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Analysis of the impact of the COVID-19 Pandemic on the mobility patterns and accessibility to public transportation in informal settlements in the municipality of São Paulo

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Authors' notes'

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Abstract

Objective: This study examines the impact of the COVID-19 pandemic on the urban mobility in informal settlements in the municipality of São Paulo, investigating accessibility and changes in mobility patterns during the pandemic.

Methods: Using complex network techniques, we analyze the proximity of bus lines and metro stations to favelas, based on temporal bus passenger data to compare mobility patterns before and during the pandemic.

Relevance: Understanding the effects of the pandemic on mobility patterns in marginalized communities is crucial for inclusive urban planning, supporting policies to improve transportation services and reduce disparities.

Results: We observe difficulties in accessing bus lines for residents of peripheral areas and changes in mobility patterns reflecting alterations in travel. Theoretical.

Contributions: The combination of complex network techniques and temporal data analysis allows for investigating accessibility, measuring the impact of the COVID-19 pandemic on public transportation, analyzing relationships between public transportation lines and favelas, and providing insights into mobility in informal settlements.

Management Contributions: The results have practical implications for urban management, highlighting the need to improve accessibility to public transportation in peripheral areas and demanding adaptive strategies and policies that prioritize the needs of marginalized communities in times of crisis.

Conclusion: This study reveals challenges to accessibility and changes in mobility patterns caused by the COVID-19 pandemic in informal settlements, providing input for decisions that promote sustainable and inclusive urban development.

Key Words: urban mobility, slum, informal settlements, COVID-19, complex networks

Análise do impacto da Pandemia de COVID-19 nos padrões de mobilidade e na acessibilidade ao transporte público em assentamentos informais do município de São Paulo

Resumo

Objetivo: Este estudo examina o impacto da pandemia de COVID-19 na mobilidade urbana em assentamentos informais do município de São Paulo, investigando a acessibilidade e as mudanças nos padrões de mobilidade durante a pandemia.

Métodos: Utilizando técnicas de redes complexas, analisamos a proximidade de linhas de ônibus e estações em relação aos assentamentos informais, a partir de dados temporais de passageiros de ônibus para comparar os padrões de mobilidade antes e durante a pandemia.

Relevância: Compreender os efeitos da pandemia nos padrões de mobilidade de comunidades marginalizadas é crucial para o planejamento urbano inclusivo, apoiando políticas para melhorar os serviços de transporte e reduzir disparidades.

Resultados: Observamos dificuldades de acesso às linhas de ônibus para moradores de áreas periféricas e mudanças nos padrões de mobilidade que refletem alterações nos deslocamentos.

Contribuições Teóricas: Combinação de técnicas de redes complexas e análise de dados temporais para investigar a acessibilidade e medir o impacto da pandemia de COVID-19 no transporte público, analisar as relações entre linhas de transporte público e assentamentos informais e proporcionar insights sobre a mobilidade nesses locais.

Contribuições para a Gestão: Os resultados têm implicações práticas para a gestão urbana, destacando-se a necessidade de melhorar a acessibilidade ao transporte público em áreas periféricas e exigências de estratégias e políticas adaptativas que priorizem as necessidades das comunidades marginalizadas em tempos de crise.

Conclusão: Este estudo revela os desafios de acessibilidade e as mudanças nos padrões de mobilidade causadas pela pandemia de COVID-19 em assentamentos informais, fornecendo subsídios para decisões que promovam o desenvolvimento urbano sustentável e inclusivo.

Palavras-Chave: mobilidade urbana, favela, assentamentos informais, COVID-19, redes complexas

Análisis del impacto de la Pandemia de COVID-19 en los patrones de movilidad y accesibilidad al transporte público en asentamientos informales del municipio de São Paulo

Resumen

Objetivo: Este estudio examina el impacto de la pandemia de COVID-19 en la movilidad urbana en asentamientos informales de la ciudad de São Paulo, investigando la accesibilidad y los cambios en los patrones de movilidad durante la pandemia.

Métodos: Utilizando técnicas de redes complejas, analizamos la proximidad de las líneas de autobús y las estaciones de metro a los asentamientos informales, utilizando datos temporales de los pasajeros de autobús para comparar los patrones de movilidad antes y durante la pandemia.

Relevancia: Comprender los efectos de la pandemia en los patrones de movilidad de las comunidades marginadas es crucial para una planificación urbana inclusiva, apoyando políticas para mejorar los servicios de transporte y reducir las disparidades. Resultados: Se observaron dificultades en el acceso a las líneas de autobús para los residentes de zonas periféricas y cambios en los patrones de movilidad que reflejan cambios en los desplazamientos.

Contribuciones teóricas: Combinación de técnicas de redes complejas y análisis de datos temporales para investigar la accesibilidad y medir el impacto de la pandemia de COVID-19 en el transporte público, analizar las relaciones entre las líneas de transporte público y los asentamientos informales, y proporcionar información sobre la movilidad en estos lugares.

Contribuciones a la gestión: Los resultados tienen implicaciones prácticas para la gestión urbana, destacando la necesidad de mejorar la accesibilidad al transporte público en las zonas periféricas y las demandas de estrategias y políticas adaptativas que prioricen las necesidades de las comunidades marginadas en tiempos de crisis.

Conclusión: Este estudio revela los desafíos de accesibilidad y los cambios en los patrones de movilidad causados por la pandemia de COVID-19 en asentamientos informales, proporcionando insumos para la toma de decisiones que promuevan el desarrollo urbano sostenible e inclusivo.

Palabras clave: movilidad urbana, favela, asentamientos informales, COVID-19, redes complejas

Introduction

The COVID-19 pandemic had significant impacts on urban public transportation systems. Restrictions on mobility, social distancing measures and health concerns led to a drastic reduction in the demand for public transportation, resulting in sharp falls in the operators' income and financial difficulty (Dong et al., 2021). Moreover, the need to implement safety protocols, such as limiting the capacity of vehicles and intensifying cleansing, increased operational costs. These sudden changes and resulting financial challenges affected the availability and the quality of public transportation services, negatively impacting the mobility of individuals, especially the most vulnerable ones, and contributing to a greater dependency on individual means of transport (Fernandes et al., 2020).

Public transportation plays a fundamental role in people's lives, mainly in urban areas, being essential to promote people's mobility, ensuring access to basic services, employment, education and health opportunities. Efficient public transportation networks can help reduce traffic and promote sustainable development (Delgado et al., 2022). By providing an accessible and efficient transportation alternative, public transportation services play a significant role in building more inclusive and fairer communities, allowing people to connect, to interact and to prosper in their daily lives.

In crisis situations, such as the COVID-19 pandemic, informal settlement residents may have faced additional challenges regarding impacts in public transportation, as compared to residents of other types of urban settlement (Fernandes et al., 2020). This may have included lesser accessibility to quality transport alternatives due to the concentration of bus lines in central areas, decreased frequency of transportation services, difficulty in meeting social distancing measures due to the overcrowding in public transportation, lack of financial resources to meet the cost of alternative transportation and less access to updated information on the changes in public transportation services. These factors may have aggravated the gap related to mobility and limited the opportunities of safe and efficient trips for informal settlement residents during the pandemic (Rocha, 2021). Despite this fact, a quantitative analysis of the impact of the pandemic on these inequalities is made necessary.

