows that can act as potential generators of congestion, costs of displacement and competition by location. The model captures a synthesis of both forces.

In this paper, we propose applying FK centrality model weighted by the amount of logistics activities in each space (node). We conceptualized it as a hierarchy, or locational advantage, related to access to transportation routes, potential for movement and

agglomeration economies. In the literature, several methods are used by researchers to assess spatial patterns of concentration and dispersion of establishments including average distance to the mean location or Gini indices to determine whether establishments are concentrated in particular areas. In this paper, we will explore a configurational method and a systemic measure, considering jointly the locational advantages of the street network and the concentration of firms expressing agglomeration economies.

3 Data and Methods

3.1 Dataset of Logistics Activities

The selection of logistics activities refers to CNAE 2.0 (IBGE) [16], a national classification of economic activities. Based on the literature [7, 17] 13 classes were selected and included as logistics activities, as shown in Table 1.

Table 1. Activities related to the transport and logistics sectors. Source: authors based on CNAE 2.0 (IBGE) [16]

Class from CNAE 2.0	Business description
49.11-6	Rail cargo transportation
49.30-2	Road freight transport
49.40-0	Pipeline transport
50.11-4	Inland shipping
50.12-2	Sea shipping
50.21-1	Transport by inland cargo shipping
51.20-0	Air cargo transport
51.11-7	Warehouse and storage
52.12-5	Loading and unloading
52.22-2	Road and rail terminals
52.32-0	Shipping agency services
52.50-8	Organization of cargo transport services
53.20-2	Mail and delivery services

Database on logistics activities comes from the national base of RAIS Microdata [18] available online. The database refers to the year 2019 and contains the following information about each registered business: activity classification, number of employees, city, and Zip Code. This data source is well documented and the methodology of collecting businesses is consolidated. Unfortunately, because of requirements for maintaining the anonymity of individual records, it is not possible to identify the exact location of the businesses, only the Zip Code is provided.

To localize each logistics firm, we used a Python code to convert the Zip Codes into geographic coordinates by converting them into addresses and them into "x,y" coordinates. With the geographic coordinates for each establishment, we were able to locate them in a GIS (Geographic Information System) environment [19]. It is important to clarify that, according to the Brazilian post system; cities under 50,000 inhabitants have only one Zip Code for the entire municipality. In our case, from the total of 34 MRPA municipalities, 14 are in this category having only one generic ZIP Code. In these 14 cases, we located the logistics firms in each city center not to lose their registries. The same method was used for some incorrect Zip Codes that could not be identified by our procedure, only the city. The original dataset contained 7,121 logistics firms' registers and 7,115 were successfully located.

3.2 The Process of Modelling MRPA Spatial System

The first step in the modelling the spatial system is to define the spatial representation of the road network. This representation allows defining the discrete unit of urban space to be used according to the study goals. We adopted a simplified version of the "road segment" representation where the spatial units (nodes) are the center portions of the roads between two intersections and the links are the connections between the roads.

We opted for using a simplified version of the road segment representation for three main reasons: a) we were interested in the results in the macro scale for the Metropolitan Area; b) the simplified version generates a lighter file, making the computer processing faster; c) the data of the logistics firms had a low level of spatial disaggregation, not requiring a network as disaggregated as the road segment representation.

The network simplification was based on the idea that urban streets are hierarchically organized in the sense that most streets are trivial, while a minority of streets is vital [20]. This hierarchy can be characterized by the 80/20 principle, where 80% of streets are less connected (below the average) in the system, while 20% of streets are well connected (above the average). Following this, we adopted a three-step simplification procedure.

