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Uncovering income and racial spatial inequalities and segregation patterns with a potential accessibility network index

Revelando desigualdades espaciais de renda e raciais e padrões de segregação com um indicador configuracional de acessibilidade potencial.

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Abstract

Urban segregation has been a central challenge in the pursuit of equity and sustainability, especially in Latin American cities. The existing body of research on segregation, however, has predominantly focused on cities in the United States and Europe. Most existing metrics on segregation do not usually explicitly address the spatial dimension and diversity of cities' spatial structures. As a result, there is still a gap in the methods to properly capture the spatial relationships implied in segregation. This paper proposes and applies a network-based method for assessing the inequalities in access to opportunities for different social groups (income and race), and the patterns of socio-spatial segregation based on urban accessibility levels. We apply the method to the city of Pelotas, Brazil, combining the street network configuration with population densities and spatial distribution of urban opportunities. Results revealed that high-income white groups dominate the accessibility levels, benefiting from a concentration of opportunities in the central district, while low-income non-white groups experience poorer accessibility. The method allowed to uncover a center-periphery segregation pattern, although more complex and spatially diversified, providing valuable insights that can inform urban planning and policy-making efforts at the intraurban scale.

Keywords: Socio-spatial segregation. Spatial inequalities. Potential accessibility. Urban networks.

Resumo

A segregação urbana tem sido um desafio central na busca pela equidade e sustentabilidade, especialmente nas cidades latino-americanas. A pesquisa sobre segregação, no entanto, tem se concentrado predominantemente em cidades dos Estados Unidos e Europa. A maioria das métricas existentes geralmente não aborda de forma explícita a dimensão espacial e a diversidade das estruturas espaciais das cidades. Assim, há uma lacuna nos métodos para capturar adequadamente as relações espaciais implicadas na segregação. Este artigo propõe e aplica um método baseado em redes espaciais

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para avaliar as desigualdades no acesso a oportunidades para diferentes grupos sociais (renda e raça), e os padrões de segregação socioespacial com base nos níveis de acessibilidade urbana. Aplica-se o método à cidade de Pelotas, Brasil, combinando a configuração da rede viária com densidades populacionais e distribuição espacial das oportunidades urbanas. Os resultados revelaram que grupos brancos de alta renda dominam os níveis de acessibilidade, beneficiando-se de uma concentração das oportunidades na área central, enquanto grupos não brancos de baixa renda experimentam uma acessibilidade mais precária. O método permitiu revelar um padrão de segregação centro-periferia, embora mais complexo e espacialmente diversificado, fornecendo informações valiosas que podem dar suporte ao planejamento urbano e à formulação de políticas em escala intraurbana.

Palavras-chave: *Segregação socioespacial. Desigualdades espaciais. Acessibilidade potencial. Redes urbanas.*

Introduction

Socio-spatial segregation is one of the oldest empirical research traditions in the study of social stratification, inequality, and spatial population distribution (Fossett, 2017). Although it has different definitions, depending on what is being considered, it usually refers to the spatial separation and unequal distribution of diverse social groups within a geographical area (Maloutas, 2020; Musterd, 2020). This separation encompasses both physical and social dimensions, with individuals being segregated based on social characteristics such as income, race, ethnicity, education, and occupation.

While existing definitions and approaches predominantly focus on residential locations (Fossett, 2017; Musterd, 2020), segregation extends beyond the residential realm. The phenomenon embraces various domains of urban life, including unequal access to services, amenities, employment opportunities, and public infrastructure. Understanding its complexity requires considering a range of social, economic, political, and geographic factors. Therefore, segregation metrics and analyses need to move towards the inclusion of these multidimensional aspects to gain a more comprehensive understanding of the phenomenon (Legeby et al., 2023; Musterd, 2020).

Although segregation is experienced by individuals, traditional measurements generally contain simplified representations of the urban structure. The urban territory is arranged into distinct area units and assumes homogeneity within these residential zones, thereby neglecting the cities' diverse fabric. (Fossett, 2017). As a result, there is still a gap in our understanding of how to properly capture the spatial relationships implied in segregation.

In attempting to fill this gap, recent studies introduced new approaches allowing for different dimensions, domains, and scales of urban segregation to be considered (Musterd, 2020; Piekut et al., 2019). Nevertheless, urban segregation research has predominantly focused on cities in the United States and Europe, nations with finer data and infrastructure (Musterd, 2020; van Ham et al., 2021). The urban patterns observed in Latin American cities, such as those found in Brazil, exhibit unique characteristics that require specific studies to comprehend segregation within its context.

This paper evaluates urban segregation in the Brazilian context by presenting a method to analyze socio-spatial inequalities in accessibility levels across different social groups, thus revealing patterns of socio-spatial segregation that arise from the distribution of urban opportunities and populations. The analysis extends beyond a purely residential perspective by incorporating spaces of other activities (work, shopping, leisure), the street networks' morphology, and the accessibility patterns influencing segregation.

The objective of this paper is to propose and apply a network modeling method for assessing a) inequalities in urban accessibility to opportunities among income and racial groups, and b) patterns of socio-spatial segregation based on urban accessibility levels. The approach builds on the spatial distribution of residential location and the city's street network, to then analyze segregation from the inequalities in accessibility of these residential locations towards the spaces of other activities, while still considering socio-economic characteristics of the areas concerning income and racial groups. This allows for an analysis of residential segregation that is not isolated from other urban domains, but that exists with them.

By integrating multiple domains and incorporating various urban elements and information, the approach allows an in-depth understanding of the complexity of segregation in the Brazilian context. Through this research, we intend to contribute to the broader knowledge of segregation and provide insights for urban planning and policy-making which can potentially promote more inclusive and equitable cities.

Socio-spatial segregation

Urban segregation has been a central topic in studies of social inequality and the spatial distribution of populations. The literature posits that differences in spatial patterns of residential locations among population groups are closely linked to individuals' access to opportunities. Urban segregation can be broadly defined as the spatial separation of social groups, with significant impacts on access to essential, reliable, affordable, and high-quality infrastructure and services (Musterd, 2020). These processes often result in unequal spatial distributions of access to urban facilities, movement within cities, and opportunities (Farrington, 2007; Feitosa et al., 2021).

Segregation arises from the interplay of multiple dimensions of urban life, including legal, political, economic, social, cultural, and spatial aspects. It is not a direct consequence of social inequalities in space but rather an independent phenomenon intrinsic to the urban system and related to the inequalities. It is a complex, multifaceted, multiscale, and multidimensional occurrence that encompasses social, spatial, and temporal dimensions (Maloutas, 2004; Oka & Wong, 2019).

In Latin American cities, residential segregation is a prevalent issue, representing an inherent phenomenon of their urban systems and frequently occurring within socioeconomic and ethnic contexts (Marques & França, 2020; Feitosa et al., 2021; Villaça, 2001). The literature on spatial patterns of urban segregation in Brazilian cities states that they are closely associated with individuals' income. Recent studies show that these patterns can be associated with both the individuals' income and race, with the spatial separation of white high-income groups and black low-income groups being more intensively observed (Bittencourt et al., 2021; Marques & França, 2020).

Latin American cities are highly segregated and unequal. Historically, cities used to have a clear center-periphery pattern of spatial segregation, with high-income population groups residing in central areas and low-income populations concentrated in the periphery (Martínez & Mina, 2021). Although Latin American cities still present a center-periphery segregation pattern, since the 1980s there has been a continuous trend of socio-spatial fragmentation characterized by urban development without defined limits. There is an increase in the concentration of high-income population groups in gated communities in peripheral areas as the appearance of low-income informal settlements both in consolidated and peripheral areas. Thus, large Latin American cities have turned into more complex socio-spatial structures, including sub-centralities and more heterogeneous areas in the periphery (Barros, 2012; Borsdorf, 2003; Feitosa et al., 2021).

Recently, as global inequality continued to rise and cities undergo significant structural changes due to an increasingly globalized world economy, there is a growing concern about how urban planning can promote equal opportunities and access to public infrastructure in cities (Feitosa et al., 2021; van Ham et al., 2021). Consequently, the topic of urban segregation has garnered attention from researchers studying urban phenomena, public officials, and the public (Piekut et al., 2019).

