Are 15-minute cities for children? Exploring the socio-economic factors in Madrid

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The emergence of 15-minute cities marks a pivotal shift in urban planning, prioritizing accessible amenities within walking distance. This study examines its application in Madrid, Spain, with a focus on children. Firstly, an algorithm is developed to delineate the maximum walkable area around each census tract. Secondly, services that are essential for children aged 6–16 within a k-minute walking time are identified, along with the census tracts in which such access is available. Finally, a spatial probit model uncovers factors affecting accessibility, revealing correlations with income level, population density, gender, and family structure. These findings offer valuable insights for policymakers and urban planners aiming to create more equitable and liveable urban environments.

Introduction

Evolution has led to the current configuration of cities, which have paradoxically lost their essence as places designed to facilitate mobility and accessibility (Shamsaei et al. 2022). What was originally conceived to improve urban life has now become a hindrance to free pedestrian movement. This phenomenon has resulted in hostile urban environments, affecting not only mobility but also air quality, leading to health problems among residents. Moreover, extensive asphalt surfaces have contributed to cities' dreaded 'heat islands'. From a social standpoint, this urban configuration raises significant issues, particularly for vulnerable demographic groups, such as children or the elderly, who grapple daily with a lack of safe infrastructure, scarcity of green spaces, and suitable play areas. This constrains their mobility and affects their physical and emotional well-being, contributing to illnesses such as childhood obesity and mental health problems (De Bont et al. 2020).

In this context, 15-minute cities are emerging as innovative responses to contemporary urban challenges (Moreno et al. 2021). These cities are designed to ensure universal accessibility by placing essential services within short distances of walking, biking, and public transit. This approach aims to improve mobility, reduce car dependency, and promote sustainable transportation. It also enhances the quality of life of citizens by reducing their daily commuting time and stress, fostering social and community interactions, and facilitating access to services and green spaces. 15-minute cities represent a paradigm shift in urban planning by prioritising accessibility, sustainability, and quality of life to create healthier and more equitable urban environments (Fritz et al. 2022).

It is essential to recognise that the urban experiences of children differ significantly from those of adults. Children require accessible and engaging environments to support their development and well-being. In a 15-minute city, this means ensuring that schools, playgrounds, and recreational spaces are within easy walking distance from home. Streets should be designed to encourage exploration and play, incorporating green spaces and amenities that cater to children's needs (Gorrini et al. 2023). By prioritising these elements, urban planners can create inclusive environments in which children can thrive, cultivate independence, and engage in social interactions. Why do we not consider the needs of these vulnerable population groups in the design of our cities? Children should be free to explore and enjoy their environment from an early age to boost their holistic development. Regarding previous literature, we found few studies examining 15-minute cities for children (Gorrini et al. 2023).

In this study, we examined children's accessibility to basic amenities that are particularly interesting to them. We analysed k-minute cities for children by identifying areas of better accessibility for this population group, focusing on the population between six and 16 years. This age range aligns with the obligatory education period in Spain ('primary education' between 6 and 12 years old and 'secondary education' for students between 12 and 16). Given that accessibility is mediated by mobility, our research focused on walking as a mode of transportation. This topic is of fundamental interest, especially for the young population, owing to children's decreasing physical activity and rising obesity rates in some of the areas analysed (e.g., Pizarro et al. 2013).

Our research focuses on Madrid (Spain). It is one of the largest cities in Europe, with 3.4 million inhabitants (320,000 between the ages of 6 and 16), and serves as a key example of how 15-minute city concepts can be implemented. In this study, we applied geographic analysis techniques to identify the maximum walkable area in k-minute using a street network from the centroid of each census tract in Madrid. Subsequently, we conducted an exploratory analysis of the spatial data to identify areas with greater accessibility and clusters or concentrations of areas with these k-minute walkable characteristics. Once these areas were identified, we proposed a spatial probit specification that allowed us to determine the most relevant variables associated with classifying a census tract as k-minute walkable.

Our results confirm a spatial autocorrelation structure at the census tract level in Madrid. Therefore, we found that the census tracts identified as k-walkable for children tend to be spatially concentrated. Subsequently, we developed a spatial probit model to characterise these k-walkable census tracts by considering factors such as income, population density, and family structure. This study contributes to the assessment of accessibility to points of interest for children, potentially serving as a useful starting point for local policymakers to evaluate the provision of these amenities in different urban areas. This could lead to a healthier lifestyle among the younger population based on more walkable minutes in their daily routines.

This study is organized as follows. Following the introduction, we present the related literature. Then, we discuss the data and methodology, then the results are presented, and finally the conclusions are discussed.

Related literature

A considerable amount of literature has been published on the concept of the k-minute city (e.g., the review by Wang–Yang 2019). This topic was analysed using empirical evidence from multiple cities. For example, three recent contributions are Gaglione et al. (2022), who analysed a 15-minute city in Naples (Italy); Hosford et al. (2022), who did the same in Vancouver (Canada); and Akrami et al. (2024) in Olso (Norway). Although the complete list is extensive, there is little evidence in Spain, with the exception of Graells-Garrido et al. (2021) in Barcelona (Spain). All these studies (and many others) treat the entire population equally without considering that different population groups may have different needs and walk at different speeds. To build inclusive cities, it is crucial to consider the unique needs and challenges of vulnerable populations (Willberg et al. 2023). In some cases, the older population is considered a vulnerable group (Zhang et al. 2023, Ulloa-Leon et al. 2023), but the research on other population groups is limited.

