Income Stratification in Urban Accessibility: the case of Barcelona

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ABSTRACT

This paper examines transportation accessibility with public transit from an equity perspective. In particular, it aims to identify disparities in access to essential services within the city of Barcelona. The performed analysis uses four types of accessibility measures, namely Cumulative Opportunities, a Gravity-based measure, a Shen-based measure, and Spatial Availability, to assess access to nine categories of Points of Interest, such as educational, healthcare, and shopping centers from Barcelona residential blocks. Sociodemographic and socioeconomic data were incorporated into the analysis to understand how different population groups experience accessibility disparities. Results proved that each measure provides a unique perspective on accessibility, highlighting distinct aspects of the disparities between income groups and other sociodemographic factors. Our findings underscore the importance of policymakers considering comprehensive accessibility measures to achieve a more accurate and equitable understanding of public transit accessibility and thus be able to implement more effective urban planning and development strategies.

Keywords: accessibility measures, accessibility equity, income, public transport, essential services

1. INTRODUCTION AND BACKGROUND

Accessibility is a fundamental aspect of urban mobility, shaping how residents perceive and experience their city. It represents the ease with which individuals can reach their desired destinations, encompassing not only physical proximity but also factors such as safety, comfort, and navigability. Therefore, accessibility is a critical measure of equity, reflecting how fairly opportunities and resources are effectively available for different population groups. Ensuring equitable access to essential services, employment, and amenities is key to fostering inclusive and thriving urban communities.

Accessibility measures differ in scope and focus, providing distinct insights based on their intended application [1]. The most suitable measure depends on the specific objectives of the study, as each approach highlights different aspects of accessibility and varies in complexity. Thus, data availability may condition the choice.

This study investigates the accessibility landscape of Barcelona, focusing on how well public transit serves diverse demographic groups, namely people with different gender, age, income levels, education, or birthplace (continent). The analysis evaluates accessibility per city residential block and targets key categories of points of interest (POIs) that represent essential aspects of urban life.

This study compares the results provided by four place-based accessibility measures: a Cumulative Opportunities (CO) measure, a Gravity-based measure (GR), a Shen-based (SH) accessibility measure [2], and the Spatial Availability (SA) measure [3]. This approach provides a nuanced understanding of accessibility, integrating spatial and social dimensions. The findings aim to inform equitable urban planning and public transportation policies.

Evaluating public transit accessibility and accessibility disparities have been central themes in recent transportation and geographical research [4]. [8] analyzed how different accessibility measures impact public transit project evaluations. The study found that the choice of accessibility measure significantly affects the appraisal of transit interventions, recommending a more robust evaluation process that considers multiple measures to improve decision-making in transit planning.

The remainder of the paper is organized as follows: Section 2 outlines the methodological approach; Section 3 presents the case study in Barcelona; Section 4 discusses the results and findings, and Section 5 concludes the paper with a summary of insights and recommendations.

2. METHODOLOGY

The methodological workflow followed is organized into four main stages, as shown in Figure 1: input data preparation, general accessibility measurement, equity assessment, and output analysis.

