Mapping Social Vulnerability Through Accessibility Patterns: The Istanbul Case

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Abstract

Cities are essential for economic, social, and cultural life, driving innovation but also creating inequalities. Challenges like rapid growth and inadequate infrastructure lead to vulnerabilities in urban areas. This phenomenon of social vulnerability extends beyond individual sociodemographic characteristics; it is also closely tied to the quality of services provided by the living environment, spatial organization, and accessibility. Within this framework, the phenomenon of social vulnerability is not limited to the sociodemographic characteristics of individuals; it is also directly related to the services offered by the living environment, spatial arrangements, and, in particular, accessibility. This study explores social vulnerability through the lens of accessibility and socioeconomic status, using the 15-Minute City model. The Mean Shift clustering algorithm was utilized to cluster buildings and a new classification of points of interest (POIs) with 12 categories was proposed. A theoretical accessibility analysis for these POIs were conducted for each building cluster, and an accessibility index was computed. Additionally, land cover analysis was performed for each neighborhood, followed by correlation analyses between the accessibility index, land cover, and socioeconomic scores. The findings show no significant link between land cover and accessibility, but there is a strong correlation with 0.57 between access to sports facilities and socioeconomic status. Lower socioeconomic groups have limited access to fragmented areas, while higher groups reside in well-planned regions with more services. The study shows that spatial inequalities are tied to income, living standards, density, and transportation, emphasising the need for future research on social dimensions.

1. Introduction

Cities are complex spaces at the center of the economic, social, and cultural activities of modern societies, where diverse opportunities, interactions, and inequalities of various scales coexist thanks to their population density, diversity, and dynamism (Bernard et al., 2023; Xu et al., 2025). Historically shaped as centers of production, trade, culture, and governance, cities have become primary arenas not only of economic growth but also of social transformation. While urban areas offer individuals several opportunities, including education, employment, healthcare, and social life, they also face significant challenges due to rapid population growth, spatial disorganization, inadequate infrastructure, and environmental pressures (Okeke and Nwachukwu, 2023; Iamtrakul et al., 2024). This contradictory structure highlights cities as spaces that both harbor potential for development and innovation and also foster the emergence of various social, economic, and environmental risks (Zhong et al., 2023). This multilayered structure within cities enables different social groups to have distinct life experiences within the same geographic area; inequalities in access to opportunities can sometimes lead to the deepening of spatial segregation (Smets and Salman, 2016). Therefore, cities are not only places where individual well-being increases, but also where social vulnerabilities and lack of resilience become visible. In this context, the concept of social vulnerability offers a critical analytical framework for understanding how social inequalities that occur in urban spaces are shaped by unexpected changes, shocks, or risks. Social vulnerability is not limited only to the sociodemographic characteristics of individuals, but is also directly related to the opportunities and limitations offered by space (Vale, 2014). At this point, accessibility emerges as a crucial parameter in understanding the spatial dimension of social vulnerability (Ryerson et al., 2022; Sansone et al., 2024). Accessibility refers to the level of accessibility of individuals to the services, resources, and opportunities they need to sustain their daily lives and effectively participate in social life (Olivari et al., 2023). The efficiency of urban transportation networks, the distribution of healthcare services, access to educational institutions, or the spatial organization of employment opportunities directly affect the quality of life of individuals and communities, while also playing a role in the reproduction of inequalities (Liu et al., 2023; Iamtrakul et al., 2024).

One prominent solution is the 15-Minute City concept was introduced by Prof. Dr. Carlos Moreno in 2016. The aim of the 15-Minute City concept is to create sustainable urban environments that enable residents to meet their daily needs—covering aspects such as housing, employment, commerce, healthcare, education, and entertainment—within a 15-minute walking radius (Moreno et al., 2021). The 15-Minute City concept is tied with chrono-urbanism principle. Chrono-urbanism views time as a resource in cities, suggesting that urban quality of life can be enhanced by reducing travel times for residents (Rojas-Rueda et al., 2024). The 15-Minute City concept aims to transform urban areas into polycentric cities through a time-based planning approach. This model prioritizes proximity, allowing cities to more effectively serve their social functions in a more equitable manner (Ferrer-Ortiz et al., 2022). The 15-Minute City concept has four key pillars namely proximity, density, diversity and digitalization (Noworól et al., 2022). The 15-Minute City concept utilizes proximity as a strategy to offer residents with more free time for leisure activities. Also, proximity is analyzed through two dimensions: temporal and spatial, highlighting the redistribution and relocation of urban resources (Khavarian-Garmsir et al., 2023). Density is reviewed as the optimal number of people in an area (Moreno et al., 2021). Diversity highlights the importance of accessibility and