First, we generate a complete network of the Metropolitan region based on OSMnx tool [21]. The second step was to calculate the frequency distribution of betweenness centrality and, as this distribution follows a power law, we selected only the streets in the head (20%) in two recursive rounds [22]. We then verified the results to check for the presence of all the highways (State and Federal), the urban main roads (arterials) inside each municipality and the paved roads relevant to the integration between MRPA municipalities. These procedures were developed in the software QGIS and were based on the official state road network shapefiles [23], as well as the limits of urbanized areas of the state, provided by IBGE [24]. The street hierarchy was checked using OpenStreetMap (OSM) and satellite imagery from Google Earth and Google Street View. The third step was to simplify the geometry of the network, directly connecting the remaining intersections with straight line segments, which is suitable for using topological distances in the model. Also, we defined a buffer of about 30 km around the limits of MRPA and included the connections to external municipalities to avoid the edge effect [25].

The final model, consisting of 3,111 road segments, was imported into GAUS (Graph Analysis of Urban Systems) software [26] a Python script developed as a QGIS plug-in. We then relate the points of each logistic establishment to the nearest road segment.

For that, the "Snap Points to Lines" feature in QGIS was used and then with the "Spatial Join" feature we were able to transfer the data from the logistics establishment's shapefile to the road segment one. The total amount of logistic employees in each road segment was included in the attribute table as a load. The software GAUS performed the configurational analysis, applying weighted FK centrality model and topological distances processed at global scale (radius n). The results obtained (tables and maps) were analyzed and evaluated, which are presented in the next section.

4 Results and Discussion

4.1 Brief Contextualization of MRPA and Logistics Activities

The MRPA) is the most densely populated area in the Rio Grande do Sul State (Fig. 1). In 2020, according to Population Estimates, it concentrated 4.4 million inhabitants or 38.2% of the total population of the State. From the 19 municipalities in the State above 100 thousand inhabitants, 9 are inside the MRPA, and the average demographic density in the region is 421.8 inhabitants/km^2 [27].

The MRPA was officially created in 1973 and was initially composed of 14 municipalities. The demographic growth of the Metropolitan Region is mainly the result of internal migrations, the interconnection of urban networks and the successive emancipations that occurred over the years. This caused new areas to be integrated into the Region, currently adding up 34 municipalities. Such municipalities have very contrasting socioeconomic indicators, reflecting an uneven distribution of economic resources and urban services and equipment such as transportation, health, education, housing, and sanitation.

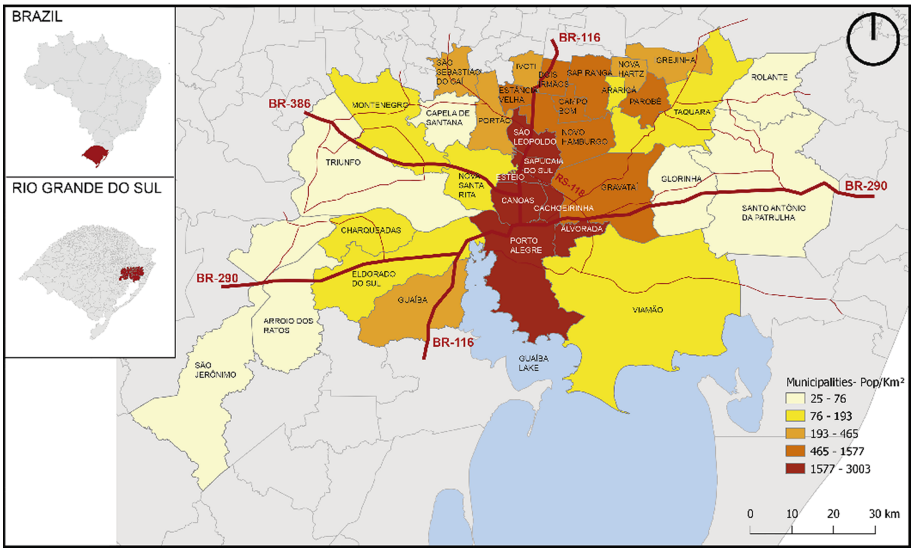

Fig. 1. Location of the Metropolitan Region of Porto Alegre, population density and main road system. Source: authors based on IBGE [24]

The Region is also a pole of attraction and functional complementarity, exhibiting an intense movement of people, attracted by the offer of services and jobs, becoming an area of intense economic expansion in the State. In 2002, industrial sector was responsible for 48% of the Region GVA (Gross Value Added), services sector was responsible for 51% and agriculture for only 1% [28]. The MRPA concentrates some important manufacturing industries, such as vehicle assemblers, petrochemicals, auto parts, plastics, food products, etc. The region is also located in a strategic position in reference to MERCOSUL (Southern Common Market), with Salgado Filho International Airport being the main gateway for passengers from countries in the Southern Cone.