Complex networks are structures consisting of a set of interconnected elements, called knots, with non-trivial connection and interaction standards. These networks can represent public transportation systems. The algorithms used in complex network models allow a thorough analysis of the interactions among elements, and thus estimating the location of weak points and bottlenecks of the system, investigating the tolerance to flaws and the presence of alternative routes, besides possible asymmetries in the system architecture (Boccaletti et al., 2006). More recent approaches allow complex networks to investigate time series, extracting patterns not obtained by traditional techniques (Zou et al., 2019).

Hypergraphs permit a more flexible representation of the complex interactions among the elements of a network as compared to the graph-based models, being particularly effective in modeling situations in which a single edge is not enough to express the relationship among several knots. In the public transportation context, in which different bus lines may converge or overlap, and the presence of multilateral transfer stations is usual, hypergraphs stand out in directly capturing these multivariate relationships (Wolf et al., 2016).

Furthermore, when derived from the conversion of time series into complex networks, visibility graphs stand out for their capacity for efficiently dealing with non-linear or non-stationary time series (Lacasa & Toral, 2010b). The visibility graphs approach is especially robust for detecting complex relationships among events over time, even in situations in which the temporal evolution presents non-linearities or significant variations.

Despite these advantages, there are few examples of hypergraphs and visibility graphs application to transport systems studies, indicating a research opportunity.

Two complementary tasks were performed in this work, both employing complex network models as a base. The first modeled the availability of access to public transportation for informal settlement residents of the city of São Paulo, obtaining the list of lines passing in each informal settlement by means of hypergraphs. From the daily passenger demand of the lines from the previous task, the second one compared the patterns observed in visibility graphs, present before and during the COVID-19 pandemic, providing evidences of the intensity of the impact caused. From this, we expect to meet the objective of examining the impact of the COVID-19 pandemic on urban mobility in informal settlements in the São Paulo municipality, investigating accessibility and the changes in mobility patterns during the pandemic using complex network techniques.

Materials and Methods

Complex networks and hypergraphs

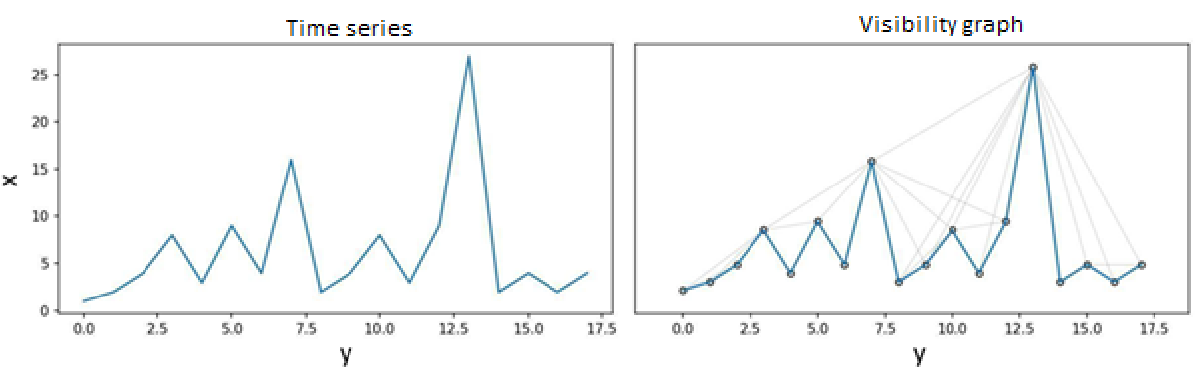
A graph is a way of representing relationships among elements. The graph comprehends a set of vertices (or knots) that can represent neighborhoods, communities or other specific points of interest in the system, and a set of edges that represent the possible connections among the vertices. For example, in a transportation system, a graph could represent a model in which the knots are the crossings with traffic lights and the edges are the streets forming the crossings. The set of edges and vertices characterizes the graph architecture, called topology (Strogatz, 2001).

Complex networks are graphs in which the relationships exhibit collective characteristics or behaviors of the system that emerge from interactions among its individual components, but are not directly predictable or explainable simply from the analysis of these components in isolation (Yerra & Levinson, 2005). These networks may be found in different contexts, such as in social networks, in transportation systems, in supply chains and in numerous other complex systems. The topologies observed in complex networks present a non-uniform distribution of connections, clusters and interdependencies among the knots. The analysis of these networks allows identifying patterns of connectivity, correlation or proximity among the elements of a system, thus helping to better understand the behaviors it presents, as well as its robustness, modularity and efficiency (Ding et al., 2019; Hearnshaw & Wilson, 2013).

The complex network theory can also be used to study time series. This is done by converting the time series into a network structure. We here adopt the visibility graph as the conversion technique. In the time series context, the visibility graph is a representation that captures the visibility relationships among the points of the series. The graph is built considering the temporal order of the data and establishing direct connections between the mutually visible points. Two points are considered mutually visible if there is no other point obstructing the line of vision between them. That is, if a point P_1 is visible from a point P_2, and vice-versa, a vertex is created between P_1 and P_2 in the visibility graph (Lacasa & Toral, 2010). Figure 1 provides an example of how the points of a time series turn into vertices and edges in a visibility graph.

Figure 1

Analogy between time series and visibility graph



Source: Elaborated by the authors

In Figure 1, each point of the time series is converted into a knot in the visibility graph. The lines in grey represent the edges.

A complex network involves interactions between knots. In turn, a hypergraph is a generalization of a conventional graph, permitting to model the more complex relationships between the elements. Whereas a traditional graph consists in knots connected by edges, a hypergraph allows an edge to connect to any number of knots. The edges of a hypergraph are called hyperedges (Lee et al., 2022). This more flexible representation is especially useful in situations in which the relationships among elements are not limited to pairs, but may involve larger groups, such as public transportation networks with multiple lines or modals (López & Lozano, 2020).

Within the hypergraphs theory, a fundamental concept is that of hyperpath. A hyperpath in a hypergraph is a sequence of vertices and hyperedges and, among other things, may indicate the existence of a path between two points not directly connected by the same hyperedge. This definition unfolds the traditional concept of path in graphs to include more complex relationships in hypergraph structures (Berge, 1984).

Data on the passenger demand per bus line

The sample in this work considered the day lines that were active in 90% of the period in the time window comprehending the pre-pandemic and pandemic periods, besides the period beginning after the end of the social isolation measures, that is, between January 2016 and December 2022. Note that although there are some statistics on the daily demand of metro passengers, the data available do not correspond to the time series, but rather to descriptive statistics, preventing the application of visibility graphs. Therefore, only the time series of passenger demand in bus lines was considered here.