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inclusiveness in urban planning (Biraghi et al., 2025). The last component is digitalisation and it is a key foundation that significantly shapes city operations, enhances service delivery, and creates value in urban systems (Allam et al., 2022). It is also closely tied to the Smart City concept, facilitating essential parameters like proximity, density, and diversity (Moreno et al., 2021). Through these components, 15-Minute Cities aims to make cities more sustainable, inclusive, and resilient. There are several studies on the concept. However, in the literature, this approach generally focuses on spatial and environmental dimensions, with a relatively limited focus on socioeconomic parameters (Büttner et al., 2022; Sdoukopoulos et al., 2024). This leads to the neglect of factors directly linked to vulnerability, such as demography, employment, income, and social structure. A study was conducted to identify potential 20-minute neighborhoods in Liverpool and to assess how their presence relates to socio-spatial inequalities. The study used some socioeconomic attributes such as car ownership, education deprivation score, etc. The results indicated that areas with a wealth of services closely align with the concept of a 20-minute city neighborhood. These locations promote the development of vibrant and healthy communities that encourage active travel, as essential services are readily accessible. Conversely, areas lacking sufficient services, which do not conform to the 20-minute city ideal, often experience disadvantages and tend to rely heavily on cars (Calafiore et al., 2022). Knap et al. (2023) aimed to develop a metric for assessing 15-minute cities based on cycling accessibility measures. They also explored the spatial and sociodemographic inequalities related to 15-minute city scores in neighborhoods across Utrecht and its surrounding towns in the Netherlands. One of their findings suggests that economically disadvantaged populations face a greater risk of transport poverty and have limited access to 10-minute cities. In another study aimed at identifying areas that align with the 15-Minute City concept, various indicators were utilized. One of the key parameters is population density, which is considered a socioeconomic factor (Gaglione et al., 2022).

This study aimed to examine and reveal social vulnerability patterns within the context of the 15-Minute City concept by conducting spatial analyses of Istanbul. A wide variety of data sets representing the physical and socioeconomic dimensions of urban structure were utilized in the analyses. In this context, land cover data contributes to understanding the spatial and environmental context, road network data reflecting the efficiency of transportation networks and mobility patterns, building records that enable detailed information about the built environment, Points of Interest (POI) that reveal the diversity of urban functions, and Socioeconomic Status (SES) indicators, which are critical for analysing social disparities, were used. Through these datasets, both the morphological characteristics of urban spaces and inequalities in social structure are examined from a multidimensional perspective, allowing for a more comprehensive assessment of the relationships between accessibility patterns and social vulnerability.

This study highlights the spatial patterns of social vulnerability, providing a valuable basis for urban planning, disaster risk management, and the formulation of social policy. Furthermore, the methodological framework developed through the integration of various data sources makes a significant contribution to the fields of sustainable urbanism and spatial justice studies.

2. Data and Methodology

The study comprises four key steps: pre-processing input data, clustering building data, analyzing accessibility by walking, and statistically evaluating the results.

2.1 Study Area

This study examines the relationship between accessibility analysis, informed by the 15-Minute City concept, and socio-economic status, with a particular focus on neighborhoods in Istanbul. Covering approximately 5,461 square kilometers, Istanbul is home to over 15 million residents. The city is divided into 39 districts, which are further categorized into 961 neighborhoods. Each neighborhood possesses distinct characteristics, including variations in land use, population density, building density, socioeconomic status, and access to various POI. A significant portion of Istanbul's population resides in the southern and Bosphorus-side areas, which are characterized by higher building densities and better access to amenities.