Rio Grande do Sul has a relatively well-structured multimodal transport network; largely based on road transportation. In 2017 highways were responsible for 88% of the total transported, while in Brazil the share of this transport reached 65% [29]. There are also inland waterway routes and important ports, such as in Porto Alegre.

Figure 2 shows the number of logistics companies in the MRPA from 2006 to 2019. The graphic shows that the number of companies grows in both, State and MRPA until 2014, when national economic and political crisis impacted this performance. The variation in the number of companies (2006–2019) was +28% for the State and only +1% in the MRPA. This data reveals a decentralization process also occurring in the State scale.

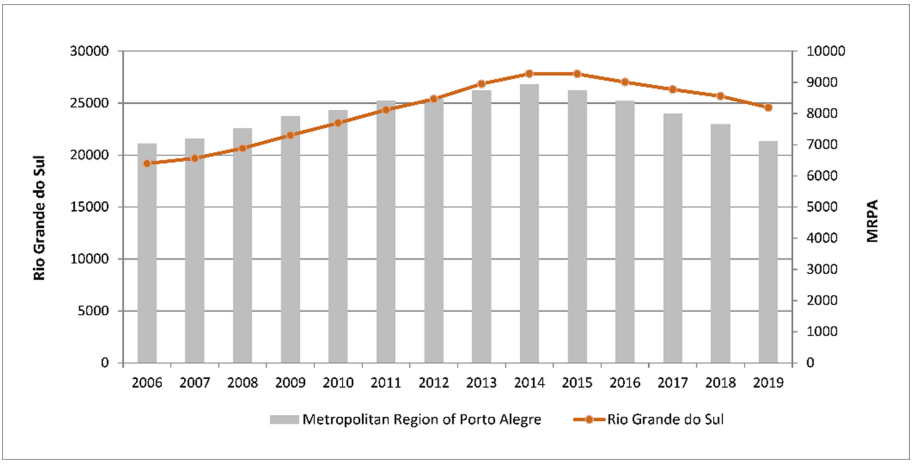

Fig. 2. Evolution on the total number of logistics companies in the MRPA and Rio Grande do Sul State, from 2006 to 2019. Source: authors, based on data from [30].

As seen in Fig. 2, the total number of logistics companies remains almost constant in the MRPA; however, the situation inside the region shows a different picture. Figure 3 shows the changes in the number of companies in each of the 34 municipalities of MRPA.

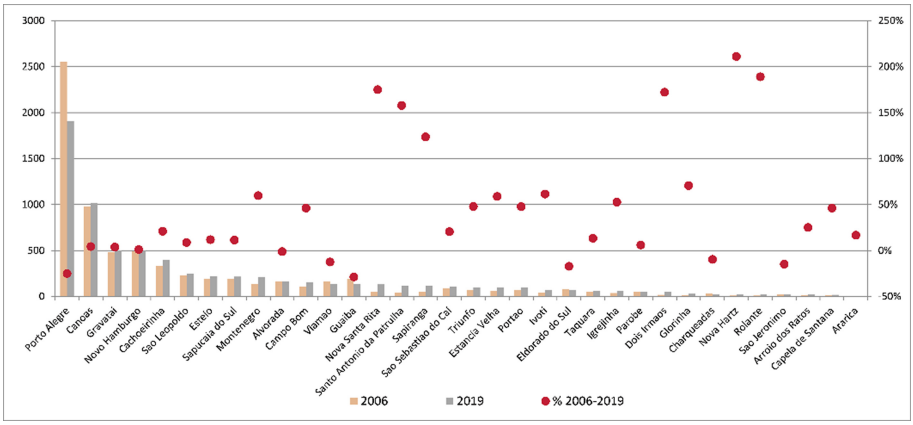

Fig. 3. Total number of logistics companies by the 34 municipalities in the MRPA 2006–2019. Source: authors, based on data from [30].