Also, the proliferation of available socio-spatial information and technological advancements enabled the development of more precise descriptions of new socioeconomic distribution and segregation patterns (Gao et al., 2019; Maffini & Maraschin, 2018). These provide new opportunities for segregation studies that can comprehensively incorporate more sociodemographic characteristics of populations and spatial information related to locations where segregation occurs (Maffini & Maraschin, 2018; Oka & Wong, 2019).

New conceptualizations and approaches have emerged for measuring segregation considering multiple aspects and domains of urban dynamics. Some research focuses on analyzing segregation from the perspective of the activity spaces of cities (Li & Wang, 2017; Zhang et al., 2019). Other studies focused on the individual's perspective, examined spatial mobility patterns and their impact on segregation (Farber et al., 2015; Rokem & Vaughan, 2019) or the possible interactions between individuals from different social groups (Legeby, 2010; Shen, 2019). Segregation studies also began considering various spatiotemporal contexts (Netto et al., 2016; Östh et al., 2018), recognizing the multi-scalar nature of segregation to incorporate different scales into their approaches (Feitosa et al, 2007; ; Johnston et al., 2016; Olteanu et al., 2019; Reardon et al., 2008).

Considering the complexity of segregation approaches that acknowledge the interconnected nature of its influencing factors are required. Network modeling allows the consideration of the urban morphology and the diverse array of urban elements, including transportation infrastructure, land uses, and public facilities that influence social dynamics (Hillier, 2008). Adopting network analysis frameworks enables researchers to gain insights into the underlying mechanisms that contribute to segregation patterns. The integrative and systemic approach of network analysis facilitates the identification of key spatial characteristics and urban features that shape social dynamics and influence the spatial distribution of opportunities and resources (Farrington, 2007; Hillier & Vaughan, 2007).

While beyond the scope of this study, it is essential to underscore the potential of network modeling for dynamic approaches and the exploration of the multi-scalar nature of segregation. Our study explores segregation patterns using a network index of potential accessibility. This aligns with a growing trend in the literature, aiming to address segregation issues at a more disaggregated scale. The network modeling approach contributes to research aiming to analyze combined segregation and accessibility.

Accessibility and spatial indicators

The concept of accessibility assumes a pivotal role when investigating segregation (Pereira et al., 2017). Urban accessibility studies date back to the 1950s, since the classic work of Hansen (1959), who conceptualized accessibility as the potential of opportunities to generate spatial interaction. Later, Ingram (1971) defined accessibility as the characteristic of a location in overcoming spatial friction, such as cost, time, or distance of displacement. Accessibility then refers to the ease of reaching different destinations within the urban system, encompassing physical proximity to essential amenities, employment opportunities, educational institutions, healthcare facilities, and other resources (Geurs & van Wee, 2004; Hanson, 2009). This notion recognizes that individuals' spatial location within the city influences their ability to engage in activities and access essential services.

Accessibility concepts have been used to build spatial indicators in a range of methods to operationalize their measurement. Most indicators are based on the discretization of space into polygonal units. Spatial indicators used to assess accessibility can be organized into at least two categories: isochrone and potential indicators (Cheng & Bertolini, 2013; Geurs & van Wee, 2004).

In general terms, isochrone indicators are based either on the minimum distance between origin and destination points or on how many destinations are reached by origin points within a given radius. One example is Pereira et al. (2019) who develop a comprehensive study of inequalities in accessing opportunities in the largest Brazilian cities. The isochrone indicators are known to require a limited amount of data and to be easily understandable and communicable, while not capturing many aspects of the phenomena of accessibility (Kapatsila et al., 2023).

The indicators of potential accessibility, based on gravity models, consider that the accessibility of origins is determined by the magnitude of the destinations (attractiveness, capacity) and decreases according to the distance between both. There are several efforts to adapt potential indicators to incorporate the effects of competition for opportunities, as in Shen (1998) and Cheng and Bertolini (2013). The idea is that competition for opportunities increases as the demand in their vicinity increases. Potential Accessibility indicators capture different aspects of the accessibility phenomena; however, the amount of data required and the difficulties in communicating results lead to parsimony in its use (Kapatsila et al., 2023).

The relationship between segregation and accessibility is intricate, as patterns of segregation can affect individuals' access to resources, opportunities, and services, which in turn affect patterns of segregation (Farrington, 2007; Gianotti et al., 2021; Pereira et al., 2017). Despite the understanding of the phenomenon's complexity and the possibilities in network analysis, many approaches focus exclusively on residential locations and street layouts (Fossett, 2017).

Materials and methods

Our approach focuses on calculating the Potential Accessibility (PA) of different social groups, classified by income and race. Through the analysis of disparities in PA outcomes among these groups, we aim to foster a more comprehensive understanding of the spatial inequalities and socio-spatial segregation patterns within the intra-urban space of Pelotas, a medium-sized city in Southern Brazil.

Our approach consists of five steps. First, we construct the network model by integrating the spatial network with socio-functional attributes. Next, we calculate the Potential Accessibility (PA), initially for the overall city population and subsequently for income and racial groups separately. In the third step, we normalize the PA results to eliminate the influence of population group size. Then, we assess the disparities in PA among the social groups relative to the PA of the entire city population and between each other. Lastly, we conduct spatial and statistical analyses to examine inequalities and socio-spatial segregation patterns.

Potential accessibility network index

The Potential Accessibility (PA) is an index designed to capture the advantages of spatial units representing origin locations (population residences, disaggregated according to income and racial groups) in the urban network system in relation to urban opportunities (destination locations) while accounting for the competition within the spatial network system. The inclusion of the competition factor intends to represent the limited capacity of opportunities, such as jobs, retail stores, school vacancies, hospital beds, etc.

The PA index is based on Shen's accessibility indicator (Shen, 1998), and was adapted to urban network modeling by Gonçalves (2022). It utilizes a weighted and ordered closeness centrality measure, building upon the Spatial Opportunity model (Krafta, 1996). Given an urban spatial network represented as a set of street segments i and j, Closeness Centrality (Ci) captures how close each i segment is from all j segments in the network (Equation 1).

$$C_i = \sum_{i \neq j}^{i,j \in G} \frac{1}{d_{ij}} \tag{1}$$

where C_i is the closeness centrality of segment i and d_{ij} is the shortest metric distance between segments i and j.

The Potential Accessibility (PA) network index is an enhanced closeness centrality measure that captures the ordered relationships between segments defined as origins (i) and destinations (j). Within the network, segments might contain origin or destination attributes. In this study, origins (i) are weighted with the number of households according to income groups (high, medium, and low-income) and the number of white or non-white individuals while destinations (j) are weighted with the sum of the number of establishments (commercial, services, hotels, educational and healthcare facilities and agricultural establishments).

To calculate PA, we first compute a Potential Demand (PDj) factor (Equation 2) assigned to destination segments (j). PD estimates the competition for destinations (or opportunities) based on the weight of origin segments and their proximity to destination segments.

$$PD_j = \sum_{j \neq k}^{j,k \in G} \frac{O_k}{d_{jk}} \qquad , \forall j \subset D, \forall k \subset O \tag{2}$$

where PD_j is the Potential Demand of destination segment j, O_k is the weight of origin segments k and d_{jk} is the shortest metric distance between j and k.