The data on passenger demand for buses are provided for free by SPTRANS [1] in its official portal, in .xls spreadsheet format. The data were opened and manipulated using the *pandas* library in *Python*. The data on passenger demand supplied by SPTRANS needed pre-processing, seeing that, for example, they contained spacings or inconsistent use of uppercase an/or abbreviations, which could make a same line be computed as two or more different lines. To solve this problem, solely the line codes were filtered from the field. Later, a file shapefile format was obtained from the Geosampa portal [2] containing all the bus lines and their respective routes, whose formats are sequences of line segments, that is, geometries of the linestring type.

Crossing the data on passenger demand with the geographic data of the bus lines, a spreadsheet was obtained containing with the bus lines, their mapped routes and their passenger demand on each day of the period studied.

Concerning demand, the total passenger demand was considered, including individuals who were exempted from fares due to older age, physical deficiency, among other conditions. Some tables were observed to present errors when opened by the *pandas* library, which required opening them with a spreadsheet reader, copying the records contained in them and saving them in other spreadsheets. The data manipulated in *pandas* were organized so as to generate a time series table.

The time series were subsequently converted into visibility graphs with weights, that is, the edges of the graph have an embedded value regarding the nature of the connection between them. Considering the pairs of points - $x_0, y_0 \text{ and } x_1, y_1$ -, the weight of the edges in this work reflects the Euclidian distance between them, given by $d_{01} = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2}$, in which $x_0 \text{ and } x_1$ represent the values measured at time instants $y_0 \text{ and } y_1$. This method for calculating the distance was chosen for helping reflect the variations in demand over time.

[1] Available at: https://www.prefeitura.sp.gov.br/cidade/secretarias/mobility/institucional/sptrans/access_a_informacao/index.php?p=343693

[2] Available at: https://geosampa.prefeitura.sp.gov.br/PaginasPublicas/_SBC.aspx

Geographic data and hypergraphs construction

The datasets contain geographic data on all the informal settlements, bus lines plus train and metro stations. All these data were obtained from the GeoSampa portal.

The geographic data were manipulated using the *geopandas* library*,* from *Python.* For establishing relations of proximity among the different geographic objects, such as informal settlements, stations, train stations and bus lines, preliminary manipulations were needed to facilitate the application of the algorithms.

The datasets on metro and train stations provide only the location of the station center. However, our aim was to identify which bus lines cross the informal settlements, as well as metro and train stations. As the data obtained only contain the stations centroids, and not the full dimension of the buildings that often act as arrival points for different bus lines, a 50-meter *buffer around the stations was created*.

After the pre-processing stage, a table was drawn to contain all the geometric intersection relationships among bus lines, informal settlements and stations/train. The data were then filtered to obtain hypergraphs representing the relationships of the existing intersections. We selected all the favelas, nuclei and slums (clustered under "informal settlements") with more than 100 households, and all the stations present only within the boundaries of the São Paulo municipality. Settlements with fewer than 100 households were excluded to prevent that, when building the hypergraph, a station were considered as very connected to the settlements when most of the connections could actually be referring to very small settlements, with few families. Moreover, when using all the settlements, the final outcome of the analysis was not significantly altered.

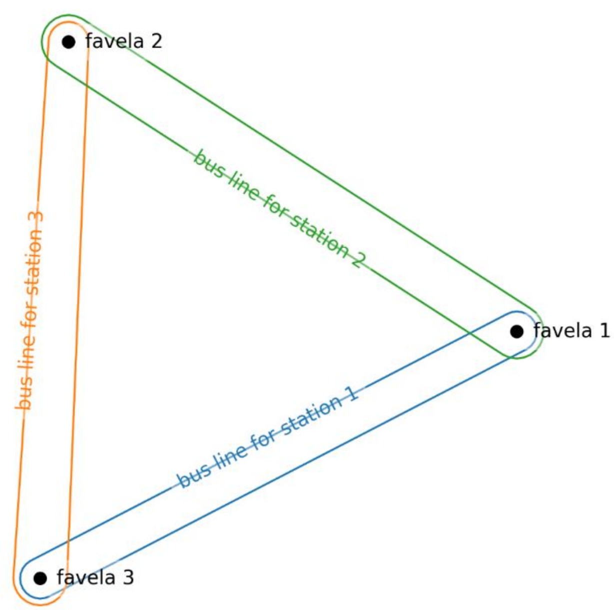
Construction of hypergraphs to analyze accessibility

To understand how informal settlements are integrated to the transportation system, different hypergraph models were built to represent the different particularities of the public transportation system.

The first hypergraph, called H_1 was built to investigate the accessibility of informal settlements to the stations by means of bus lines. For this, each informal settlement was considered a knot and each hyperedge, a station reached by at least one bus line. Thus, two informal settlements are connected between themselves if they can reach the same station using at least one bus line. Some stations are possibly reached on foot, or via transport applications such as Uber, but we here opted for investigating access via bus modal only, for understanding how multiple public mass transport modals interconnect to provide mobility. An example of hypergraph H_1 is presented in Figure 2.

Figure 2

Illustration of an example of hypergraph H_1.



Source: Elaborated by the authors

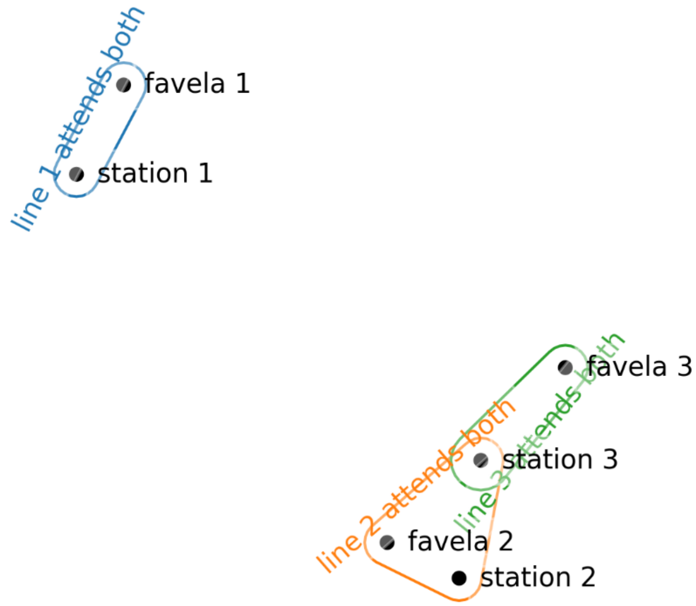
The access to the stations can also be more realistically assessed if considering that it is sometimes necessary to use more than one bus line to reach a certain location. Therefore, to represent this aspect of reality, the stations and the informal settlements had to be inserted as knots in a second hypergraph, H_2, and the hyperedges as bus lines, such that two elements belong to the same hyperedge if intersected by the same line.

Consequently, the distance between informal settlements and stations is the number of hyperedges which a resident has to go through to reach a certain station. According to the Origin-Destination research conducted by the São Paulo Metro in 2017 (Metro de São Paulo, 2019), only 9.14% of the trips taken, be it by bus, metro or train, required two transfers. For three transfers, the number fell to 1.43%.

