

Urban core-periphery structure: Exploration of an emergent phenomenon

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Abstract: This paper revisits the longstanding problem of the urban core-periphery structure through the lens of complexity and network theories. We argue that this relation remains central to urban science, requiring cities to be interpreted as dynamic systems in which urban form and social structure co-evolve through continuous interaction. Building on classical geographical and economic models, as well as developments in complexity science, the study proposes a systemic approach to describe and simulate the emergence of multicentricity. Using Porto Alegre (Brazil) as a case study, we examine how socio-spatial centralities emerge and interact within the urban system. The results suggest that polycentricity is not merely decentralization, but an emergent property of urban complexity shaped by path-dependent dynamics and social inequality. The study contributes to linking Latin American urbanization to broader discussions on emergence, self-organization, and peripheral urbanization.

Keywords: core-periphery; polycentricity; spatial structure; network models; employment centers; Brazil

1. Introduction

The urban core-periphery problem has been a subject of sustained scholarly attention since the early nineteenth century. Subsequent theoretical and empirical advances, particularly the consolidation of the multi-nuclei model in the mid-twentieth century, demonstrated that urban spatial organization frequently encompasses multiple centers and differentiated peripheral areas rather than a single dominant core. Even for Latin-American cities, evidence as well as a theoretical framework are available since 2002 [1].

Within territorial and urban planning, polycentric development strategies have been promoted as a response to the limitations associated with monocentric urban forms, including excessive commuting distances, traffic congestion, and the concentration of employment and services in central areas. The objective of fostering more evenly distributed growth across multiple, interconnected subcenters constitutes a central principle of several contemporary planning paradigms, including the “15-Minute City” [2].

Whenever any deep thinking about cities is required, it is the core-periphery problem that is called out, usually just echoing its fundamentals. Nevertheless, as science unfolds, it has been revisited and updated, so that the topic is still of interest [3–5]. This study intends to map out some of its most notable, smart statements and identify where we stand in terms of theory and models of representation of cities today, before going any further.

Cities are characterized by intricate internal structures shaped by various factors, including socio-demographic shifts, economic influences, policy decisions, cultural dynamics, and morphological-spatial constraints. The interplay of these factors contributes to the continuous evolution of urban centers and peripheries, which significantly impacts the socioeconomic development of cities and regions. Urban problems often stem from this spatial structure [6].

Economic studies have challenged the traditional monocentric model of urban spatial structure, revealing the emergence of multiple employment subcenters [7]. Some scholars argue that metropolitan decentralization has not necessarily led to polycentricity but rather to a widespread pattern of dispersion [8]. The transition from monocentricity to polycentricity has sparked considerable debate, with some suggesting that urban development follows cyclical patterns governed by evolutionary laws [9].

An emerging body of literature, drawing on complexity theory, views the evolution of urban structure as an emergent phenomenon [10]. Centrality is not a singular process but rather encompasses diverse and sometimes contradictory tendencies that evolve concurrently. New methodological approaches are being developed to study these processes, particularly those based on network theory [11]. Cities are conceived as constellations of interactions, communications, relations, flows, and networks, rather than locations [12]. Network theory provides a framework to describe and analyze urban complex processes such as the core-periphery structure.

This paper aims to contribute to the literature from both theoretical and methodological perspectives. Its objectives are: (a) to discuss mainstream core-periphery theory in geography and economics, as well as recent contributions offering potential insights into the core-periphery problem, and (b) to present a framework for the description, analysis, and simulation of urban systems based on network theory, through the empirical case of Porto Alegre, Brazil.

Our methodological framework describes the emergence of multicentricity in its various concomitant forms: strict spatial centrality, diverse social multicentricity layers derived from specific social groups and their relationship to other components of the city, all of them underpinned by the spatial network. To this purpose, social agents are assumed to occupy fixed places in the system, households, and travel to other locations, attracted by services and employment supply; pools of services and jobs act by means of vector forces and attraction fields through spatial and transport networks. Partial superposition of different centrality layers will, then, show areas of the city that support social interaction among multiple groups, the centrality structure itself. The spatial system of Porto Alegre is represented as a network of segments loaded with households and jobs, and we apply a directed measure of centrality to account for different centralities [13].

The main contribution of this paper lies in proposing an analytical framework that links core-periphery theory and network-based centrality analysis to examine multicentricity as an emergent, socially differentiated urban process. The empirical case of Porto Alegre is employed to illustrate the phenomenon of polycentricity and to demonstrate how distinct layers of centrality can be identified from the interaction between residential groups, employment locations, and the urban spatial network.

The paper is organized into six sections following this Introduction. The subsequent three sections present theories and models concerning urban spatial structure, encompassing both classical perspectives and contemporary approaches. Furthermore, we introduce our framework for comprehending the emergence of urban centralities. Following this, a methodological exploration is undertaken, elucidating the data sources, collection methods, and analytical techniques utilized, alongside preliminary findings derived from our investigation in Porto Alegre.

2. Theories and models of urban spatial structure

Cities exhibiting spontaneous growth are repeatedly reported having a center, which is both historic and functional, yet it also serves its inhabitants in a special, different way than the rest, concentrating activities and land uses that concern the whole population: that is the center; the rest, which is of mere local interest and utility, is the periphery [14–16]. Centers may result from a path-dependent circular process, since from its very inception it creates an advantaged location (the first building, the first activity, the first landmark) to which new ones are continuously added, increasing the location's privilege. In this way, centers feed themselves back, provoking land use specialization and land value differentiation. But not forever; with growth, travel from the most faraway locations becomes increasingly costly and time-consuming, as land values at the core become increasingly high. All this, in time, slows down the centrality growth, prompting the introduction of transport infrastructure and eventually the formation of secondary centers and poles.

The first attempt to explain this phenomenon was incredibly sharp and far-reaching, remaining to this day as a fundamental theoretical statement [17]. Having a town at the center of a piece of territory holding homogeneous conditions of fertility, accessibility and isolation from the surrounding region, the land use of this entire territory will self-organize according to two factors: the distance from the town and the land availability at each ring around the town. Organization includes not only the kind of agricultural use each ring will support but also the rent value of each one. According to von Thünen's theory, given a location holding some kind of advantage (in his isolated state, a town where agricultural production is traded), a hierarchical system of land use is set up around it, due to incremental distances from the center, which are monetized. The first ring presents the shortest distance (least transport cost) but also the least land availability, resulting in the sort of activity allowing for the most intensive land use and so the highest land rent; the next rings follow suit.

The second beautiful moment of this story is when Park and Burgess, mapping violence outcomes in Chicago, realize that they discovered something about the city beyond violence location: its actual land use structure [18]. A core holding the vast majority of jobs, and some concentric rings, each one holding a specific land use; a transitional one, right after the core, presenting mixed uses, and others used as residential locations for different socioeconomic groups of population. Rings are under constant pressure for change from their inner neighbor, prompting the authors to name their theory the ecologic model. Later research confirmed that feature, leading to a pattern of socio-spatial organization of cities.

The basic core-periphery model was soon challenged in what appeared as its main weakness: the assumption of periphery homogeneity. Hoyt notes that homogeneity would only happen if the city were not connected to anything else [19]. Each road linking the core to any other core, pole, urbanized or agricultural area outside the town's limits, forms a sector of differential occupation, so a heterogeneity, defended by the sector theory. The sectors theory was, in turn, amended by Harris and Ullman, who identified that beyond core and sectors, cities also presented nodes, that is, a concentration of certain activities that generate polarization and attraction, stating a general theory of city structure as based on centrality, transportation, and polarization [20].

It is relevant to note that these early theories were based on generalized empirical evidence, therefore vulnerable to many possible falsification or refutability; nonetheless, they stand as a corpus of structured knowledge on the city's inner structure, largely applied to urban descriptions and research. One of interest is the Borsdorf, Bähr and Janoschka application to describe the Latin-American cities (**Figure 1**) [1]. According to the authors, these cities develop a process obeying, firstly, a core-periphery configuration that evolves to a sector structure; then, to a polycentric formation, differing from the classical American and European configuration only for the extent and quantity of their specialized poles, which almost destroy their previous core and sectoral configuration.