Finally, we calculate the PA index (Equation 3) assigned to origin segments (i), determined by the weight of destination segments (j) and the distance between these and the origin segments. Here, PD is incorporated as inversely proportional to PA. As a result, PD accounts for the impact of population distribution on the indicator, leading to PA values that may be lower in areas with a larger population.

$$PA_i = \sum_{i \neq j}^{i,j \in G} \frac{D_j}{PD_j . d_{ij}} \quad or \quad PA_i^C = \sum_{i \neq j}^{i,j \in G} \frac{D_j \ . \ d_{ij}^{-1}}{\left(\sum_{j \neq k}^{j,k \in G} O_k . d_{jk}^{-1}\right)} \quad , \forall j \subset D, \forall i,k \subset O \tag{3}$$

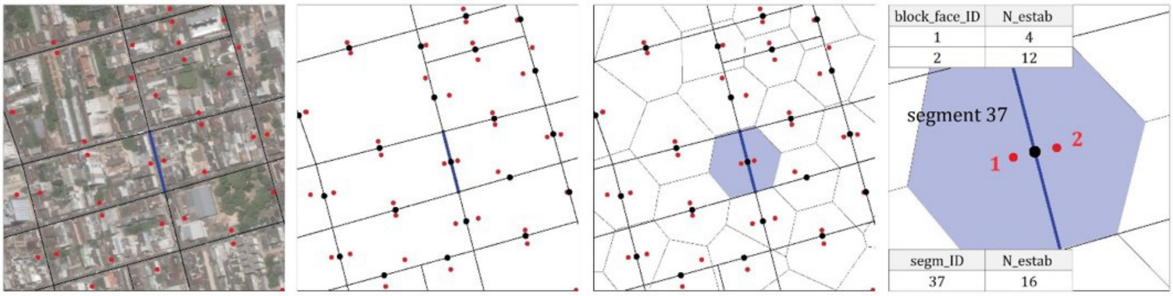
$$while\, d_{jk} = \frac{l_k}{2} if \ j = k \, and \, d_{ij} = \frac{l_i}{2} if \ i = j$$

where PA_i is the Potential Accessibility of origin segment i, D_j is the weight of destination segments j and d_{ij} is the shortest metric distance between i and j.

Data

The street network data was obtained from OpenStreetMap and transformed into a segment network model, where each spatial unit represents a segment between two intersections. To achieve this, an initial simplification process was implemented, considering for the model only publicly accessible streets, and excluding service access roads, planned roads, and roads under construction. This simplification was necessary to remove segments exclusively dedicated to a single mode of transportation. Next, the network was converted into a segment network model by splitting the vector layer at segments' intersections. The resulting model was subjected to error-checking procedures, involving manual inspection and application of metrics to ensure proper connectivity and reachability within the network.

To compose the weight of destination segments (j), land-use attributes were gathered from the National Register of Addresses for Statistical Purposes (CNEFE) database, maintained by the Brazilian Institute of Geography and Statistics (IBGE), year 2010. From the available land-use categories, collective households (hotels and similar establishments), agricultural establishments, educational institutions, healthcare facilities, and other purpose places (such as commercial and service establishments) were selected for the analysis. The database contains the number of establishments aggregated by block-faces. The sum of the number of establishments is assigned from the block faces to the nearest street segment based on the procedures illustrated in Figure 1.



a. Midpoints of block-faces (red) containing the total number of establishments (CNEFE)

b. Midpoints of street segments (black)

c. Voronoi polygons (grey) to join and summarize number of establishments to street segments

d. Total count of establishments per segment

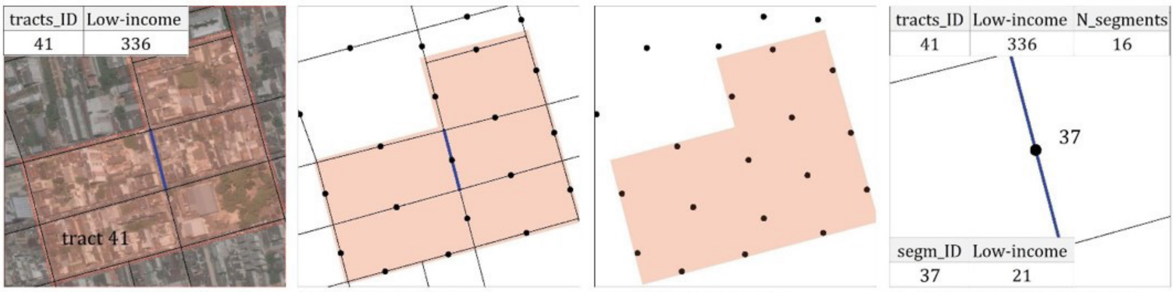
Figure 1 - Procedures to determine the weight of destination segments. Source: authors.

To compose the weight of origin segments (i), we obtained data from the IBGE 2010 Population Census database. We utilized data on the number of households per income range and the number of individuals per race. Data on household income was categorized into three groups (high, medium, and low-income), and data on individuals' race was categorized into two groups (white and non-white).

To categorize the households into three income groups, we adopted the classification proposed by the Brazilian Secretary of Strategic Affairs (Kamakura and Mazzon, 2016). Accordingly, households with a monthly per capita income of less than ½ of the minimum wage are classified as low-income, between ½ and 2 minimum wages are classified as medium-income, and more than 2 minimum wages are classified as high-income (Kamakura and Mazzon, 2016).

To classify the population into two racial groups, the data was aggregated to include black, brown, indigenous, and yellow individuals as non-white, while the remaining group encompassed the white population. Despite our binary categorization (white and non-white), it is notable the heterogeneity within these groups. In Brazil, a significant portion of the Asian population belongs to upper-middle or high-income groups and resides in more central areas. In the southern region of Brazil, the presence of Asian populations is less pronounced than in cities like São Paulo. In the specific case of Pelotas, yellow individuals constitute only 0.19% of the population.

The census data is aggregated in census tracts. The procedures in Figure 2 illustrate the methods used to transfer information from the census tracts to the street segments to compose the weight of origins (i). We divided the total number of households (for income groups) or individuals (for racial groups) by the number of segments intersecting with each census tract and assigned the result to these segments. Consequently, we assume that the number of households or individuals is evenly distributed within each census tract.



a. Census tracts (polygons) containing population and households data (for income and racial groups)

b. Midpoints of street segments (black)

c. Divide number of households/individuals by the number of segments within each census tract

d. Assign the division result to each segment within the census tract

Figure 2 - Procedures to determine the weight of origin segments. Source: authors.

Analysis criteria

We aim to examine and compare the PA levels among different social groups based on a fixed set of urban opportunities. However, direct comparison of the results is hindered by the indicator's sensitivity to variations in group sizes. Therefore, we employ a two-step approach. First, we execute the PA index using the entire population as the origin input, estimating the General Potential Accessibility (GPA). This step simulates a scenario where the entire population competes for the available urban opportunities, regardless of their social group affiliation.

Next, we multiply the origin attribute (social group) of each segment by the corresponding GPA value for the same group, as specified in Equation 4. This generates PA values that are specific to each social group, enabling comparisons between them. By adjusting the PA values, we ensure that the analysis can reflect the disparities in accessibility levels across the social groups under investigation.

$$PA_i^C = GPA_i \, . O_i^C \tag{4}$$

where PA_i^C is the Potential Accessibility of origin segment i for group C, GPA_i is the General Potential Accessibility of segment i and O_i^C is the weight of the origin segment i.

Another issue addressed was the adoption of two distinct units to quantify the weight of origin locations: the number of households for income groups and the number of residents for racial groups. To ensure comparability, we normalize the PA values for each group. This entails dividing the PA values of each segment by the sum of the origin weights of the corresponding group (Equation 5).

$$PA_i^{C'} = \left(PA_i^C / \sum_{i=1}^{i \in G} O^C \right) .1.10^7 \tag{5}$$

where $PA_i^{C'}$ is the normalized PA of origin segment i for group C and $\sum_{i=1}^{i \in G} O^C$ is the sum of the weightsof origin segments for group C (number of households for income groups and number of individuals for racial groups).

Here, the sum of the segments' origin weights ($\sum_{i=1}^{i \in G} O^C$) refers to both households for income groups and individuals for racial groups. The resulting values from this normalization are extremely low, hindering the comprehension of the numerical results. We used the scale factor (1.10^7) to aid interpretability.

After normalizing the PA values, we employ the Potential Accessibility Differences (PAD) measure, allowing the assessment of variations between different social groups, here denoted as groups C (first group) and S (second group) (Equation 6).

$$PAD_i^{C-S'} = PA_i^{C'} - PA_i^{S'} \tag{6}$$

$PAD_i^{C-S'}$ is the Potential Accessibility Difference of segment i between groups C and S, $PA_i^{C'}$ is the normalized PA of segment i for group C and $PA_i^{S'}$ is the normalized PA of segment i for group S.

The Potential Accessibility Difference (PAD) results encompass positive and negative values, offering insights into the relative performance of group C in comparison to group S. Positive values indicate a higher PA for group C, whereas negative values suggest a higher value for group S. By considering both spatial distribution and numerical differences, the PAD facilitates a comprehensive comparative evaluation of the performance of population groups.