2.2 System Architecture

The study introduces a system architecture designed to assess the relationship between the 15-Minute City concept and the socioeconomic status of neighborhoods. This framework encompasses four primary steps: Pre-processing, Clustering, Accessibility Analysis, and Evaluating Relationships. A brief explanation of each step is provided following sections. The system architecture is illustrated in Figure 1.

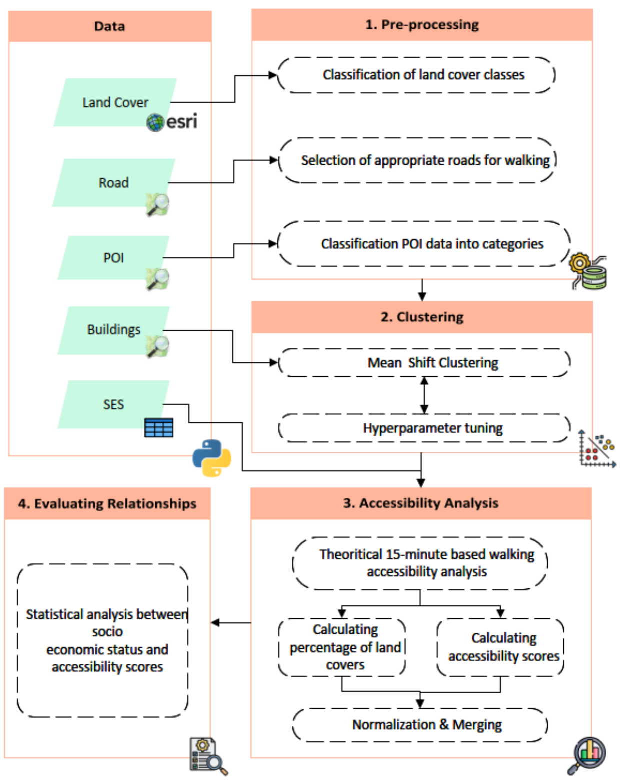

Figure 1. System architecture.

The proposed framework utilizes five distinct types of data. Land cover data is obtained from the ArcGIS Living Atlas of the World dataset, which features satellite imagery from the European Space Agency's Sentinel-2. This dataset provides land cover and land use information at a resolution of 10 meters and covers the period from 2017 to 2024. It classifies land into nine categories: water, crops, snow/ice, trees, built-up areas, clouds, flooded vegetation, bare ground, and rangeland (Esri - Sentinel-2 Land Cover Explorer, 2025). Road, POI, and building data are retrieved from OSMnx, which includes geospatial features from OpenStreetMap using Python (Boeing, 2017). Finally, socioeconomic status data for each neighborhood in Istanbul is sourced from the National Smart City Open Data Platform (ULASAV). This data encompasses socioeconomic status scores and grades (ULASAV, 2025).

2.3 Pre-processing

In the pre-processing phase, the acquired spatial data was systematically organized. Initially, the land cover data was classified into five distinct categories: water, green areas, built environments, agricultural land, and bare ground. This classification was conducted to mitigate potential negative impacts on the analytical outcomes. Next, a selection of road data was performed to remove inappropriate road types for pedestrian walking. Finally, a categorization of POI data was conducted. In the literature, different approaches exist to categorize POIs for accessibility analysis. Moreno et al. (2021) proposed six categories which are living, working, commerce, healthcare, education and entertainment. Calafiore et al. (2022) conducted a 20-minute analysis employing food, transit, sports, green spaces, recreational areas, education, health, places of worship, and entertainment. In another study, nine categories were identified: food and grocery stores, commercial stores, cultural venues, educational facilities, parks and green spaces, restaurants, health facilities, sports facilities, and others (Abdelfattah et al., 2022). Therefore, a customized categorization scheme was developed to encompass all relevant aspects of daily urban life in this study. This classification integrates widely accepted categories from existing literature and the available data for the study area.