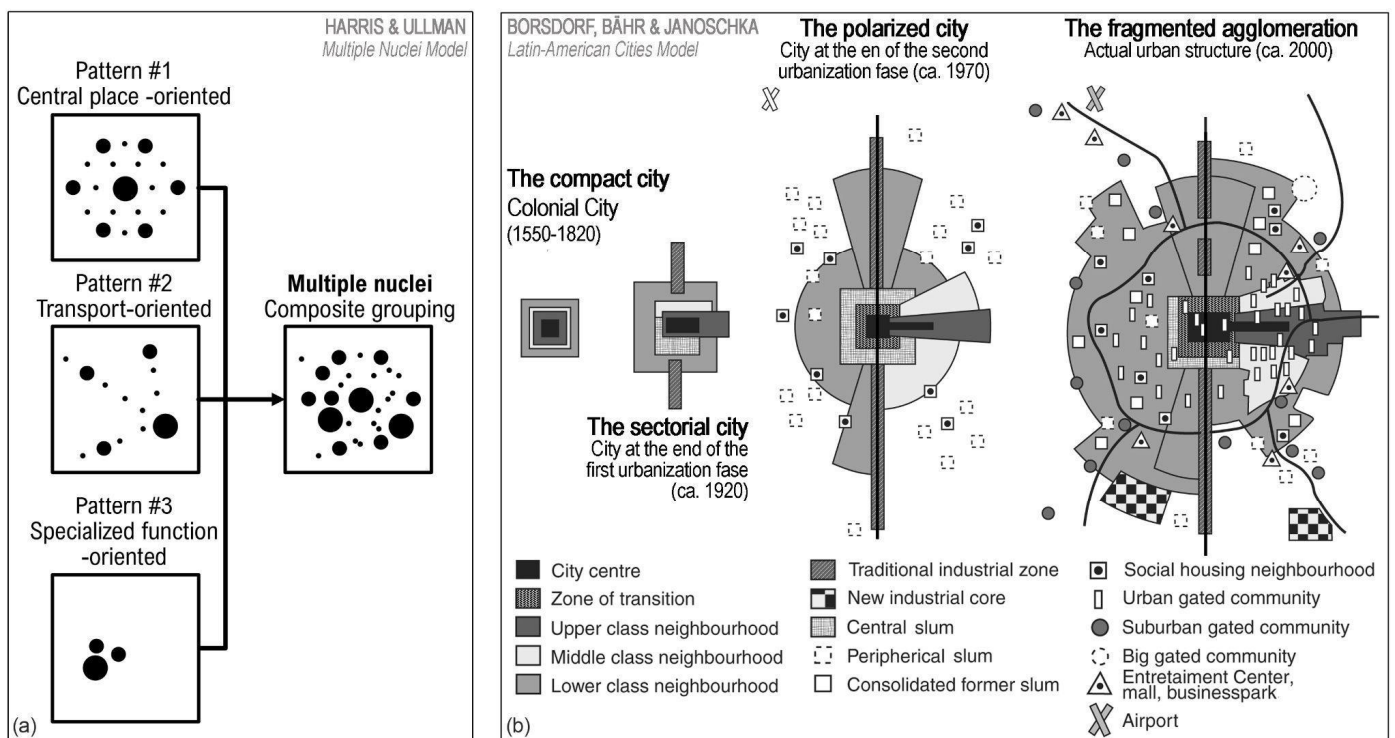


Figure 1. (a) Genesis of the Harris & Ullman's multiple nuclei model; (b) Borsdorf, Bähr & Janoschka's model of Latin-American cities. Source: (a) Harris and Ullman [20]; (b) Buzai [21] based in Borsdorf, Bähr and Janoschka [1].

With the basic descriptive models of urban structure reaching their limit, novel approaches took on adding economic variables. Their first proposition is, predictably, the monocentric model; it starts from the assumption that all jobs are located at the

urban core, and housing is distributed unequally around it, next, modeling the distribution of housing in the periphery (which was found to be a negative exponential decline of density with distance from the core) [22]. As it is, the model deals more with the housing periphery than the core itself, although it becomes clear that for a negative exponential distribution of housing, the core location is optimal for productive land use. Alonso developed a theory on urban location and land-use, applying accessibility requirements to the city core for distinct types of land use, showing that each land use has its own rent gradient or bid rent curve [23]. Households, commercial and industries compete for locations according to each bid rent curve. The model shows that, first, commercial land use will concentrate on the core, while housing will be distributed around it at different degrees of density. This distribution is an exponential function that concentrates larger numbers of households in the proximity of the core and a smaller number of households on the border; households near the center will be smaller than the ones at the border. This configuration, according to Alonso, who named it the "general urban form", will show the spatial feature already quoted and a socioeconomic feature of concentration of lower-income populations near the core.

Anas added new elements to cope with city growth; he assumed that households need buildings to be in, and that buildings are forever, so that to grow, cities must add rings of new structures [24]. Each ring will be erected according to the same principle as the very first one, that is, showing a negative exponential of density. This would bring to the cities an interesting feature: the border between the first, original ring and the second will show more density in the new side than in the old one. This could be understood as secondary center formation opportunities. The same opposition of lower-higher densities would appear subsequently in newer rings, suggesting a multiple core structure. Anas also suggests that older rings of housing would be abandoned as general income rises.

Wheaton, "the father of urban economics", provides a fresh approach, this time viewed through a rent-seeking logic [25]. He says that when a building is completed, it is at its maximum potential to generate rent. As time goes by, the city grows and buildings, originally erected at the edge, increase their centrality; at the same time, buildings get old and lose functionality. These two tendencies are opposite to each other: the first increases rent opportunity and the second decreases it. The process goes on until a point at which the costs of destroying and replacing it with a new one become lower than the rent loss over its lifetime. In other words, every building provides a real and an expected rent which, at its inception, are the same but over time describe opposite tendency curves. Wheaton's model shows that for fast-growing cities, these two tendencies also grow apart faster, configuring a scenario of inner growth comparable to the external one, providing opportunities for sub-centres to appear. Building replacement could take three ways, first one maintaining the old one's size when the new building must increase its unit value by roughly three times, second one maintaining unit value, in which case the density must increase by about seven times, and third a combination of the previous ones.

It has been seen that both geographic and economic approaches have delivered models of the city that range from simple monocentric configurations down to more elaborate theories of multicentricity. Nevertheless, they seem to fall short of providing

a real explanation for the phenomenon; the core, for example, apart from sheer observation, we have Alonso's simple accessibility dependence on various land uses. It is almost a tautology to say that commercial activities require maximum global accessibility and minimum local one, so we are left with no robust thesis on the emergence of urban cores, and consequently also with a limited hypothesis on periphery assembly around it. Even secondary centers have not been convincingly explained, apart from simple geometric and geodesic induction (e.g., Sasaki [26]).

3. State of the art

Science (physics, basically) has come to terms with one of the most striking paradoxes – the order formation, or self-organization in nature, apparently opposed to the second law of thermodynamics, which says that all tends to disorder, through representing the universe as a complex system. In its simplest description, a complex system is an orderly assembly of many components whose configuration keeps changing all the time, not out of any general rule or principle. On the contrary, in such systems, components interact with others not on an all-to-all basis, but on a one-to-many basis, with this 'many' changeable, that is, each component interacts with many different sets of others each time. Each interaction, moreover, depends on the previous ones, meaning that they are path dependent. This is particularly relevant to cities, where inherited spatial structures shape later accessibility patterns, land values and functional concentration.

Complex systems, beyond that, are continuously submitted to random changes (mutations) and external influences. Looking that way, complex systems are: (i) unpredictable, that is, their macro state is always emergent, resulting from a whole and new set of interactions; (ii) in constant change (its main characteristic is the process) and (iii) out of equilibrium, meaning that change inputs and outputs are not always proportional and the same. They clearly are neither static sorts of models nor any cause-and-effect ones [27,28]. They are about space-time interaction. This helps comprehend how cities are shaped by the cumulative interaction of households, firms, infrastructures, land uses and institutions, rather than by single organizing rules. Moreover, cities are continuously adjusted through redevelopment, expansion, densification and functional reallocation, rather than moving toward stable forms.

