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Evaluating the impact of urban design scenarios on walking accessibility: the case of the Madrid ‘Centro’ district.

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ABSTRACT

Walking accessibility planning is seen a powerful approach for moving towards sustainable mobility paradigms; however little attention is paid to determining which factors influence this accessibility and why. This paper addresses this gap between the theory and the practice, and evaluates how far variations in walking accessibility are related to four specific walking needs: attractiveness, comfort, safety, and ease-to-walk. Taking the ‘Centro’ district in Madrid (Spain) as a case study, exploratory scenarios are simulated by altering certain urban design factors for each walking need. Walking accessibility levels are calculated and compared across the exploratory scenarios to gain an insight into how each urban design factor affects walking accessibility. The results show a similar spatial pattern of accessibility for the four walking needs, with higher accessibility values in the north than in the south due to the greater density of destinations. Urban factors related to attractiveness and comfort are found to produce the most significant variations in walking accessibility. The paper concludes with a discussion on the practical usefulness of the findings, particularly in terms of prioritising urban design policies that increase walking accessibility levels.

Introduction

Accessibility planning is considered key for balancing the needs of today’s mobile society with sustainable planning outcomes (Bertolini, 2017), an approach that has led to conceptual and methodological innovations in accessibility analysis in recent decades (Straatemeier & Bertolini, 2008; van Wee, 2016). Although accessibility has commonly been conceived as a function of the availability of opportunities dependent on transportation supply (Bocarejo et al., 2014), this conceptualisation gives an incomplete picture. For example, route choice using a specific transport mode varies between users (Morency et al., 2011), and is shaped by factors such as individual preferences, physical constraints, route attractiveness, safety and comfort issues and others (Pereira et al., 2017). This highlights the limitation of considering accessibility standards as universal prescriptions for society as a whole. In particular, little attention is given to how urban design affects accessibility levels (Páez et al., 2012). The case of walking accessibility – as a universal transport mode – to major destinations is a case in point, in which urban design plays a decisive role in increasing (or not) accessibility for everyone (Arranz-López et al., 2019a).

Previous research on accessibility has increasingly recognised the need to actively promote walking accessibility (Millward et al., 2013). Some benefits of walking accessibility have been previously documented, such as clean air, less use of space than motorised modes (Tight, 2016), and its health benefits (Giles-Corti et al., 2016). Individual willingness to reach opportunities on foot depends on individual preferences, which are shaped by socio-economic characteristics, cultural norms and urban design factors. In the context of this research, urban design factors refer to specific aspects of street design (e.g. tree density, space occupied by each transport mode, pavement width, slope, etc.)

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that make walking itineraries more or less friendly and usable for pedestrians. These factors have been classified by academics into four main walking needs, which act as a key determinant of walking accessibility (Talavera-García & Soria-Lara, 2015): attractiveness, comfort, safety and ease-to-walk[1]. Attractiveness is understood as the potential of street design to create socialization environments while walking, including pedestrians' capacity to interact with retail activity and the cultural offer along walking routes (Gehl, 1971; Peters, 1981; Salingaros et al., 2005; Venturi et al., 1977). Comfort covers a wide range of urban design factors that make walking trips friendly, such as protection from weather conditions (Nikolopoulou & Lykoudis, 2006; Stathopoulos et al., 2004) and shade from trees (Jacobs, 1993; Delclòs-Alió & Miralles-Guasch, 2018). The third walking need is safety, in the form of urban design factors that produce a feeling of security in pedestrians, such as lighting, safe intersection design with motorised modes, etc. (Landis et al., 2001; Young, 2007). Finally, the ease-to-walk walking need refers to urban factors deriving from the street design in terms of the ability to access destinations, such as distances to the main locations, pavement type, pavement width, networked walking infrastructures, etc. (Delclòs-Alió & Miralles-Guasch, 2018; Vale et al., 2016).

While there is a prominent group of studies analysing how individual preferences affect levels of walking accessibility to major destinations (Arranz-López et al., 2019b; Morency et al., 2011; Lucas et al., 2016; Bibina et al., 2020), little attention has been focused on understanding how urban design factors modify walking accessibility and their effects on potential users. Some key points are: (i) there may be numerous urban design factors, which increases the need for research to identify which factors are essential and which are not, and why (Valenzuela-Montes & Talavera-García, 2015); (ii) it is unclear how individual preferences interact with urban design factors, creating a subjective notion of preferences for certain walking routes that can vary across geographies and contexts; and (iii) there is a lack of experimentation in designing exploratory scenarios in which urban design factors are drastically varied in order to determine their relevance for policy-making. If these barriers persist, the study of walking accessibility will focus mainly on analysing individual factors affecting the willingness to walk, whereas by overcoming these barriers we can obtain key findings as to how urban planners can alter walking accessibility by making decisions on urban design factors.