We classify the PAD results into four classes: high positive difference (HPD), positive difference (PD), negative difference (ND), and high negative difference (HND). HPD represents the top 1% of street segments with the highest positive values (99th percentile), PD includes the values between 1% and 10% of the dataset of segments with higher positive values (between the 99th and the 90th percentile), ND consists of the values between 10% and 1% of the segments with the lowest negative values (between 10th and 1st percentile), and HND represents the bottom 1% of segments with the most negative values (1st percentile).

Results and discussion

The city of Pelotas in Southern Brazil was chosen as our case study because it exhibits a certain level of socio-spatial complexity, characterized by a non-concentric distribution of social groups. Also, the city is not part of a metropolitan or conurbated region, minimizing possible edge effects in our analysis (Gil, 2017).

Pelotas had 328,275 inhabitants according to the Brazilian Institute of Geography and Statistics (IBGE, 2011), and it is divided into seven administrative regions (Figure 3). The city presents a concentratedistribution of opportunities and amenities in the historical Central District (CD). The street layout of the CD follows a planned grid that spreads along the riverside, and the remaining city regions' street layouts are interrupted by empty areas, such as green areas, wetlands, a dam, and an airport. Consequently, the CD is connected to other regions through a limited set of main streets, especially in the Eastern region.

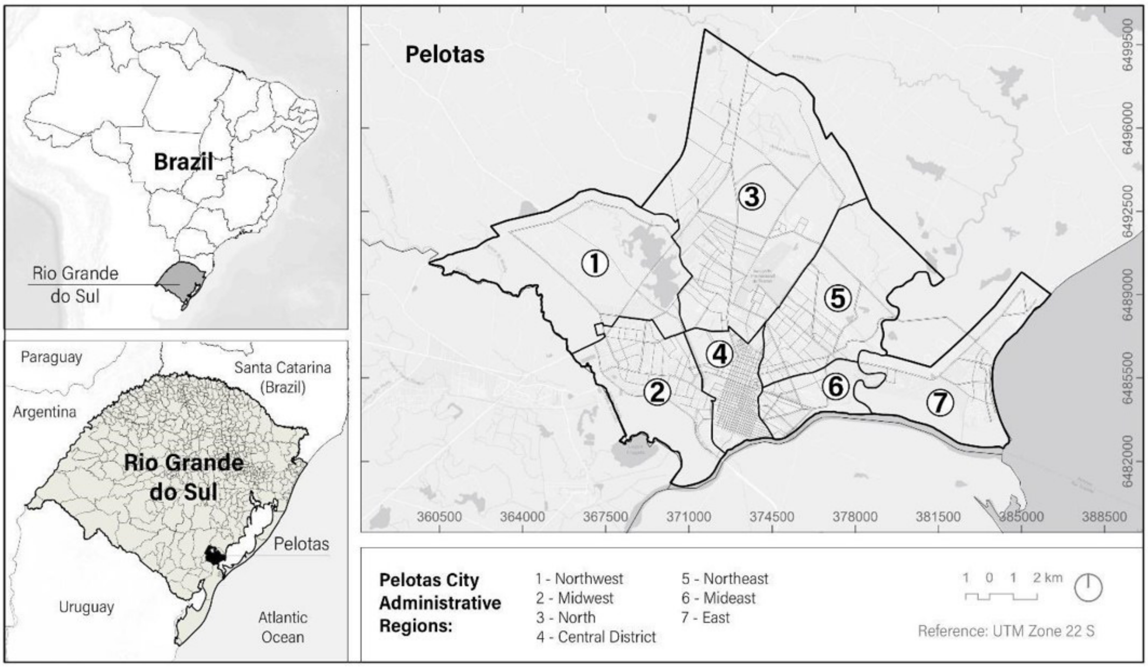


Figure 3 - Location of the city of Pelotas and its administrative regions. Source: authors.

Distribution of social groups and general inequalities

In Pelotas, the middle-income group is evenly distributed throughout the territory. To enhance the comprehension of inequalities resulting from socio-spatial segregation patterns we only analyze the high and low-income groups, which exhibit significant differences in their spatial distribution (Figure 4). This facilitates comparative analysis with the racial groups. Figure 4 shows a noticeable concentration of high-income households in the CD and along the axis connecting it to the Eastern region. These areas also have a lower presence of low-income households, more likely to be found in peripheral or residual areas closer to the CD.

The distribution of racial groups' residential locations in Pelotas, however, is more complex. The white group is dispersed without any discernible patterns of concentration. This is probably due to this group making up most of the city's population (nearly 86.55%), a common situation in southern Brazil. The non-white group, which makes up 13.45% of the city population (7.28% black, 5.88% brown, 0.19%

yellow, 0.09% Indigenous), exhibits residential locations with similarities to the distribution of low-income households, being primarily concentrated outside the CD.

The results of the Potential Accessibility (PA) analysis (Figure 5) reveal a pronounced concentration of access to opportunities in the Central District (CD), indicating the influence of both the street network layout and the spatial distribution of destinations in the central area. A comparison between the PA results and the Closeness Centrality measure demonstrates the significant impact of destination concentration on the outcomes. The Closeness Centrality measure results highlight a much larger area compared to the more localized concentration identified by the PA analysis.

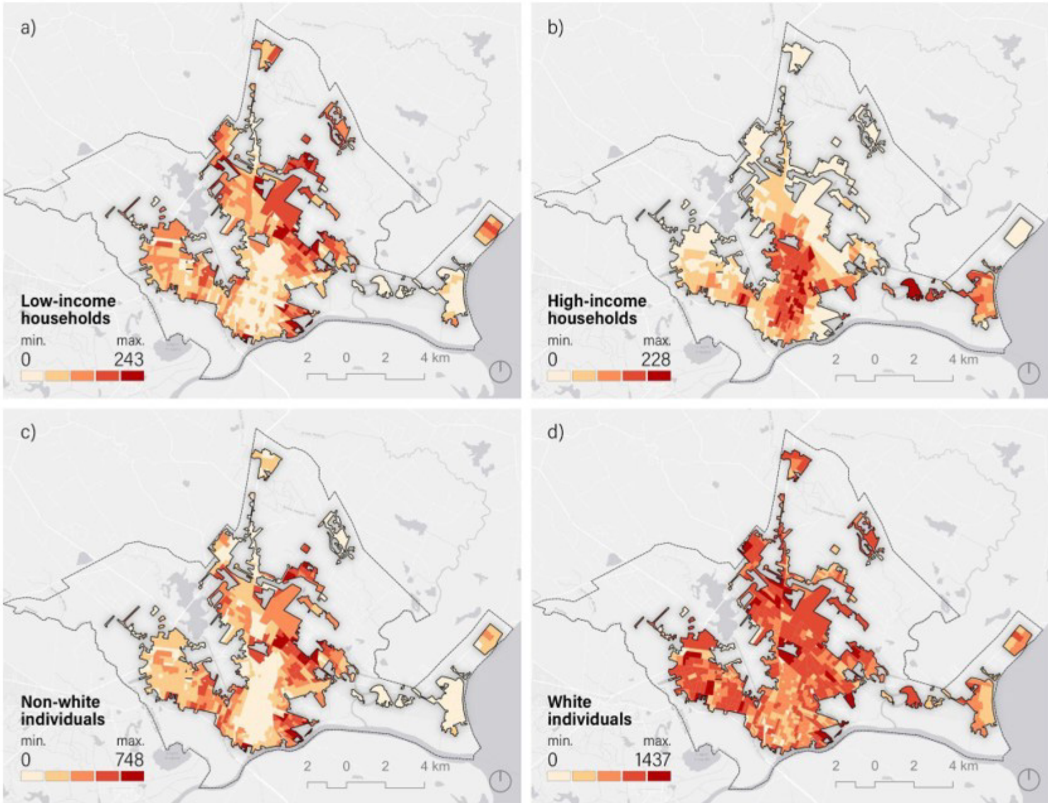


Figure 4 - Spatial distribution of (a) low-income, (b) high-income, (c) non-white, and (d) white population groups by Census tracts. Source: authors, based on Brazilian Institute of Geography and Statistics (IBGE, 2011).