We can observe that logistics companies are concentrated in a few cities, mainly at the capital, Porto Alegre. The first eight cities make up 70.33% of MRPA companies in 2019. All these eight cities are connected by two important federal highways, BR-116 and BR-290. We can also observe a decentralization process, with Porto Alegre losing 25% of its establishments, reducing its share from 36.19% to 26.84% in 13 years. According to Alonso and Brinco [28], there is clear evidence of a process of loss of relative economic importance of Porto Alegre in the metropolitan context, as shown by the decrease from 34.70% to 30.09% of its GDP in the total aggregate of the MRPA, between 1999 and 2002. This decline affects especially the manufacturing sector of the capital city, in a movement whose origin dates to the early 1970s. This decentralization process of the manufacturing industry has affected logistics services, which are showing a similar trend.

4.2 The Spatial Centrality of Logistics Activities in the MRPA

This section initially presents the spatial distribution of logistics companies in MRPA (Fig. 4). As previously mentioned, there is a strong concentration along the main highways BR-116 and BR-290. The northern portion of Porto Alegre also concentrates logistics activities and is conceived as a Development Corridor by the local Masterplan. This area is in direct interface with the Metropolitan Region and the main highways, receiving incentives for the location of large-scale investments, including logistic ones.

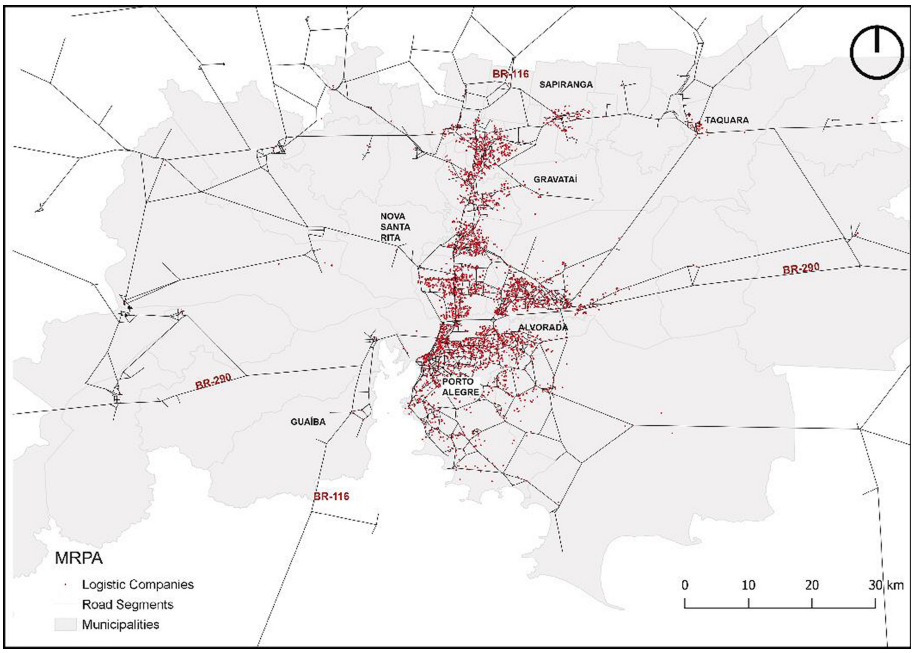

Fig. 4. Spatial distribution of the logistics companies in the MRPA in 2019 over the road segment model. Source: authors, based on data from [18].

In the historical process of urbanization of the metropolitan territory, the municipalities with the greatest economic development and population growth tend to have a more consolidated spatial structure with greater density of the road network and shortest paths. Small municipalities, on the other hand, often have only one road connection with the rest of the MRPA and, depending on their location, can be very isolated from the point of view of the global system. The metropolitan road network shows this asymmetry (Fig. 4). The weighted logistic centrality measure captures this asymmetry in the network and associates it with the uneven distribution of logistics companies, resulting in a measure that expresses this spatial differentiation (Fig. 5).