To gain insights into these issues, this paper aims to evaluate how walking accessibility levels vary with the application of urban design measures, considering the four walking needs: attractiveness, comfort, safety, and ease-to-walk. The empirical focus is the 'Centro' district in Madrid, Spain, where a wide range of exploratory scenarios are simulated and assessed using the concept of street walking quality (Ortega et al., 2020a). The methodology used to achieve our goal is based on calculating the walking accessibility levels in these exploratory scenarios using Geographic Information Systems (GIS). The built environment of the 'Centro' district is modified in each scenario to simulate interventions in urban design factors aimed at improving walking quality. We hypothesise that these improvements lead to greater street walking quality and enhance walking accessibility. These scenarios do not constitute real templates for implementation by practitioners, but are intended to offer a set of hypothetical situations to explore the influence of walking needs on accessibility values. The results serve as a starting point for analysing how interventions on specific urban factors can influence walking accessibility, and are a valuable instrument for urban design planners in an exploratory and open analytical approach, while providing evidence-based geographically-dimensioned information to prioritise actions for improving active mobility in the case study.

This paper is structured as follows. This introduction section presents our research framework, identifies the research gap and formulates the objectives of the paper, while the following section describes previous studies on how urban design factors affect walking accessibility levels. In the third section, we present the case study: the 'Centro' district in Madrid. The fourth section outlines the methodology designed to assess the improvement in walking accessibility when the street walking quality is enhanced by changing certain urban design factors. The fifth section contains the results of applying the assessment, and the last section describes the most important findings, limitations and the final conclusions of this paper in terms of the objectives formulated, and offers some recommendations for future research studies.

Literature review

Academic literature is increasingly set on obtaining a better understanding of how to achieve more efficient walking accessibility to major destinations (Fransen et al., 2019; Tight, 2016). Greater levels of walking accessibility affect decarbonisation programmes (Givoni and Banister, 2013), health issues (Giles-Corti et al., 2016) and local businesses (Arranz-López et al., 2019a; Lee et al., 2017), among others. This section explores this notion by examining previous studies on how different walking needs – namely attractiveness, comfort, safety and ease-to-walk – influence accessibility. These needs were chosen for several reasons: (i) they include urban design factors that had previously been reported by the academic literature and offer an excellent framework for obtaining comparable results with earlier studies (Alphonzo, 2005; Valenzuela-Montes & Talavera-García, 2015; Talavera-García & Soria-Lara, 2015); and (ii) they comprehensively cover a wide range of urban design factors that influence walking accessibility. It is worth mentioning that another classification of walking needs would be also possible, but the classification in this research combines urban design factors that previously worked well to offer a better understanding of how walking accessibility operates at the urban level.

Attractiveness is the first walking need described, and refers to the potential of street design to create socialisation environments while walking. Giles-Corti et al. (2005) demonstrated how attractiveness was a key issue for designing public open spaces that are highly usable by pedestrians by comparing three pairs of pedestrian places with high and low attractiveness. In the same line, Yoo and Kim (2017) assessed the influence of attractiveness in pedestrians' use of public space by means of 90 walking tours, semi-structured interviews and qualitative mapping, and determined that attractiveness and social interaction were key parameters for walking and physical activity. In other research, Mirzaei et al. (2018) collected data from 863 respondents in six diverse neighbourhoods in Isfahan, Iran, and showed that a place's attractiveness was a relevant factor for walking activity. Cysek-Pawlak and Pabich (2020) also demonstrated the close relationship between attractiveness and walking activity in the context of commercial areas in Carré de Soie, France.

The second walking need to be addressed is safety, which refers to urban design factors that create a feeling of security in pedestrians, such as lighting, safe design of intersections with motorised modes, etc. The relationship between walking and safety is widely recognised in the existing literature. Buehler and Pucher (2021) compared pedestrian fatality rates in USA, UK, Germany, the Netherlands and Denmark for the period 1990-2018 and concluded that traffic speed limits and high-quality pedestrian infrastructure are key to avoiding fatalities. According to Debnath et al. (2021), the way pedestrians experience and use streets and roads is key for understanding the relationship between safety and walking. Sealens and Handy (2008) also showed how the feeling of personal safety is crucial for increasing levels of non-motorised activity. Another example is seen in Pucher and Dijkstra (2003), who determined that urban design in American cities creates a greater

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[1] In this study, the term "ease-to-walk" is used to denote the so-called "accessibility" walking need. We reserve the term "accessibility" to refer to pedestrians' possibility of reaching potential destinations, while the "ease-to-walk" walking need is related to urban design factors such as pavement type, pavement width or slope; that is, factors that facilitate or hinder the action of walking.

likelihood of accidents for pedestrians than in European cities.