To the best of our knowledge, research focusing specifically on young populations and 15-minute cities consists of only Gorrini et al. (2023). They assessed walkability levels for children in the city of Bologna, Italy, to identify priority urban areas for interventions that improve walkability. Their findings revealed areas with higher walkability scores offering more amenities, such as parks and playgrounds, fostering physical activity and outdoor play for children. They also identified areas with low utility, comfort, safety, and attractiveness, highlighting the need for infrastructure improvements and safety measures to promote child-friendly environments.

It is possible to find research analysing children's accessibility to certain basic services, but there are no specific studies on 15-minute cities. Martori et al. (2020) developed an accessibility index for playgrounds and green spaces and presented empirical evidence for Barcelona (Spain). This study provides an extensive review of the literature that will not be reproduced here to save space. In another study, Reyes et al. (2014) analysed children's walking accessibility to parks on Montreal Island (Quebec, Canada) and evaluated the spatial disparities of urban parks. The results underline variations in mobility patterns based on socio-economic and demographic attributes as well as differences in accessibility by location, showing higher levels of accessibility in suburban areas and for male children with higher incomes. Similarly, there have been several studies on children's access to parks and green spaces, such as those by No et al. (2023) in Seoul, South Korea, Rigolon (2017) in Denver (EEUU), and Robillard et al. (2023) in Quebec (Canada). A survey of the accessibility of playgrounds was conducted by Moore–Lynch (2015). Rehling et al. (2021) examined how socio-economic factors affect the time children and adolescents spend walking in public green spaces in urban Germany. They found that children from low and medium socio-economic backgrounds required more time to reach these spaces than their peers from higher socio-economic backgrounds. This unequal access may exacerbate existing health inequalities.

Data and methodology

In this section, we describe the basic services included in this study and define the concept of the k-walkable census tract. We explain the method used to determine the maximum accessible area within a walking distance of k-minute via the street network. Additionally, we briefly describe the methodology employed to analyse the factors associated with k-walkable census tracts.

Data and definition of k-walkable census tract

Madrid, the largest municipality in Spain and its capital city, is a unique and compelling setting for this study. Its large population, exceeding 3.4 million, provides a diverse and extensive demographic landscape, offering rich opportunities for analysis and insight into urban dynamics. Additionally, Madrid's well-developed infrastructure and public services make it an ideal case study for investigating the practical application of initiatives, such as 15-minute cities, providing valuable lessons and potential models for other urban centres worldwide. Thus, the selection of Madrid as the study area offers a robust foundation for comprehensive research and meaningful contributions to urban planning discourse and practice.

In addition, the data used in this study were collected at the beginning of 2024 and were obtained from official statistical sources, ensuring accuracy under current urban conditions. It includes data on population distribution, infrastructure, and socio-economic variables. Using recent data allowed for a more up-to-date analysis of accessibility and walkability, providing insights that reflect the current urban landscape and demographic patterns of Madrid.

Table 1

List of basic services, a short description, and data sources

Basic service	Description	Data source	Date
School	Primary and secondary education schools, whether public or private (mandatory education from ages 6 to 16).	Madrid Open Data https://datos.madrid.es/	Dataset of February 2024. This website publishes a quarterly file of microdata from the census of locals/ establishment of the Madrid City Council, classified according to the activity performed. The database includes the longitude and latitude coordinates of each establishment. It was filtered to select only premises whose activity was classified as 'Education', selecting only public and private educational centres for children under 16 years old.
Playground	An open dataset downloaded from OpenStreetMap includes objects tagged with leisure=playground. This dataset comprises two sets of objects: one set consists of data points representing individual playgrounds, and the other consists of polygons representing small playground areas. The centroid of each polygon was obtained, and both sets of points were included.	OpenStreetMap https://www.openstreetmap.org/	Downloaded in January 2024 from https://overpass-turbo.eu/. Overpass Turbo is an interactive and visual tool for performing queries on OpenStreetMap (OSM) data using the Overpass API query language.
Park/Garden	Main parks and green areas of Madrid whose conservation is the responsibility of the Madrid City Council, along with their detailed characteristics. The list includes both gardens and small green areas.	Madrid Open Data https://datos.madrid.es/	Downloaded in February 2024

Regarding the analysed population, children are a particularly sensitive population group in the context of 15-minute cities because of their reduced mobility and specific need for access to basic services (Reyes et al. 2014). A total of 320,616 children live in Madrid, and by focusing on these groups, researchers can identify areas where improvements in the proximity and accessibility of facilities, such as healthcare centres, parks, and recreational areas, are needed. In this study, we focused exclusively on the youngest population, considering that a child should have access to at least three basic services within a 15-minute walkable census tract: an educational centre (primary or secondary school, public or private), a playground, and a recreational area (park or garden). Table 1 lists the basic services included in this study and their primary sources of information.