Eventually, complex systems started to look like a possible explanation for cities, and their arsenal of analytic tools became a valuable resource for urban models and analysis. Indeed, cities are large, some very large assemblies of entities that interact with others in a small-world fashion [29] (i.e., lots of relatively small groups of interacting individuals, having, however, some or all of them also interacting in other groups, so that showing a predominance of small group interaction but not isolated from another). They are clearly path dependent, in the extent that from their interaction result spatial (buildings, infrastructures, adapted spaces) and social (land uses, social and political organizations, laws, rules) patterns that remain, influencing subsequent further development. They also suffer from random changes (hideous actions of mayors and councilors, bad development initiatives, innovative organizations and activities, natural disasters) and external influences (country's economic performance, demographics, regional infrastructures, housing, and even agricultural markets).

Instead of an equilibrium general model (cities would remain unchanged unless something from outside would cause one, and then change would occur according to a general rule), cities could now be seen as an organism that changes all the time, according to its own local rules of interaction, the external forces being not causes but stimuli to its dynamics. Urban scientists and physicists soon started to see cities as a case of complex systems, and to take the endeavor of translating general theories of self-organization into operational models of urban evolution [12,30,31].

Considering an unstable order generator dynamic, how can this be explained? Some theories have been assessed against natural world phenomena. Prigogine's dissipative structures suggest that thermodynamic steady states, such as hurricanes and turbulent flows, are propped up by flows of energy and kept up as long as such energy flow is maintained [32]. The framework of dissipative structures as a mechanism to understand the behavior of systems in constant interchange of energy has been successfully applied to several fields, including population dynamics and urban growth. Allen updated the central-place theory by showing that the classic nested hexagon-shaped configuration is a particular case of a process driven by the interplay of two flows: population and jobs, which would feed back into each other and so lead to an unstable, changing configuration of centers [10,33]. Allen also focused on intra-urban evolution, updating Lowry's model, another classic of urban dynamics [34]. The Lowry model explores the interplay of two populations (total and working) groups and two classes of jobs (basic and reproductive employment) to model an equilibrium configuration of a city. Allen sustains that such a model is unable to generate new variables, thus predicting only new configurations of existing ones. His model includes two radically new components: the industrial base and the business and financial employment, as well as two levels of required services (long and short range) and two types of employment (white x blue collar). Population and jobs are still the flows that generate and keep an unstable steady state of the city. Workers continuously assess existing services and jobs, migrating in and out of the city, as well as within it, according to the level of fulfillment of their expectations. As workers and jobs move around the different urban zones, the effects of distance and crowding are considered both on workers' preferences and housing prices. The simulations' results are emergent multi-centrality structures, very responsive to small changes in spatial, service/jobs organization and people's preferences.

Another explanation for order formation comes from synergetics, a multidisciplinary framework offered by Haken, based on observed spontaneous cooperation among an open system's components, which, initially showing chaotic behavior, can, under certain conditions, evolve into a pattern [35]. The conditions are, first, to have an external stimulus able to excite the whole system. Second, to have a component capable of acting as an attractor, that is, showing a somewhat superior behavior (fastest, hottest, biggest, richest, depending on the system) and leading others to behave in the same way. An attractor may be understood, for instance, as an emerging central area, a strategic node or a highly accessible location capable of concentrating activities and guiding urban development. Third, to have a sort of threshold beyond which the changes would occur, and patterns are formed. Likewise, a threshold may be interpreted as the critical point at which incremental local changes begin to produce wider urban reorganization. In Haken's words, attractors are order

parameters, and thresholds are control parameters. Synergetics has been relevant in different fields, such as sociology, psychology, cognition, AI, urbanism and the science of cities. Portugali, and previously Dendrinos and Sonis, explore the complex adaptive features of cities, based on the assumptions that they are, in fact, chaotic and unpredictable and then unplannable, but can develop order and display patterns [31,36]. His main hypothesis is that within cities, one can find different processes going on, each one at a particular speed and involving different groups of agents. Faster processes would influence slower ones, making some of them keep up with the fast changes and others fall back and eventually disappear. One of his remarkable works deals with the migration waves to Israel, coming from the ex-USSR countries, showing how the central government plan failed and the self-organized process thrived. Cities are chaotic, even attaining steady states of order within, each one with a proper order parameter, changing at a specific speed and configuring an evolving core-periphery organism.

Self-organized criticality (S-O-C) is a framework, provided by Bak, Tang and Wiesenfeld, to deal with spatially extended dynamical systems, that is, systems with spatial and temporal degrees of freedom [37]. It is demonstrated that these systems naturally evolve into self-organized critical states, showing scale invariance, self-similarity and robustness. This means that those systems tend to a critical point and also tend to stay around it (resilience). Batty and Xie argue that such a framework is suitable to explain urban evolution, with cities' growth leading to a critical point (maximum size under certain conditions), remaining there until new conditions arise, when growth is rapidly resumed, toward a new critical point [38]. Here, a critical point can be understood as a condition in which the existing urban arrangement becomes unstable and a more abrupt spatial change becomes likely. It has been suggested that S-O-C may explain other inner-city dynamics, such as built form replacement and the interplay of expansion × densification processes [39,40]. S-O-C describes a city that grows around its core up to a limit, stays there until discrete changes in parameters lead to sudden growth to new limits, as well as inner changes with the rapid emergence of new centers.

The New Economic Geography (NEG) sees cities and urban regions forming and evolving as industries, agriculture and workers interact in space, submitted to two opposing forces of agglomeration and dispersion. One possible outcome is a core–periphery structure in equilibrium, which persists as long as agglomeration forces, such as comparative advantages, increasing returns to scale, lower transport costs, and circular cumulative feedbacks, outweigh dispersion forces, including land costs, moving costs, high wages, and rising transport costs. In such tension and undergrowth pressure, however, the core–periphery equilibrium may become increasingly unstable until a kind of phase transition occurs, that is, a sudden qualitative change, leading to dispersion followed by new patterns of secondary agglomeration [41–43]. NEG has updated early core and central place theories by joining geographic and economic variables together.

Two emerging areas of complex systems development, entropy and free energy, have offered fresh approaches. Entropy, originally derived from thermodynamics, deals with the concept as a general trend toward decaying, against what self-organization strives, has more recently acquired a new perspective, given by Shannon,

linked to the exchange of information [44]. Shannon argues that differences in frequency and sequence in symbols and words produce differences in the probability of occurrence and an increased probability of certain combinations, so that the message components become more predictable, and communication becomes possible [45]. Cities, on the other hand, are very much based on information exchange, be it of the simplest kind, such as travel choices, to more elaborate ones, such as land uses, housing preferences, urban densities, and expansion. In every situation, minimizing entropy to enforce interaction seems the way to optimize actions and revenues.

Free energy is, in Schrödinger's words, the opposite of entropy, or negative entropy [46]. Friston has developed theories on the free energy principle, in which the basic hypothesis is that any interesting system that has an aleatory dynamic attractor, in the effort to adjust to it, will reduce entropy, or self-organize within a limited number of possible states [47]. In the context of urban science, it suggests a dynamic in which every agent's action is reduced to a few possibilities to reduce surprises. In this way, the idea that the first few buildings and spaces of a settlement become a core by repeated actions of built form and land use accretions; in the same way, peripheries tend to replicate and extend city's limits, core characteristics will extend to streets irradiating from the core, configuring a dendritic structure; as global entropy increases, new nodes of interest emerge as entropy reducers, evolving to new centers that, nonetheless, mimic the core, seems consistent with entropy, as well as free energy general theories.

4. Where we stand, and how

Self-organization, particularly from the viewpoint of entropy and free energy, does not mean cities going wild and assuming any configuration imaginable. On the contrary, a general tendency towards entropy and free energy reduction leads to a set of a few possibilities. Indeed, resilience, often identified as the capacity of returning to known forms after unusual changes or disasters, could be understood as a city configuration being led by a few attractors, and assuming some version of an already experienced form or configuration. Urban well-known phenomena, such as traffic congestion, land use specialization, spatial segregation, densification, and dispersion, far from being particularities of certain cities, or of some stage of urban evolution, have proved to be an essential part of a general dynamics experienced by all cities, independent of nationality, age, and size. Polycentricity seems to be one of such dynamics; not a matter of being good or bad, desired, or unwelcome, just being, well, a city.