Although it is unusual for a user to try and reach a station by successive transfers on the bus modal just to reach the train and metro modals, it should be noted that stations generate intense socio-economic impact on their surroundings, generating jobs and entrepreneurship, also affecting real estate speculation, which is translated into a relevant component to assess the potential of attraction of the place. Also to be noted is that, in general, the transfer between modals costs more than using the same modal until reaching the destination. Figure 3 presents an example of hypergraph H_2.

Figure 3

Illustration of an example of H_2.



Source: Elaborated by the authors.

Assessment of the changes occurred during the COVID-19 pandemic

Hypergraph H_2, explained in section 3.3, has the bus lines as hyperedges. For each bus line, a time series of passenger demand was selected, obtained according to the method described in section 3.1, and the visibility graph built. Being N be the number of knots in a graph, i any of the knots, $|E_i|$ the number of edges by which the knot connect to other knots, k_i the number of neighbors of the knot, E_{vi} the sum of the weight of the edges that the neighbors of the knot have among themselves, and $d(i,j)$ the distance of the shortest path between two knots, three parameters were selected, as described in Table 1.

Table 1

Definition and explanation of the parameters used to assess the impact of the COVID-19 pandemic on the visibility graphs generated from the time series of passenger demand before and during the pandemic

Parameter	Definition	Equation
Average value of degree (k) of a knot	Sum of the weights of the edges of a knot i of the visibility graph.	$G_i = \sum E_i$
Average value of the *clustering* coefficient	Measures the trend of the neighbors of a knot i being interconnected.	$C_i = \frac{2E_{vi}}{k_i(k_i - 1)}$
Minimum average path	The path between two knots i and j is the number of edges to be crossed from one knot to the other. The minimum path is the one that, among all the possible paths, has the smaller number of edges.	$L = \frac{1}{N(N-1)} \sum_{i \neq j} d(i,j)$

Source: Elaborated by the authors

Results and Discussion

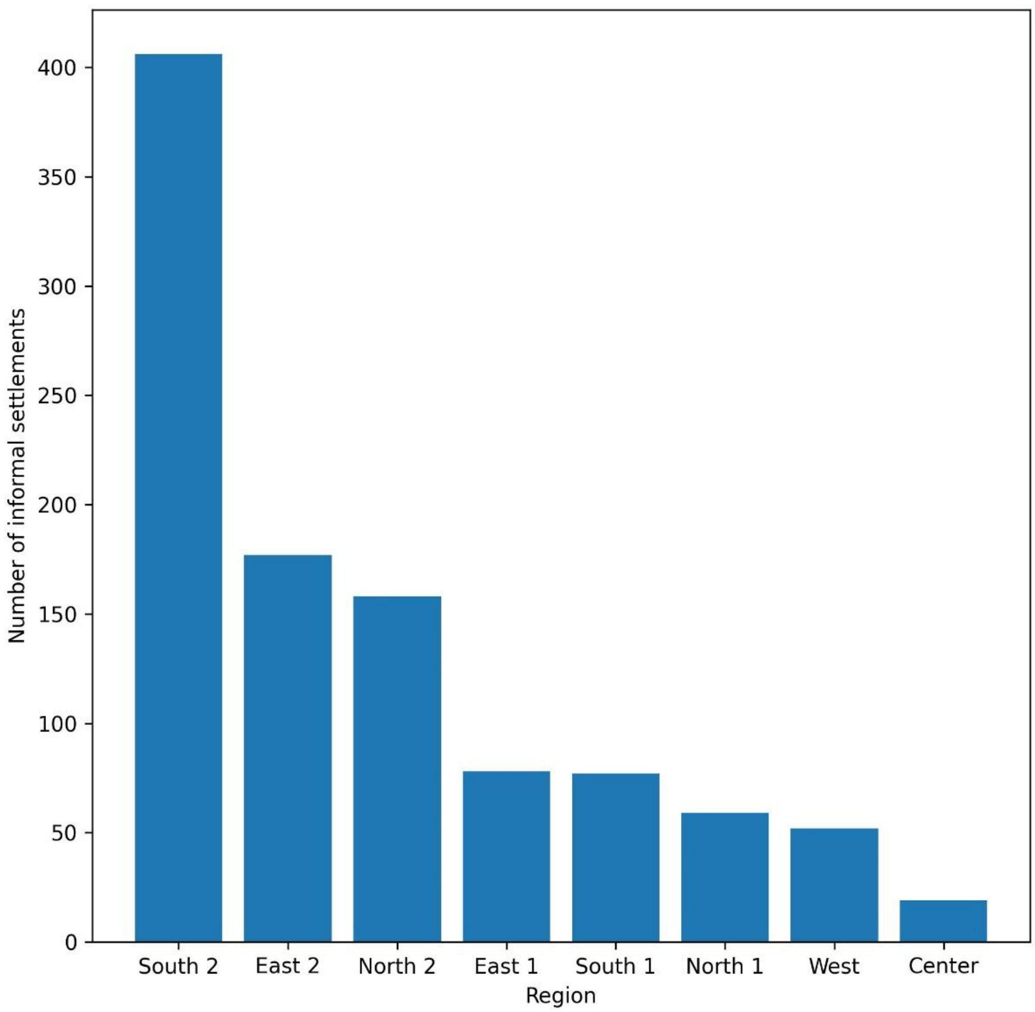
Infrastructure available

This section presents the results that describe the public transportation structure available to the communities in hypergraphs H_1 and H_2, built employing the method described in 2.4 and 2.5. Informal settlements are usually located in peripheral regions or of difficult access, hindering the mobility of their residents . For better contextualizing the discussion on the results, Figure 4 presents a bar chart showing the number of informal settlements with over 100 households per region of the São Paulo municipality, according to the division of the São Paulo Municipal Government[3]. Region South 2 is observed to have the largest number of settlements. In second and third places, are Region East 2 and North 2, that is, those the farthest from the city center.

[3] Available at: https://www.prefeitura.sp.gov.br/cidade/secretarias/upload/infocidade_mapabase_subp+regiao8_A3_retrato_2.pdf

Figure 4

Number of informal settlements with over 100 households per region. São Paulo Municipality, 2021