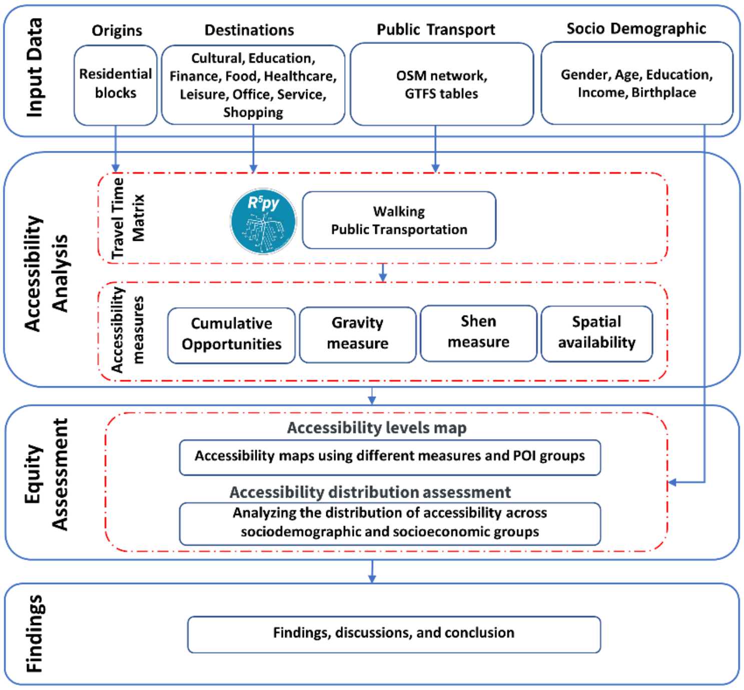

Figure 1 Research methodology framework

The process begins preparing input data, where origins are represented as spatial units (e.g., residential blocks), and destinations are categorized as POIs. Transportation data, including road networks and public transit schedules, simulates the transportation offer. Sociodemographic information is incorporated to analyze accessibility disparities among target groups. In the accessibility analysis, travel times for walking and public transportation are calculated and used to estimate accessibility measures. The equity assessment phase involves creating maps to visualize accessibility levels and examining their distribution across different sociodemographic groups based on their residence.

As indicated, four accessibility measures were selected for this study in order to assess their goodness in unveiling accessibility disparities. They will be explained next (please refer to the notations included in Table 1). First, CO measure, determined using Equation 1 and Equation 2, is chosen for its simplicity and ease of interpretation, while GR measure accounts for differences between closer and more distant locations. GR measures are also represented by Equation 1. However, instead of using an arbitrary cut-off time, they involve the analyst selecting an impedance function that assigns weights to the number of opportunities at each destination, depending on their travel cost from the origin. The impedance function can take different forms [9], but the most usual one is given by Equation 3.

$$A_i = \sum_{j=1}^{n} O_j f(c_{ij}) \tag{1}$$

$$f(c_{ij}) = \begin{cases} 1, & c_{ij} < C \\ 0, & otherwise \end{cases} \tag{2}$$

$$f(c_{ij}) = e^{-\beta c_{ij}} \tag{3}$$

The SH accessibility measure and the SA measure are included because they incorporate competition effects, providing a more nuanced understanding of accessibility dynamics. The Shen measure was defined considering a one-to-one share of people and opportunities (e.g., to obtain a job). [2] defined SH accessibility including the demand potential, as shown in Equation 4 and Equation 5:

$$A_i = \sum_{j} \frac{O_j f(c_{ij})}{D_j} \tag{4}$$

$$D_j = \sum_{k} P_k f(c_{kj}) \tag{5}$$

[3] proposed the SA measure, which relies on the proportional allocation of opportunities by population demand, thus balancing factors such as the impedance-based and the population-based factor (see Equations 6 to 9).

$$A_i = \sum_{j=1}^{n} O_j F_{ij}^t \tag{6}$$

$$F_{ij}^t = \frac{F_i^P \cdot F_{ij}^c}{\sum_{i=1}^{n} F_i^p \cdot F_{ij}^c} \tag{7}$$

$$F_i^p = \frac{P_i^\alpha}{\sum_{i=1}^{n} P_i^\alpha} \tag{8}$$

$$F_{ij}^c = \frac{f(c_{ij})}{\sum_i^n f(c_{ij})} \tag{9}$$

In principle, accessibility measures that account for competition are more accurate but also more complex and data-demanding. In the following case study, we check the different results they provide and evaluate to which extent their choice is worthwhile.

Table 1 Summary of notations

Accessibility measure	Notations	Description
CO GR SH SA	i	Origins
	j	Destinations
	n	The total number of destinations
	c_{ij}	Travel cost between origin *i* and destination *j*
	C	Travel cost threshold
	f	Impedance function
	β	Decay factor
	A_i	Accessibility at origin *i*
SH	Dj	Demand potential for each location *j*
	P_k	Number of people in location *k* seeking the opportunities
SA	F^t	Overall balancing factor
	F^p	Population-based balancing factor
	F^c	Impedance-based balancing factor
	α	Empirical parameter that adjusts the influence of population demand. When α < 1, smaller population origins receive opportunities more quickly than larger ones, while α > 1 favors larger origins.

3. CASE STUDY

Barcelona City

Barcelona, known for its extensive public transport system, serves as the study area. Public transport accounts for 25.8% of weekday trips [10]. Managed by Àrea Metropolitana de Barcelona (AMB), the network includes 8 metro lines and 210 bus routes, serving over 600 million passengers annually across 4,400 kilometers [11], depicted in Figure 2. Public transport operators in Barcelona are included in Table 2 [12].

