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Research article

Analyzing patterns of accessibility to schools: A gravitational metrics study in València

Aida Villalba[1], **Luis E. Vila**[2] **and Jose Miguel Carot**[1,*]

[1] Dept. of Applied Statistics and Operational Research, and Quality, Universitat Politècnica de València, Spain

[2] Dept. of Applied Economics, Universitat de València, Spain

* **Correspondence:** Email: jcarot@upv.edu.es.

Abstract: A gravity-based accessibility metric, the Two-Step Floating Catchment Area (2SFCA) enhanced with gaussian smoothing, is proposed to clarify the distribution of opportunities for compulsory education. Along with the physical locations of the homes and schools, the metric considers the population age structure and capacity to measure the population's accessibility to school services. The application of the 2SFCA within the '15-minute city' model and the analysis of València's urban environment revealed two main findings. First, the distribution of the accessibility scores after a spatial autocorrelation analysis closely reflected the per capita income across the city, irrespective of the type of school and level of compulsory education considered. Second, for most school age children, accessing a charter school is easier than access to a public school for primary and secondary education. The 2SFCA metric appears to adequately capture the uneven spatial distribution of educational opportunities, thus offering new insights into some of the forces the drive school segregation processes and their territorial foundations.

Keywords: spatial segregation; gravity-based metrics; 15-minute city; chrono-urbanism; equity
Mathematics Subject Classification: 62P20, 62P25

1. Introduction

Easy access to basic services such water and food supplies, health care, or education is crucial for a human quality of life. Regarding education, the analysis of accessibility to schools is essential to implement public policies, since the locations of schools, the changing residential distribution of students, and the choice of school and the associated admission processes are key elements that shape the equity of school systems [25, 26]. School segregation is at the root of the accessibility to schools, which can be broadly defined as the unequal distribution of students into schools based on personal

or social characteristics. School segregation constitutes a central element of educational inequity with direct and persistent impacts on social and economic inequalities. Accordingly, the current regulation of the access to education in Spain explicitly establishes explicitly that educational administrations must regulate the admission process to avoid school segregation, while keeping the proximity to the school as a priority in the admission process, along with the lower per capita income of families [14].

Consequently, abundant research exists on the persistence of diverse types of school segregation, thereby highlighting how certain types of students tend to unevenly cluster in particular schools located in specific neighborhoods. The analyses typically focus on the enrollment of students from ethnic minorities, students from socio-economically disadvantaged backgrounds, foreign students, students at risk, or students with special educational needs. A large part of the research on school segregation approached the phenomenon by calculating ratios or indexes designed to analyze different aspects of the segregation processes [4, 8, 10, 12, 17–19, 33]. The calculation of such indexes provides a general insight of the educational system in different territorial and time contexts, thus allowing for comparisons on the prevalence of school segregation among them [5, 23, 31]. The analysis from De Madaria and Vila [20] provided evidence on the school segregation of foreign students in València, thereby showing a lower prevalence of segregation in public schools compared to privately owned schools, with the segregation of foreign students reflecting mainly residential segregation.

However, most studies on school segregation, did not pay attention to the physical, social, or political conditions in the diverse territorial and educational contexts that might have helped to clarify the factors that condition the prevalence of diverse types of segregation in the corresponding environments. On the contrary, other research related to the phenomenon of school segregation did consider the political, social, economic, and physical conditions by adopting qualitative and ethnographic approaches to the particular experiences in specific case studies [7, 15, 16]. To our knowledge, the work of Rodriguez Victoriano, Junquero, and De Madaria [30] was the first study that combined both visions in a comprehensive analysis of the school system in the city of València.

The processes that foster school segregation are consequences of the interaction of a variety of factors of a diverse nature whose relative importance evolves over time and space. The accessibility to school is one of those factors, since school's location along with the residential concentration of social groups in particular districts or neighborhoods is often at the root of segregation in the schooling of particular groups of students. Of course, many other factors contribute to explain the greater concentration of specific groups of students in specific schools. Elements such as the global and local migratory dynamics, feelings of social or educational rejection to ethnic and cultural minorities, or the prevalence of mechanisms of social emulation in urban dynamics such as gentrification processes can influence the segregation processes. Besides, the educational policy and the models of legal regulation of the access to schools can also help to explain the persistence of trends towards a greater concentration of groups at an educational risk in specific schools [2]. Moreover, the interaction between educational policies and school managerial styles may contribute to social segregation through mechanisms such as higher housing prices near more desirable schools. In this sense, some authors point to the progressive introduction of quasi-market mechanisms in school assignment as a fundamental cause of polarization in the access to education because they encourage the spatial mobility, both residential or by commuting, of the most advantaged social groups [3].

The sorting dynamics of students into schools appears to be endogenous to a number of demographic, economic, social, political, and urban development underlying forces; however,

research on school segregation most often neglects the accessibility to schools as a potential determinant of segregation because the causal effects of the school location on school segregation are complex to identify and difficult to measure. Some research takes the distance between residences and schools into account as a driver for school segregation, although most often the metrics actually utilized ignore the population dynamics, either by prioritizing technical simplicity or by using population figures as weights in their formulations [21].

We propose the adoption of a gravity-based metric for the accessibility to schools, the two-step floating catchment area (2SFCA) approach [34] augmented with Gaussian smoothing, to measure the population's proximity to schooling services as an instrument to help explain some of the underlying forces that drive the processes of school segregation. The 2SFCA methodology paves the way to address the evident discrepancies found in the spatial allocation of educational facilities within urban areas, as well as the divergent demographic patterns observed in diverse neighborhoods and districts within the same city landscape. By integrating the local population dynamics into the accessibility analysis, the study aims to offer the means for a more comprehensive understanding of spatial segregation patterns around the educational facilities of urban environments [28].