2.4 Clustering

The study utilizes the Mean Shift clustering algorithm, a widely used machine learning method that is also applied in spatial clustering contexts (Peng et al., 2025). Mean Shift is a non-parametric clustering algorithm derived from concepts introduced by Fukunaga and Hostetler (Hajihosseinlou, et al., 2024). The Mean Shift clustering does not require prior knowledge of the number of clusters. Additionally, the geometric shapes of the clusters can vary and are determined by the user, allowing for greater flexibility in clustering analysis (Turčaník, 2021). The study employs the Mean Shift algorithm to cluster building data and incorporates hyperparameter tuning to optimize the identification of clustered areas based on building density.

2.5 Accessibility Analysis

Literature encompasses different methods to evaluate accessibility. The differences stem from several factors, including the time periods analyzed, the selection of starting and target points, and the modes of transportation considered in accessibility assessments, such as walking and cycling. Additional variations arise from differing travel speeds and the application of distinct limit values across the analyses (Sdoukopoulos et al., 2024). In the literature mostly 15-minute based analysis have been conducted (Abdelfattah et al., 2022; Gorrini et al., 2023; Knap et al., 2023). Moreover, several studies have conducted analyses based on durations of 5-10 minutes (Staricco, 2022; Kesarovski and Hernández-Palacio, 2023) and also 20 minutes (Calafiore et al., 2022). Additionally, a substantial number of these studies have conducted their analyses using census tracts, city blocks, cadastral parcels, postal code areas, and designated cells, primarily due to the lack of population data at an adequate resolution (Sdoukopoulos et al., 2024). Additionally, the analyses predominantly focused on walking as a mode of transportation. In contrast, a limited number of studies have centered on cycling as the foundation for their examinations (Papadopoulos et al., 2023). Lastly, a considerable number of these studies have reported travel speeds ranging from 4 to 5 km/h (Papadopoulos et al., 2023).

This study conducts an accessibility analysis based on the cluster centers of buildings identified through the Mean Shift unsupervised clustering algorithm. The focus is on pedestrian accessibility, utilizing a designated travel time of 15 minutes. Accessibility scores for the clusters were aggregated at the neighborhood level by calculating their average scores, resulting in a 15-minute walking score for each neighborhood. Additionally, the proportion of selected land cover classes were determined for each neighborhood. Next, the socioeconomic status scores of the neighborhoods were integrated with this data. These scores are classified into eight categories: A+, A, B+, B, C+, C, D, and E, listed from highest to lowest. Finally, the relationships between socioeconomic status, accessibility scores, and land cover proportions were assessed.

3. Results and Discussion

3.1 Pre-processing

In the pre-processing stage, the coordinate systems of the acquired spatial data were transformed to the projected national coordinate system (EPSG:5254). This transformation enabled accessibility analyses to be conducted using metric coordinates. Subsequently, the categories within the land cover dataset were revised. Initially, the snow/ice and cloud classes were removed. Following this, the bare ground and rangeland classes were combined into a single category known as bare ground areas, while the crops and flooded vegetation classes were merged to create an agriculture category. As a result, a comprehensive land cover dataset was established, encompassing five key land cover types. The evaluation of the road dataset revealed that specific types of roads, such as motorways, trunk roads, and primary roads, are not suitable for pedestrian use. Consequently, these unsuitable road types were excluded from the dataset to ensure a focus on pedestrian-friendly infrastructure. In the pre-processing of POI data, a new classification system was introduced, consisting of 12 categories: education, daily essentials, other daily essentials, public services, small industrial areas, cultural facilities, healthcare services, social infrastructure, sports, commerce and economy, transportation, and recreational areas. The POI types were categorized into these new classes. Some of the POI types are summarized in Table 1.

POI Classes	POI types
Education	School, kindergarten etc.
Daily Essentials	ATM, supermarket etc.
Other Daily Essentials	Fast food, restaurant etc.
Public Services	Police, fire station etc.
Small Industrial Areas	Workshops, forestry etc.
Cultural Facilities	Cinema, theatre etc.
Healthcare Services	Hospital, pharmacy etc.
Social Infrastructure	Place of worships etc.
Sport	Gym, sport centre etc.
Commerce and Economy	Jeweller, optician etc.
Transportation	Stations, taxi etc.
Recreational Areas	Playground, park etc.