Source: Elaborated by the authors

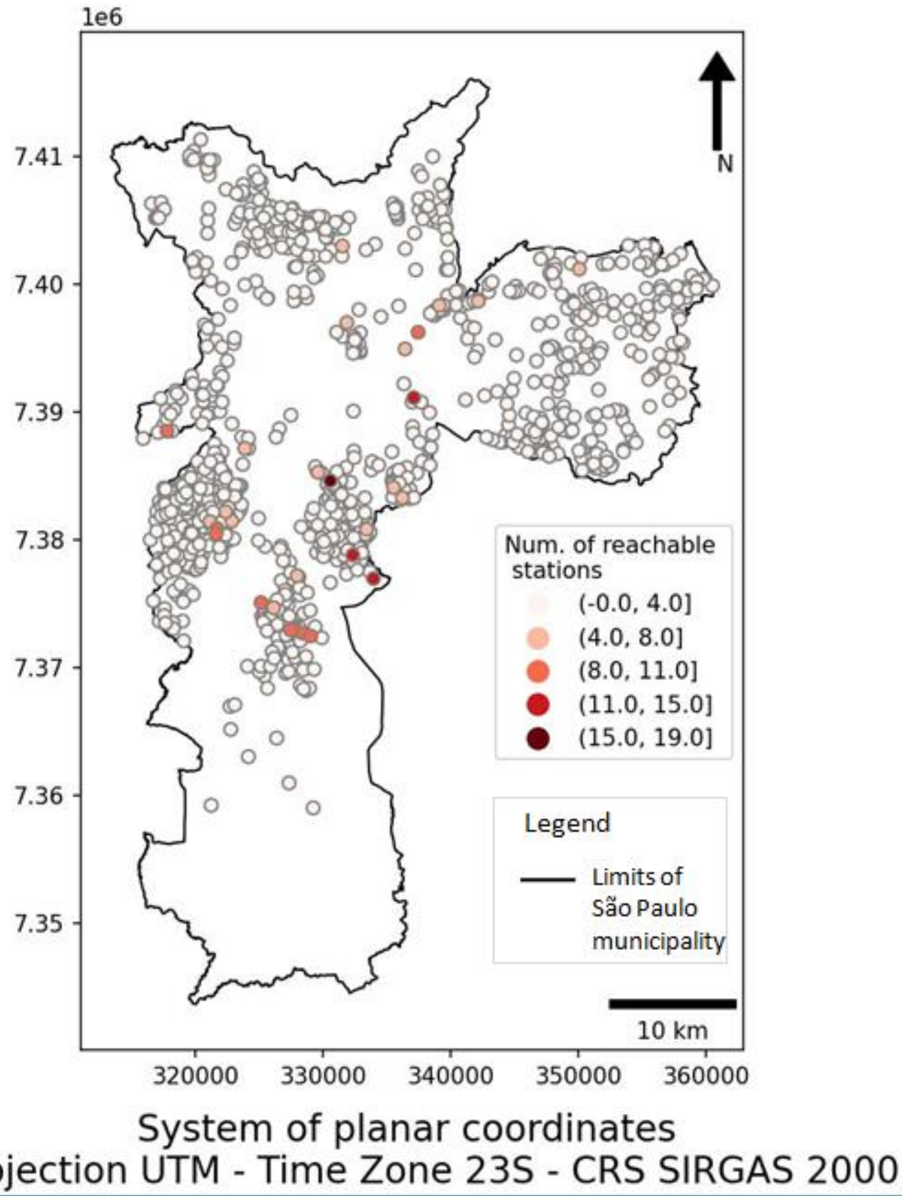
A large quantity of knots of hypergraph H_1 (representing the settlements) were identified to have a null degree, meaning that they do not belong to any hyperedge (no bus line simultaneously intersects a settlement and a station). Naturally, people may eventually access stations by other means, such as bicycles, rides, app drivers, or on foot, but the results presented herein specifically refer to those obtained from hypergraphs H_1 and H_2. The informal settlements with the largest number of reachable stations are located in Region South 2, which are verified to be close to the crossings of different metro and train lines. Also, a concentration of train and metro networks are perceived to surround the urban center of São Paulo, where the volume of informal settlements is small-scale compared to the outskirts.

Figure 5 presents the train stations and, from these stations, the number of informal settlements reachable by bus lines. Figures 5 and 6 show that the knots of H_1 with a higher degree represent settlements located in Regions South 1 and South 2. Likewise, the size of the hyperedges (the number of communities reachable by the stations) is relatively larger in these regions, Although a station in the West Region is observed to reach numerous communities.

The access to stations has a notorious additional difficulty, overcrowding at peak hours. Even so, these modals are faster than buses, which compete for space with a huge volume of private vehicles, cyclists and pedestrians, besides being subject to complex urban and environmental aspects, such as floods, potholed roads etc. Therefore, the difficulty in accessing these modals is very harmful to the mobility of informal settlement residents.

Figure 5

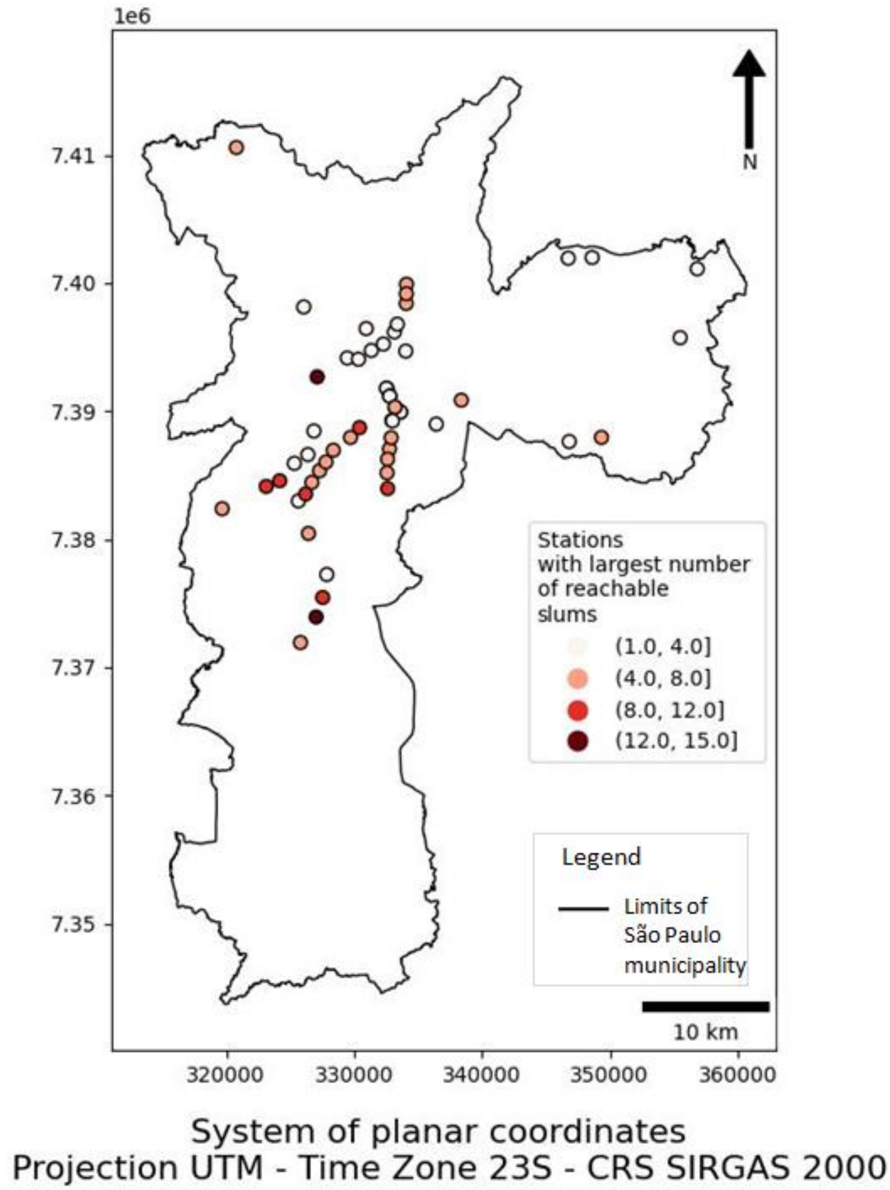
Maps depicting the position of each informal settlement, colored in function of the number of close bus lines reaching a train or metro station. São Paulo Municipality, 2021