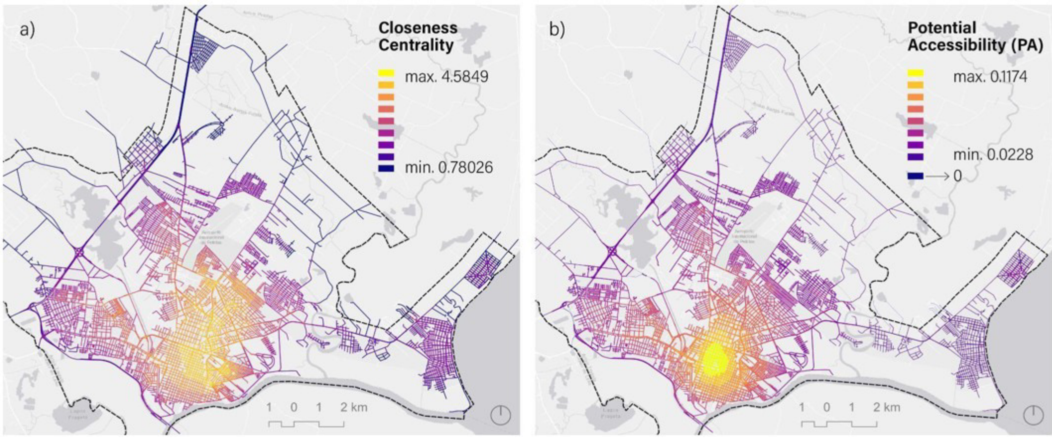


Figure 5 - (a) Closeness Centrality and (b) Potential Accessibility (PA). The results were classified using the Jenks method. Source: authors.

The high-income group is advantageously positioned to access opportunities due to their concentrated presence in central areas. Conversely, the low-income and non-white groups are predominantly located in areas with lower PA values, indicating greater challenges in accessing opportunities.

These findings provide insights into the socio-spatial segregation patterns in Pelotas, which primarily emerge from income disparities but are not limited to them. Racial characteristics are also evident in the segregation patterns in the city. Since the white group is distributed across the territory, not all these individuals benefit from a high PA. Yet, the results indicate that most of the non-white group lives in areas with lower PA values.

Inequalities in potential accessibility across city regions

We proceed to investigate the disparities in PA across various city regions for different social groups. The PA results are influenced by the distribution of origins and their proximity to urban opportunities. Figure 6 compares the median PA normalized values among the social groups and the General Potential Accessibility (GPA) in the city regions.

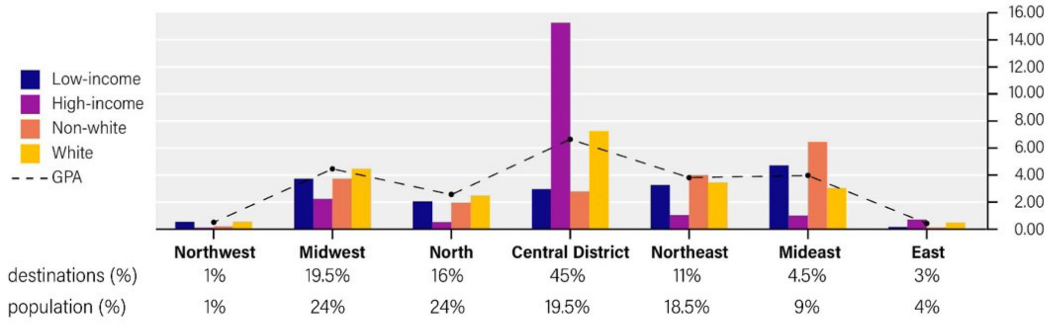


Figure 6 - Median PA values (normalized) by city region. The dashed line shows the General Potential Movement (GPA). The percentages at the bottom refer to the concentration of destinations and population in each region. Source: authors.

The contrasting PA patterns observed in different regions highlight the spatial disparities in access to opportunities among income groups. In the Central District, the high-income group has higher median PA values, indicating better access to opportunities compared to the low-income group. The high-income group also presents the highest PA values for the East Region. Even though this region does not present high PA levels, the proximity to the beach at the east limit attracts high-income groups. In the remaining regions, the median PA values are higher for the low-income group, implying a relatively less favorable accessibility profile for this group. It is noteworthy that the Mideast region exhibits the highest median PA values among low-income groups.

Regarding racial groups, the overall inequalities across city regions are not as strong. The exception is in the CD and the Mideast regions. The white group exhibits elevated values within the CD, characterized by high PA levels, whereas the non-white group demonstrates higher values within the Mideast, characterized by medium PA levels.

The white population generally achieves slightly higher median PA values compared to the non-white population in most areas. This can be attributed to the broad dispersion of the white population, as they constitute a significant majority. Consequently, their median PA values tend to be higher than the non-white results, indicating relatively better access to opportunities. The findings suggest that spatial dispersion and population composition play significant roles in shaping the accessibility profiles of racial groups.

This unveils distinct spatial advantages associated with the high-income and white populations. Notably, high-income values reach their peak in the CD, which concentrates 45% of the destinations. Furthermore, the white population demonstrates higher median values compared to other groups across most city regions.

The observed PA variations across city regions among income groups can be attributed to structural disparities prevalent in Latin American cities. High-income groups tend to reside and work in central areas with better infrastructure, leading to a higher spatial concentration of accessibility values. In contrast, low-income groups typically reside in underserved peripheral areas and face longer travel distances when commuting to the CD in search of opportunities and services.

The low-income and non-white groups exhibit similar median PA values, except in the Northeast and Mideast regions, where the non-white population achieves higher median values. This suggests that in most regions, non-white populations may also represent a significant proportion of the low-income group. These findings also highlight the intersectionality of income and race in shaping accessibility disparities in the city.

Potential accessibility differences and socio-spatial segregation patterns

We then examine the Potential Accessibility Differences (PAD) for income and racial groups (Figure 7) against the General Potential Accessibility (GPA). The idea is to highlight the segments in which specific groups reach accessibility levels above or below the GPA. Following the methodology, the maps in Figure 7 present four color-coded classes to illustrate these differences, corresponding to the high positive difference (HPD), positive difference (PD), negative difference (ND), and high negative difference (HND). Segments depicted in gray display accessibility levels similar to the GPA.

The CD exhibits a positive PAD for high-income groups, indicating that their PA surpasses the reference value (GPA). The high positive difference (HPD) segments for the high-income group are concentrated in central areas. Conversely, the PAD values for low-income groups show negative values in the CD and more dispersed positive values in peripheral spaces. These reinforce the previous analysis showing high-income groups with better PA results. However, the low-income group also exhibits scattered HPD segments in areas closer to or within the CD.

The PAD results for racial groups exhibit similar patterns to the income analysis. The CD displays a concentration of high positive differences for the white group, while the periphery harbors more positive differences for the non-white group.

Comparing the PAD results for the low-income and the non-white groups, distinct patterns emerge. The low-income group possesses fewer segments with negative results in the CD, suggesting a relatively better performance compared to the non-white group. These findings imply that, although both groups experience lower PA outcomes in the central district compared to the GPA, the non-white group faces even greater challenges.

We then examine the PAD values in the form of boxplots (Figure 8). They illustrate the distribution of PAD values for social groups in comparison to values observed exclusively within the CD and for all other remaining regions.

The box plots indicate a narrower range of PAD values for the white group. This can be attributed to the white population comprising most of the total population, resulting in their PA outcomes being similar to the reference values (GPA). However, there are variations observed in specific regions. The white group presents a positive PAD when the analysis is limited to the CD, which concentrates the urban opportunities. When the city is analyzed excluding the CD, the white group exhibits more negative PAD results. These findings indicate that, despite similarities to the GPA, the white group performs better in terms of PA in the CD.

When the maximum PAD value for all regions aligns with the maximum value for the CD, it indicates that the group achieves its highest PAD result in the central area. This pattern is observed for both the high-income and white population groups. Conversely, the low-income and non-white population groups exhibit significantly lower maximum values in the CD. The negative difference values for the low-income and non-white groups are significantly higher in the CD than when all the city regions are considered.