The third walking need analysed is comfort, which refers to providing pedestrian-friendly walking routes and environments (Nikolopoulou & Lykoudis, 2006); this involves designing of pedestrian itineraries in which pedestrians feel comfortable, and ensuring that these itineraries protect pedestrians from weather, are attractive for socialisation, etc. For example, Zou et al. (2020) demonstrated the importance of weather conditions for non-motorised mobility – particularly walking – through big-data modelling. Rahman and Nahiduzzaman (2019) also highlighted the importance of both weather and tree location for walking activities in making walking routes friendlier and more usable.

The fourth factor impacting on walking accessibility is ease-to-walk, which concerns aspects such as pavement width, slope, intersection distances, etc. For example, Soria-Lara et al. (2015) analysed how distances between motorised transport intersections strongly affect walking mobility environments in Granada, Spain. Another example can be found in Delclòs-Alió and Miralles-Guasch (2016), who explored how street connectivity and obstacles were key aspects for walking accessibility levels in compact cities, with a practical application to Barcelona, Spain. Finally, Vale et al. (2016) analysed how ease-to-walk factors were critical for determining variations in walking accessibility to major destinations.

Another large body of work in the literature measures the walkability of an area according to its urban factors. Walkability can be understood as “the extent to which characteristics of the built environment and land use may or may not be conducive to residents in the area walking for either leisure, exercise or recreation, to access services, or to travel to work” (Leslie et al., 2007). For example, the widely used WalkScore® (Duncan et al., 2013; Knight et al., 2018) measures the walkable access to daily amenities with a score from 0 to 100 (100 equals maximum walkability). The method analyses hundreds of walking routes to amenities, and measures pedestrian-friendliness considering population density and road metrics. Taleai and Taheri Amiri (2017) developed a spatial group multi-criteria method based on a range of urban planning indices to evaluate and rank the walkability of pathways at street level in Teheran, using available 2D-GIS data, 3D analysis and multi-criteria evaluation (MCE) tools. In the Spanish context, in Madrid, Gullón et al. (2015) assessed the walking environments in three neighbourhoods in Madrid, taking into account the walking surface, street characteristics, permeability, safety, streetscape, views and facilities. Gullón et al. (2017) measured walkability in the municipality of Madrid using a composite index of four indicators: residential density, population density, retail destinations and street connectivity. Al Shammas and Escobar (2019) proposed a GIS-based walkability index for the city of Madrid which considers the comfort-related aspects of walkability, namely noise, sun/shade, and other aspects such as population density, diversity of business activities and connectivity. Ortega et al. (2020a) created four street walking quality maps of the ‘Centro’ district in Madrid based on the four urban design factors in this research, and classified them from least to most walkable according to the four walking needs: attractiveness, comfort, safety and ease-to-walk. The recent work of Carpio-Pinedo et al. (2021) mapped the potential for walkable trips in the Madrid Region based on micro land-use data and route network analysis.

In all the above-referenced works, GIS constitute essential tools to quantify walkability, thanks to their efficiency for managing and exploring the relationships among the built characteristics stored in the geospatial data (for example land use and street network data, environmental audits, commercial databases, etc.) (Buttler et al., 2011). Furthermore, the core meaning of walkability also included facilitating and encouraging walking by providing attractive routes, destinations, and functional paths (Fitzsimons D’Arcy, 2013), and GIS network analysis has been widely used to calculate, model and examine walking routes (Delso et al., 2018, Delso et al., 2019, Carpio-Pinedo et al., 2021).

Based on the review, it can be concluded that there is a rich body of literature confirming that certain urban design factors and walking needs play a significant role in walking accessibility. There is also an extensive literature on measuring walkability and street walking quality in urban environments using aggregated indicators. However, only a limited number of studies analyse the degree to which urban design factors and walking needs alter walking accessibility levels, although this kind of study would be highly valuable for supporting decision-making. This is the real distinctiveness of this research: the capacity to explore empirically how far the urban design factors in the four groups of walking needs originate variations in walking accessibility, and why. In this respect, the outcomes obtained are particularly useful for policy-makers and urban planners during the decision-making process.