Using these basic services as criteria, we define a k-walkable census tract for children, where at least these three services are available within a walkable distance of k-minutes using the street network. This means that children residing in these tracts can access essential amenities, such as playgrounds, parks, and schools, without the need for motorised transportation. A census tract is defined as non-walkable if some of the three basic services are not available on foot in k-minute using the street network. Defining a census tract as walkable or non-walkable allows the association of socio-economic indicators. This categorisation can provide valuable insights into the relationship between walkability and various socio-economic factors such as income level, education, and demographic characteristics. Figure A1 (see in Appendix) shows the distribution of basic services in the study area.

Methodology. The maximum walkable area

Madrid is divided into 2,443 census tracts that serve as crucial units for demographic and socio-economic analyses. On average, each census tract accommodated 1,235 residents and spanned an area of 853,764 square meters, with a minimum size of 44,298 square meters and a maximum of 112,053,026 square meters.

This subsection describes the methodology used to calculate walkable areas assigned to each census section. A specific methodology was used to quantify walkable areas associated with each census section in Madrid. First, the municipality was divided into hexagons using the H3 geospatial indexing system developed by Uber Technologies. This system efficiently partitions the Earth's surface into hexagonal units, providing flexibility in terms of spatial resolution. In this study, the municipality of Madrid, covering 606 km^2, was tessellated into 211,255 hexagons, each measuring 316 m^2 (H3 unit size 12), using the h3 R-package (Kuethe 2022).

Subsequently, road networks from OpenStreetMap (OSM) were obtained using the R package r5r (Pereira et al. 2021), which comprised 1,820,008 roads. These road networks were used to calculate the walking time achieved using the R package r5r. The shortest walking times between the centroids of the census sections (origins) and hexagons (destinations) were computed assuming an average walking speed of 3.6 km/h. This process yielded travel time matrices encompassing 2,443 × 312,130 origin–destination pairs within the study area.

Finally, for each census section, hexagons within a walking distance of less than k-minute (k = 5 or 15 in our case) from the centroid were identified, and the surface area (in square kilometres) of each walkable area was calculated. Figure A2 (see in Appendix) shows two examples of maximum walkable areas obtained using this algorithm.

Methodology. Statistical tools

All of Madrid's census tracts are coded as 1 if they are classified as walkable (k-walkable) and 0 otherwise (non-k-walkable), following the definition described in Subsection 3.1. Two methods were used to identify the factors related to classifying census tracts as k-walkable or non-k-walkable.

First, exploratory joint count statistics (Cliff–Ord 1981) were used to confirm the presence of spatial autocorrelation in the binary variable. These statistics are used to test the null of a random co-localised pattern, counting the number of possible 'joins' between neighbours. The possible joins are walkable–walkable (WW), non-walkable–non-walkable (NN), and walkable–non-walkable (WN). The statistics J_{WW}, J_{NN}, and J_{WN} count the observed number of joins and compare them with the expected number under the null. To join the census tracts, we selected a binary weight matrix $W=(c_{ij})$ based on a connectivity criterion, where $c_{ij}=1$ if census tracts i and j are neighbours (with common borders) and 0 otherwise (with $c_{ii}=0$ for all i). Joint count statistics (J_{WW}, J_{NN}, and J_{WN}) were defined as follows:

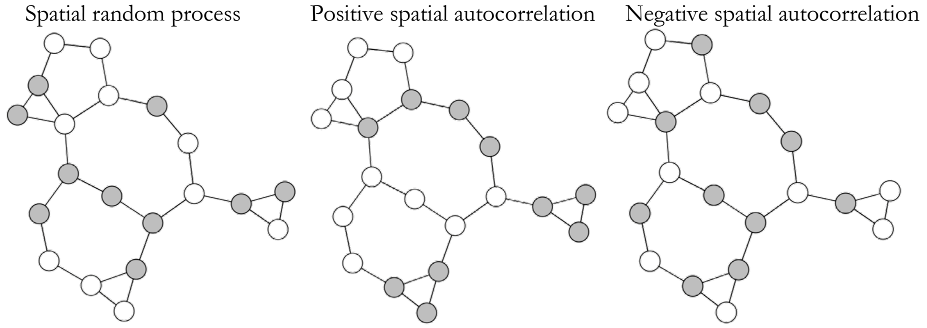
$$JC_{WW} = \frac{1}{2}\sum_{i,j} c_{ij}\, WW_{ij}\, ;\, JC_{WN} = \frac{1}{2}\sum_{i,j} c_{ij}\, WN_{ij}\, ;\, JC_{NN} = \frac{1}{2}\sum_{i,j} c_{ij} - (JC_{WW} + JC_{WN})$$

where c_{ij} represents the elements of the weight matrix, WW_{ij} = 1 if census tracts i and j are defined as walkable, WW_{ij} = 0 otherwise, WN_{ij} =1 if units i and j belong to different categories, and WN_{ij} =1 otherwise. The R package spdep (Bivand–Wong 2018) was used to obtain statistical data. Figure 1 presents an example of three alternative spatial distributions of binary variables.

Figure 1

Example spatial correlations in dichotomic spatial processes

Spatial random process — Positive spatial autocorrelation — Negative spatial autocorrelation



	JC	Expected	z-value		JC	Expected	z-value		JC	Expected	z-value
JC_{WW}	4.00	4.74	–0.63	JC_{WW}	8.00	4.74	2.81	JC_{WW}	3.00	4.74	–1.49
JC_{NN}	5.00	4.74	0.23	JC_{NN}	6.50	4.74	1.52	JC_{NN}	2.50	4.74	–1.92
JC_{WN}	11.00	10.53	0.23	JC_{WN}	5.50	10.53	–2.45	JC_{WN}	14.50	10.53	1.93

Notes: links represent neighbourhood join criterion. White circles represent walkable and grey circles non-walkable.