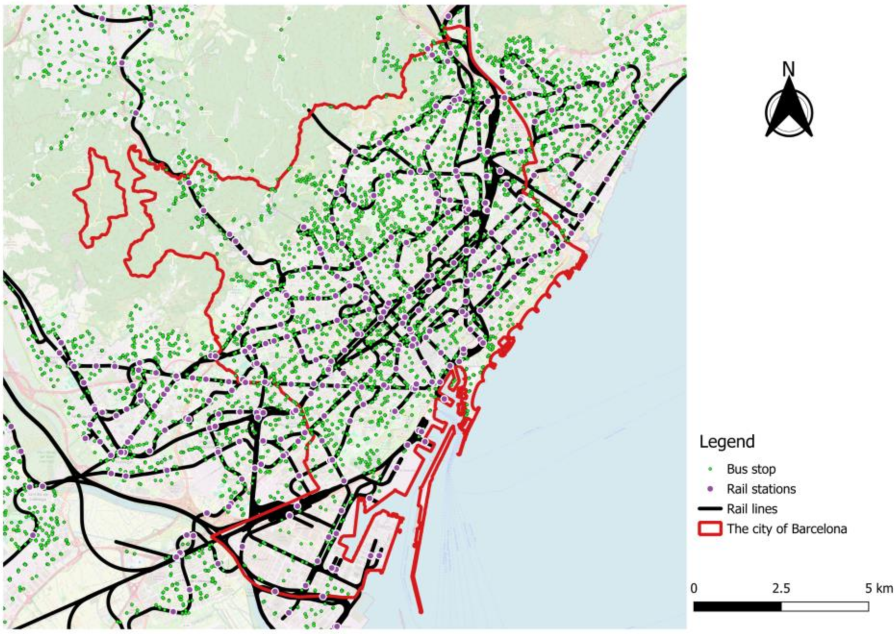

Figure 2 Study area, the city of Barcelona

Table 2 Public transport operators in Barcelona

Operator	Description
Transports Metropolitans de Barcelona (TMB)	TMB is the primary operator, managing both metro and bus services
Tram (Trambaix and Trambesòs)	Six lines, including Trambaix (T1, T2, T3) and Trambesòs (T4, T5, T6)
Ferrocarrils de la Generalitat de Catalunya (FGC)	Urban train services on lines L6, L7, L8, and L12, along with interurban and regional lines
Rodalies de Catalunya	The suburban train network, operated by Renfe, including lines R1, R2, R2 North, R2 South, R3, R4, and R7.

Data Preparation and Travel Time Matrix Calculation

In this study, the centroids of the Barcelona municipality's residential blocks are considered the origin points. For the destinations, nine categories of POIs are included. The primary sources of data are presented in Table 3.

Once origins, destinations, transport network, and General Transit Feed Specification (GTFS) tables were prepared, the travel time matrix was calculated using the R5py routing engine [13]. The summary of the travel time matrix calculation parameters is presented in Table 4.

Table 3 Summary of primary sources of data

Type	Subject	Description	Source
Origins	Blocks	Centroid of residential blocks (2020)	Barcelona City Council open data service [14]
Destinations	POIs	Cultural, Education, Finance, Food, Healthcare, Leisure, Office, Service, and Shopping (published in 2021, updated frequently)	
Transport Network Data	Road network	Extracted data from the OpenStreetMap (OSM) (2024)	BBBike [15]
Public transit schedules	GTFS tables	Considered operators (2024): AMB, TMB, Trambaix, Trambesòs, FGC Renfe	TransitFeeds [16]
Sociodemo-graphic and Socioeco-nomic	Gender	Number of males and females (2024)	Barcelona City Council open data service [16] (disaggregated pro-portionally based on the population from the census tract level)
	Age	Aggregated by five-year age groups from the Municipal Register of Inhabitants (2024)	
	Education	Academic qualifications for the population aged 16 and over (2024)	
	Birthplace	Population of Barcelona aggregated by conti-nent of nationality (2024)	
	Income	Average gross tax revenue per person (€) (2023)	