The research objective is twofold. First, we seek to introduce an accessibility metric that explicitly takes both the population age structure and school capacity into account, along with their locations. Second, we seek to use the 2SFCA procedure to identify spatial patterns of inequalities regarding accessibility to compulsory educational services within the city of València. The study adopts the concept of the '15-minute city' as the theoretical framework [22], which is a decentralized urban planning model in which each local neighborhood should contain all the basic social functions for living and working. Although the 15-minute city model was primarily developed to reduce carbon emissions by decreasing the use of cars and motorized commuting time, a 15' walk at a moderate speed seems a sensible choice to form the catchment areas of individual locations within the 2SFCA method to evaluate the citizens' accessibility to primary and compulsory secondary schools.

After the introduction, the article is organized as follows. Section 2 analyzes the inequality of educational opportunities in València by examining at the district level the spatial distribution of the supply of compulsory schooling services at the district level along with the spatial distribution of the demand for such services, since there is evidence of marked differences in the age structure of the population across the districts of the city. The territorial foundations of school segregation become apparent through the analysis of spatial disequilibria in the provision of educational services related to the potential demand they must serve at the district level. Next, Section 3 describes the data and its sources, as well as the procedures involved in the 2SFCA methodology and its application to València. Section 4 contains a summary of the empirical results and some discussion. Finally, Section 5 concludes by acknowledging the limitations of the study and proposing further developments.

2. The supply and demand of compulsory education services in València

The historical and urban analysis of the inequalities regarding the educational supply and demand may help to understand the territorial foundations of the school segregation processes in the urban area of València. The consequences of those processes partially reflect the uneven spatial distribution of the supply of, and the demand for, educational services in the city, which determines the unequal educational opportunities for people residing in different neighborhoods. The analysis covers the 16

districts and 70 neighborhoods within València's Ciutat Central, and focuses on the two tracks of compulsory education, primary education(age 6–11), and compulsory secondary education (age 12–16).

2.1. The dual nature of the school network and its uneven territorial distribution

Like many other Spanish cities, València experiences a persistent shortage of public schools to serve its school population and, consequently, private educational institutions are required to guarantee a citizens' right to compulsory education, as it happens in the rest of Spain, although with different degrees of intensity. Regarding compulsory schooling, the scarcity of public supply is mainly due to the rapid expansion of València's urban area in the second half of the 20th century, which is a process that was driven almost exclusively by market forces, without any proper urban nor educational planning from public administrations.

The insufficiency of public provision to guarantee compulsory education was resolved by allocating public educational funds to privately owned schools through the so-called Educational Agreement (Concierto Educativo) in the mid-80s, which became an essential instrument to guarantee the right to education. As a consequence, nowadays the school network that offers compulsory education in the city has a dual nature because it is composed of publicly owned and managed schools, on the one hand, and of publicly-funded, privately owned and managed schools with Educational Agreement, also referred to as charter schools, on the other [1]. The Educational Agreement was intended to guarantee equal educational opportunities for the population regardless of the type of school; however, public and charter schools do differ in the effective management of the admission, curricula, hiring, and assessments because their managerial teams naturally respond to different sets of objectives.

Although there are a few small public schools in the city center, most publicly owned schools that are currently operating were established during the 70s and 80s to serve newer peripheral zones as the city expanded. Those zones were privately developed as residential areas to accommodate massive flows of young rural populations migrating to the city, from the late 50s to the late 70s, in search for economic opportunities in the industry and services sectors. In contrast, most large charter schools that are operating today were established by religious orders during the 50s and 60s, before the massive expansion. They are either located in the central districts or in what at the time were extra peripheral districts -the periphery at present-, in accordance with their traditional functions of training the elites, on the one hand, and to assist the most disadvantaged people, on the other [20]. Additionally, there is also a number of secular charter schools that are operating, which are generally smaller than the religious ones, and are spread across the city.

Table 1 summarizes the supply oriented to provide compulsory education in the districts of the city in terms of the number of schools and their capacity, which is measured as the number of educational seats offered for primary and compulsory secondary tracks, as well as the proportion of publicly owned schools and study seats in relation with the total supply.

The 16 districts of the Ciutat Central house a total of 153 primary schools and 103 secondary schools, offering 37,498 and 29,163 study seats, respectively. Nonetheless, the distribution of school locations among the districts of the city is markedly unequal in relation to the number of schools, their capacity to admit students, and the proportion of public and private charter schools. The number of primary schools in the city districts ranges from three (Benimaclet) to 16 (Poblats Maritims), with a median value at 9.5 schools per district. The number of secondary schools varies between three

(Algirós) and 11 (La Saïdia), with a median value at 6.5. The proportion of schools that belong to the public network widely varies across districts, from a modest 20% (El Pla del Real) to a substantial 81.8% (Algirós), with a mean value of 45.2% for all districts. The spatial distribution of the number of educational seats offered in the districts follows that of the schools. The number of seats offered in primary education varies among districts from 840 (Benimaclet) to 3580 (La Saïdia), with a median value of 2416 school seats per district; in secondary education, the number of seats offered ranges from 1032 (Algirós) to 2883 (La Saïdia), with a median value of 1659 per district. The proportion of seats of compulsory education that are offered by public schools varies even more, from a minimum value of 15.3% (El Pla del Real) to a maximum of 90.26% (Benimaclet), with a mean value of 45.4% across districts. The proportion of seats in public schools tends to be higher in peripheral districts and, accordingly, the proportion offered by charter schools tends to be higher in the central districts. Noticeably, the supply of primary education exceeds that of secondary education in the city as a whole and in most districts, although there are two exceptions which correspond to the two smallest districts, one in the city center (Ciutat Vella) and the other in the east periphery (Benimaclet).

Table 1. Supply of compulsory education by districts.