Second, a spatial probit model (Martinetti–Geniaux 2021) is employed to evaluate the importance of certain socio-economic variables. The spatial probit model is expressed as

$$y^* = \begin{cases} 0 \ if \ y \geq 0 \\ 1 \ if \ y < 0 \end{cases} \qquad (1)$$
$$y^* = \rho W y^* + X\beta + \varepsilon, \varepsilon \sim N(0, I_n)$$

where y is the observed value of the limited-dependent variable, y^* is the unobserved latent dependent variable, X is a matrix of explanatory variables, W is the $N \times N$ spatial weight matrix defining the neighbourhood structure, and ρ is the spatial autoregressive parameter. If $\rho = 0$, the spatial probit model collapses to the standard binary probit model. If $\rho \neq 0$, the $(N \times 1)$ vector Wy^*, consisting of an average of the k-walkable census tract, creates a mechanism for modelling interdependence in walkable areas. Finally, ε is the error term.

Results

Descriptive analysis

Table 2 outlines the availability of services reachable within a walking distance of k-minutes from the centroid of each of the 2,443 Madrid census tracts. These findings highlight the notable variations in service accessibility between 5 and 15 minutes. On average, there were 0.9 schools within a 5-minute walk, contrasting with 8.23 within a 15-minute walk. Similar differences emerged for playgrounds, with 1.23, available within 5 minutes and 12.77 within 15 minutes. Lastly, parks and gardens are the least accessible on foot, with 0.12 within 5 minutes compared to 1.52 within 15 minutes. When considering all services together, the algorithm identified 475 census tracts that did not have any services accessible within a 5-minute walk and 28 census tracts that did not have any services accessible within a 15-minute walk.

Table 2

Descriptive statistics of the number of basic services in k-walkable census tracts

Denomination	Services in 5 minutes on foot			Services in 15 minutes on foot		
	school	playground	park/garden	school	playground	park/garden
Mean	0.90	1.23	0.12	8.23	12.77	1.52
Standard deviation	1.23	1.42	0.35	4.76	7.43	1.4
1st quartile	0	0	0	5	7	1
3rd quartile	1	2	0	11	17	2
Maximum	16	10	2	30	46	11
Without services	1,202	941	2,158	70	48	592
Non-k-walkable			2,314			621

Figures 2a and 2b show the localisation of the non-5-walkable and non-15-walkable census tracts, respectively, most of which are located on the outskirts of Madrid.

The results obtained in this analysis of accessibility to basic services for children show that most census tracts classified as non-walkable lack a park or garden (Reyes et al. 2014). Figures 2a and 2b show the k-walkable census tracts. Most of them are in the centre of Madrid, within the 'central almond' enclosed by the M-30 highway. This is a relevant result because most children live outside the 'central almond'.

To increase information about the accessibility to basic services, eight typologies of census tracts can be identified, depending on whether they have access to each of the three basic services within a k-minute walking distance. These range from census tracts with no access to any of these basic services to tracts with access to all three. Table 3 lists the number of census tracts of each type, indicating the population of children included in each type. Most children (65%) had access to all three basic services within a 15-minute walk and resided in a 15-walkable census tract, whereas the remainder (35%) lacked access to one or more of these services, primarily parks and gardens. A total of 8,985 children did not have access to basic services. In the case of the 5-walkable census tracts, only 14,364 had access to all three services within a 5-minute walk.

Figure 2

Walkable and non-walkable census tracts

a) 5-walkable census tracts

Non-5-walkable   5-walkable

b) 15-walkable census tracts

Non-5-walkable   5-walkable

Table 3

Type of (non-)k-walkable census tracts and childhood population

Denomination	Has the service?			5-walkable		15-walkable	
	school	playground	park/ garden	census tracts	population 6–16	census tracts	population 6–16
Non-walkable	No	No	No	475	75,411	28	8,985
	No	No	Yes	29	3,216	1	135
	No	Yes	No	598	81,678	21	4,962
	No	Yes	Yes	100	12,840	20	4,893
	Yes	No	No	410	48,867	11	4,977
	Yes	No	Yes	27	2,913	8	1,386
	Yes	Yes	No	675	81,330	532	86,742
Walkable	Yes	Yes	Yes	129	14,364	1,822	208,539

The results shown in Table 3 confirm that in the municipality of Madrid, more than 300,000 (5-minute) and 100,000 (15-minute) children live in census tracts without access to basic services within 5- and 15-minute walking distances, respectively.

A clear spatial pattern emerges from this distribution. In the centre of Madrid, there is a smaller child population, whereas in peripheral neighbourhoods, there are more children. Despite this demographic difference, areas with walkable access within 5 and 15 minutes tended to be situated more prominently in the central areas of Madrid. This can be attributed to the urban characteristics of the city, where streets are more traversable, and services are more concentrated. In these central areas, services such as schools, playgrounds, and parks are more readily available and are clustered together, facilitating easier access within designated walkable distances. Thus, while the outer areas may have a larger child population, the central areas of Madrid offer more access to basic services within the defined walking distances.