Table 1. POI classification approach

3.2 Clustering

The analysis of theoretical walking areas based on a 15-minute radius was conducted. The identification of starting points for this analysis was achieved through Mean Shift clustering, utilizing data on buildings. The building data is obtained from OSMnx package via Python. In the clustering step, in order to employ Mean Shift algorithm, the centroids of buildings were determined. In the Mean Shift clustering algorithm, the bandwidth parameter is crucial for clustering outcomes. It determines the kernel radius for estimating data density, affecting the number, size, and shape of clusters. A larger bandwidth produces fewer, broader clusters, while a smaller bandwidth creates more, smaller clusters that capture local variations. To identify the optimal bandwidth, hyperparameter tuning was performed, evaluating both quantitative metrics and visual interpretations of the clusters. In the analysis of Istanbul's 39 districts, the average Silhouette score was determined to be 0.38. While this score is relatively low—suggesting some overlap among clusters—the visual representations of the clustering results indicate that the classification of buildings was carried out effectively. The observed patterns imply that, despite the low Silhouette score, the clustering successfully captures the underlying structure of the data, skilfully distinguishing between various types of buildings and their distributions across the districts. The example in Figure 2 illustrates the clustering results for a particular district.

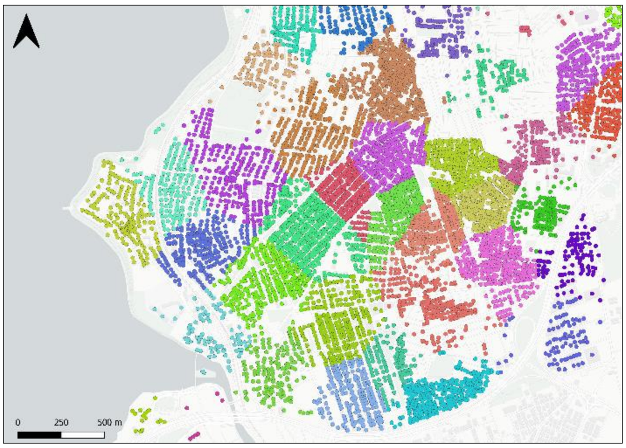

Figure 2. A sample of clustering result for a district (Each colour represents different cluster).

3.3 Accessibility Analysis

This study investigates the 15-Minute City concept across various districts of Istanbul. Accessibility analyses were performed with cluster centers serving as the primary starting points for evaluation. This approach effectively addressed challenges related to acquiring sufficient population data and managing low-resolution starting points, such as grid systems or postal code areas. Through these analyses, theoretical pedestrian walking areas within a 15-minute radius of each cluster center were identified. For each walking area, the number of accessible POIs in each category was calculated. The neighborhoods and accessibility outcomes of the cluster centers were then spatially analyzed to determine which cluster centers corresponded to each neighborhood. Following the establishment of these relationships, accessibility scores for the identified cluster centers within each neighborhood were calculated using the arithmetic mean. After obtaining the average accessibility scores for each neighborhood, a land cover analysis was conducted. In this analysis, the proportions of various land cover classes were calculated. Later, both accessibility scores and land cover portions are normalized with utilizing minimum-maximum normalization method. Subsequently, the socioeconomic status data of neighborhoods was integrated with the preceding dataset. This integration was facilitated by the presence of district and neighborhood names in both datasets, ensuring a coherent merge.

3.4 Evaluating Relationships

After acquiring a dataset that encompasses accessibility scores for 12 distinct classes of POIs, land cover proportions, and socioeconomic status for each neighborhood, statistical analyses were performed to examine the relationships between these parameters and socioeconomic status. Initially, correlation between accessibility scores and land cover proportions were evaluated. The results were presented in Figure 3.