Case study description: the Madrid ‘Centro’ district

The case study is the so-called ‘Centro’ district of Madrid, Spain (Figure 1). This is a densely populated area, home to roughly 15% of the city’s 6.6 million inhabitants (Instituto de Estadística de la Comunidad de Madrid, 2019). Due to its social and economic weight, its mobility policy strategies are of crucial importance in the Madrid Region as a whole. Pedestrian mobility in the case study is of particular interest, since the main objectives of several municipal policies such as the air quality and climate change plan for the city of Madrid (Plan A, (Ayuntamiento de Madrid, 2016) and its redesign Madrid 360 (Ayuntamiento de Madrid, 2019a) include improving the public space for pedestrians. Plan A was launched in 2016 as part of the Sustainable Urban Development Strategy, with the aim of ensuring air quality for Madrid’s inhabitants and preparing the city for the effects of climate change. The main objective is to consolidate a low-emissions city in the long term – by 2030 – in a complex urban system that combines mobility, urban development, and the management of energy and resources. Ultimately, the choice of central Madrid is not random but highly appropriate, since the area is facing key challenges such as the massive influx of tourists – where the Airbnb platform plays a significant role in facilitating and lowering the cost of accommodation, thus increasing the number of visitors – and an increasingly ageing population, both of which influence pedestrian mobility.

Although the population in the city centre has fallen in the same period (from 143,908 to 134,881), the percentage of over 65s has remained almost constant (from 16.02% to 16.05%), while the 0-15 and 16-64 age ranges have declined. The average income is below the city average (32,456 for the ‘Centro’ district and 39,613 for the city as a whole). It is interesting to note that the level of sedentarism is well below the city average: 26.9% vs 30.0%, and this is one of the districts in Madrid’s inner ring that is least concerned about air quality and traffic congestion.

According to Comunidad de Madrid (2020), there are 9,927 building entrances in the ‘Centro’ district (Figure 1). Almost 50% of the population of the district are tourists (45.7%), and according to Inside Airbnb, for every 100 residents in the Sol quarter – the city’s most popular destination with tourists – there are 65.96 Airbnb beds (Ayuntamiento de Madrid, 2017a). In 2019, data from the municipality of Madrid shows that of the 11,756 homes for use by tourists, 7,177 are located in this district. This massive *touristification* is provoking a replacement (or loss) of the population living in the centre, which at the very least is endangering the district’s distinctive character. Likewise, the centre of Madrid attracts the greatest volume of international spending (23.9%) and a large number of retail outlets and other services (see Figure 1). According to Ayuntamiento de Madrid (2021), in the whole ‘Centro’ district there are 11,160 establishment entrances, which account for 10% of the total in Madrid. Of these, 4,354 are retail outlets (8%), 229 hotels (10%), and 3,239 restaurant businesses (6%). Other geodatabase data sources (OSM Contributors, 2018) show 1,461 points representing food stores, retail outlets, bank branches and education facilities (Figure 1), which account for the highest percentages in the whole city, indicating that the city centre district is the densest in terms of retailers and restaurant venues and has the most vibrant commercial