The join-count statistics

A clear and expected spatial pattern in the distribution of the dichotomous variables distinguishes each census tract as either k-walkable or non-k-walkable. Table 4 presents the results of joint count statistics. The statistics reject the null hypothesis, indicating a spatial trend in which k-walkable tracts tend to cluster with other k-walkable tracts, and non-k-walkable tracts tend to cluster with other non-k-walkable tracts. For instance, where k=15, the value of JC_{NN} is 1,315; significantly higher than the expected value of 513.66 under spatial random distribution. Similarly, JC_{WW} = 5,181; which is significantly higher than the expected value of 4,426.37. Therefore, around (joined to) k-walkable (resp. non-walkable) census tracks are more likely to find another k-walkable census tract (resp. non-k-walkable). These results confirmed the presence of a spatial structure in a dichotomous variable.

Table 4

Join-count tests for spatial autocorrelation

Denomination	5-walkable				15-walkable			
	JC	expected	variant	z-value	JC	expected	variant	z-value
Non-k-walk: non-k-walk	7,204	7,140.5	710.61	2.38	1,315	513.66	473.3	36.83
K-walk: k-walk	100	22.03	21.84	16.68	5,181	4,426.37	1,908.3	17.27
K-walk: non-k-walk	655	796.48	695.44	–5.36	1,463	3,018.97	1,846.62	–36.21

The spatial probit model

Substantial differences in walkability are associated with socio-economic and demographic factors (Adkins et al. 2017). Most previous studies on the relationship between walkable environments and socio-economic status have been conducted in the North American and Australian contexts, where the spatial distribution of socio-economic groups is more pronounced (Gullón et al. 2017). By contrast, the European context exhibits different development patterns and spatial factors that shape population distribution (Muñoz 2003).

In this subsection, we developed an econometric model to identify the socio-economic factors that determine whether a census tract is walkable in Madrid's urban environment. Considering the spatial structure identified using join-count statistics, a spatial probit model is an appropriate econometric specification (Martinetti–Geniaux 2021). We select a spatial autoregressive probit model (SAR-probit) following De la Llave–López (2024).

The specific SAR probit for the empirical application of our analysis follows equation (1).

$$= \beta_0 + \rho WY^* + \beta_1 \text{DistSol} + \beta_2 \text{Dens} + \beta_3 \text{Income} + \beta_4 \text{Child} + \beta_5 \text{Spanish} + \beta_6 \text{MF} + \varepsilon \quad (1)$$

where Y^* is the binary variable of being a k-walkable census tract, β_h are the coefficients of each explanatory variable, and ρ is the spatial autoregressive parameter. W is the spatial weight matrix that evaluates the contiguity order between the different census tracts. WY^* is the spatial lag that evaluates the fact of having k-walkable census tracts surrounding each analysed census tract. Thus, a significant coefficient indicates a spatial autoregressive structure in the spatial probit model. Figure A3 (see in Appendix) presents the quantile maps for each independent variable.

Table 5 shows the results of the SAR probit model estimated using the maximum likelihood. A strong spatial structure is identified with a positive and significant coefficient. This result confirms the presence of a spatial structure and the correct estimation of the β parameters. This model highlighted the complex interactions between urban characteristics and walkability in Madrid, Canada.

First, proximity to the Puerta del Sol (DistSol), the main public square in downtown Madrid and the most famous and bustling location, emerged as a significant determinant of walkability, reinforcing the role of central urban hubs in promoting pedestrian-friendly environments (Mazumdar et al. 2020, Cao–Duncan 2019). This underlines the importance of central locations in facilitating access to amenities and services and enhancing walkability within the city.

Second, the analysis revealed a moderately significant effect of population density on walkability (Dens). While densely populated areas tend to facilitate shorter walks to amenities, as evidenced by the negative and non-significant coefficients in the 5-walkable model, the positive coefficients in the 15-walkable model highlight the potential challenges of congestion and reduced accessibility over longer distances (Molina-Garcia et al. 2020, Xiao–Wei 2021). This highlights the need for balanced urban planning strategies that consider population density and accessibility.

Table 5

Spatial probit model estimation results

Explanatory variables	5-walkable			15-walkable		
	coeffi-cient	p-value	VIF(†)	coeffi-cient	p-value	VIF(†)
Intercept	–0.953**	0.032**	--	0.641*	0.068	--
Distance to 'Puerta del Sol' (DistSol)	–0.015**	0.033**	1.789	–0.067***	<0.000	1.789
Population density (habitant/m^2) (Dens)	–2.428**	0.029**	1.364	2.139*	0.079	1.364
Income (10^3 euros)	–0.010**	0.022**	1.848	–0.020**	<0.000	1.848
Families with children (%) (Child)	–2.298***	0.003***	1.523	–3.790***	<0.000	1.523
Native Spanish population rate (%) (Spanish)	0.010**	0.010**	1.829	0.018***	<0.000	1.829
Ratio male/female (MF)	–0.247**	0.048**	1.164	–0.664**	0.018	1.164
ρ	0.479***	<0.000	--	0.280***	<0.000	--
Log-likelihood		485.453			1,259.257	
AIC		3.629			1.709	
BIC		50.037			xxx	

Note: VIF(†) (variance inflation factor) indicates the degree of multicollinearity among explanatory variables.