Table 4 Summary of the travel time matrix calculation parameters

	Origins	Destinations								
	Residential blocks	Cultural	Education	Finance	Food	Healthcare	Leisure	Office	Service	Shopping
Count	5326	3003	2707	1242	11226	2309	445	3464	53	162
Departure time window		17-18	8-9	8-9	14-15	8-9	18:30-19:30	8-9	8-9	18:30-19:30
Departure time		Working day (Monday, January 15, 2024)								

Some accessibility methods, such as CO, rely on defined cost thresholds (e.g., time thresholds), whereas methods like GR, SH, and SA do not inherently require them. Nonetheless, to evaluate public transit performance and simulate competition for nearby destinations, a 15-minute travel time threshold was applied for all methods. This adjustment matches the size and condensed nature of Barcelona and prioritizes closer, potentially more attractive destinations. Therefore, only POIs within the 15-minute isochrone from origin were considered accessible. Given that the average perceived duration of trips for residents of Barcelona is 21 minutes, this threshold can be considered a demanding standard for accessibility [10].

In the original SH and SA frameworks, destination attractiveness (Oj) typically represents a location's utility, such as the number of jobs in a region. However, due to the unavailability of data on individual POI characteristics (e.g., size, capacity, or utility), this study assumed equal attractiveness for all POIs, setting $Oj = 1$. While this simplification is not ideal, as it treats all destinations as equally important, it still offers a reasonable approximation for revealing accessibility disparities.

A negative exponential function (Equation 3) was chosen as an impedance function for the SH and SA methods. The β value (0.1392) was calibrated through a regression procedure using trip counts and travel times obtained from the Barcelona Metropolitan Area Weekday Mobility Survey 2023 [10].

The accessibility distribution for each combination of POI category, accessibility measure, and target group was analyzed using boxplots (box-and-whisker plots) considering the population of each residential block. Since the accessibility measurements are on different scales and units, direct comparisons are not possible. To preserve the ordinal accessibility values within each target group and analyze trends across all measures, we selected the median (2nd quartile) as the representative value for each subgroup within the target groups. These values were then normalized using min-max normalization, converting them to a 0-1 range. The normalized values were plotted on the same graph, preserving the ordinal accessibility levels and enabling trend comparison (not value comparison).

4. RESULTS AND DISCUSSION

Analysis of Accessibility Distribution

Results showed no significant accessibility disparities linked to gender, age, or education. Only some disparities were observed among immigrant groups, particularly in access to food, shopping, and cultural centers. These differences, though present, were minimal and did not consistently favor any specific group, except for the Oceania group, which exhibited better overall accessibility when considering per-capita measures due to their smaller population size.

However, accessibility across income groups revealed clear disparities. As shown in Figure 3, the city exhibits a distinct spatial share of income levels, with higher-income individuals typically residing in areas such as the Pedralbes or Sarria-Sant Gervasi neighborhoods, while middle- and lower-income individuals are concentrated in other zones. Consequently, meaningful trends in accessibility distributions are observed across different income deciles.

Accessibility levels, considering different measurement approaches, have been mapped for various income deciles using boxplots. For example, the boxplots illustrating accessibility to cultural amenities are shown in Figure 4.

The heat map shown in Figure 5 illustrates the density of cultural amenities in Barcelona. As expected and depicted in Figure 6, the CO measure is higher in regions with a greater concentration of amenities.

Figure 7 reveals distinct patterns in accessibility to cultural amenities across income deciles, depending on the method used. CO and GR measures exhibit similar trends, with accessibility increasing until decile 3, dropping for deciles 4 and 5 (middle class), rising again until decile 8, and then decreasing drastically for the wealthiest groups in deciles 9 and 10. Conversely, SH and SA