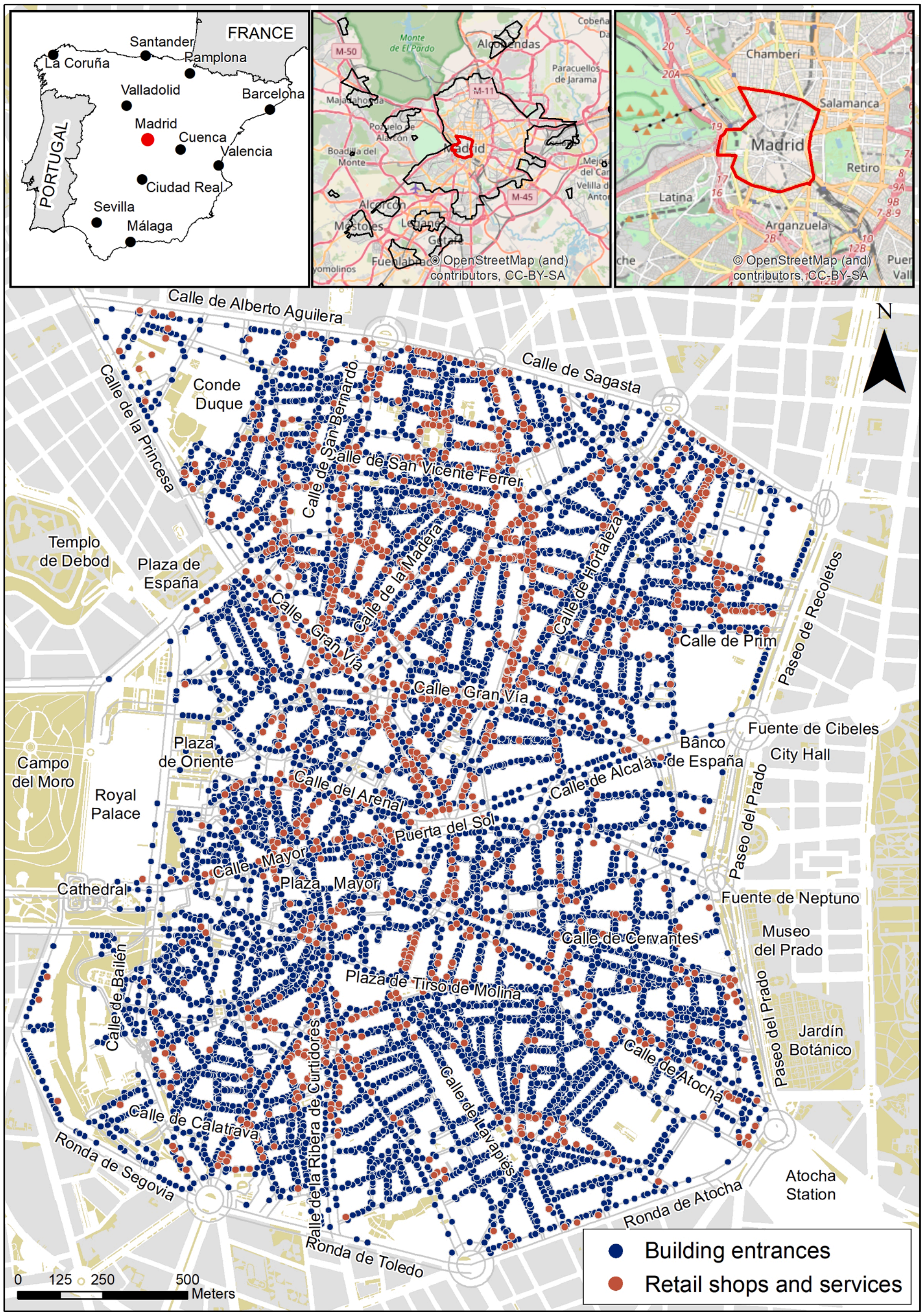

Figure 1. Location of the 'Centro' district in Madrid, building entrances and retail outlets and other services considered in walking accessibility calculations.

activity.

The ratio of jobs per inhabitant in the 'Centro' district is also very high compared to the rest of the region, as it contains 29% of the workplaces of the region's residents, which is a high ratio to be considered when planning mobility policies in both the city and the region. In terms of mobility patterns, 40% of the trips in the 'Centro' district are completed on foot, a substantial modal share compared to other European cities (CRTM, 2019; EMTA, 2019).

Methods

Changes in urban design factors – street-related features that make walking itineraries more or less friendly and usable for pedestrians – imply an improvement in street walking quality and hence an improvement in walking accessibility. Figure 2 outlines the proposed approach, consisting of three main stages which are described in detail in the following subsections. In the first step (Stage 1), some of the urban design factors in the street sections[2] are modified while the others remain unaltered in order to generate several exploratory scenarios (ES). These scenarios allow an analysis of the variations in walking accessibility due to the increase in the street walking quality as a consequence of the changes in urban design factors. Reference scenarios (RS) are also

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[2] The streets are divided when they are intersected by another street, so we consider street sections instead of streets.