Regarding socio-economic factors, the results indicated that income level (income) plays a significant role in children's access to basic services. The literature offers contrasting evidence of its impact. For example, Arvidsson et al. (2013) provided evidence of a positive relationship, suggesting that areas with higher income levels tend to be more walkable because of better-maintained infrastructure, improved amenities, and greater investment in urban development. In contrast, Cadima–Pinho (2024) argued that wealthier neighbourhoods often follow urban development patterns designed primarily for automobile use, which restrict walking accessibility to schools and parks. Similarly, Smoyer-Tomic et al. (2004) identified high-income areas featuring fewer playgrounds accessible on foot and attributed this to less dense, car-dependent urban forms. In other cases, there is no relationship between walkability and access to basic services is found (e.g. D'Haese et al. 2014 for schools). In Madrid, the spatial probit model yielded a negative coefficient for the income variable, indicating that wealthier neighbourhoods tend to be less walkable because of more dispersed development patterns and greater reliance on automobiles.

Conversely, the negative association between walkability and the percentage of families with children (Child) and walkability underscores the challenges faced by family-oriented households in accessing pedestrian-friendly environments. Research suggests that neighbourhoods with more families and children may prioritise vehicular accessibility over pedestrian infrastructure (Zhang et al. 2022), potentially reducing walkability in these areas. This is consistent with the observation that such families usually reside in the outer areas surrounding city centres.

Lastly, demographic characteristics, such as the male-to-female ratio (MF) and the percentage of the native Spanish population (Spanish), also influence walkability. Undoubtedly, gender leads to differences in walking behaviour (e.g., Clifton–Livi 2005, Golan et al. 2019). In both models in Table 5, the male/female ratio is negative and significant (only 15-walkable model), indicating that a high percentage of women in the census tract increases the probability of the tract being k-walkable. There were several reasons for this finding. Previous research suggests that women are likely to walk in neighbourhoods with certain characteristics, such as new urbanist designs (Clifton–Livi 2005), convenient destinations within walking distance, and high pedestrian walkability scores (Trude et al. 2014). Jensen et al. (2017) concluded that '*complete and walkable streets may attract more people overall and more females in particular*'. Siu et al. (2012) found that older women residing in the city centre were more likely to walk than those living in the periphery, suburban communities, and urban fringes with poor commercial access. The Spanish population (Spanish) presented a positive and significant sign in the spatial probit model, indicating that the national population preferred to live in census tracts where their children had access to basic services. This observation aligns with the research linking ethnicity to walkability (e.g., Conderino et al. 2021).

Marginal effects

Table 6 shows the marginal effects derived from the spatial probit model, with direct and indirect influences on the likelihood of a census tract being classified as either 5-walkable or 15-walkable. Notably, indirect effects account for the impact of each variable's value in neighbouring areas, providing a comprehensive understanding of the spatial dynamics at play.

Population density was the most significant driver of walkability in both models**.** For the 5-walkable model, the direct effect of population density is negative (–0.2233), reflecting that densely populated areas may face challenges such as congestion or reduced accessibility at shorter distances. However, in the 15-walkable model, the direct effect of population density was positive (0.6211), indicating that at larger spatial scales, density fosters accessibility and enhances walkability by ensuring a greater variety of amenities and services within reachable areas. Families with children (Child) also exhibited strong and consistent negative direct effects across both models (–0.2113 in the 5-walkable model and –1.1009 in the 15-walkable model). These findings suggest that neighbourhoods with a higher concentration of families prioritise vehicular access or lack pedestrian-friendly infrastructure, particularly at longer distances.

For indirect effects, the spatial spillover of population density is highly relevant, as shown by the substantial positive indirect effect in the 15-walkable model (0.2411). This underscores the importance of spatial interconnectedness, where dense neighbouring areas contribute to walkability in adjacent tracts by offering shared services and facilities. In the 5-walkable model, however, the indirect effect of population density is negative (–0.2025), further emphasising the challenges of congestion and limited accessibility in compact areas at shorter spatial scales.

Both the male-to-female ratio (MF), both direct and indirect effects were negative for the MF ratio, particularly in the 15-walkable model (–0.1841 direct, –0.0715 indirect). This suggests that areas with a higher male population are less likely to be walkable, possibly reflecting gendered differences in urban mobility needs and preferences, as documented in related studies.

Proximity to the Puerta del Sol (DistSol) was another significant variable. The direct effect is strongly negative in the 15-walkable model (–0.0193), with a smaller indirect effect (–0.0075), indicating that proximity to this urban hub strongly enhances walkability within central areas but has a diminishing influence on neighbouring tracts.

Table 6

Marginal effects for the spatial probit model

Explanatory variables	5-walkable			15-walkable		
	direct	indirect	total	direct	indirect	total
Distance to 'Puerta del Sol'	–0.0014	–0.0012	–0.0026	–0.0193	–0.0075	–0.0268
Population density (habitant/m^2)	–0.2233	–0.2025	–0.4258	0.6211	0.2411	0.8622
Income (10^3 euros)	–0.0009	–0.0008	–0.0018	–0.0057	–0.0022	–0.0079
Families with children (%)	–0.2113	–0.1916	–0.4029	–1.1009	–0.4273	–1.5282
Native Spanish population rate (%)	0.0009	0.0008	0.0018	0.0051	0.0020	0.0071
Ratio male/female	–0.0227	–0.0206	–0.0433	–0.1841	–0.0715	–0.2555

Conclusions

In this study, we analyse walkable accessibility to three essential services for children: schools, parks, and playgrounds for all census tracts in Madrid (Spain). Our study combined an algorithmic approach and spatial models to identify walkable areas and the factors affecting accessibility to these services. First, an algorithm was developed to delineate the maximum walkable area around each census tract. Using this information, we classified each tract as walkable or non-walkable based on whether children could access all three essential services within a 5- or 15-minute walking distance. Next, we employed a spatial probit model to identify the factors associated with children's accessibility to these services, accounting for the spatial structure revealed in the exploratory data analysis.