	SCHOOLS		**% of**	**SCHOOLS' CAPACITY**		**% in**
DISTRICT	**Primary**	**Secondary**	**public schools**	**Primary**	**Secondary**	**public schools**
1. Ciutat Vella	5	6	27.27	1084	1340	30.90
2. L'Eixample	8	6	28.57	2455	1929	28.88
3. Extramurs	9	7	25.00	3166	2284	25.12
4. Campanar	10	10	30.00	2531	2411	31.67
5. La Saïdia	14	11	28.00	3580	2883	28.24
6. El Pla del Real	6	4	20.00	2114	1448	15.27
7. L'Olivereta	14	10	41.67	2951	2673	40.54
8. Patraix	11	4	73.33	2360	1530	72.29
9. Jesus	11	7	50.00	2104	1493	58.69
10. Quatre Carreres	13	8	47.62	3130	2368	49.27
11. Poblats Marítims	16	9	52.00	2549	1588	42.62
12. Camins al Grau	14	7	42.86	2807	1730	35.75
13. Algirós	8	3	81.82	1729	1032	80.33
14. Benimaclet	3	5	75.00	840	1881	90.26
15. Rascanya	4	2	46.15	2377	1449	39.05
16. Benicalap	7	4	54.55	1721	1124	57.54

Source: Conselleria d'Educació, Cultura i Esport, Generalitat Valenciana.

Summarizing the aforementioned data, the location of the schools, and consequently that of the school seats, appear unevenly distributed across the city districts regarding both the track of compulsory education and the type of school considered. It should be noted that individual schools differ among them regarding many other characteristics in addition to the location, ownership, and capacity. Most of those features are difficult to observe and quantify, as is the case of a school's pedagogical tradition, its academic prestige, or the social desirability of its location. Although they have a bearing on the

school's role as a provider of educational services and may influence people's preferences, they do no influence people's accessibility to schools. The uneven distribution of the supply of compulsory educational services across the city generates imbalances in the schooling process that may encourage the massive and undesirable commute between residential neighborhoods and educational centers, thus triggering further and deeper dynamics of school segregation, as well as hindering progress toward the goals of the '15-minute city' model.

2.2. The uneven evolution of the demand for educational services

Demographic forces are at the root of the demand for any educational services, and almost exactly determine the demand for compulsory schooling. València's aggregate population decreased from figures of around 0.81 million in 2010 to 0.78 million in 2016, thus reflecting the consequences of the 2008 financial crisis, then increased to reach 0.8 million in 2020, when the COVID-19 pandemic cut the incipient recovery short. From 2021 to 2023, total population increased again to 0.8 million and is expected to remain stable in next few years.

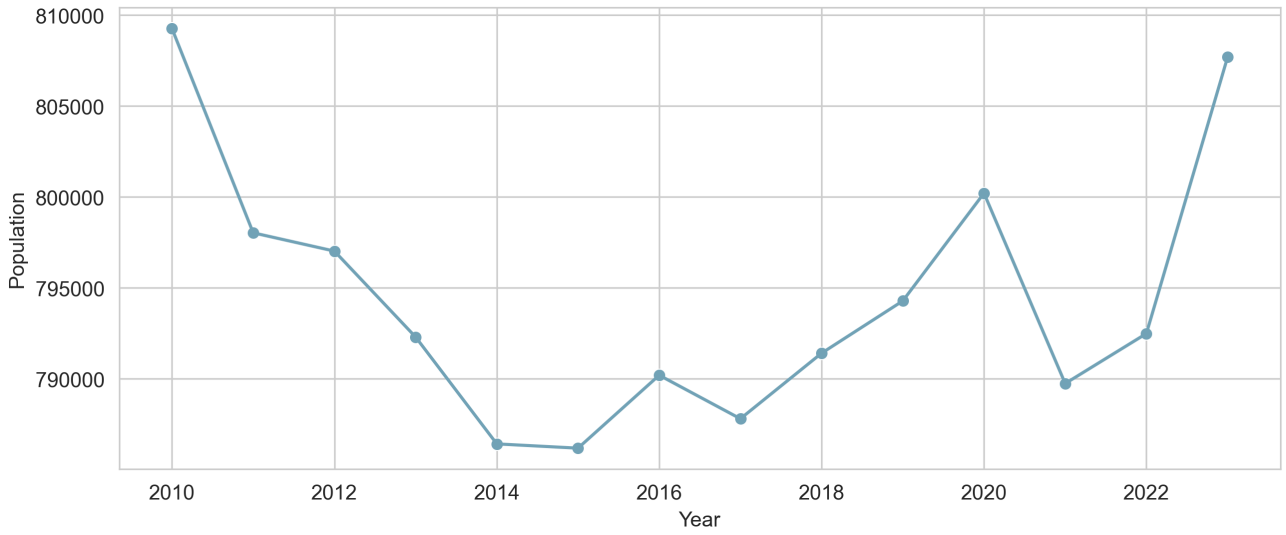

Figure 1. Evolution of Valencia's total population 2010–2023. Source: Population census. Instituto Nacional de Estadística.

The demand for compulsory education exerted from any residential area directly relates to the number of compulsory school-age children living within that area. Table 2 illustrates the districts of the city regarding the number of residents with the appropriate ages to require services from one of the two tracks of compulsory education, which, in Spain, are 6–11 years for primary education, and 12–16 years for secondary compulsory education. In addition, Table 2 shows the population between 0 and 5 years, who will be the next cohort demanding compulsory education, as well as the total population of districts as a size reference.

Remarkably, the population group aged 6–11 is larger than that of those aged 12–16 in all the districts, thus implying that there will be more children requiring compulsory secondary education in the foreseeable future than there are currently; this will result in higher demands, which will ultimately

add new pressures on those schools that provide compulsory secondary education. On the contrary, the group aged 0 to 5 is smaller than those aged 6–11, which implies that there will be less children demanding primary education in the near future than there are at present, and that primary schools will need to somehow compete to attract the shrinking demand.

Table 2. Current and future demands for compulsory education by districts.