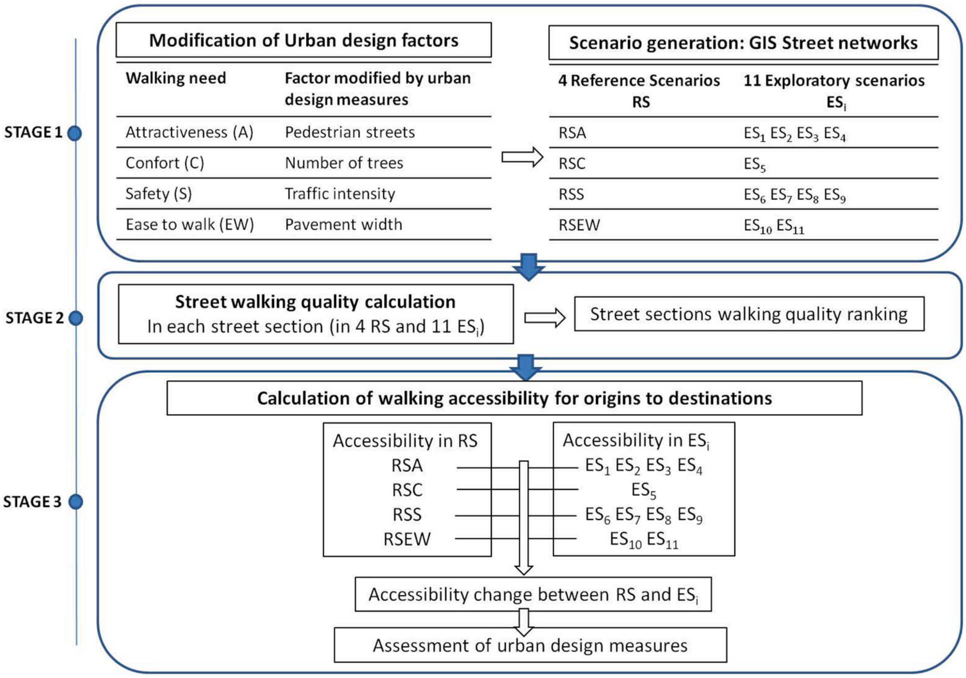

Figure 2. Outline of the methodology

created to assess the effectiveness of these changes, related to each of the four walking needs (attractiveness (A), comfort (C), safety (S) and ease-to-walk (EW)). This stage also includes the implementation of the street network geodatabase. In the next step (Stage 2), the street sections are ranked from least to most walkable to define the street walking quality for each of the reference and exploratory scenarios, from the values for all the urban design factors – both modified and unaltered – defined in Stage 1. Finally in Stage 3, the accessibility is calculated from each origin to the destinations. The cost of reaching the destinations considers the walking travel time using the street network, weighted by the street walking quality value computed in Stage 2. The accessibility is calculated for the set of exploratory scenarios and for the reference scenarios created in Stage 1. The comparison of the accessibility values permits the effectiveness of the urban design measures to be assessed in terms of the improvement in accessibility. The assessment compares scenarios in relative terms. The accessibility values of the reference scenario for each walking need are compared with the accessibility values of the exploratory scenarios for the walking need.

Stage 1. Modification of the urban design factors and generation of scenarios

The exploratory accessibility scenarios are designed to analyse the variations in walking accessibility in subsequent stages after undertaking actions in a single urban design factor, while the rest remain unaltered. This decision was taken to isolate the effects of each intervention and facilitate a further discussion of the results, and to serve as starting point for understanding how interventions on specific factors can influence walking mobility.

The selection of the design factors to be altered is based on the following rationale. Talavera-García and Soria-Lara (2015) identified 48 relevant pedestrian urban design factors from the literature on active mobility and built environment. They grouped them according to four categories of walking needs: attractiveness, comfort, safety and ease-to-walk; i.e. (i) attractiveness, linked to the opportunity for social interaction and participation in various activities along the streets; (ii) comfort, which ensures pedestrian-friendly walking routes and environments and includes factors ranging from weather to the presence of trees; (iii) safety, related to factors that make pedestrians feel safe, such as fences or traffic management; and finally (iv) ease-to-walk, based on the physical difficulty pedestrians encounter to walk, comprising aspects such as pavement width, slope and intersection distances. Ortega et al. (2020a) selected a set of urban design factors for the ‘Centro’ district in Madrid (Spain) that can be spatially represented (see Table 1) from the factors proposed by Talavera-García and Soria-Lara (2015).

In this set of urban design factors, shade, building height, street width, slope and intersection distance cannot be modified. In the case of green, facilities, public spaces, amenities and art, urban planners have a limited capacity to change these elements owing to urban space limitations or because they do not depend directly on the planners. The factors that can be modified by urban planners are therefore: public transport, pedestrian streets, furniture, noise, trees, fences, traffic intensity, vehicle on-street parking, traffic management, pavement width and obstacles. However, the results of a survey of a 1,297 people carried out as part of a research project in the study area in 2018 show that the main factors when choosing a walking route are: trees, pavement maintenance, pavement width, traffic intensity and obstacles. In the same survey, the interviewees stated their dissatisfaction with these same factors when choosing to walk. For this group of factors, no data on pavement maintenance are available, and obstacles are furniture, which is considered positive. Hence pedestrian street, trees, pavement width and traffic intensity were selected as relevant urban design factors to be modified to generate the exploratory scenarios.