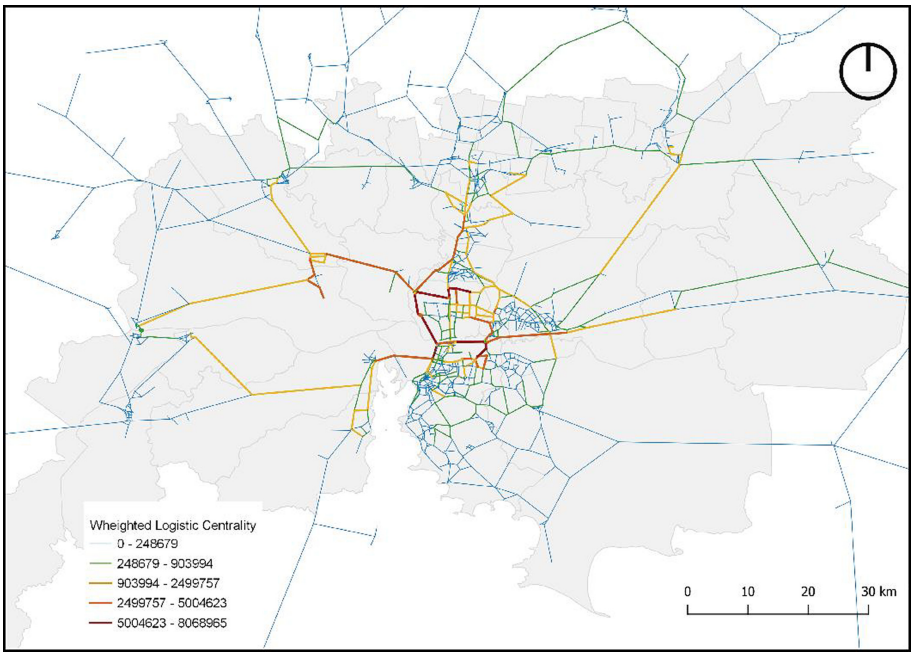

Fig. 5. Logistic centrality in the MRPA - weighted by the number of employees (5 classes, natural breaks). Source: authors.

Logistic centrality is concentrated in the region around the crossing of the main highways (BR-116 and BR-290). Another highway in the northwest (BR-386) connects industrial areas and shows high centrality values.

As previously mentioned, this hierarchical distribution can be characterized by the 80/20 principle, where 80% of streets are less connected, while 20% of streets are well connected; out of the 20%, there is 1 percent of streets that are extremely well connected [20]. Figure 6 shows that the ranking of the logistic centrality values follows a power law, with few road segments having extremely high values.

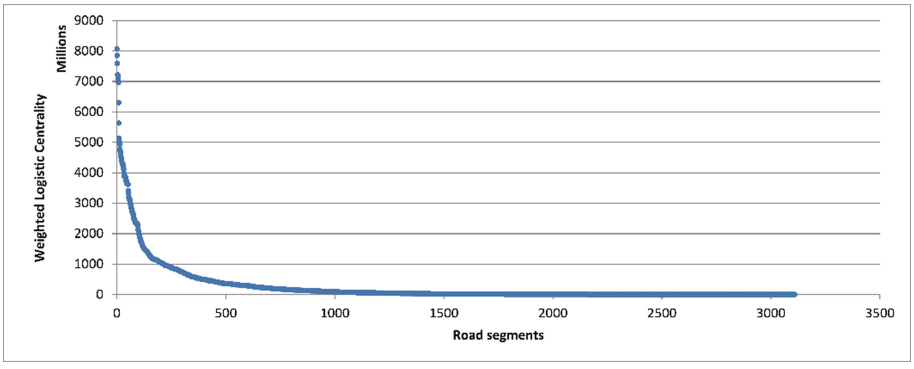

Fig. 6. Ranking of the values for weighted logistic centrality. Source: authors.