	POPULATION				
DISTRICT	**Total**	**Age 0–5**	**Age 6–11**	**Age 12–16**	**% Ages 6 to 16**
1. Ciutat Vella	28763	1110	1320	953	7.90
2. L'Eixample	43565	2030	2219	1732	9.07
3. Extramurs	49335	2185	2468	1769	8.59
4. Campanar	39846	1929	2620	1834	11.18
5. La Zaïdia	47499	2012	2302	1630	8.28
6. El Pla del Reial	30680	1653	1807	1318	10.19
7. L'Olivereta	49583	2069	2332	1842	8.42
8. Patraix	58333	2260	2789	2194	8.54
9. Jesus	52585	1951	2533	1977	8.58
10. Quatre Carreres	76572	3290	4142	3152	9.53
11. Poblats Marítims	55897	2272	2769	2211	8.91
12. Camins al Grau	66245	2789	3586	2940	9.85
13. Algirós	35819	1209	1523	1052	7.10
14. Benimaclet	28317	1109	1351	834	7.72
15. Rascanya	54605	2534	3229	2539	10.56
16. Benicalap	48706	2355	2938	2027	10.19

Source: Oficina d'Estadística de l'Ajuntament de València [27].

Additionally, districts differ as well regarding the size of the school-age population relative to the total population. The number of compulsory school age children (6-16 years) in Campanar, El Pla del Real, Rascanya and Benicalap represent more than 10% of the corresponding district population, while school age children in Algirós, Benimaclet and Ciutat Vella represent less than 8% of the total district population. The present and future demands for compulsory educational services appear unevenly distributed across the city considering both the current and future numbers of school-age children by the districts, as well as their corresponding percentages in the district population.

A more disaggregate analysis of the population dynamics corresponding to the 70 neighborhoods of the Ciutat Central confirms that the requirements for educational services are, and probably will remain, as unevenly distributed in the urban area as it is the supply of such services, which is represented by the unbalanced locations and sizes of the dual network of schools.

Figure 2 illustrates examples of the three types of population pyramids commonly found across the city, thus representing divergent population dynamics patterns at the neighborhood level. For most neighborhoods in the city, the population pyramid belongs to the third type, which is markedly bulb-shaped, thus indicating a regressive demography, with negative rates of demographic growth for the period of 2010–2020. Those neighborhoods are characterized as having low birth and mortality rates, with the majority of the population in the central groups, thus exerting a relatively weak demand

for educational services. Some other neighborhoods present the second type, the stagnant pyramid shape, where the population distributes more or less uniformly across ages, with slightly lower values for the youngest and oldest cohorts. Additionally, neighborhoods with a stagnant pyramid shape have negative rates of demographic growth, and consequently exert a relatively weak demand for educational services.

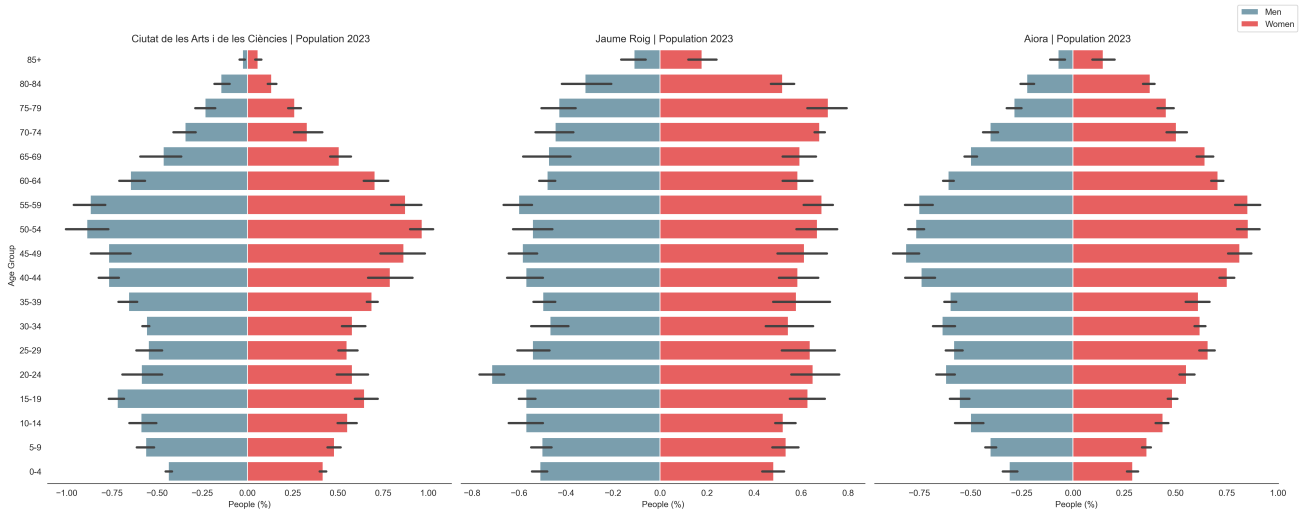

Figure 2. Three types of population pyramids prevalent among the neighborhoods of València's Ciutat Central. Source: Oficina d'Estadística de l'Ajuntament de València.