Source: Elaborated by the authors

Figure 6

Stations colored in function of the number of communities reachable by bus lines. São Paulo Municipality, 2021



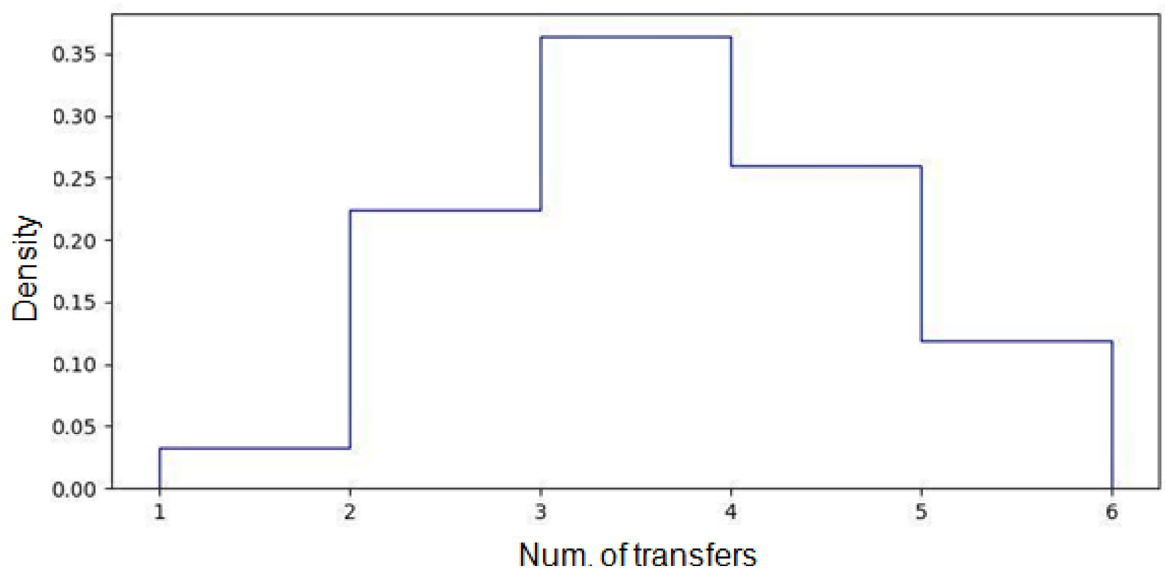
Source: Elaborated by the authors

Hypergraph H_2 allowed calculating the number of necessary transfers from an informal settlement to a metro or train station. The histogram in Figure 6 presents the results. Note that in hypergraph H_2, stations and informal settlements are knots, whereas bus lines are hyperedges.

A major advantage of hypergraphs is permitting the adequate representation of situations in which a graph-based model would not so simply allow, as for example, when two hyperedges coexist, being one hyperedge a subset of the other, but representing different lines. Moreover, it would not be possible to distinguish relationships involving three or more elements, since all the relationships would be transformed into peer-to-peer relationships (Wolf et al., 2016). This allows further investigating the minimum number of transfer between two locations.

Figure 7

Histogram containing the distribution of the number of transfers between informal settlements and train and metro stations. São Paulo Municipality, 2021



Source: Elaborated by the authors

Figure 7 was built from calculating the smallest quantity of hyperedges (bus lines) a resident of an informal settlement has to use to reach any station by a bus line or, in graph theory language, the minimum path between two knots in hypergraph H_2. To better contextualize this information, a simple efficiency ratio is calculated for an informal settlement, given by equation 1:

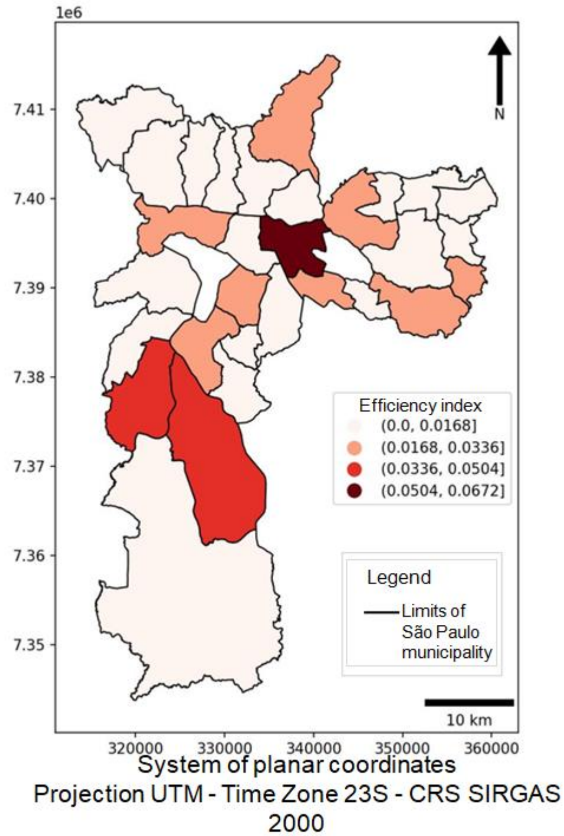
$$E_i = \sum_{m}^{M} \frac{1}{d_m} \tag{1}$$

where E_i is the efficiency ratio of settlement i, and d_m is the number of transfers between informal settlement i and station m. When there is no path between a settlement and a station in hypergraph H_2, $d = \infty$ and $\frac{1}{d} = 0$. The greater the E_i, the more alternatives of stations are available to the settlement and the smaller the number of transfers needed to reach a station.

Figure 8 provides the average value of the settlements efficiency ratio in each sub-municipality.

Figure 8

Efficiency distributions for the sub-municipalities of São Paulo. São Paulo Municipality, 2021



Source: Elaborated by the authors.

Hypergraph H_2 presents some interesting details that could be observed from the analysis of hypergraph H_1 (both hypergraphs were described in Section 2.4). Most informal settlement residents do not count on a direct bus line to the metro or train station, whereas the average of necessary transfers between the settlements and the stations is between 3 and 4. Pointing out that, in hypergraph H_2 (exemplified in Figure 3 and effectively represented in Figures 7 and 8), the hyperedges are bus lines, making this mechanism the only one allowing a user present in a certain place to commute in this model. An even more realistic model would also take into account the transfer between the different modals. Even so, hypergraph H_2 brings additional elements to aid the perception of the difficulty of a significant parcel of society in obtaining means of integration with the public transportation system.

Changes occurred during the COVID-19 pandemic analyzed by visibility graphs

The COVID-19 pandemic distinctly affected the different social groups. Favela residents, generally informal and autonomous workers, had to keep working as usual (Gonçalves & Malfitano, 2022).