Figure 7 highlights the road segments with 1% and 20% highest values of this centrality. We observe that these very high values of centrality cover an area that goes from Porto Alegre to the north, east northwest.

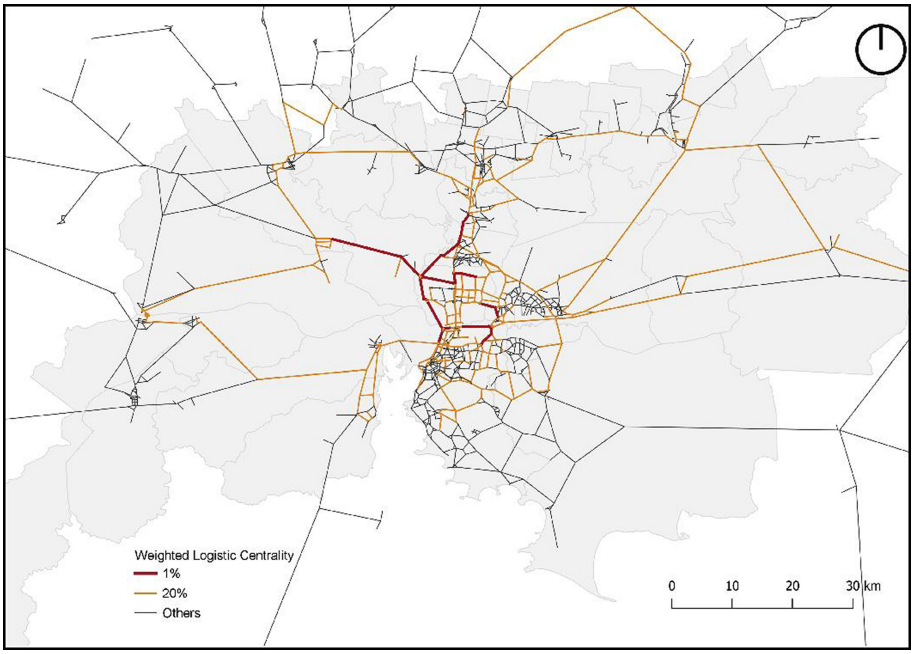

Fig. 7. Selected highest values of weighted logistic centrality in the MRPA (1% and 20%). Source: authors.

In order to analyze the share of this centrality, Fig. 8 shows the calculation for the aggregate logistic centrality by each municipality. Porto Alegre captures 32% of the total Logistic Centrality and Canoas, its neighbor to the north, captures 20%. Together, both cities are responsible for half of all centrality.

Figure 8 also shows the number of logistic employees, used as our indicator to weight the centrality. This comparison allows us to discuss losses and gains in centrality, due to the regional road network configuration. Cities like Novo Hamburgo, Triunfo e Guaíba have better performance in logistic employees than in aggregate centrality. This indicates that their location in the road network is not so strategic but, other reasons may justify their attraction of logistics activities. Triunfo, for example, hosts a large petrochemical complex having its own river port, which connects with Lake Guaíba and the southernmost sea port. Guaíba is a similar case, having an important pulp and paper industry complex and its production is also drained by the Guaíba Lake. Novo Hamburgo has a consolidated industrial park, focused on the production of shoes for export, but from the point of view of the metropolitan region, its location is more distant (far north) and its performance on the road network is weaker.