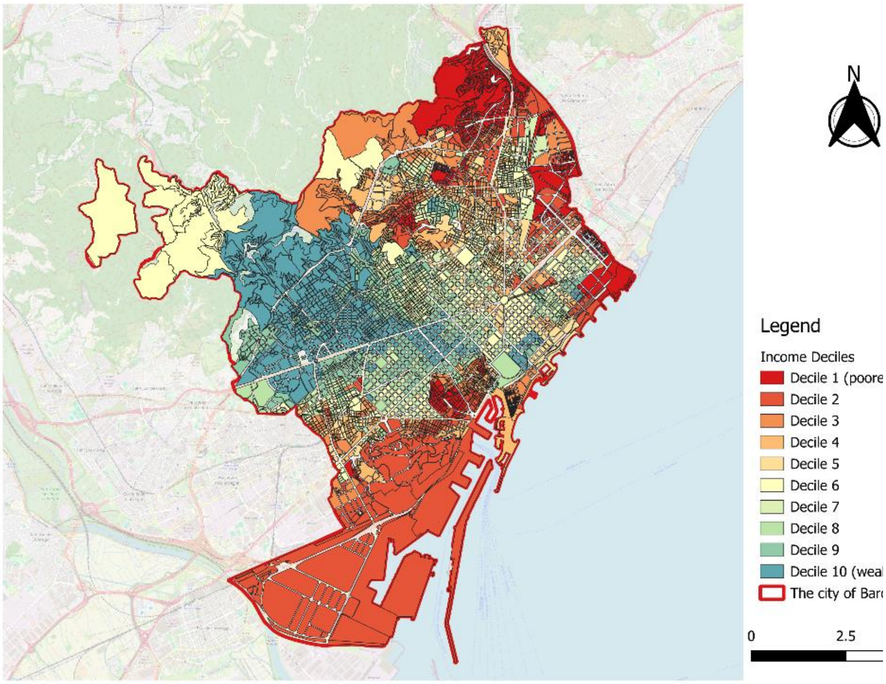

Figure 3 Income deciles of residents in Barcelona

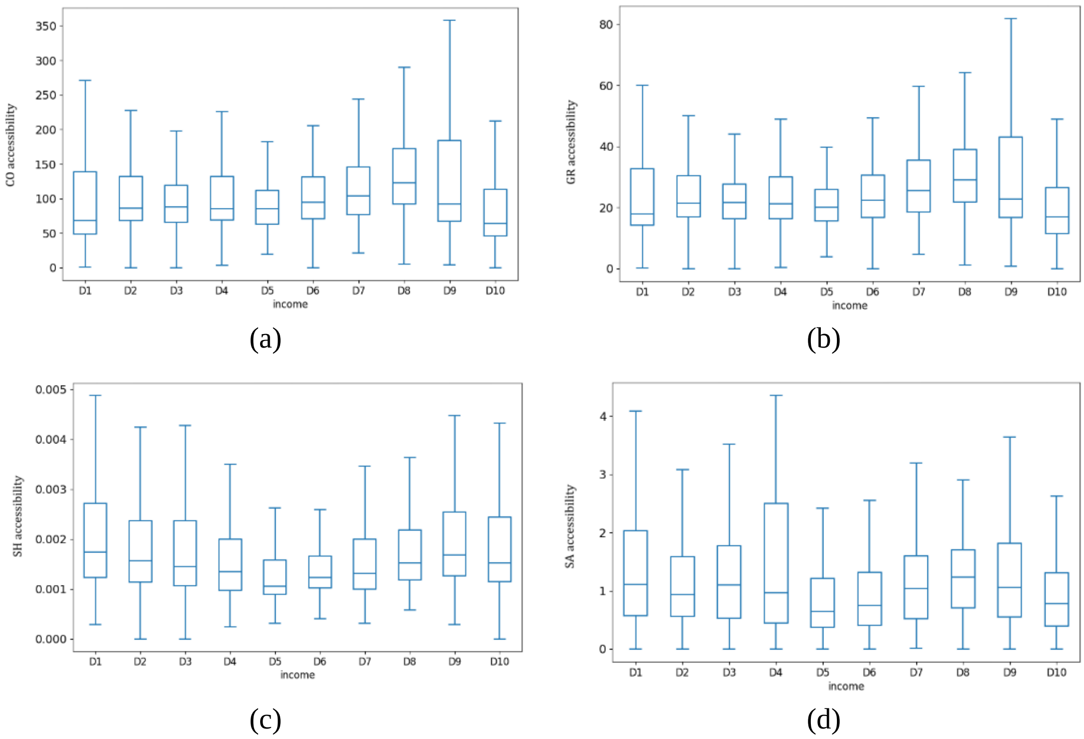

Figure 4 Distribution of accessibility to cultural amenities by income decile, (a) CO measure, (b) GR measure, (c) SH measure, (d) SA measure