This analysis considers two scenarios – one is the pre-pandemic and the other starting in 2020, that is, the beginning of the pandemic. When observing the number of knots in a hyperedge, we have an estimation of the number of locations a bus line serves. Figure 7 exhibits *boxplots* representing the distribution of values for the following parameters: average degree, average *clustering* coefficient and minimum average path (obtained by the visibility graph, as explained in Section 2.5) of the 50 hyperedges of H_2 with the largest number of knots. Care was taken to arrange the bus lines into three clusters, ranked according to the average values of demand before 2020, namely, clusters with low, medium and high demand.

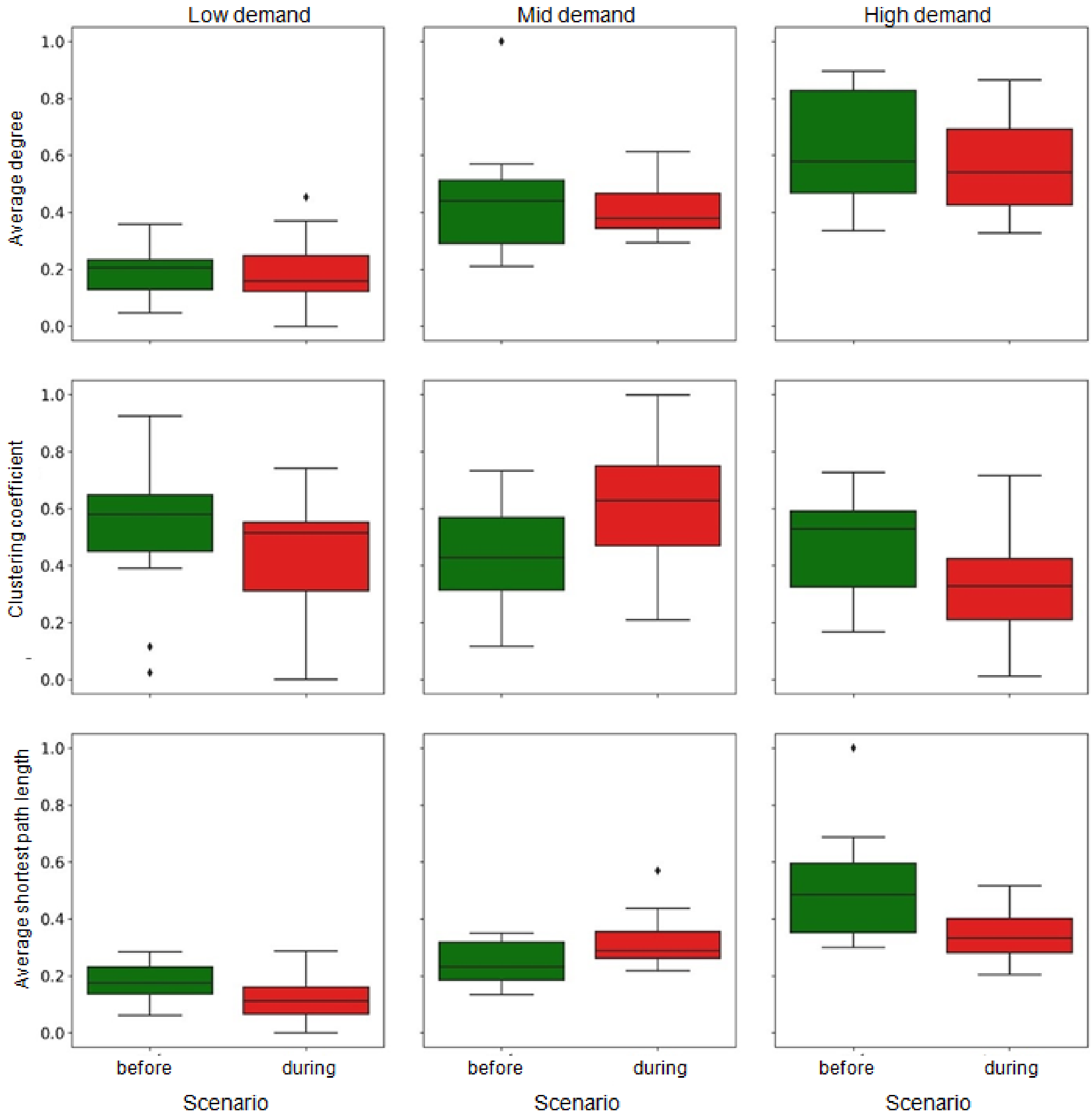
The average degree of a visibility graph brings an indication of the edge weights (the difference in passenger demand between two points of the time series). A higher average degree may indicate a greater variability in passenger demand or a greater magnitude in the values observed. Here, the average and the variability of the average degree are observed to have fallen for the lines with medium and high demand during the pandemic, which can be related to the fall in demand. However, the change was observed to be very modest for the low demand lines.

The average clustering coefficient *is* an indication of distribution of local minima in a time series, since a point of local minimum is usually visible for the first and the last points, and both points are also visible to one another. In this case, these three points are connected among themselves forming a triangular pattern, and the point of local minimum thus has a high clustering coefficient. Therefore, a variation in the average clustering coefficient of a graph indicates a change in the visibility relationships. For the average demand cases, an increase in the average clustering coefficient was observed in the pandemic period, which may either indicate a predominant peak in the time series after the beginning of the pandemic (the peaks are visible by the majority of the knots) or that there are periodicities or seasonalities in a more consistent way, in which peaks and valleys of the time series alternate more regularly. The latter alternative is the most probable, once the presence of peaks in the time series would also influence the variability in the average degree far more significantly than that observed. The result differs for the low and high demand lines, in which the values of the average clustering coefficients fell.

Lastly, the minimum average path follows the same trend observed for the average clustering coefficient. The fact that the average and high demand lines have lesser variability during the pandemic is an indication that the demand presents a stabler periodicity in these lines in the period. These variabilities fell even more for the high demand cases. For the low demand lines, the variability in the minimum average path was practically stable.