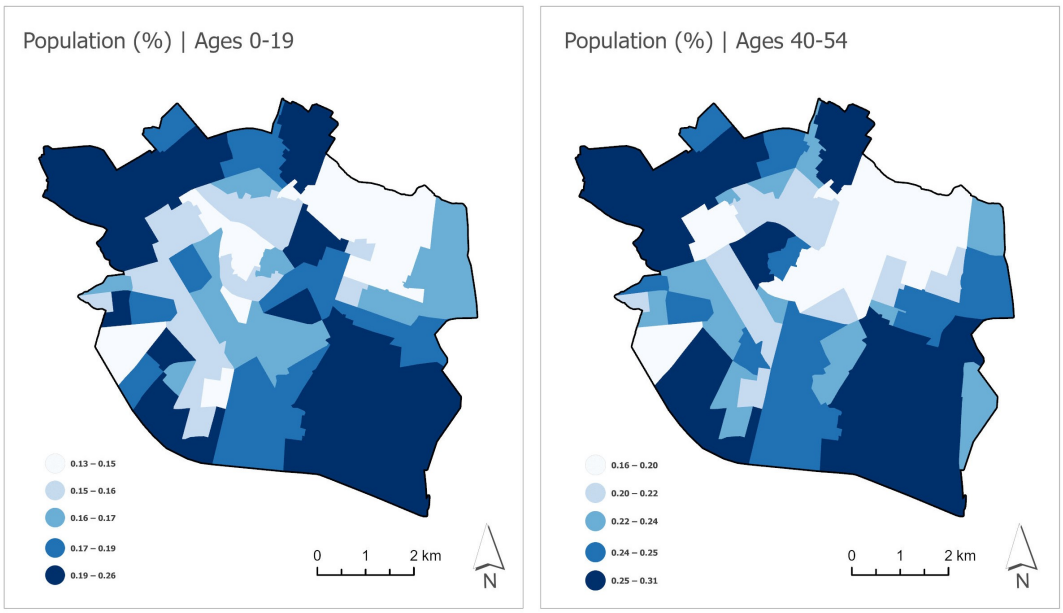

Figure 3. Population ages 0–19 (left) and 40–54 (right) as proportion of total population in the neighborhoods of València's Ciutat Central. Source: Oficina d'Estadística de l'Ajuntament de València.

Nonetheless, the actual demand for educational services emerges from the behavior of the families when they actually search for a school to enroll their school age children, particularly for the first courses of primary education and secondary education tracks. The parental school choice strategies respond to the legal framework of the state and may influence the extent of the inequality of educational opportunities in a territory through various types of actions based on the social perception of different schools' desirability, and the possibilities of entering them [7]. Once the access rules are established, and depending on the preferences, income, and social status, some families will go to great lengths to access the most desirable schools. This may imply longer commutes or residential mobility decisions. On the contrary, other families may choose solely because of the proximity or they seek an easier admission process, even though they do not apply for their preferred educational options. Moreover, school segregation can also influence the residential choices, as parents with may wish to avoid a proximity of their residence to highly segregated schools.

3. Materials and methods

3.1. The data set

We propose a model that uses three types of data inputs, all from open sources. The first represents the topography of the city, and includes the line shapes of those walkable pedestrian areas the corresponding intersection points from Open Street Map, as well as 70 area shapes of the neighborhoods within Ciutat Central available from the Oficina d'Estadística de l'Ajuntament de València (2020).

The second type is the georeferenced locations of all the educational centers operating in the city, which is provided by the Conselleria d'Educació, Cultura i Esport de la Generalitat Valenciana (2021), and all the cadastral parcels within the city's neighborhoods, which is gathered from European Commission INSPIRE Registry of cadastral parcels (2024) [13].

The third type of data is the supply-side characteristics of schools and the demand-side characteristics of residential parcels. School data is derived from the Conselleria d'Educació, Cultura i Esports de la Generalitat Valenciana (2021) [9] and includes the administrative school type and the number of places offered in primary and compulsory secondary education. The demand-side characteristics of residential cadastral parcels are estimates of the number of residents and its corresponding age structure, which is calculated with data from the Global Human Settlement Layer (GHS) in conjunction with census-derived population percentages from the Oficina d'Estadística de l'Ajuntament de València (2020).

Extensive data management using different Geographic Information Systems (GIS) tools from Python [32] and QGIS [29] allow us to process the data for different purposes. First, we seek to combine the pedestrian network of the city with the locations of schools and the parcels, and to connect those locations with the supply-side characteristics of schools and the demand-side characteristics of the parcels. Second, the demand-side population percentages of students aged from 6 to 11 and from 12 to 16 is calculated thorough the spatial interpolation of the census sections using Kriging technique; later, this raster layer is multiplied by the GHS layer, and the approximate amount of children in every cadastral parcel is obtained.

3.2. Gaussian-based 2 steps floating catchment area (2SFCA)

In order to calculate the accessibility scores of residential parcels to educational services, the first task is the definition of the travel costs between the supply and demand locations. Regarding the educational services, schools are the supply locations and the residential cadastral parcels are the potential demand locations. We express the travel costs between the locations as distances in meters using the walkable network of the city, thus establishing paths between the supply and demand locations and their respective nearest nodes in the city's network of walkable paths. We determine the shortest path between the centroid of the cadastral parcels and the educational centers using Dijkstra's algorithm [11], with the sum of the path lengths as weights. Then, the distances in meters are then transferred to a time scale using a constant walking speed of 4.5 km/h [24].

The result is a matrix (D) of travel costs expressed as the walking time distances (d_{ij}) between each school (i) and each residential parcel (j) located within the 70 neighborhoods of the Ciutat Central. According to the theoretical model, the analysis of isochrones defines the catchment area of each location, either the school or the parcel, that we set to the surface covered by a 15-minute walk radius from that location using the city's network of walkable paths. An isochrone is a line connecting multiple points that are simultaneously reached from a common origin, thereby delineating an area of influence for that origin point [6]. Mathematically, it can be expressed as $I(\tau, \lambda)$, where τ represents the origin and λ denotes the maximum time range. Each intersection along the isochron is considered a central node, from which a subgraph is generated, thus encompassing the nearest neighboring points that can be reached within a maximum time interval of λ minutes ($\lambda = 15$), thereby assuming an average walking speed of 4.5 km/h. The most distant neighboring nodes conform the boundary of the area of influence, which subsequently defines the isochrone. The intersection surfaces between the catchment areas of both schools and cadastral parcels allow us to identify the set of schools that are accessible from each parcel, as well as the set of parcels that are accessible from each school, according to the 15-minute walk radius. To ensure a complete coverage of the supply and the ratio of people with access to schools (first step of the 2SFCA indicator calculation), the isochrones and population estimates for the entire metropolitan area of the city of Valencia are calculated. Conversely, the coverage of demand in the second step is limited to the territory encompassed by the Ciutat Central.

Once the walking time distance (d_{ij}) between the schools (supply locations) and the residential parcels (demand locations) and the identification of the cadastral parcels within the catchment area of schools and vice-versa were calculated, the Gaussian-based Two-step Floating Catchment Area accessibility score for residential parcels was subsequently determined.