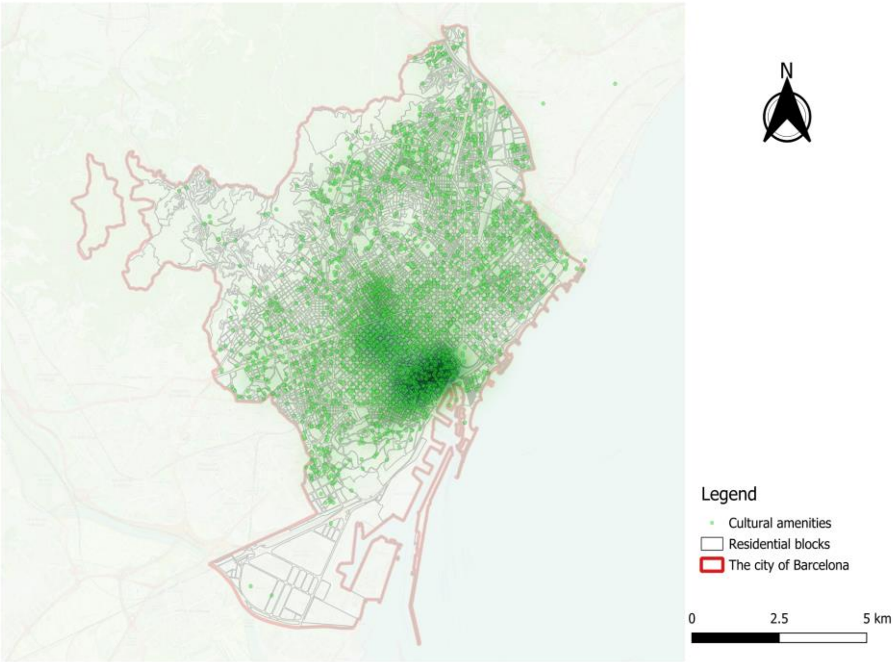

Figure 5 Distribution of cultural amenities across Barcelona

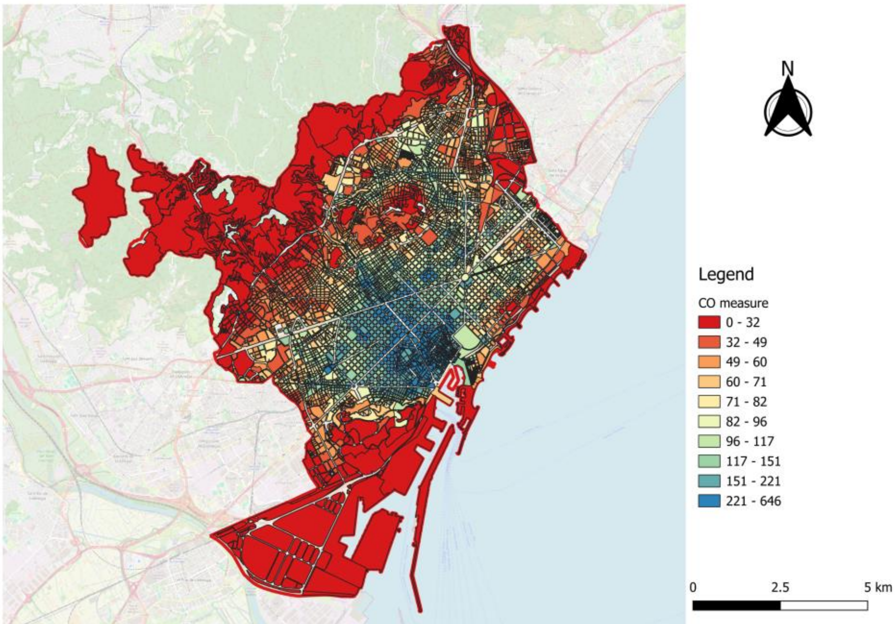

Figure 6 Accessibility map to cultural amenities using the CO measure

measures show a consistent decrease in accessibility from decile 1 to decile 5 (middle class), with fluctuations between deciles 2 and 3 in SA. After decile 5, accessibility improves for higher-income groups, peaking at decile 9 for Shen and decile 8 for SA before dropping for the wealthiest individuals. With some exceptions, CO and GR methods indicate better accessibility with increasing income, except for wealthy groups, whereas SH and SA show declining accessibility for poorer groups and the middle class, followed by improvements for higher-income individuals, before declining again for the wealthiest.