Figure 9

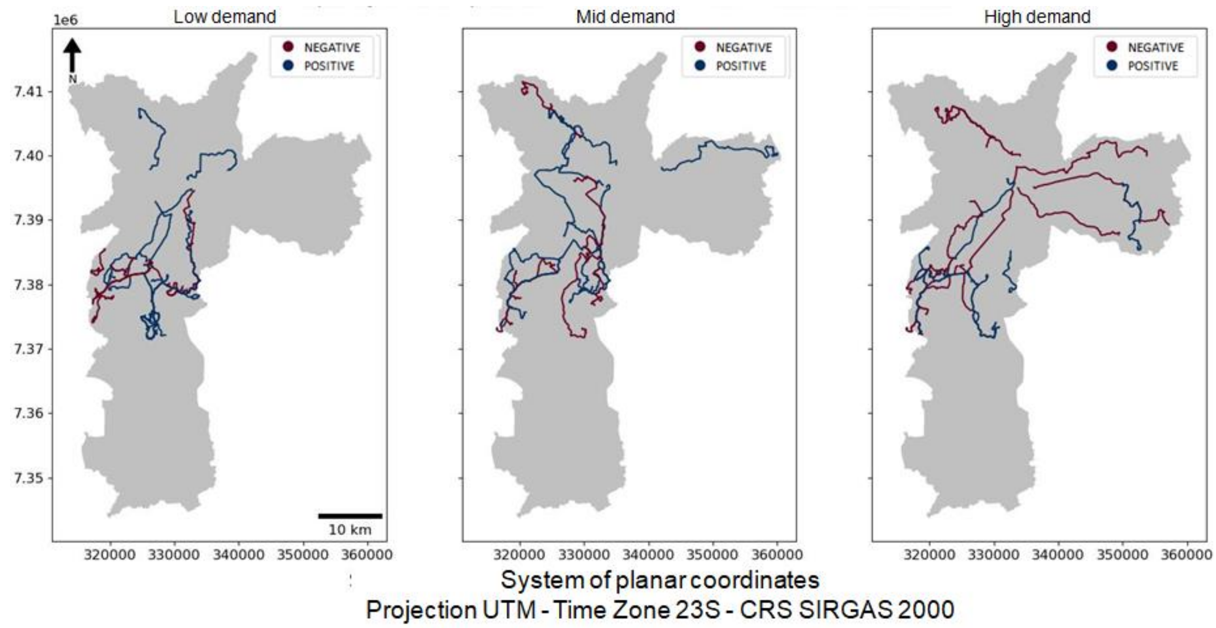
Boxplots of the visibility graphs parameters, according to the type of demand. São Paulo Municipality, Jan/2017 to Dec/2022



Source: Elaborated by the authors

Figure 10

Variation in the average degree of the visibility graphs between the first period (Jan/2016-Dec/2019) and the period during the pandemic (Jan/2020-Dec/2022). São Paulo Municipality. Period: Jan/2016 to Dec/2022



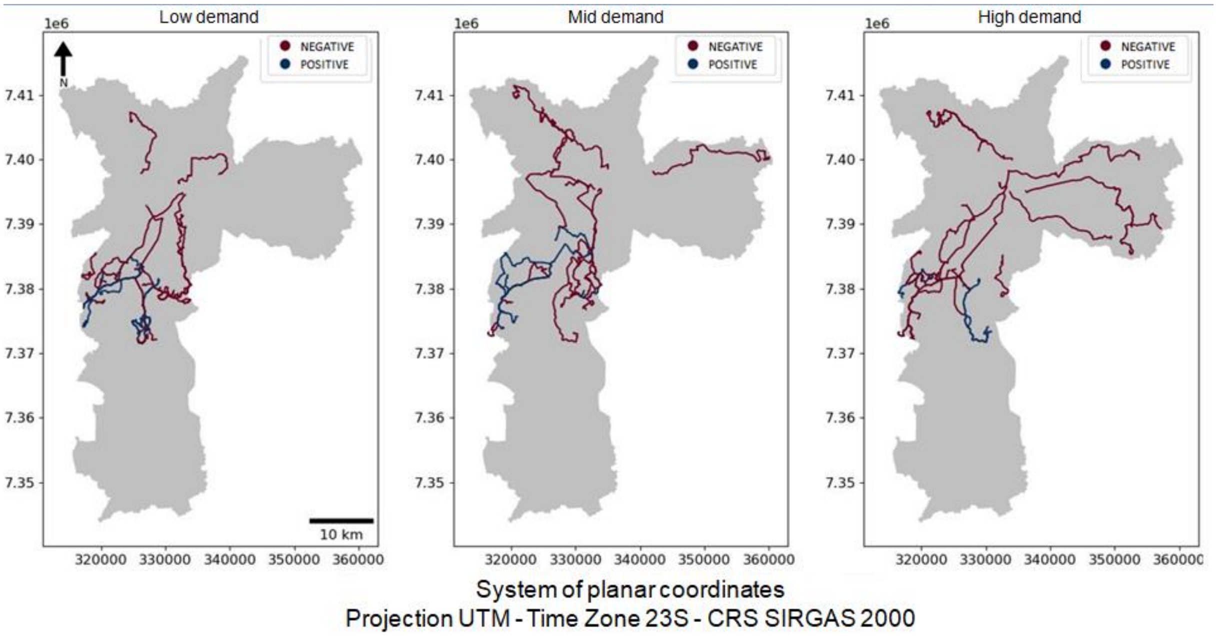
Source: Elaborated by the authors.

From Figure 10, one can observe that, for low and medium demands, the lines presenting a negative variation in average degree are farther away from the city center in relation to the ones with a positive variation. In turn, for the high demand cases, some of the lines with a negative variation seem to be closer to the city center, whereas most of the lines with a positive variation are farther.

In Figure 11, the same analysis is performed taking as a metric the variation in the average clustering coefficient. Note that the lines with routes closer to the city center suffered a reduction in the average clustering coefficient, indicating that the demand turned more irregular. A positive variation in the average clustering coefficient was verified in lines closer to Regions South 1 and South 2 of the municipality.

Figure 11

Variation in the average clustering coefficient of the visibility graphs between the first period (Jan/2016-Dec/2019) and the period during the pandemic (Jan/2020-Dec/2022). São Paulo Municipality, Jan/2016 a Dec/2022



Source: Elaborated by the authors.

Final Considerations

The use of different techniques based on complex networks allowed modeling and representing the spatial relations among informal settlements, bus lines, train and metro stations. It was possible to verify that there are still different challenges to better integrate the population of informal settlements to the public transportation system in the São Paulo municipality, providing better conditions of access to employment, health and education. The monocentric model and the difficulties in integrating the peripheral regions to the center by multiple modals can be a hindrance to the development of those regions.

Based on the information obtained, we analyzed how the user demand patterns were modified during the COVID-19 pandemic. The changes were verified to unequally affect the different regions of the city. Furthermore, lines with greater volumes of demand presented a differentiated behavior as compared to the lines with lower demand volumes. The former tend to present a center-periphery movement and its average degree fell, as well as the periodicity of the time series, indicating that the demand was modified. The average clustering coefficient and the minimum average path corroborate this information, and also point to a possible effect of a more restrict planning, since the variabilities observed in Figure 7 dropped in some cases.

As a limitation, we point out that it is still necessary to further estimate how each property of the time series is reflected on the visibility graph. A possible furthering of this work could be decomposing the horizontal and vertical weights of the series instead of using the Euclidian distance among the observations, which would permit to better isolate the effects deriving from the demand and the changes in periodicity. This work can still be expanded from the assessment of other, more complete hypergraphs or highlighting other spatial aspects, such as the proximity of the population to hospitals and schools.

The relationships detected by the hypergraph can be used to assess inequalities of access to job hubs, hospital or schools, or to modify the routes of bus lines to increase the system redundancy. The patterns captured by the visibility graphs allow discriminating different modifications in the dynamic of transport systems, such as the sensitivity of demand due to an alteration in transportation policy, the effect of holidays, exemptions of transport fares, mass events, among others. The combined use of both techniques facilitates directing the analysis to the critical elements of interest, without the need of applying filters to non-stationary series.

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