Two groups of scenarios are defined: i) the first group consists of the reference scenarios, which consider the current street urban design factors. Four scenarios are created, one for each walking need, entitled: RSA (attractiveness-related reference scenario), RSC (comfort-related reference scenario), RSS (safety-related reference scenario), and RSEW (ease-to-walk-related reference scenario). Each reference scenario is developed considering its corresponding factors, shown in Table 1. A second group contains the exploratory scenarios (*ES*), which include the modifications to the four urban design factors detailed above (street, trees, pavement width and traffic intensity), while the other factors remain unchanged as described below. The development of these scenarios involves modifying the current street structure in the study area in a GIS environment. The values for the factors in each street section –

Table 1

Factors and indicators grouped by walking need selected by Ortega et al. (2020a) from the factors proposed by Talavera García and Soria-Lara (2015). The table also shows the weight values α assigned to each factor according to its importance (see next subsection); and in italics, the urban design factors selected as relevant for generating the exploratory scenarios in this study.

Walking needs											
Attractiveness			Comfort			Safety			Ease-to-walk		
Factor	Indicator	α value	Factor	Indicator	α value	Factor	Indicator	α value	Factor	Indicator	α value
Green	Green area	4.3	Shade	Street aspect	3.7	Fence	Line formed by the bollards	2.1	Slope	Mean slope	4.0
Public transport	Number of bus and underground stations	2.3	Noise	Level of noise	3.8	*Traffic intensity*	Average traffic intensity	4.2	*Pavement width*	Pavement width	3.4
Facilities	Number of food stores, commercial establishments, restaurants or similar establishments	3.4	Building height	Mean building height	2.3	Vehicle parking	Areas allocated for car parking	2.3	Obstacles	Number of furniture elements (bus shelters, underground accesses, permanent constructions, etc.)	4.3
Pedestrian street	Pedestrian street	4.3	*Trees*	Number of trees	4.3	Traffic management	Number of pedestrian traffic lights	3.2	Intersection distance	Number of street intersections	3.5
Furniture	Number of furniture elements (bus shelters, underground accesses, permanent pavement constructions, etc.)	2.6	Street width	Mean street width	3.3						
Public spaces	Number of hospitals, police stations, etc.	2.2									
Amenities	Number of playgrounds, museums, libraries, cinemas, etc.	2.9									
Art	Monuments and fountains	3.2									

which are used in Stage 2 to compute the street-walking quality and weight the travel time for the accessibility calculations in Stage 3 – are calculated using the indicators in Table 1, according to the methodology developed in Ortega et al. (2020a).

Attractiveness: pedestrian street

In this case, four exploratory scenarios are simulated (ES_1, ES_2, ES_3 and ES_4), each involving an increase in the number of pedestrianised street sections according to the criteria below. In all of them, the existing pedestrian streets are maintained.

- Low pedestrianisation scenario (ES_1). Street sections with a width of > 10 m and high commercial activity are pedestrianised. It has been considered that streets with high commercial activity are in the third tercile in terms of the number of commercial establishments. To preserve the continuity of the streets for motorised transport, the minimum number of potential street sections to pedestrianise have been added or eliminated. This scenario involves the pedestrianisation of 141 street sections, approximately 15,700 m in length.
- Mid pedestrianisation scenario (ES_2). Street sections with very low traffic levels (1 over 5) (see Ortega et al. (2020a) for details of the definition of traffic levels) and < 7.5 m in width are pedestrianised. To preserve the continuity of the streets for motorised transport, the minimum number of potential street sections to pedestrianise have been added or eliminated. This scenario involves the pedestrianisation of 276 street sections, approximately 29,700 m in length.
- High pedestrianisation scenario (ES_3). Street sections ≤ 7.5 m are pedestrianised. This scenario involves the pedestrianisation of 301 street sections, approximately 31,800 m in length.
- Very high pedestrianisation scenario (ES_4). Street sections with a very low traffic level (1 over 5) are pedestrianised. This scenario involves the pedestrianisation of 474 street sections, approximately 52,900 m in length.

Comfort: trees on the streets

One exploratory scenario (ES_5) is based on the guidelines for the design of the public thoroughfare in the Madrid municipality (Ayuntamiento de Madrid, 2000), a set of mandatory and non-mandatory rules for designing the public space in large areas of the city and in its streets. The guidelines advise on the number of trees and the distance between them according to the street characteristics. ES_5 was defined based on these recommendations, with the following criteria: (i) for street sections with a width of 4.5 m or less, the number of trees does not change. Most of these streets currently have no trees, and planting trees on these streets would consume the walking space; (ii) for street sections ranging from 4.5 to 10 m in width, a small top tree is placed every 5 m, but only on one pavement; (iii) for street sections wider than 10 m, a medium top tree is placed every 7 m on both pavements; and (iv) if the number of existing trees is higher than the number of trees under the previous criteria, the amount remains unchanged.