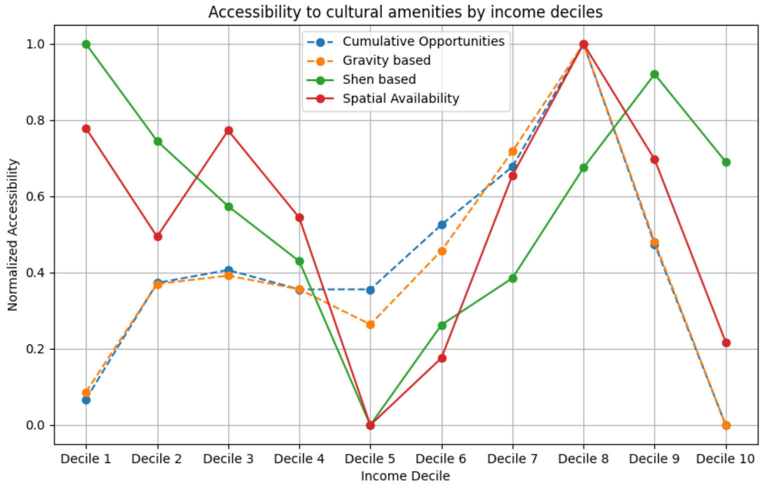

Figure 7 Distribution of normalized accessibility to cultural amenities by income decile

Figure 8(a) shows accessibility to educational centers. All four measures indicate an increasing trend from the poorest individuals to wealthier groups, with a drop observed for deciles 9 and 10 (the wealthiest). Additionally, the SA measure shows a notable decline in accessibility between deciles 4 and 5.

With regard to accessibility to finance, food, healthcare, leisure, office, and service centers, respectively shown in Figure 8(b)–8(g), all four measures generally show an increasing trend from the poorest individuals to wealthier groups, again with a decline observed for deciles 9 and 10. The SA measure consistently shows a notable drop in accessibility between deciles 4 and 5 (poor-to-middle classes) before rising again. Similarly, the SH measure displays a decline with a gentler slope for finance, food, healthcare, leisure, and service centers (Figure 8(b), 8(c), 8(d), 8(e), and 8(g)) among the middle-to-poor classes, with the decline occurring either between deciles 2 and 3 or between deciles 3 and 4.

Accessibility to shopping centers, as shown in Figure 8(h), follows a trend similar to accessibility to cultural centers, with one key difference: the GR measure also indicates that the poorer class has better accessibility compared to the middle class. This is consistent with the patterns observed in the SH and SA measures.

Discussion

Accessibility measures CO and GR generally exhibit similar trends. On the other hand, SH and SA often display a similar pattern, which occasionally diverges from CO and GR. This makes sense, as the latter do not account for competition effects.