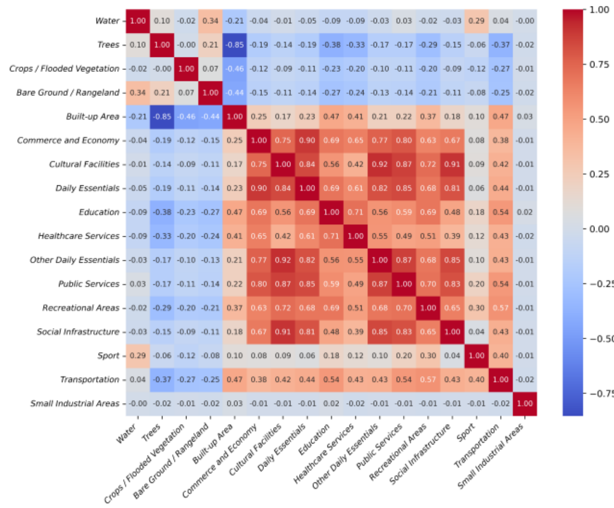

Figure 3. Correlations between accessibility scores and land cover proportions.

The correlation analysis highlights a significant distinction between urban accessibility scores and natural land cover variables. Most elements of urban services—including daily essentials, commerce, healthcare, education and others—exhibit moderate to strong positive correlations with one another, with correlation coefficients ranging from 0.39 to 0.92. This suggests that these amenities tend to cluster in the same areas. In contrast, natural land cover variables, such as trees, crops, flooded vegetation, and bare ground, demonstrate negative correlations, reflecting the more peripheral and less urbanized nature of these locations. Interestingly, the built-up area does not show strong correlations with urban service indicators, indicating that physical building density alone is not a reliable measure of service accessibility. In Istanbul, numerous neighborhoods possess high structural density but lack adequate public services and amenities, particularly in unplanned or low-income areas. Consequently, while the built-up area illustrates the extent of development, it does not necessarily capture the quality or diversity of urban functions.

Subsequently, Spearman's correlation coefficient was utilized to evaluate the relationship between socioeconomic status and the accessibility-land cover portion values. This correlation specifically quantifies the strength of a monotonic relationship between two sets of paired data. The formula of that correlation is given in Equation 1.

$$\rho = 1 - \frac{6 \times \sum d_i^2}{n \times (n^2 - 1)}, \quad (1)$$

The Spearman's coefficient correlations are depicted in Figure 4. The data reveal that the majority of correlations range between 0 and 0.57, suggesting weak to moderate relationships with socioeconomic status. Interestingly, the parameter most strongly correlated with socioeconomic status is access to sports facilities, closely followed by other daily essentials. This observation implies that neighborhoods with improved access to sports amenities and essential services tend to demonstrate higher levels of socioeconomic status. The pronounced relationship with sports facilities may indicate that such resources are often concentrated in well-planned, socioeconomically advantaged areas, where there is greater investment in public infrastructure and community services. In contrast, variables associated with natural land cover—such as trees, crops, and bare ground—exhibit negative correlations with socioeconomic status. This suggests that regions with more natural or agricultural land are typically characterized by lower levels of urban development and, consequently, diminished socioeconomic status.

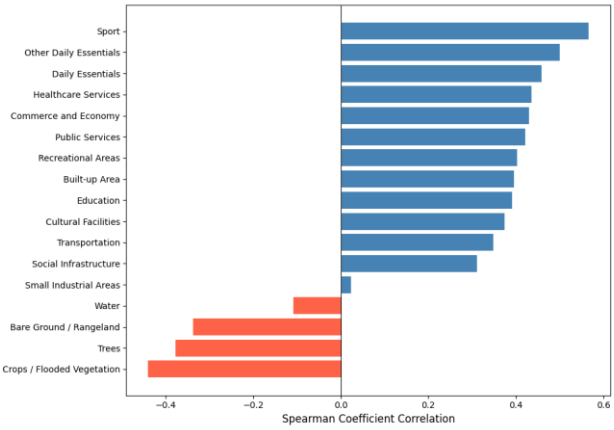

Figure 4. Spearman's coefficient correlation results.