This study highlights significant differences in accessibility when comparing 5-minute and 15-minute walking distances between children in Madrid. Within a 5-minute walk, there was an average of 0.90 schools, 1.23 playgrounds, and 0.12 parks accessible. In contrast, a 15-minute walk expanded these averages to 8.23 schools, 12.77 playgrounds, and 1.52 parks. Moreover, while central Madrid shows better accessibility within both radii, owing to higher service density and connectivity, peripheral areas face significant limitations. A total of 475 census tracts lacked services within a 5-minute walk, compared to only 28 within a 15-minute radius. These findings underscore the critical role of distance in urban planning and the necessity of enhancing service accessibility, particularly in underserved peripheral regions with higher child populations and car-centric infrastructure.

A spatial probit model identified socio-demographic variables associated with children's accessibility to essential services, accounting for the underlying spatial structure. Peripheral areas, particularly those with a high percentage of families with children and lower income levels, face the greatest accessibility deficits. This highlights the pressing need for equitable planning measures to bridge the gap between central and peripheral neighbourhoods.

Based on these findings, policymakers should prioritise targeted interventions to enhance accessibility for children within the framework of k-minute cities. The stark contrast in service availability within 5-minute and 15-minute walkable distances highlights the need for urban strategies that address spatial inequalities and improve infrastructure in peripheral areas. Central Madrid, with its dense clustering of services, serves as a model for accessibility. Peripheral areas lack walkable infrastructure and access to essential services despite having higher child populations, creating a significant disparity. Policymakers should focus on expanding the distribution of essential services such as schools, playgrounds, and parks to underserved areas through mixed-use development and enhanced pedestrian infrastructure. Additionally, socio-economic factors such as income levels and family demographics significantly influence walkability. Policies should integrate these considerations to ensure equitable access and reduce inequality.

Furthermore, public-private partnerships could be leveraged to encourage investment in child-focused amenities in low-income areas. Investments in safe and pedestrian-friendly infrastructure, such as walkways and child-oriented public spaces, are crucial for bridging these gaps. Improving connectivity between walkable neighbourhoods by addressing spatial autocorrelation could enhance citywide accessibility. By adopting these strategies, policymakers can create more inclusive urban environments that support children's well-being and foster sustainable development.

Finally, this study highlighted the distinct insights offered by the 5-minute and 15-minute walkability models. While a 5-minute walkable city provides greater immediate access, its scope is limited to fewer services and amenities. By contrast, the 15-minute model offers access to a much wider range of services and amenities, including schools, playgrounds, and parks, which are critical for children's social and physical development. This emphasises the value of the 15-minute model as a long-term urban planning tool to promote greater independence and mobility for children while reducing reliance on motorised transport.

Acknowledging the limitations of this study is essential. While this study focuses on accessibility metrics, which are crucial elements in urban planning, this is only one piece of the puzzle. Future research should incorporate a broader range of variables, such as social dynamics, lifestyle preferences, and community amenities, to provide a more comprehensive understanding of children's urban liveability. A holistic approach to urban planning that considers diverse population needs and accommodates different demographic profiles is vital for creating vibrant and inclusive urban environments. Collaboration and innovation are critical for advancing the vision of k-minute cities that prioritise the needs of families and communities and foster sustainable and equitable development.