In the first step of the procedure, we calculate a supply-to-demand ratio for the schools by dividing the capacity of each school by a distance-weighted sum of the number of potential users from the parcels located within the school's catchment area.

$$R_i = \frac{s_i}{\sum_{j \in \{d_{ij} d_0\}} G(d_{ij}, d_0) P_j}. \tag{3.1}$$

In Eq 3.1, R_i is a supply-to-demand ratio of school i, s_i is the number of students the school can accommodate, the subscript j denotes those parcels within the school's catchment area, d_{ij} are time distances between the schools and the parcels, d_0 is the catchment area border, P_j denotes the school-

age population resident in housing parcels within the school's catchment area, and G is a Gaussian distance decay function to account for variations in proximity between schools and parcels.

$$\begin{cases} G(d_{ij}, d_0) = \frac{e^{-(1/2)(d_{ij}/d_0)^2)} - e^{-(1/2)}}{1 - e^{-(1/2)}} & \text{if } d_{ij} \leq d_0, \\ G(d_{ij}, d_0) = 0 & \text{if } d_{ij} > d_0. \end{cases} \tag{3.2}$$

The empirical result of the first step of the 2SFCA method is a vector of supply-to-demand ratios Ri for schools, thus representing the supply of educational services provided by each school relative to the potential demand that arises from the population residing within the school's catchment area.

Consequently, $(R_i)^{-1}$ indicates the demand pressure exerted by the population residing within the school's catchment area on the supply provided by the school.

The second step of the 2SFCA method consists of deriving the final score of accessibility to the educational services for each housing parcel in the city as a distance-weighted sum of the supply-to-demand ratios corresponding to those schools within the parcel's catchment area.

$$A_j = \sum_{i \in \{d_{ij} d_0\}} G(d_{ij}, d_0) R_i. \tag{3.3}$$

In Eq 3.3, A_j denotes the final accessibility-to-education score corresponding to parcel j, the subscript i denotes the schools within the parcel's catchment area, and all other notations are the same as in Eq 3.1.

The empirical result of Eq 2.3 is a vector A score that measures the accessibility of the residential cadastral parcels to the educational services provided by schools. The accessibility scores of each parcel to services of primary education and secondary compulsory education were measured separately, first considering public schools only, charter schools only, and both types of schools simultaneously.

4. Results and discussion

The results can be examined at different levels of spatial aggregation, such as census sections, neighborhoods, or districts, depending on the objectives of the analysis.

The final accessibility scores A_j have been calculated at the lowest aggregation level, which corresponds to 29695 cadastral parcels, to check for spatial autocorrelation patterns in the accessibility to education services using the local Moran's I test. Local spatial autocorrelation statistics, such as Moran's I, provide a means to analyze the relationship between each accessibility score and its immediate surroundings. In this context, each score is assessed based on its own value and on those of the neighboring observations. The first quadrant (HH) represents scores where both the values of the observation and its neighbors are high. The second quadrant (LH) includes scores with low values, surrounded by neighbors with high values. The third quadrant (LL) contains scores with low values for themselves and their neighbors. Finally, the fourth quadrant (HL) represents scores with high values, while the neighbors exhibit low values. Figures 4 and 5 summarize the results at the neighborhood aggregation level (70 spatial units) for the primary and secondary schools, respectively.

When examining the accessibility to educational services irrespective of the school type, the results show a certain degree of spatial homogeneity, thus suggesting that the population's effective

accessibility to compulsory educational services across the city is relatively fairly distributed. Nonetheless, the 2SFCA scores do widely vary across the census sections, with the highest values corresponding to sections located north and west of the central ring of the city, and the lowest values corresponding to the census sections located in the north and southeast peripheries. Local Moran's I test values delineate two large HH zones on the central ring of the city, one along the east arch of the ring, and the other covering the north arch and reaching the west periphery. Each HH zone is buffered by smaller LH zones, and there are some small, isolated HL zones as well. Accordingly, the LL sections concentrate on the north and southeast peripheries of the central ring of the city.

Nonetheless, the 2SFCA scores themselves do widely vary across the census sections. The highest values correspond to sections located north and west of the central ring of the city, where the per capita income tends to be higher than the city average, and the lowest accessibility values correspond to sections located in the north and southeast peripheries, where the per capita income tends to be lower than the average. Apparently, the distribution of the 2SFCA accessibility scores irrespective of the type of school closely follows that of the per capita income across the city.