Being bottom-up self-organized (not excluding partial top-down ordering as well), cities require descriptive and analytical resources compatible with very large systems, finely detailed, variables ranging from the hardware cities are made of, such as adapted spaces and built forms, up to their software, agents, social organizations, and interactions. Descriptions are able to reveal at least some of the layered socio-spatial structures living within the same city, each one having a proper dynamic and evolution, and affecting the others. In this sense, polycentrism would not be only a matter of simple core-periphery differentiation but a superimposition of differentiated

cities, each one with its own core and periphery, brought together by means of forces of attraction and repulsion.

Our efforts have been directed to representing the urban systems from the bottom up, involving fine data disaggregation and theoretically sound interaction mechanisms. It starts by identifying the fundamental building blocks of a city, urban form and human components, forces of attraction, and interaction engines. Urban form is represented by a network of elementary urban open spaces, with their interstices occupied by unevenly distributed built forms. Humans are classified by convenient features, age, income, occupation, and allocated to built-forms according to households' average sizes. The interaction engine is a standard representation of collective activities, such as domestic, commercial, and co-presence, etc., allocated to built forms and open spaces. Attraction forces are spatial as well as functional and social links among spaces' building blocks and agents, representing vectors of one-to-one and one-to-many interaction potentials, as well as one-to-all attraction fields. These are abstract networks superimposed on the morphological one. Attraction forces encompass distance-based relationships, functional tensions, cultural bonds and preferences, symbolic and cognitive orientation, transport facilities, which allow for quantitative as well as qualitative graph analysis (**Figure 2**).

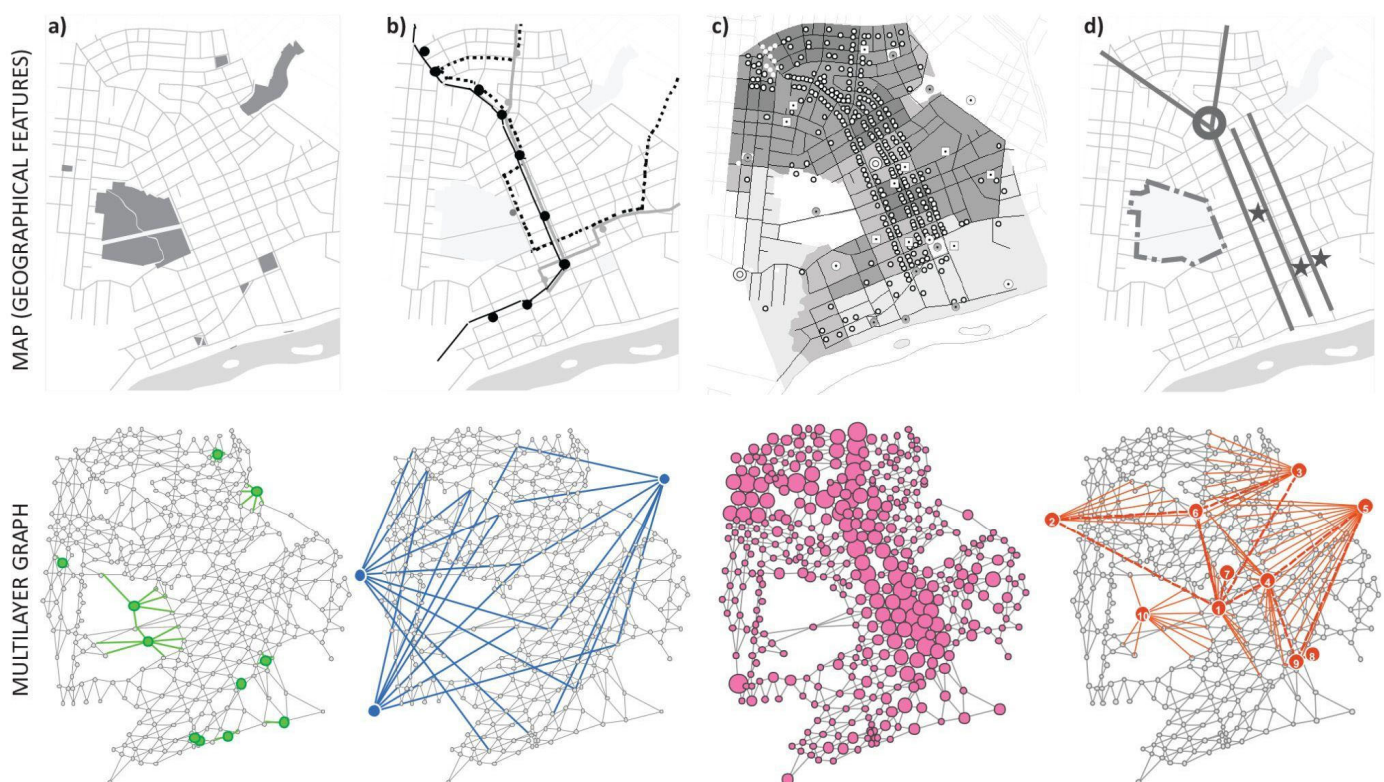


Figure 2. Map description and the corresponding multilayer graph of (a) parks and squares; (b) public transport routes; (c) land use—residential density, retail, and urban equipment; and (d) information units—paths, districts, nodes, and landmarks. (Source: [48]).

Quantitative estimates are obtained using models based on principles of interaction—distance, affinity relationship, relative position, spatial opportunity, and polarity algorithms that extract different relationships among specified components of

the system. Data is stored in as many layers as the active components, calibrated and combined according to criteria specified by the models.

Distance-based algorithms capture potential for interaction among places, assuming that closeness favors it, whereas longer distances hinder it or even prevent it. A location's accessibility index is the sum of distances from it to a group of specified others, or all others. Relative position models capture the spatial distribution of tensions between specific pairs of locations that hold land uses, equipment, activities, or social groups that are proven complementary. Their tension can be admitted as being relayed through interstitial spaces or directly. Polarity models are directed to describe relationships among certain social groups and their set of locations holding activities, equipment, or other social groups considered complementary [49].

In the recent literature, the discussion on core, periphery and multicentricity is far from closed. On the contrary, it has been renewed by the availability of large spatial datasets and by the convergence of urban studies with network science, accessibility research and complex systems analysis

Fanelli et al. identify functional cores, intermediate areas and peripheries through the distribution of urban opportunities and accessibility conditions, showing that urban structure may be more adequately understood as a differentiated field of concentrations and gradients than as a simple opposition between center and outskirts [50]. Particularly relevant here is the fact that their study includes Latin American cases, cities such as Fortaleza (Brazil) and Bogotá (Colombia), suggesting that the problem of core-periphery reconfiguration is not restricted to the classic Euro-American debate, but is also central to contemporary urbanization in the region.

New data sets, such as those derived from social media platforms as well as mobile phones, help reveal intraurban functional flows and support the identification of polycentricity [51,52]. Other studies have sought to conceptualize polycentricity from human mobility variability to reframe accessibility in terms of inclusive proximity, and to expose inequalities of access in urban systems through new comparative measures [53–55]. Altogether, these works suggest that centrality is increasingly being understood as a differentiated, relational and measurable condition, rather than as a fixed geometric property of urban form.

Studies that link polycentricity with network-based approaches offer profound insights into how real-world systems are organized and function [56]. Ozuduru et al. explore the role of street network configuration and its potential to generate centrality [57]. In their work, clusters of commercial activities are correlated with street centrality metrics. Studies linking polycentricity and spatial network analysis in Latin America are scarce. The work of Dalberto and Amaral adopts a regional perspective and examines the 26 largest urban agglomerations in Brazil [58]. The regions are analyzed as spatial networks in which each municipality is treated as a node, and centrality measures are employed to infer their capacity to attract commuting flows.