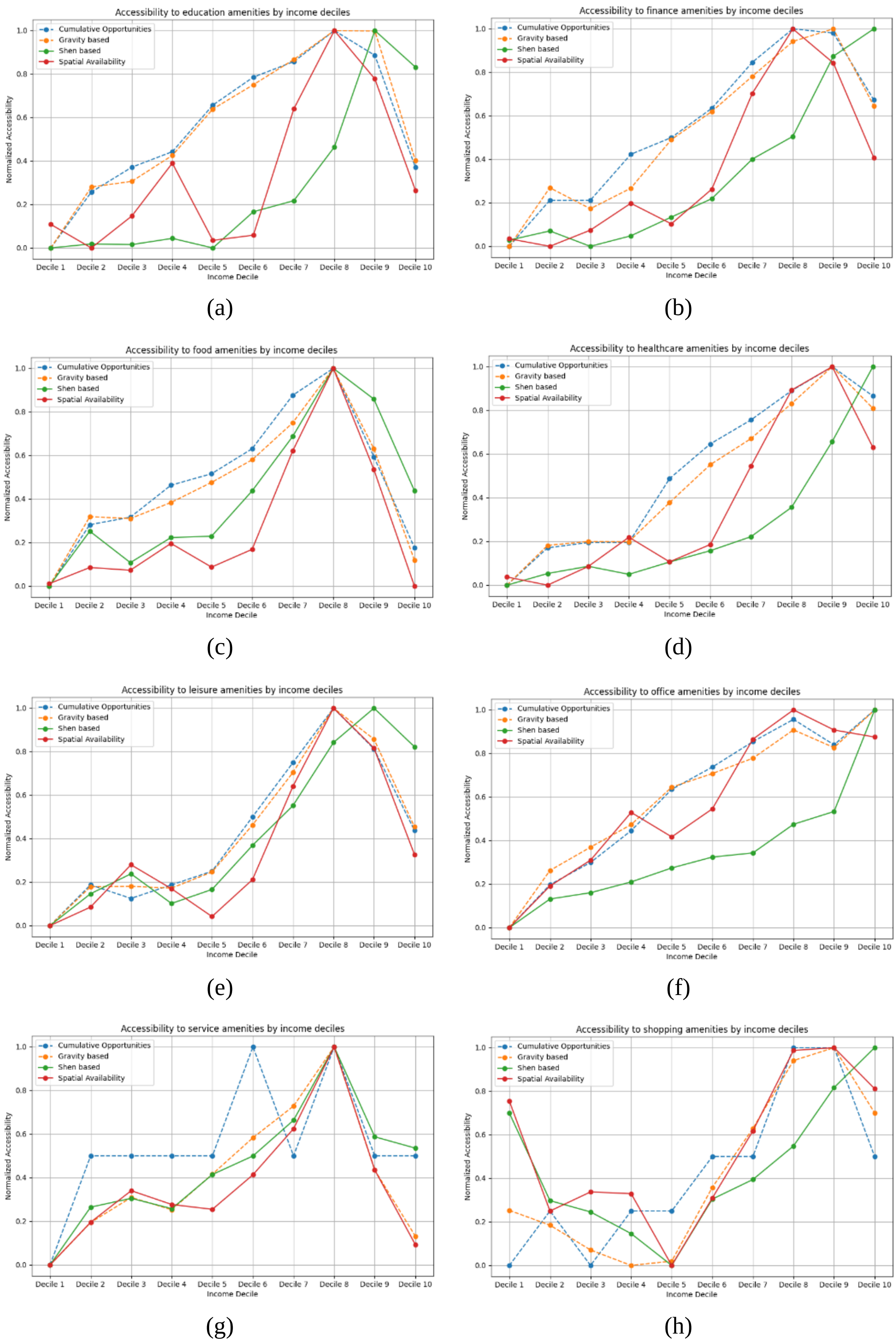

Figure 8 Distribution of normalized accessibility to (a) education, (b) finance, (c) food, (d) healthcare, (e) leisure, (f) office, (g) service, and (h) shopping amenities by income decile

Focusing on income disparities, CO and GR measures generally (though not consistently) show an increasing trend in accessibility from the poorest groups to the middle-high class (up to decile 8). However, when competition is considered, a different pattern emerges, and a decreasing trend in accessibility to some essential services is observed among the poor-to-middle class. These different results highlight the need for accounting for competition when doing accessibility analyses, especially in areas such as major cities where accessibility is sometimes taken for granted. Otherwise, existing disparities could not be unveiled.

Moreover, for the wealthiest groups (deciles 9 and 10), accessibility tends to decline. This is likely due to their preference for living in quieter, less densely populated areas of the city, which are often less served by public transit. With their access to private cars, this reduced public transport accessibility might not involve significant issues.

The number and distribution of POIs play a crucial role in accessibility analysis. For amenities like restaurants, cafes, and supermarkets, their quantity in a region often approximates their relative utility, as these are typically well-distributed across the city. However, for essential services like hospitals, factors such as size, number of beds, and service capacity must be considered, making it vital to account for competition in accessibility measures.

5. CONCLUSIONS

This study highlights the existing disparities in public transit accessibility across different income groups in Barcelona, with trends emerging from various accessibility measures and different POI categories. Generally, CO and GR measures exhibited similar patterns, while SH and SA followed comparable trends, though differences emerged in the details. For lower- to middle-income groups (deciles 1 to 5), accessibility trends varied depending on POI category and the measure, showing either an increase or decrease for increasing income levels. For middle-income to upper-middle-income groups (deciles 5 to 8), accessibility consistently increased. However, for high-income to the wealthiest groups (deciles 8 to 10), accessibility typically showed a decline. These findings underscore the importance of considering different accessibility measures, competition effects and the broader social and spatial context when evaluating urban accessibility, especially for critical services. The performed analysis has shown that, even when the public transport offered in Barcelona is comprehensive, and no areas with very low accessibility exist, accessibility levels are not optimally balanced either spatially or socially

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