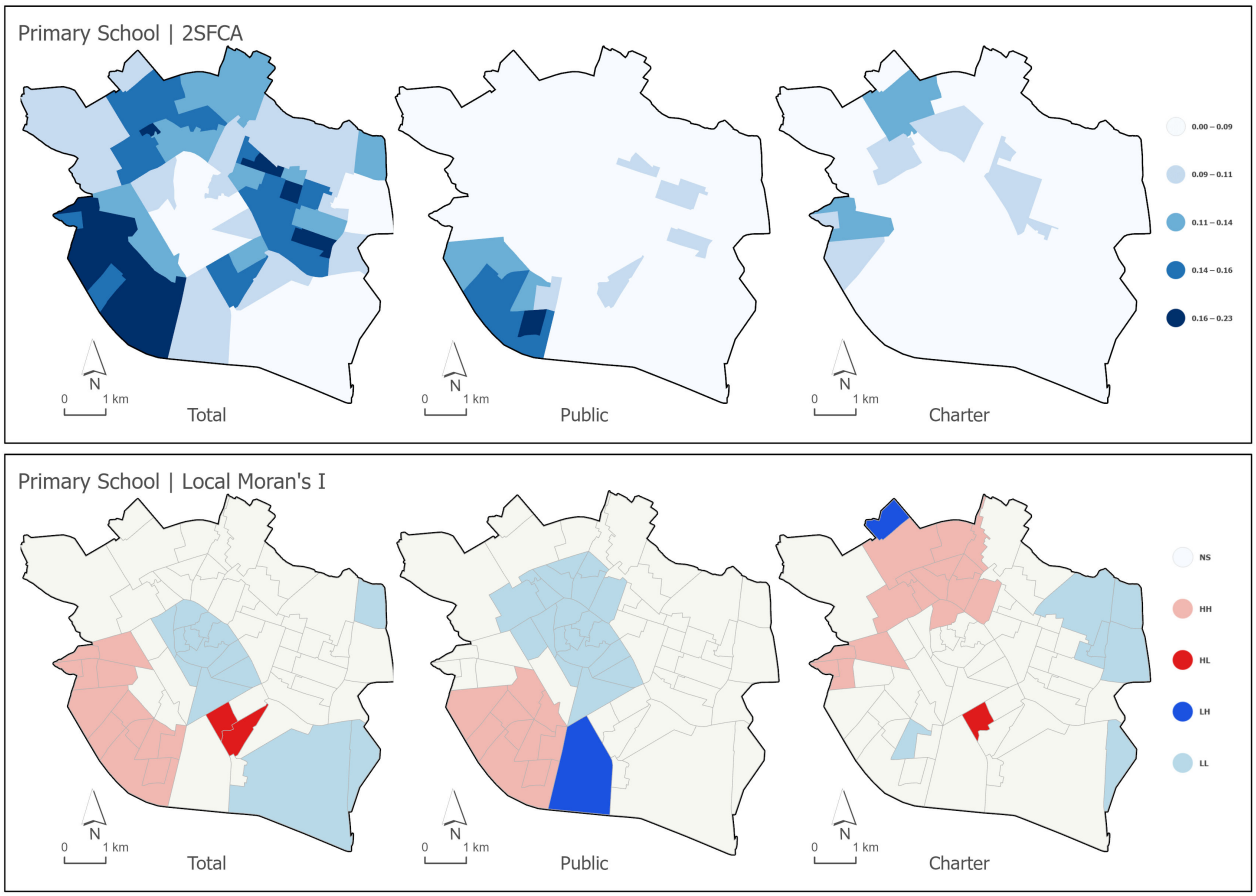

Figure 4. Primary School Gaussian-based 2SFCA scores for neighborhoods and the correspondent local Moran's I test results.

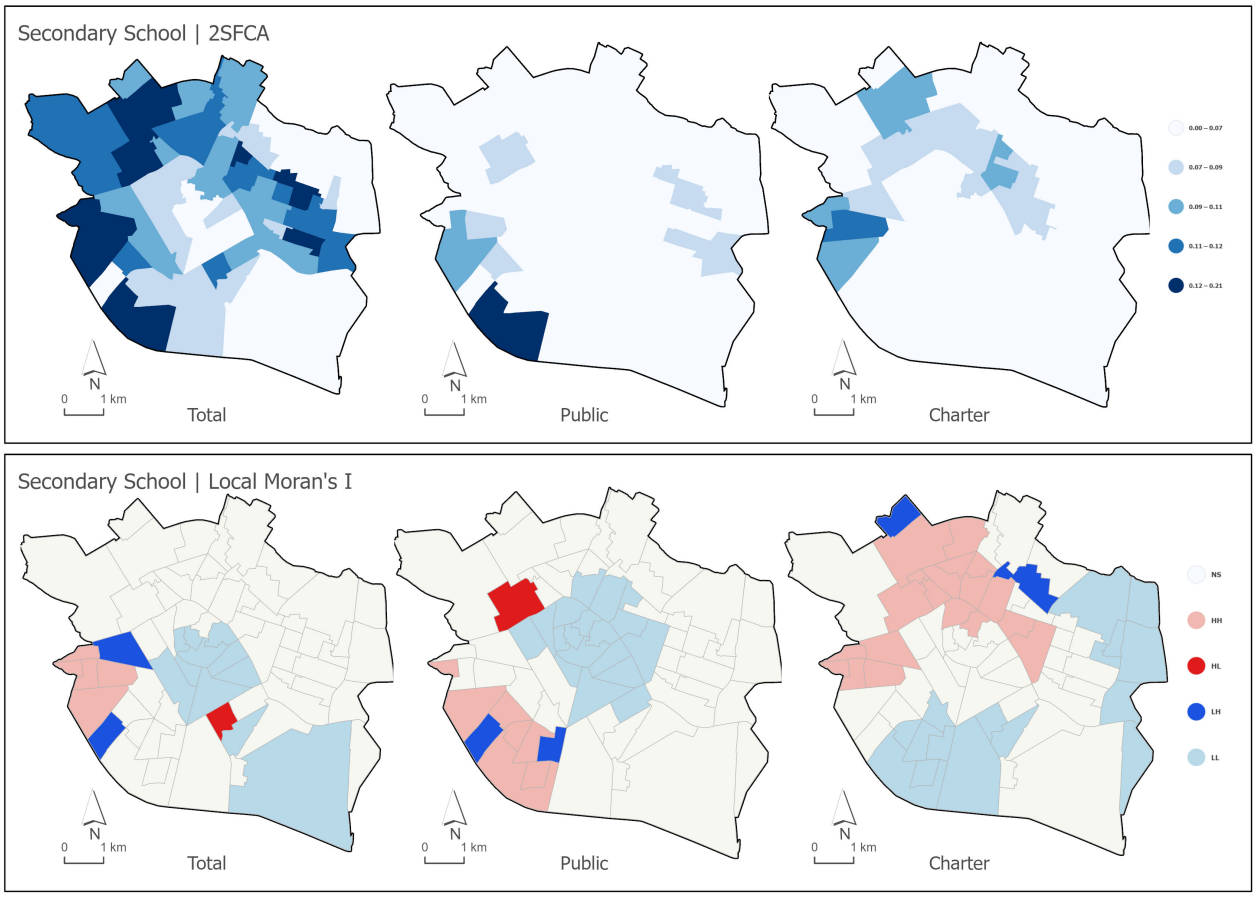

Figure 5. Secondary School Gaussian-based 2SFCA scores for neighborhoods and the correspondent local Moran's I test results.