Recent empirical studies suggest that urban structure is rarely reducible to a single centric logic [53]. Rather, concentration, dispersion, and polycentricity may coexist, overlap, and vary in intensity according to scale, context, and analytical approach. This point is especially important for our purposes. If multicentricity is not a fixed morphological state but an emergent condition, then its description cannot rely only on the spatial concentration of jobs, services or amenities. It requires analytical

resources capable of capturing the differentiated interaction fields through which centralities are produced. This is where our approach seeks to contribute. Rather than identifying subcenters only from aggregate distributions or mobility intensities, we represent multicentricity as the result of selective relations among residential groups, employment locations and the street network. Most network-based analyses focus primarily on the street network properties, establishing external correlations with socio-functional attributes of centrality (jobs, retail establishments). In contrast, we model a weighted network that systemically integrates social groups, economic activities, and the street network configuration.

5. Materials and methods

In this paper, we execute a methodological exploration to describe the emergence of multicentricity within urban networks, focusing on Porto Alegre, RS. The method is based on the Polarity model and combines three main inputs: the street network, residential origins represented by population groups, and employment destinations represented by jobs [13,59]. This section details the formulation of the model, the data acquisition and processing and the analysis criteria adopted.

5.1. Street network data

To model the spatial network, we obtained road network data from OpenStreetMap, using the method OSMnx [60]. The resulting street network was segmented by dividing streets into sections between two intersections, generating a network composed of 37,354 segments, including a 1 km buffer to minimize edge effects. This buffer was later removed for further analysis.

5.2. Polarity model specification

To investigate the emergence of multicentricity within urban networks, we build different layers of centrality based on the Polarity model [13,59]. Polarity can be understood as a measure of intra-urban relative attractiveness derived from selective interactions between residential and employment locations. Only pairs with opposite attributes are considered, resulting in a model that assigns fractional centralities to all spaces acting as connectors. This makes it possible to estimate both the location and intensity of these selective interactions by measuring the network centrality for different social groups and types of attractors (jobs).

More specifically, the computation of Polarity on a street network G is based on a set of street segments i and j . Origins (segments i) are defined by the number of households, classified into two income groups: low-income and high-income. Destinations (segments j) are defined by the number of jobs, classified by skill level into low- and high-skilled. Polarity is therefore expressed as a weighted and ordered betweenness centrality measure, as shown in Equation 1.

$$PO_{ij}(k) = \sum_{\substack{i,j \in G \\ k \neq i \neq j; d_{ij} \leq d_0}} \frac{W_i \times W_j}{d_{ij}} \times \frac{g_{ij}(k)}{g_{ij}} \quad \forall i \in O, \forall j \in D, \forall k \in G \quad (1)$$

where $PO_{ij}(k)$ is the Polarity of segment k , where all the segments i contain origins and all segments j contain destinations, W_i is the weight of origin segments i and W_j is the weight of segments j , d_{ij} is the length of the shortest path between i and j (distance), $g_{ij}(k)$ is the number of shortest paths between i and j that pass through k , and g_{ij} is the total number of shortest paths between i and j , within a catchment radius d_0 .

5.3. Data for population and jobs

The number of jobs by skill level was obtained from Pereira et al., an official report from the Brazilian Institute for Applied Economic Research (Ipea), which presents data from RAIS (Annual List of Social Information, Brazilian Labour Ministry), for the year 2017 [61]. The data is aggregated in 0.11 km² hexagons and includes the total number of jobs as well as the number of high-skilled, medium-skilled and low-skilled jobs. It should be noted that job positions in the public sector were omitted from the analysis due to unreliable workplace data made available by RAIS. Public sector jobs, though dispersed, are recorded at a few addresses, causing undue concentration.

Data from the 2010 Population Census by IBGE were the basis for the origins [62]. We selected only two social groups for our analysis, categorizing household income: low income (monthly per capita income less than ½ minimum wage), and high income (more than 15 minimum wages). This selection explores different centralities associated with these contrasting income groups. We used population data from 2010 because it remains the most suitable source for identifying income groups at the intra-urban scale in Brazil. Although more recent census data are available, equivalent census tract-level income data for segmenting income groups are not yet available. Thus, we acknowledge the temporal mismatch between residential and employment data as a limitation. However, because our analysis focuses on broad and relatively stable socio-spatial patterns of centrality, rather than short-term demographic change, this mismatch is unlikely to alter the main interpretation of the results.

We used a set of geoprocessing tools to transfer numerical information regarding origins (from census tracts' polygons) and destinations (from the hexagonal mesh) to the street segments. First, we determined influence areas for each street segment using Voronoi polygons [63]. Next, we clipped the polygon inputs (census tracts and hexagons) with influence areas to determine the total counts of households or jobs spatially coincident to each street segment. This procedure resulted in the street segments layer weighted with the origin and destination attributes. The full methodology employed to transfer origins and destinations attributes to the street network line layer is detailed in **Supplementary Materials**.

To mitigate the influence of the size disparity between the two income and type of job groups on the results, the model was weighted based on the percentage of the population and jobs of each type in each street segment.

5.4. Analysis criteria

We conducted our analysis using the Graph Analysis of Urban Systems - GAUS script, implemented in QGIS [64]. Three distinct simulations were executed in order to capture centrality variations. First, we considered the whole population and the whole job supply as origins and destinations, respectively. Then, we narrowed the analysis seeking to encounter centralities resulting from compatible income groups and job types, therefore pairing the high-income group with high-skilled jobs and the low-income group with low-skilled jobs.

Polarity calculation was also restricted to a local analysis encompassing six topological steps ($d_0 = 6$), meaning that the distance threshold from every street segment considered to establish its interactions with the other segments was around 600 meters. This local threshold was defined to keep the analysis focused on the emergence of neighbourhood-scale centralities rather than on the overall citywide structure. Recent evidence on service-population proximity research also supports treating this distance as consistent with a short walking-scale range [65]. In this sense, the threshold functions less as a universal behavioral cutoff than as an analytical parameter intended to reveal differences in subcentralities emerging from the interaction between residential and employment locations of different social groups.

6. Results: Multicentricity in Porto Alegre

Porto Alegre, the capital of the state of Rio Grande do Sul, has a population of 1,332,845 inhabitants and serves as the core of a metropolitan region with over 4 million inhabitants [66]. It is predominantly a service-oriented city, with over 90% of the municipality's GDP stemming from the tertiary sector [67]. The spatial organization of Porto Alegre is characterized by a network of radial and perimeter avenues, which converge towards the historic center (CBD). Situated adjacent to Lake Guaíba, this central district marks the city's origin and serves as a focal point for its urban development (**Figure 3**).