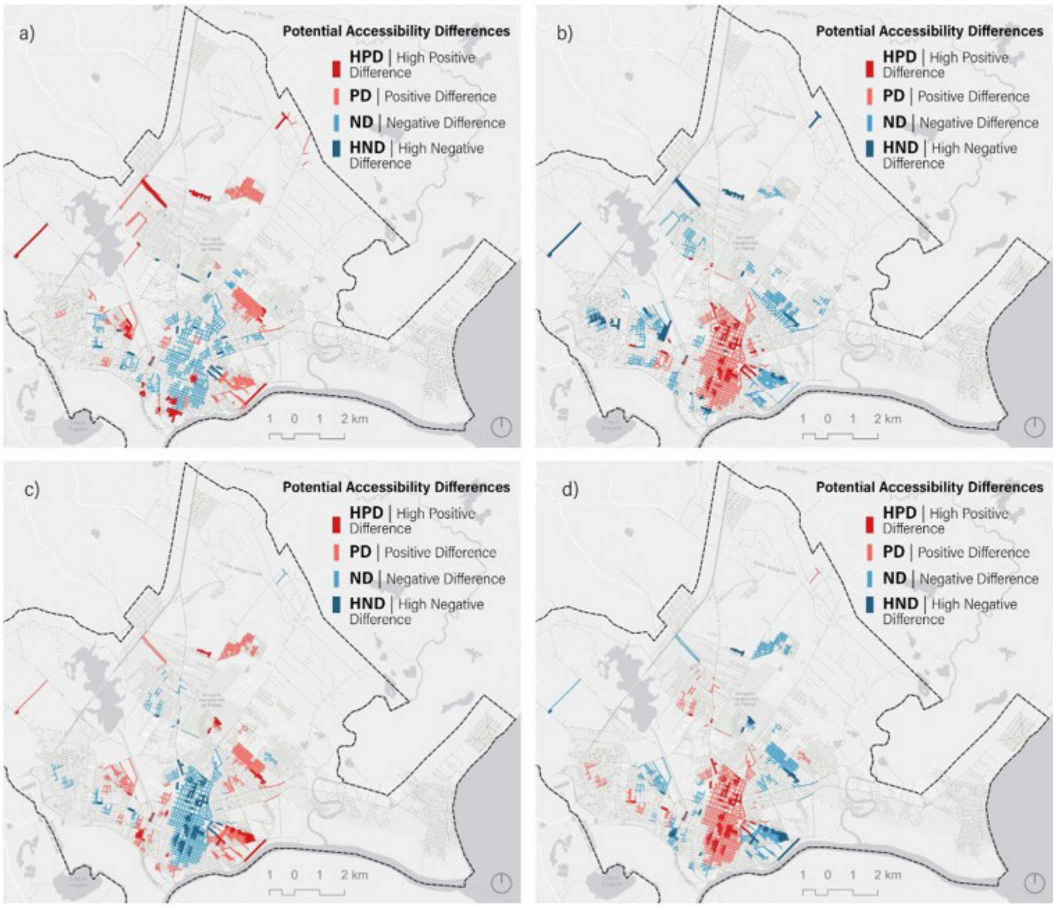


Figure 7 - Spatial distribution of Potential Accessibility Differences (PAD) values for (a) low-income, (b) high-income, (c) non-white, and (d) white population groups. Source: authors.

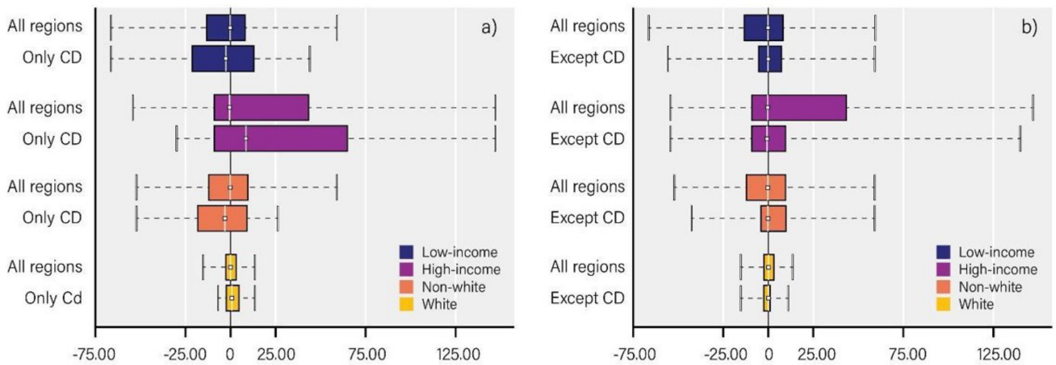


Figure 8 - Box Plots comparing the Potential Accessibility Difference (PAD) values for each social group in the entire city with a) values only in the Central District (CD), and b) values in all other regions. The right limit of the boxes represents the 99th percentile (High Positive Difference - HPD) and the left limit of the boxes represents the 1st percentile (High Negative Difference - HND). The medium lines of the boxes represent the median values. Source: authors.

Intergroups potential accessibility differences

Following the previous analysis, we compare the Potential Accessibility (PA) values between the high-income and white groups, and between the low-income and non-white groups through the PAD measure. In Figure 9, the PAD was calculated with the income groups as the primary factor of the equation, representing the C group in the PAD measure, while racial groups are the secondary factor, representing the S group. Consequently, segments with positive values indicate areas where the income groups have higher PA values compared to the racial groups.

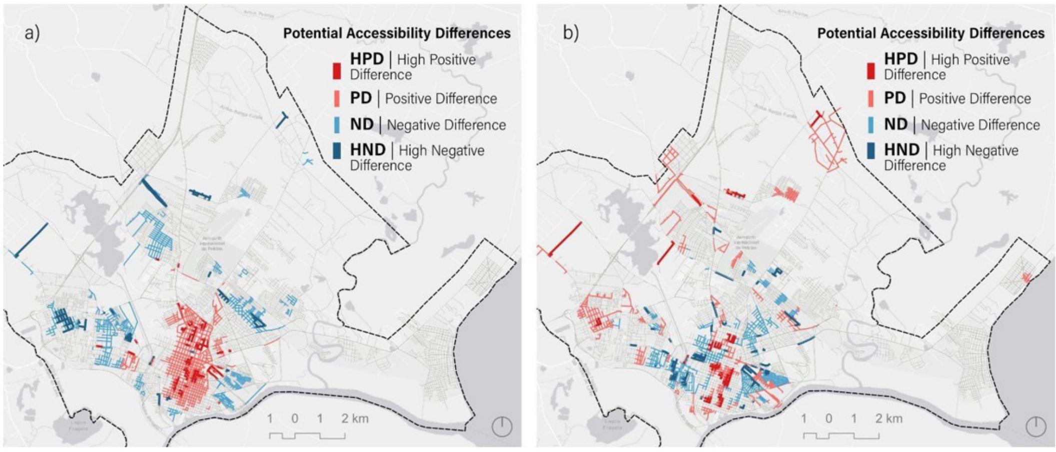


Figure 9 - Potential Accessibility Differences (PAD) values for a) High-income x White, b) Low-income x Non-white. Source: authors.

The maps in Figure 9 reveal distinct patterns of socio-spatial segregation. When analyzing the CD, where most of the urban opportunities are concentrated, the high-income group presents better performance than the white one. When comparing the low-income and non-white groups, the disparity is less pronounced.

To assist in the analysis of disparities in accessibility levels among income and racial groups, we also examine their PAD values across different city areas, including the entire city, the Central District, and the remaining regions (Figure 10).

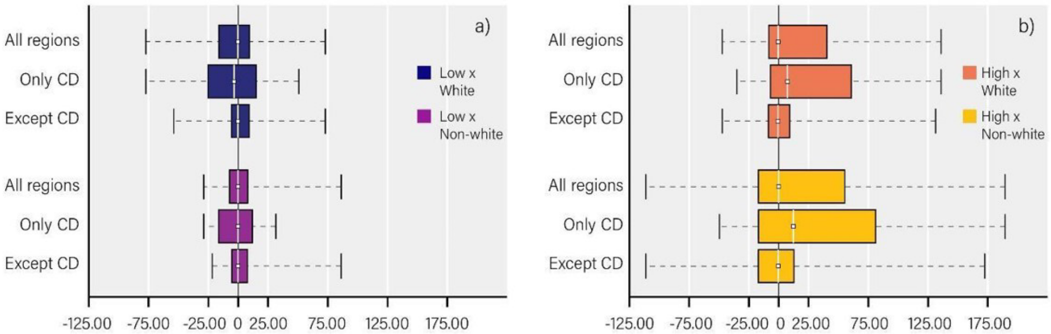


Figure 10 - Potential Accessibility Differences (PAD) values among pairs of income and racial groups in the entire city, the Central District (CD), and all other regions without the CD for a) low-income x racial groups and b) high-income x racial groups. The right limit of the boxes represents the 99th percentile (High Positive Difference - HPD) and the left limit of the boxes represents the 1st percentile (High Negative Differences - HND). The medium lines of the boxes represent the median values. Source: authors.