Then, to analyse the relationships between urban service scores and land use portions in relation to socioeconomic status, boxplot analysis was conducted. The relationship between built-up area and socioeconomic status is given in Figure 5. The distribution of built-up areas across socioeconomic status groups reflects a distinct gradient. The lowest SES category (E) reveals the weakest mean with 0.37 and median with 0.17, accompanied by high variability, which suggests a mix of rural and peripheral environments. Starting with socioeconomic status category D, both mean and median values rise significantly, with the median reaching to 1.0, indicating that these neighborhoods are nearly fully developed. Higher socioeconomic status categories (B to A+) consistently demonstrate very high levels of built-up area, with means ranging from approximately 0.92 to 0.98 and low standard deviations, suggesting a compact urban form. The findings reveal that, as expected, socioeconomic status is notably lower in the rural areas of Istanbul. The analysis of built-up areas across socioeconomic status categories reveals distinct patterns related to outliers. In the lowest socioeconomic status group (E), numerous upper-tail outliers indicate neighborhoods with unexpectedly high building densities, often associated with informal settlements or compact urban enclaves situated in peripheral areas. In contrast, the middle socioeconomic status groups (D and C) exhibit downward outliers, suggesting the presence of partially developed zones within predominantly dense urban contexts. For the upper-middle socioeconomic status categories (C+ to A), both the number and magnitude of outliers decrease significantly, reflecting more stable and planned residential layouts.

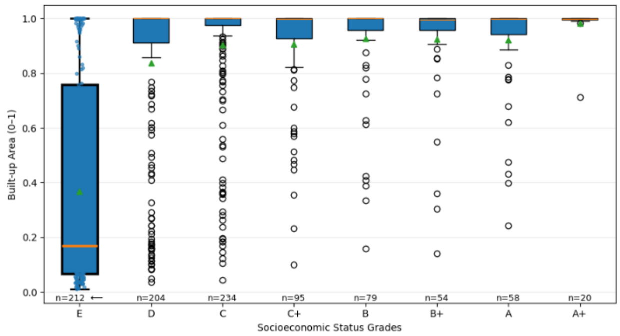

Figure 5. Relation between built-up area and socioeconomic status.

In Figure 6, relations between daily essentials POI class and socioeconomic status are presented. The lowest socioeconomic status group (E) has almost no access, with a mean close to zero and a median of 0.000. Accessibility significantly increases in middle socioeconomic status groups (D, C, C+), where both mean and median values rise, indicating greater spatial diversity. In contrast, higher socioeconomic status groups (B to A+) show stabilized accessibility at moderate levels, with means around 0.04 to 0.05. These results indicated that, in the lowest socioeconomic status group (E), service values are nearly absent, with only a few outlier observations representing local hubs like district centers or traditional marketplaces within deprived neighborhoods. The lower-middle socioeconomic status categories (D and C) show the highest number and magnitude of outliers, indicating significant spatial variability. Some neighborhoods have a high density of shops and services, while others are under-served. In the upper-middle socioeconomic status groups (C+ and A), both the frequency and size of outliers decrease, suggesting that predominantly residential areas have more dispersed daily services. Finally, in the highest SES group (A+), only a few outliers remain, indicating that strong concentrations of daily services are rare in wealthier neighborhoods. This finding shows that higher socioeconomic status does not always lead to greater availability of daily essentials.

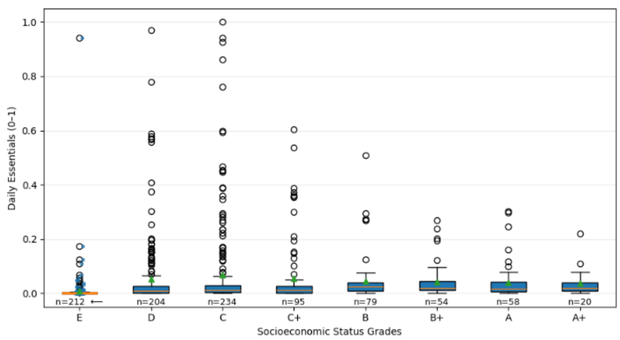

Figure 6. Relation between daily essentials and socioeconomic status.