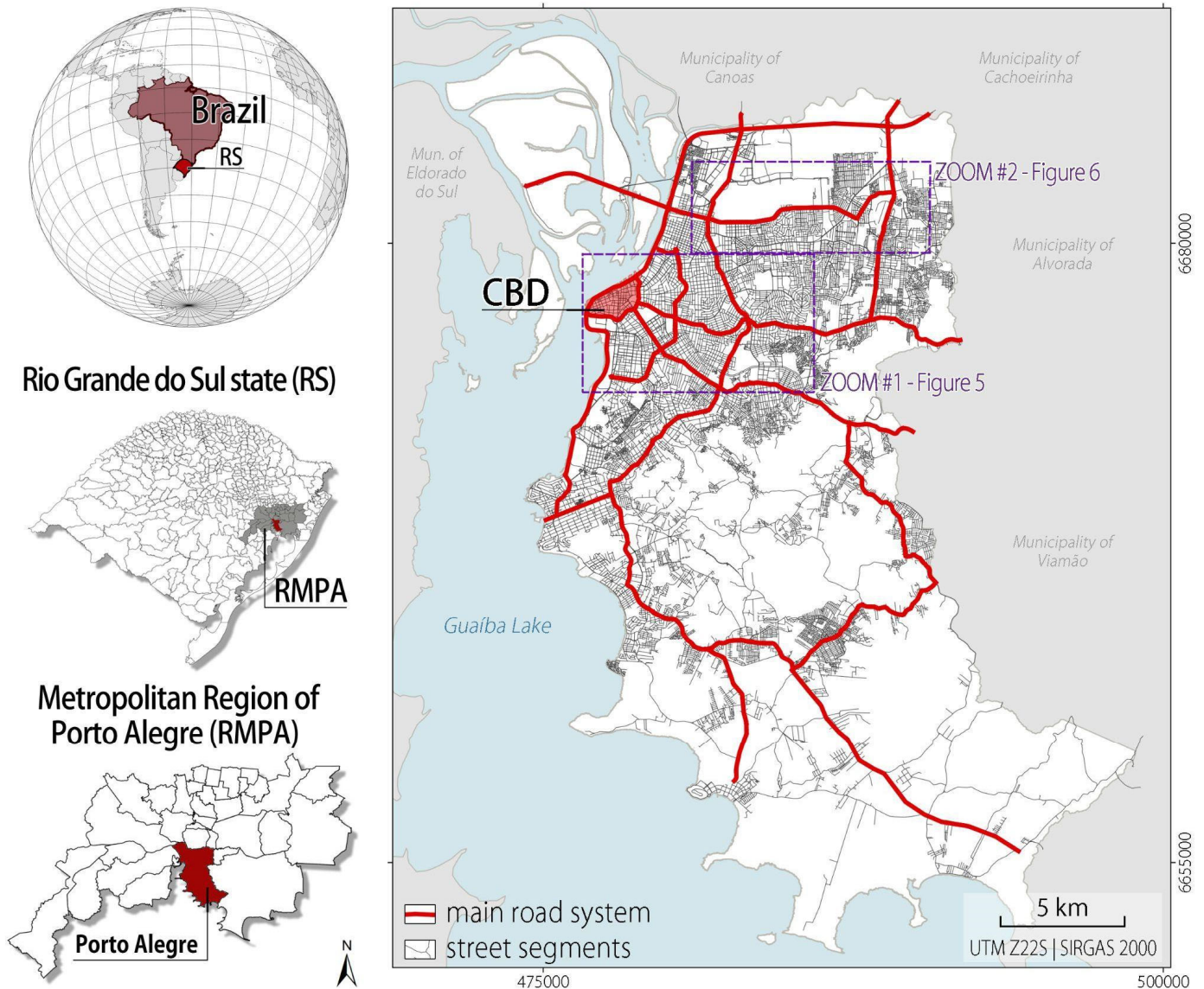
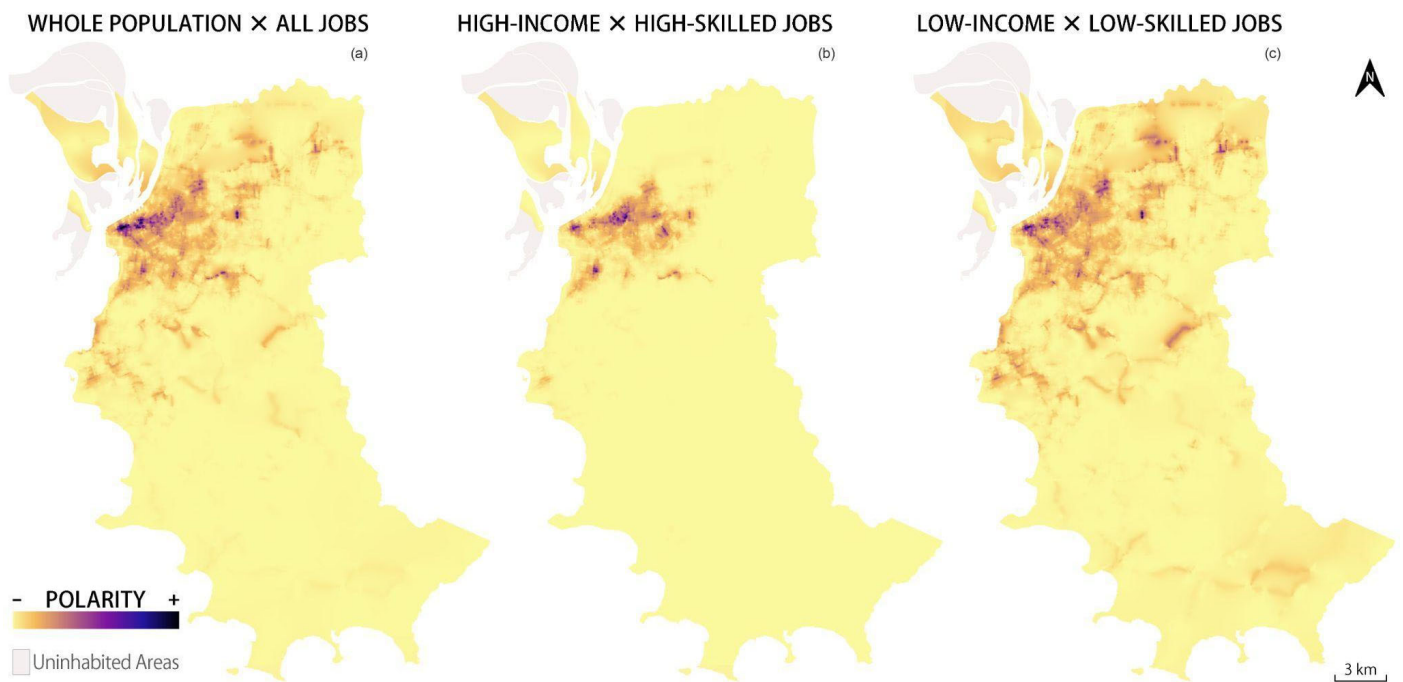


Figure 3. Location and spatial structure of Porto Alegre (Source: authors, 2026).

Figure 4 displays the outcomes for local centrality, weighted by various combinations of income groups and types of jobs. These results show distinct centrality patterns across income groups emerging from the interplay of residential locations, employment opportunities, and the street network. High-income groups tend to concentrate in specific areas, notably in the CBD-east region, while low-income groups exhibit a more dispersed pattern, particularly in peripheral regions. Jobs categorized by skill level also exhibit specific spatial distributions: high-skilled positions are concentrated in the CBD and in selected clusters, whereas low-skilled jobs in the industrial sector tend to be located in the northern region, and those in retail and services are more evenly distributed throughout all regions.



To enhance visualization of polarity measure, the maps are presented through interpolated surfaces generated with Inverse Distance Weighting (IDW) (Shepard, 1968).

Figure 4. Local centralities weighted by different combinations of social groups and types of jobs. (Source: authors, 2026).

Figure 5 illustrates the CBD (A) as a region with high centrality for both income groups. It presents the highest concentration of jobs (across all skill levels) and a diverse mix of income groups. Regions B and C are centralities predominantly for high-income groups, housing numerous offices and corporations in upscale surroundings. Regions D and F represent centralities associated with both income groups, offering a broad spectrum of high and low-skilled jobs.