The study reveals that the high-income group outperforms the white group in accessing urban opportunities, as evidenced by significantly higher positive values of PAD. This pattern holds for both the entire city and the central district, with the CD exhibiting even higher PAD values. The results indicate that the high-income group has a privileged position in accessing opportunities within the CD compared to the white population. This highlights the presence of a socioeconomic spatial segregation pattern, where segregation is primarily driven by income.

When comparing the high-income group with the non-white group, the results reveal an even higher positive PAD. Moreover, the PAD values outside the CD exhibit a higher proportion of negative values, indicating a lower representation of individuals from the high-income group and a greater concentration of the non-white group outside the CD.

Of all the PAD comparisons, the one between low-income and non-white groups has the smallest range of values, indicating a similarity in their PA results. This could be attributed to a higher degree of shared residential spaces between the two groups.

Based on the index results and analyses, Pelotas exhibits significant socioeconomic spatial segregation. The high-income group attains the highest accessibility outcomes in the CD, a hub of opportunities. The results also highlight a pattern of ethnic and racial segregation, where both low-income and non-white groups have lower and similar PA results, particularly in the CD.

Conclusion

This paper introduces a novel perspective to investigate segregation and accessibility in a combined way. While the existing literature on accessibility concentrates on inequalities in public transport access, mostly focusing on large metropolitan cities, studies on network analysis examine socio-spatial inequalities mostly based on residential segregation, focusing on income disparities. Our research employs network analysis to bridge the gap between two fields of study. Specifically, we introduced a method for evaluating accessibility inequalities and segregation patterns at a disaggregated level, demonstrated through a case study of a medium-sized city.

Our study combined various analysis criteria to depict spatial inequalities between social groups and uncover socio-spatial segregation patterns resulting from the distribution of urban opportunities and population densities. Applying this method to the city of Pelotas demonstrates its ability to identify and compare accessibility disparities between different social groups in greater detail.

We modeled the street network considering population densities and urban opportunities. Our findings reveal that accessibility levels in the Central District, characterized by a concentration of opportunities, are predominantly favorable for high-income and white groups, while low-income and non-white groups face poorer accessibility in the area. The method unveils a complex and spatially diverse pattern of center-periphery segregation.

Our analysis criteria not only capture accessibility inequalities between social groups but also provide insights into segregation patterns arising from these inequalities. The Potential Accessibility Differences metrics offer a clearer and easily communicable comprehension of the phenomena while maintaining consistency with the statistical properties of the indicator.

We must acknowledge some limitations. Currently, the index overlooks public transportation networks and distance decay functions, essential for estimating variations in population willingness to travel as distances increase. However, the absence of data on travel behavior necessary to estimate these functions presents a significant challenge, particularly given the scarcity of such data for medium-sized in Latin America. The study also does not account for the differences in the sizes of establishments, such as their capacity and number of employees, in weighting destination segments. This oversight may impact the accuracy of the results, exposing the need for further research to address these aspects and enhance the comprehensiveness of the index application.

Future research may also consider disaggregating the analysis by considering additional social groups. Examining PA levels based on factors such as gender, age, household structure, and more could provide a broader understanding of inequalities. Combining different social groups could also offer a more comprehensive picture of these inequalities. Additionally, it would be beneficial to disaggregate the analysis by targeting specific destinations for investigations. For example, studying the PA of single mothers in elementary schools or young black adults in universities could provide more detailed insights into socio-spatial inequalities. These studies, however, would require finer data still unavailable at a disaggregated level for Brazil.

When it comes to the competition factor in the PA index, future research may consider defining suitable origin and destination parameters based on different interests, desires, and needs of social groups. For instance, when evaluating job accessibility, the analysis could be performed separately for each social group, considering only job positions relevant to their skill levels. This could provide a more nuanced understanding of how competition influences accessibility for different groups.

This paper contributes to the literature on urban accessibility and segregation, introducing a network-based approach for identifying socio-spatial inequalities in accessibility levels across diverse social groups. This approach is particularly relevant for segregation studies as it can enhance methodologies to incorporate multiple domains, scales, and dimensions of the phenomenon. Overall, this research expands our understanding of urban accessibility and segregation, providing new insights and analytical tools that have potential implications for evidence-based urban planning and design as well as policy-making strategies, particularly at the disaggregated intra-urban scale.

Data availability statement

The dataset that supports the results of this paper is available at SciELO Data and can be accessed via https://doi.org/10.48331/scielodata.WLFPSY.

References

Barros, J. (2012). Exploring urban dynamics in latin american cities using an agent-based simulation approach. In A. Heppenstall, A. Crooks, L. See & M. Batty (Eds.), *Agent-based models of geographical systems* (pp. 571-589). Springer: Dordrecht. http://doi.org/10.1007/978-90-481-8927-4_28

Bittencourt, T. A., Giannotti, M., Marques, E. (2021). Cumulative (and self-reinforcing) spatial inequalities: Interactions between accessibility and segregation in four Brazilian metropolises. *Environment and Planning B: Urban Analytics and City Science*, 48(7), 1989–2005. http://doi.org/10.1177/2399808320958426

Borsdorf, A. (2003). Cómo modelar el desarrollo y la dinámica de la ciudad latinoamericana. *Eure Revista Latinoamericana De Estudios Urbano Regionales*, 29(86), 37–49. http://doi.org/10.4067/S0250-71612003008600002

Cheng, J., & Bertolini, L. (2013). Measuring urban job accessibility with distance decay, competition and diversity. *Journal of Transport Geography*, 30, 100–109. http://doi.org/10.1016/j.jtrangeo.2013.03.005

Farber, S., O'Kelly, M., Miller, H. J., Neutens, T. (2015). Measuring segregation using patterns of daily travel behavior: a social interaction based model of exposure. *Journal of Transport Geography*, 49, 26–38. http://doi.org/10.1016/j.jtrangeo.2015.10.009

Farrington, J. H. (2007). The new narrative of accessibility: its potential contribution to discourses in (transport) geography. *Journal of Transport Geography*, 15(5), 319–330. http://doi.org/10.1016/j.jtrangeo.2006.11.007

Feitosa, F. F., Camara, G., Monteiro, A. M. V., Koschitzki, T., Silva, M. P. (2007). Global and local spatial indices of urban segregation. *International Journal of Geographical Information Science*, 21(3), 299-323. http://doi.org/10.1080/13658810600911903

Feitosa, F., Barros, J., Marques, E., Giannotti, M. (2021). Measuring Changes in Residential Segregation in São Paulo in the 2000s. In M. van Ham, T. Tammaru, R. Ubarevičienė &Janssen, H. (Eds.), *Urban socio-economic segregation and income inequality* (The Urban Book Series, pp. 507-523). Berlin: Springer. http://doi.org/10.1007/978-3-030-64569-4_26

Fossett, M. (2017). *New methods for measuring and analyzing segregation*. Cham: Springer. http://doi.org/10.1007/978-3-319-41304-4.

Gao, J., Zhang, Y. C., Zhou, T. (2019). Computational socioeconomics. *Physics Reports*, 817, 1–104. http://doi.org/10.1016/j.physrep.2019.05.002

Geurs, K. T., van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography*, 12(2), 127–140. http://doi.org/10.1016/j.jtrangeo.2003.10.005

Gianotti, M., Barros, J., Tomasiello, D., Smith, D., Pizzol, B., Santos, B., Zhong, C., Shen, Y., Marques, E., Batty, M. (2021). Inequalities in transit accessibility: contributions from a comparative study between Global South and North metropolitan regions. Cities, 109, 103016. http://doi.org/10.1016/j.cities.2020.103016

Gil, J. (2017). Street network analysis "edge effects": examining the sensitivity of centrality measures to boundary conditions. *Environment and Planning B: Urban Analytics and City Science*, 44(5), 819–836. http://doi.org/10.1177/0265813516650678

Gonçalves, G. M. (2022). *Indicadores de acessibilidade aos empregos baseados na abordagem configuracional* (Master's thesis). Universidade Federal do Rio Grande do Sul, Porto Alegre.

Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Planning Association*, 25(2), 73–76. http://doi.org/10.1080/01944365908978307

Hanson, S. (2009). Accessibility. In D. Gregory, R. Johnston, G. Pratt, M. J. Watts & S. Whatmore (Eds.), *The dictionary of human geography* (5th ed., pp. 2-3), Chichester: Wiley-Blackwell.

Hillier, B. (2008). Space and spatiality: what the built environment needs from social theory. *Building Research & Information*, 36(3), 216–230. http://doi.org/10.1080/09613210801928073

Hillier, B; Vaughan, L. (2007). The city as one thing. *Progress in Planning*, 67 (3), 205-230. http://doi.org/10.1016/j.progress.2007.03.001

Ingram, D. R. (1971). The concept of accessibility: a search for an operational form. *Regional Studies*, 5(2), 101–107. http://doi.org/10.1080/09595237100185131

Instituto Brasileiro de Geografia e Estatística – IBGE. (2011). *Censo Demográfico de 2010.* Retrieved in 2022, August 7, from https://censo2010.ibge.gov.br/.

Johnston, R., Jones, K., Manley, D., Owen, D. (2016), Macro-scale stability with micro-scale diversity: modelling changing ethnic minority residential segregation – London 2001–2011. *Transactions of the Institute of British Geographers*, 41(4), 389-402. http://doi.org/10.1111/tran.12142

KapatsilaI, B., Palacios, M. S., Grisé, E., El-Geneidy, A. (2023). Resolving the accessibility dilemma: Comparing cumulative and gravity-based measures of accessibility in eight Canadian cities. *Journal of Transport Geography*, 107, 103530. http://doi.org/10.1016/j.jtrangeo.2023.103530

Krafta, R. (1996). Urban convergence: morphology and attraction. *Environment and Planning B: Planning and Design*, 23(1), 37–48. http://doi.org/10.1068/b230037

Kamakura, W., & Mazzon, J. A. (2016). Critérios de estratificação e comparação de classificadores socioeconômicos no Brasil. *Revista de Administração de Empresas*, 56(1), 55-70.

Legeby, A. (2010). From housing segregation to integration in public space: a space syntax approach applied on the city of södertälje. *The Journal of Space Syntax*, 1(1), 92–107.

Legeby, A., Koch, D., Duarte, F., Heine, C., Benson, T., Fugiglando, U., & Ratti, C. (2023). New urban habits in Stockholm following COVID-19. Urban Studies, 60(8), 1448-1464. http://doi.org/10.1177/00420980211070677

Li, F., Wang, D. (2017). Measuring urban segregation based on individuals' daily activity patterns: a multidimensional approach. *Environment and Planning A: Economy and Space*, 49(2), 467–486. http://doi.org/10.1177/0308518X16673213

Maffini, A. L., Maraschin, C. (2018). Urban segregation and socio-spatial interactions: a configurational approach. *Urban Science*, 2(3), 55. http://doi.org/10.3390/urbansci2030055

Maloutas, T. (2004). Editorial: urban segregation and the European context. *The Greek Review of Social Research*, 113, 3–24. http://doi.org/10.4337/9781788115605.00027

Maloutas, T. (2020). Vertical social differentiation as segregation in spatial proximity. In S. Musterd (Ed.), *Handbook of urban segregation* (pp. 325-345). Cheltenham: Edward Elgar Publishing. http://doi.org/10.4337/9781788115605.00027.

Marques, E., França, D. (2020). Segregation by class and race in São Paulo. In S. Musterd (Ed.), *Handbook of Urban Segregation* (pp. 36-54). Cheltenham: Edward Elgar Publishing. http://doi.org/10.4337/9781788115605.00010

Martínez, A. L., Mina, O. E. C. (2021). Socioeconomic residential segregation and income inequality in bogotá: an analysis based on census data of 2005. In M. van Ham, T. Tammaru, R. Ubarevičienė & H. Janssen, (Eds.), *Urban socio-economic segregation and income inequality* (The Urban Book Series, pp. 433-450). Berlin: Springer. http://doi.org/10.1007/978-3-030-64569-4_22

Musterd, S. (2020). *Handbook of urban segregation*. Cheltenham: Edward Elgar Publishing.. http://doi.org/10.4337/9781788115605.

Netto, V. M., Soares, M. P., Paschoalino, R. (2016). Segregated networks in the city. International *Journal of Urban and Regional Research*, 39(6), 1084–1102. http://doi.org/10.1111/1468-2427.12346

Oka, M., Wong, D. W. S. (2019). Segregation: a multi-contextual and multi-faceted phenomenon in stratified societies. In T. Schwanen & R. van Kempen (Eds.), *Handbook of urban geography*. Edward Cheltenham: Elgar Publishing. http://doi.org/10.4337/9781785364600.00028

Olteanu, M., Randon-Furling, J., Clark, W. A. V. (2019). Segregation through the multiscalar lens. Proceedings of the National Academy of Sciences, 116(25_: 12250-12254. http://doi.org/10.1073/pnas.1900192116 PMid:31147462.

Östh, J., Shuttleworth, I., Niedomysl, T. (2018). Spatial and temporal patterns of economic segregation in Sweden's metropolitan areas: a mobility approach. *Environment and Planning A: Economy and Space*, 50(4), 809–825. http://doi.org/10.1177/0308518X18763167

Pereira, R. H. M., Braga, C. K. V., Serra, B., & Nadalin, V. (2019). *Desigualdades socioespaciais de acesso a oportunidades nas cidades brasileiras, 2019*. Texto para Discussão Ipea, 2535. Retrieved in 2022, August 7, from http://repositorio.ipea.gov.br/handle/11058/9586

Pereira, R. H. M., Schwanen, T., Banister, D. (2017). Distributive justice and equity in transportation. *Transport Reviews*, 37(2), 170–191. http://doi.org/10.1080/01441647.2016.1257660

Piekut, A., Pryce, G., van Gent, W. (2019). Segregation in the twenty first century: processes, complexities and future directions. *Tijdschrift Voor Economische En Sociale Geografie*, 110(3), 225–234. http://doi.org/10.1111/tesg.12355

Reardon, S. F., Matthews, S. A., O'Sullivan, D., Lee, B. A., Firebaugh, G., Farrell, C. R., Bischoff, K. (2008). The geographic scale of metropolitan racial segregation. Demography, 45(3), 489-514. http://doi.org/10.1353/dem.0.0019 PMid:18939658.

Rokem, J., Vaughan, L. (2019). Geographies of ethnic segregation in Stockholm: the role of mobility and co-presence in shaping the 'diverse' city. *Urban Studies*, 56(12), 2426–2446. http://doi.org/10.1177/0042098018795561

Shen, Q. (1998). Location characteristics of inner-city neighborhoods and employment accessibility of low-wage workers. *Environment and Planning B: Planning and Design*, 25(1), 345–365. 23http://doi.org/10.1016/j.jtrangeo.2019.02.007

Shen, Y. (2019). Segregation through space: a scope of the flow-based spatial interaction model. *Journal of Transport Geography*, 76, 10–23. https://doi.org/10.1016/j.jtrangeo.2019.02.007

van Ham, M., Tammaru, T., Ubarevičienė, R., Janssen, H. (2021). Rising inequalities and a changing social geography of cities. an introduction to the global segregation book. In M. van Ham, T. Tammaru, R. Ubarevičienė & H. Janssen (Eds.), *Urban socio-economic segregation and income inequality* (The Urban Book Series, pp. 3-26). Berlin: Springer. http://doi.org/10.1007/978-3-030-64569-4_1

Villaça, F. (2001). *Espaço Intra-Urbano no Brasil.* São Paulo: Studio Nobel.

Zhang, X., Wang, J., Kwan, M.-P., Chai, Y. (2019). Reside nearby, behave apart? Activity-space-based segregation among residents of various types of housing in Beijing, China. *Cities*, 88, 166–180. http://doi.org/10.1016/j.cities.2018.10.009

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