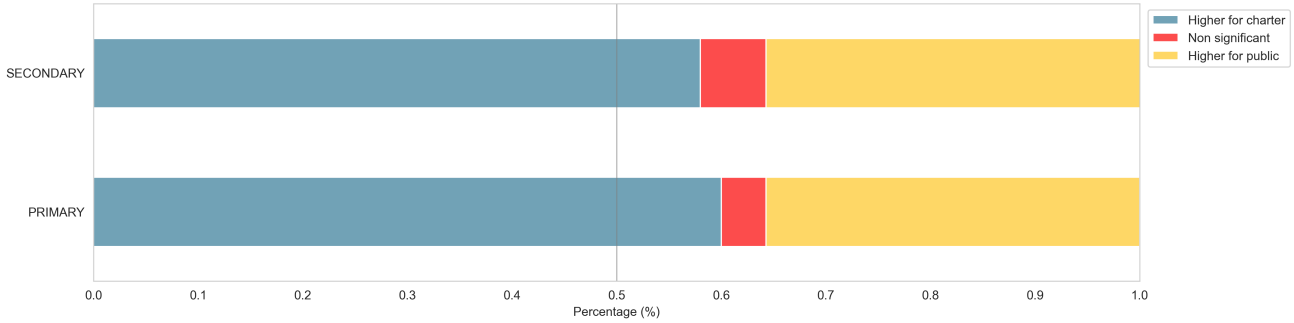

Figure 6. MWW tests results on accessibility scores to public and charter schools by education track.

However, five specific peripheral neighborhoods -Camí Real, Sant Pau, Penya-Roja, Sant Llorenç, and Ciutat de les Arts i les Ciències- located in different districts stand out, reaching positive demographic growth rates in the past ten years. Their population pyramids show the first shape type,

with the majority of the population belonging to the 0 to 19-year olds and to the 40 to 54-year old groups. Figure 3 illustrates the distribution of those particular age groups across the neighborhoods of the city. Assuming that this pyramid type corresponds with a high prevalence of the nuclear family model, those five peripheral neighborhoods shall be the object of special attention by education planners now and in the near future, as they are expected to be crucial demand locations for compulsory educational services in the next years.

In addition, distinct spatial patterns emerge when the accessibility scores to public and private charter schools are separately explored, thus indicating contrasting distributions of accessibility scores to the dual network of schools across census sections. Specifically, the accessibility to public schools appears to be more favorable for residential parcels located in the northeast and southwest peripheries, while the accessibility scores to private charter schools are more favorable for cadastral parcels of census sections located in the city center and the northwest periphery. Again, the poorest accessibility scores to both public and private charter schools correspond to parcels within the census sections located in the southeast periphery of the city. Generally speaking, the distribution of the 2SFCA accessibility scores to private charter schools show higher values for parcels located in the most affluent districts, while the accessibility to public schools shows higher values for residential parcels located in less affluent districts.

The analysis of the discrepancies between the accessibility scores to public and private charter schools by level of education using the Mann–Whitney–Wilcoxon test reveals a tendency towards significantly higher values of the 2SFCA accessibility score for private charter schools compared with public schools for both tracks of compulsory education (Figure 3). Specifically, more than 50% of the cadastral parcels within the Ciutat Central census sections exhibit significantly higher accessibility scores to private charter schools than to public schools for primary education and secondary education services, while the opposite is only true for less than 30% of the parcels. Thus, according to the results, most of the school age population in the city enjoys an easier access to private charter schools than to public schools for both tracks of compulsory education.

5. Conclusions

The study proposed the adoption of the 2SFCA approach, which is a gravity-based accessibility metric augmented with Gaussian smoothing, as a spatial instrument to evaluate the population's access to educational services within the city. Proximity is a key element that guides the choices of families during the schooling process of their children, and further impacts the school segregation and, in turn, on social inequality. The application adopted the concept of the 15-minute city and targeted the specific context of València.

Two main findings emerged from the analysis of accessibility to schools in València. First, the distribution of accessibility scores after spatial autocorrelation analysis reflected the per capita income across the city, irrespective of the type of school and level of education considered. Second, for most school age children, the access to a private charter school was easier than the access to a public school both for primary and secondary compulsory education.

The method satisfactorily addressed the noticeable heterogeneities in the spatial location of public and private charter schools, as well as in the population settlement within the urban landscape. By integrating the population dynamics into the accessibility analysis, it offers instruments for a more

comprehensive understanding of the forces that foster the patterns of school segregation observed in urban environments.

The potential for extending the analysis to different walking speeds, and to incorporate other modes of transport, such as public transport and biking, highlights the versatility of the procedure to explore the topic. The scalability of the model to other cities and education systems emphasizes its utility as a valuable tool for educational planners, as they will be able to evaluate the effects of future actions or policies on the accessibility to education across the entire city beforehand. Additionally, the 2SFCA method can be adapted to explore spatial disparities in the population's accessibility regarding any other locate urban equipment, either public or private, such as hospitals and health centers, sports facilities, recreational parks, cultural amenities, or commercial clusters. The procedure is easily adjustable because the user can decide both the definition of the travel costs and the size of the catchment areas; therefore, it may be useful for urban planners and policymakers seeking to enhance the accessibility to any type of services oriented to mitigate inequalities among the population of urban environments.

Nonetheless, the accessibility scores calculated at the cadastral parcel level can be aggregated at the census section, neighborhood, district, city, or country level, while segregation indexes calculated for individual schools can also be aggregated using the school location. By choosing appropriate references and aggregation levels, future research can address hypotheses on the mutual influences between the accessibility to schools and school segregation. The 2SFCA method opens new roads towards the implementation of evidence-based educational policies and planning, which are specifically oriented to reduce the prevalence of school segregations.

Author contributions

Aida Villalba: Conceptualization, Methodology, Investigation, Data curation, Visualization; Luis E. Vila: Investigation, Writing- Original draft preparation; Jose Miguel Carot: Supervision, Project administration, Funding acquisition, Investigation.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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