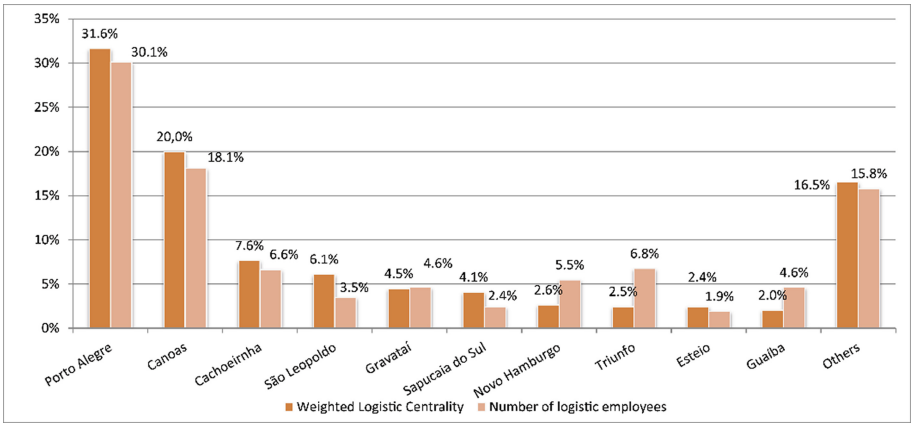

Fig. 8. Logistic centrality aggregated by municipalities and total number of employees. Source: authors.

We can also observe the opposite situation, with some municipalities having better performance in aggregate centrality than in logistic employees (São Leopoldo e Sapucaia do Sul). Both cities are very well integrated in the road network and show a great potential of the growth of logistics activities.

Our results show that logistic centrality, despite the dominance of Porto Alegre, is already decentralized; only 30% of the centrality is captured by the capital city. In the scale of the Metropolitan Region of Porto Alegre, this process of decentralization is showing a more polycentric pattern, concentrating the logistic centrality in some specific areas and corridors. In this sense, our findings converge to the studies of Masson and Petiot [6] about the trend of polarization and clustering of logistics activities. The location of the logistics activities tends to be close to market cities with the greatest demand, but external to them in search of large areas of land at low cost. An example of this decentralization can be seen in Nova Santa Rita, in MRPA, where an Amazon Distribution Center was opened in a logistic park in the margins of BR-386 in 2020. The park is about 24 km from central area of Porto Alegre, but it is strongly connected with the most populated cities of the region.

One important issue to be considered is the fact that this process of decentralization transfers the territorial effects of development of large logistics structures to small municipalities in the metropolitan suburban crowns. Coquillat [2] states that the greater territorial complexity generated by the disorder of logistics dispersion will have to be added to the attraction-inducing effects of new residential developments. The presence of large investments that requalify the suburban areas and improve the infrastructure produces, as an indirect effect, the increase of the centrality factor, and the attraction of new uses for these areas, mainly the residential one. In Brazil, the territorial planning in the metropolitan scale is not well established, raising questions about these issues in the future.

5 Conclusion

This paper presented an application of configurational models to perform a spatial analysis of the logistics activities. One positive aspect of the methodology is to be flexible; it and can be applied to the spatial analysis of other types of economic activities, for example, retail trade, industries in different sectors, among others. Also, the methodology is based on open and available data. An advantage of weighted spatial networks models is to bring together spatial and functional particularities of urban structure. These models allow to compute geometric or topological distances, and also to consider impedance effects to generate shortest paths in the street grid (not used in this work).

However, it should be noted that some simplifications were adopted in the methodology. We modelled a simplified road network of the region due to the limitations of the companies' database. Also, the network model considers only the road transportation system, not including other infrastructures, such as railways or waterways, since in our case, the highways covers the large majority of the total transported. Other studies should consider the share of transportation modals and include these networks as different layers of the basic road network. Our centrality analysis was developed only at the global scale (radius n), from the point of view of all the metropolitan system. The model also allows the exploration of intermediate scales in metropolitan networks [31]. Future studies could also focus on temporal dynamic of logistic centrality by analyzing different time periods, with different spatial configurations and distributions and intensities of logistics activities. Understanding this dynamic is crucial to planning and control.

Network analysis is on the base of several methodologies that can support public policies as they are systemic and allow the production of "what-if" scenarios. The opening of new roads or highways can be simulated, as well as the development of new logistics zones or companies and assessing their impact on the centrality of the system, both on a local or global scale. Finally, we highlight the potential of this methodology in unveiling the spatial patterns of economic activities. We expect to continue this research and develop models that consider different infrastructures with different time frames databases and network representations to get a more complete comprehension of the spatial patterns of logistics activities in the Metropolitan Region of Porto Alegre.

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