The relationships between transportation and socioeconomic status are illustrated in Figure 7. The analyses shows that there is no strong relationship between transportation accessibility and socioeconomic status groups. The lowest socioeconomic status category (E) experiences minimal access, with mean and median values of 0.06 and 0.00, respectively, highlighting a significant lack of provision. Accessibility increases sharply in the lower- and middle-income groups (D, C, C+), where median values rise to approximately 0.13 – 0.14 and interquartile ranges expand, indicating greater variability. The upper-middle socioeconomic status categories (B and B+) demonstrate the highest levels of accessibility, with median values around 0.18 and a concentration of upper-quartile values, underscoring the presence of major transportation infrastructures in these areas. In contrast, the highest SES categories (A and A+) show a slight decline, with medians near 0.11 – 0.12, suggesting that affluent neighborhoods tend to be more residential and less characterized by dense transportation networks.

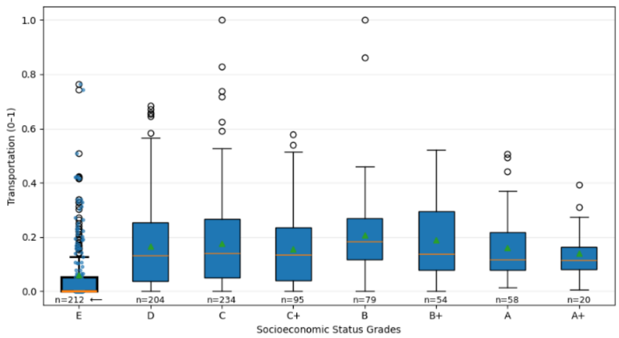

Figure 7. Relation between transportation and socioeconomic status.

4. Conclusion

This study introduces a novel approach to examining socioeconomic status through the lens of the 15-Minute City concept. It employs the Mean Shift clustering algorithm to analyse building data, serving as a foundation for a theoretical accessibility analysis based on the 15-Minute City framework. Furthermore, the study presents an innovative POI classification methodology, encompassing 12 distinct categories developed from extensive literature and available data within the study area. The research incorporates land cover data to evaluate urban accessibility to services and the distribution of land covers across various neighborhoods. Initially, a correlation analysis between accessibility scores and land cover proportions is conducted, revealing no significant correlation. However, a subsequent analysis of the relationship between accessibility and socioeconomic status uncovers a noteworthy correlation coefficient of 0.57 associated with sports amenities. This finding suggests that neighborhoods with enhanced access to sports facilities and essential services are associated with higher socioeconomic status levels. The study further compares built-up areas, daily essentials, and transportation accessibility with socioeconomic status. Boxplot analyses highlight significant disparities among socioeconomic status groups in Istanbul concerning urban form, service accessibility, and transportation availability. The lowest socioeconomic status group (E) is characterized by fragmented and limited urban development, reminiscent of rural or peripheral areas. Conversely, higher socioeconomic status groups (D and above) exhibit enhanced urban density and improved access to essential services, though variability remains within the middle socioeconomic groups (D, C, and C+). While the higher socioeconomic status groups (B to A+) demonstrate more consistent accessibility, transportation options reach their peak within the middle socioeconomic status groups before experiencing a slight decline in the highest groups (A and A+), which tend to be characterized by lower density and greater exclusivity. Moreover, natural surfaces prevalent in the lowest socioeconomic status groups diminish as socioeconomic status increases, resulting in denser urban development.

The findings reveal that spatial inequalities within Istanbul are intricately linked to income levels, living standards, urban density, service accessibility, and transportation connectivity. Low socioeconomic status groups frequently inhabit fragmented, rural-like areas with limited access to services and transportation. In contrast, middle socioeconomic status groups exhibit significant diversity, while high socioeconomic status groups are positioned in compact, well-planned urban areas that provide moderate service diversity coupled with lower transportation intensity.

Future research is recommended to incorporate social aspect parameters alongside quantitative analyses to deepen the understanding of these dynamics.

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