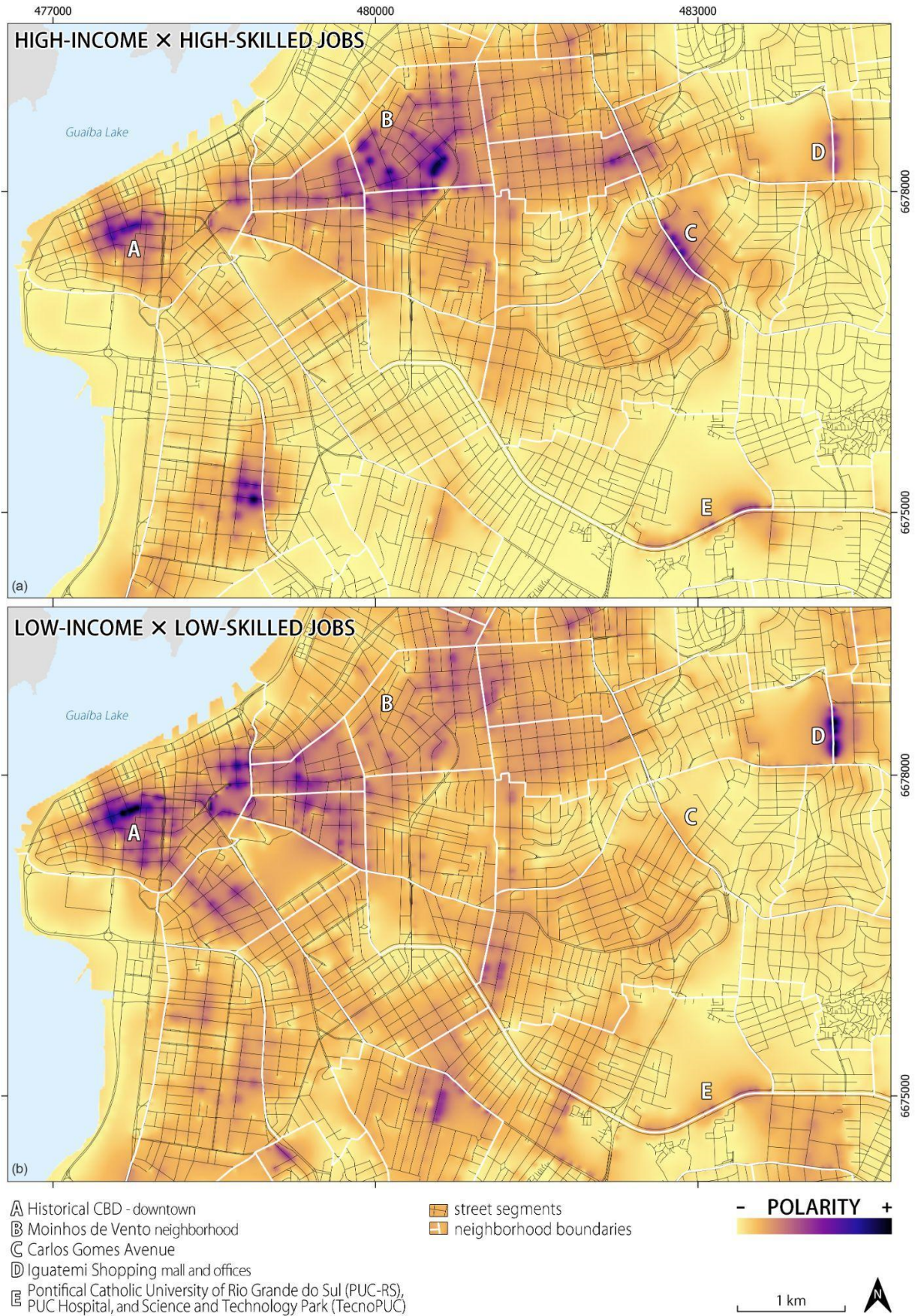


Figure 5. Local centralities in the central and peri-central region of Porto Alegre. (Source: authors, 2026).

Figure 6 depicts a traditional industrial and logistical hub in Porto Alegre that exhibits direct connectivity and accessibility to the Metropolitan Region via important highways such as BR-116 and BR-290. This is a poverty region, with many slums and low-standard housing, offering predominantly low-skilled industrial jobs. Region F is characterized as a low-skilled employment zone situated in close proximity to Salgado Filho Airport. Region G encompasses former slum areas (Vila Dique and Vila Nazaré), which have already undergone removal. Regions H and I also serve as instances of low-income centralities, with the latter situated near a shopping mall (Bourbon Assis Brasil) and exhibiting a more heterogeneous job and income composition.

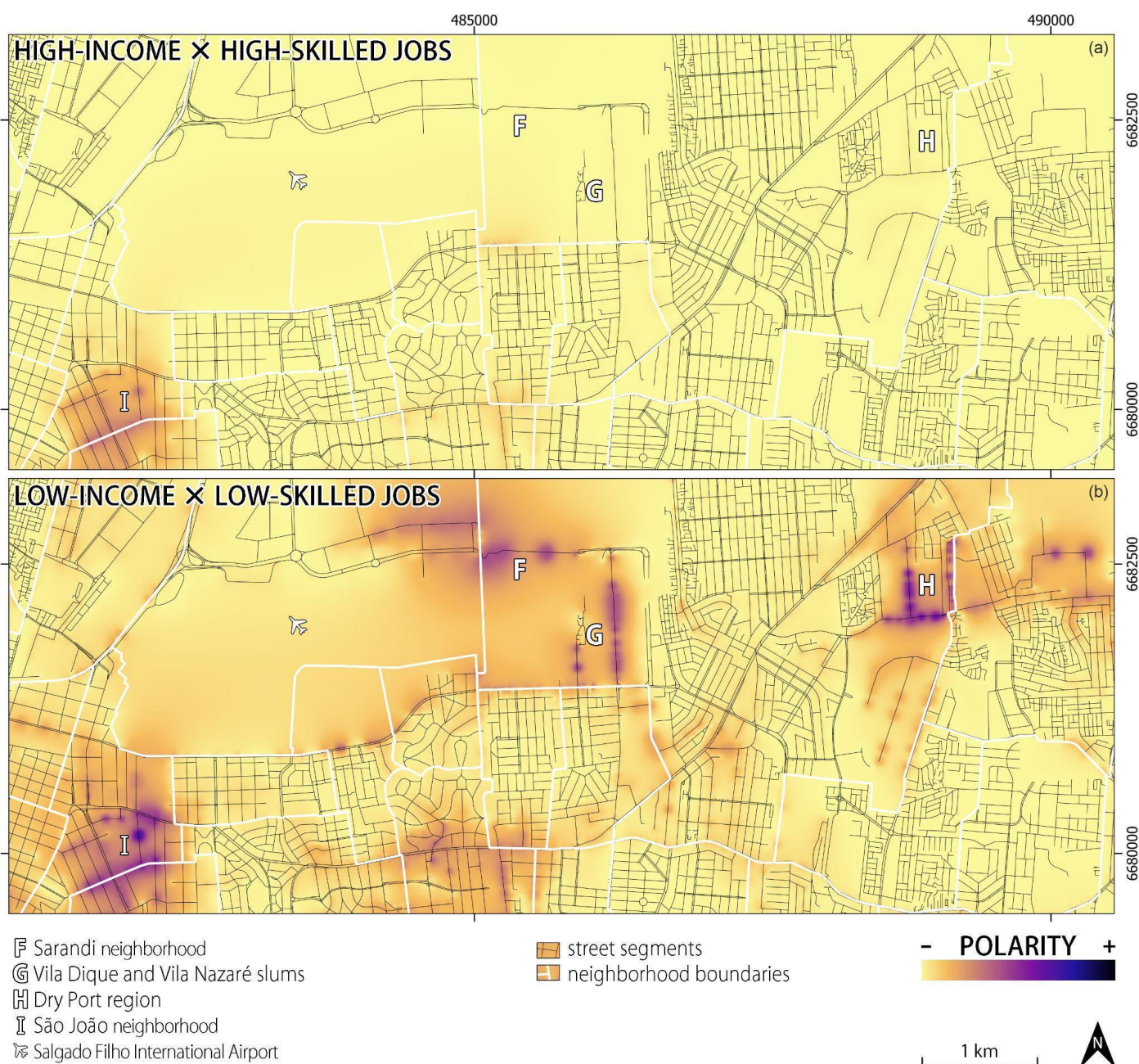


Figure 6. Local centralities in the northern region of Porto Alegre. (Source: authors, 2026).

We observe that the CBD maintains the highest local centrality values for all groups—the total population, as well as low and high-income groups (**Figure 7**). Centrality tends to diminish towards the periphery (greater distances). However, the decline in centrality for the high-income group is steeper compared to that of the low-income groups, indicating a strong association with central regions. It is possible to observe an increase in centrality related to high-income groups at the 22- and 24-km rings. In this distant area, there is a large high-income gated community (Terra Ville) comprising 180 hectares. This aligns with Borsdorf, Bähr and Janoschka’s [1] thesis of spatial juxtaposition of different income groups in peripheral regions facilitated by separation through barriers (walls).