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Appendix

Figure A1

Spatial distribution of basic services and children population

Child population density (6–16 years old) and service locations

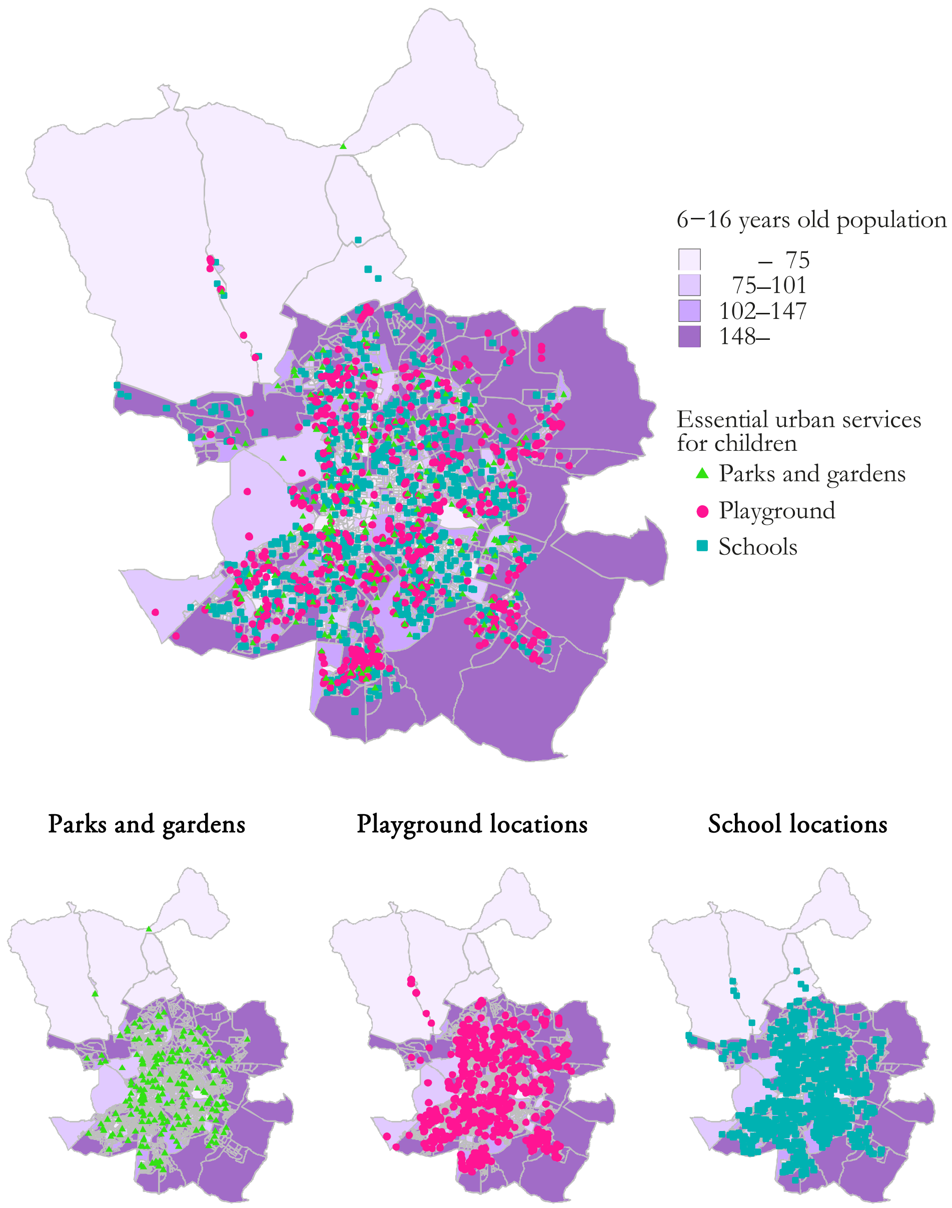
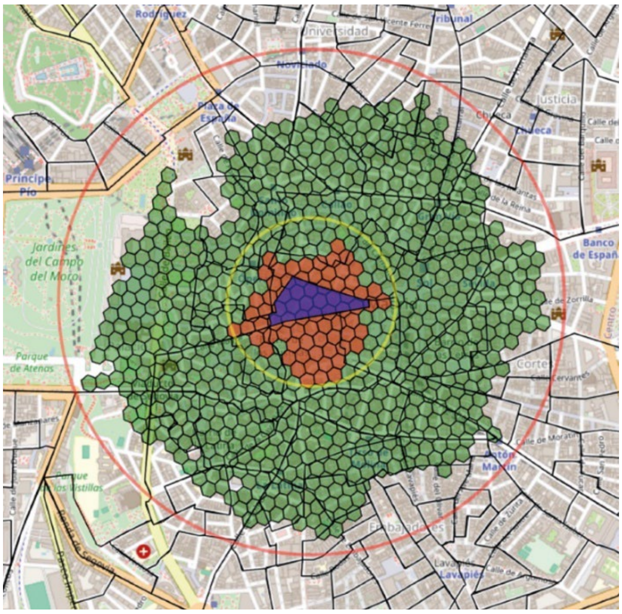


Figure A2

Maximum k-walkable area for two census tracts

Sample a)



Sample b)

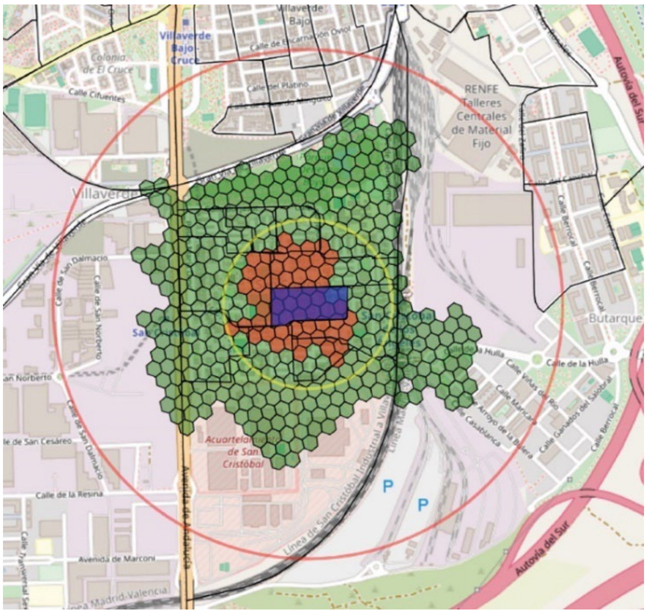


Figure A3

Quantile maps of the independent variables in the spatial probit model

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