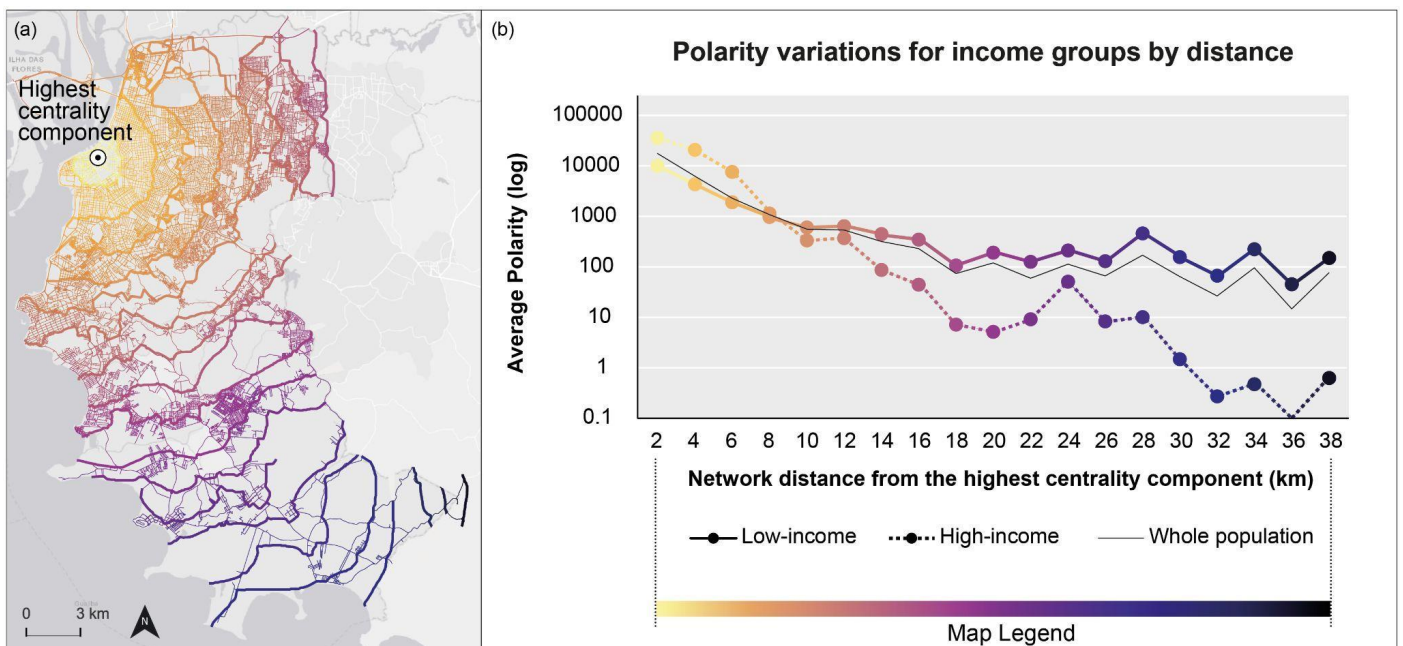


Figure 7. Multicentricity emerging from the spatial distribution of distinct population groups. (a) street segments classified according to the network distance from the highest centrality component; (b) chart illustrating the numerical discrepancies of Polarity for distinct income groups as the network distance from the highest centrality component increases. (Source: authors, 2026).

Our investigation in Porto Alegre yields important insights: (1) The center-periphery model, while somewhat nuanced by the emergence of other areas of interest, still remains predominant from the point of view of jobs; (2) polycentricity is constrained by spatial configuration, with distance from the CBD playing an important role. The development of new centers follows a dendritic pattern from the historic core, implying the maintenance of a distance threshold between centers and the periphery; (3) emerging centrality is not exclusively tied to income; although lower-income groups are disadvantaged by distance and thus establish their own centers, major emerging centers still facilitate cross-income interactions, especially within the CBD; (4) the overall formation of centers appears to be influenced by the urban mass of the Metropolitan Region, particularly in a northward direction.

7. Discussion

Our exercise of centrality description and mapping has been based on assumed relationships among spaces, infrastructures, people and activities, each one presenting a particular behavior, lifetime and entanglement with each other [12]. In this way, each layer of the city functions according to its own principles and laws but affects other layers and is affected by them, resulting in a multifaceted centrality. By multifaceted, it is understood a centrality that emerges from the interface of many agents, both human and socio-technical devices, and so are subjected to fluctuations and rapid changes in intensity and extension [31].

In a system characterized by the interaction of multiple agents, a variety of internal dynamics are expected to unfold. While it is not the aim of this study to explicate all of them, some well-established dynamics are captured by our experiment and can be related to the fundamental concept of emergence [12].

Our study shows Porto Alegre's CBD maintains the highest local centrality (**Figure 5a**), reinforcing the idea that urban systems evolve toward relatively stable spatial configurations, such as centralities, subcenters, and mobility patterns. This aligns with the idea that systems minimize free energy by limiting unpredictability [47]. Concepts like polycentricity or core-periphery structures can be understood as attractor configurations. Once established, they channel flows (people, goods, information) in ways that reinforce their own stability, analogous to the system "learning" its environment.

Since the 1980s, Porto Alegre's CBD (**Figure 5a**) has been through processes of transformation, losing higher-income residents, as well as more specialized retail and services [68]. The degradation of the physical structures may be interpreted as a localized increase in entropy that weakens the capacity to sustain interactions. Yet, through functional transformations, such areas may reconfigure their role within the urban network, generating new interaction patterns and enabling the re-emergence of centrality. In this context, centralities operate as shifting attractors, shaped by path-dependent trajectories and adaptive responses that, as suggested by Friston, can be interpreted as systemic efforts to reduce uncertainty through the stabilization of spatial interaction patterns [47].

Figure 5D shows a centrality associated with the regional Shopping Center Iguatemi. It illustrates a novel centrality formation where vacant land inside the urban tissue can eventually be filled up by concentrated capital (large commercial and residential developments), generating polarization and inducing rapid change in their surroundings. This process may be linked to complexity theory, in which specific localized interventions can trigger nonlinear, system-wide effects through self-reinforcing feedback mechanisms, whereby increased accessibility and activity intensify flows and consolidate new attractors within the system [32].

Figures 5 and 6 illustrate that centrality is spatially distributed in an irregular and non-homogeneous manner, overcoming traditional configurations of centre/periphery models and generating not only centrality in origins and destinations of flows but also in other locations along the way. Centrality is continuously produced through relational dynamics, reflecting nonlinear feedback processes and self-

organization, in which the urban system reorganizes itself through the circulation and redistribution of flows across space.

Recognition of those classic intraurban dynamics under the framework of urban centrality reveals a rather mobile and unstable configuration of the core-periphery structure and allows for an alternative vision of it: a vision where cores multiply, change places, are turned on and out, are created and destroyed over time. In light of the theories presented and our methodological exploration, characterizing intraurban multicentricity in terms of one or more centers and the remaining areas as peripheral seems increasingly less meaningful.

8. Conclusion

In this paper, we examine the mainstream core-periphery theory alongside recent contributions that offer promising insights into this issue. Additionally, we introduce a framework for describing, analyzing, and simulating urban systems based on network theory, utilizing the empirical case study of Porto Alegre, Brazil.

According to Ren, the periphery is linked in multiple ways to the center, and what happens at the center invariably shapes the urban structures and processes on the periphery [69]. Therefore, instead of focusing on "either" the center "or" the periphery, it is more constructive to study the linkages and connections between the two and examine how they reshape and reproduce one another. This underscores the necessity for new theories and methodologies, particularly those enabling systemic analysis, as explored in this paper.

Our study revealed the potential to investigate the heterogeneity present in peripheral areas, encompassing economic, social, and spatial dimensions in an integrated manner, through quantitative modeling. This methodological approach is crucial given the complexity and fragmentation often observed in peripheries, particularly in Latin American cities.

One limitation of this study is that centrality is modeled using cross-sectional data representing a single moment in urban evolution. Newly available data from the 2022 Brazilian Population Census may enable updated analyses and temporal comparisons. Extending the analysis to compare scenarios across time would be a valuable next step; however, in Latin American cities, limited data availability, particularly longitudinal datasets, constrains such efforts. Future research should also expand empirical applications to other cities in the region. Additionally, multi-scalar approaches could elucidate how centrality emerges across spatial scales, bridging local and metropolitan dynamics.

Another issue that deserves attention in future research is the role of extreme events associated with climate change in reshaping land-use allocation decisions and, consequently, affecting core-periphery dynamics. In Porto Alegre, the 2024 flooding event has raised concerns regarding the future of the historical center. Although its location remains highly advantageous, the area may lose its original attractiveness.

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Data curation: CM, BG and GMG; Formal analysis: CM, BG, GMG and LBS; Project administration: CM; Visualization: BG, GMG and LBS.

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