The increase therefore affects 758 street sections.

Safety: traffic intensity

In this case, four exploratory scenarios are created (ES_6, ES_7, ES_8 and ES_9), each assuming a decrease in the current traffic. The percentages of reductions in traffic are 5% (ES_6), 10% (ES_7), 15% (ES_8) and 20% (ES_9), which were estimated based on the experiences of the main pricing schemes in Europe – London, Stockholm and Milan –, where traffic reductions of up to 20% have been achieved over the years (Croci, 2016).

Current average traffic intensity was extracted from the historical data provided by Madrid City Council in its SICTRAM database (Sistema Integral de Control de Tráfico de Madrid) (Ayuntamiento de Madrid, 2019b). Intensity values (vehicles/hour) are measured at 221 measurement points in 97 streets. The average monthly value (May) was calculated for each point. The traffic intensity data were reclassified into five quantile classes, and the rest of the street sections were assigned the value of the nearest street with a similar traffic intensity value and characteristics in terms of street width and noise.

In the streets where the SICTRAM database was used, traffic is reduced by the corresponding percentage. The traffic reduction is checked against the five current quantile classes, and (i) if the values do not change to the next lowest quintile class, the street section is kept in its current class; (ii) if the values change to the next lowest quintile class, the new quintile class is assigned to the street section; iii) the street sections closest to those that have changed are checked and changed manually; and (iv) in the street sections with no traffic data from the SICTRAM database and which have not been changed manually, the same value is assigned as in the current situation.

Ease-to-walk: pavement width

Two exploratory scenarios are created (ES_{10} and ES_{11}) for the ease-to-walk walking need, each assuming an increase in pavement width. The scenarios were generated according to the following criteria:

- In scenario ES_{10} the pavement width is increased as follows: (i) if the street section width is $\geq$ 10 m, then the pavement will equal the street width x 0.26[3] to allow different types of pedestrians to circulate simultaneously (e.g. disabled people, people walking in groups, etc.) (Soria-Lara, 2011); (ii) if the street section width is $\geq$ 7.5 and $<$ 10 m, then the pavement will equal 2.5 m (minimum value), as this width guarantees that two pedestrian can simultaneously use the pavement (Soria-Lara, 2011); (iii) if the street section width is $<$ 7.5 m, then the pavement will be equal to the street width minus 2.5 m – to allow traffic to flow –, and divided by 2 – one half for each pavement; (iv) in the case of a pedestrian street, the pavement width is the same as the street width; and (v) if the current pavement width is more than the pavement width according to the previous criteria, or if it is widened by less than 0.5 m (this value is considered the minimum to make the expansion worthwhile), the pavement width remains the same. This scenario means an increase in the pavement width for 296 street sections, a length of around 45,000 m.
- In scenario ES_{11} the pavement width is increased as follows: (i) if the street section width is $\geq$ 10 m, the pavement will equal the street width x 0.26; (ii) if the street width is $\geq$ 7.5 and $<$ 10 m, then the pavement will equal 2.5 m; (iii) if the street section width is $<$ 7.5 m, then the pavement will be 2.5 m (this means that some streets do not allow traffic flow, only motorbikes and bicycles); (iv) in the case of pedestrian streets, the pavement width is the same as the street width; and (v) if the pavement width is greater than the pavement width according to the previous criteria, or if it is widened by less than 0.5 m, it remains the same. This scenario represents an increase in the pavement width for 409 street sections, a length of 56,100 m.

This stage also includes the implementation of the street network geodatabase (Table 2). The street network is a linear layer representing the street pavement, created from a street axes network (Instituto de Estadística de la Comunidad de Madrid, 2018) by editing and using GIS capabilities. The attributes of the pavement in each street section are its length, average walking speed considered as 1.1 m/s (Gates et al., 2006; Knoblauch et al., 2007; Ortega et al., 2015), and walking travel time, which takes into account the waiting time at pedestrian crossings and traffic lights. Adapting data from Ortega et al. (2015), 3 s and 6 s were considered at pedestrian crossings located in low- and high-traffic streets respectively, and 46 s at traffic lights. This geodatabase also includes the values for the urban design factors in each street section for the 15 scenarios considered.

The origins of the walking trips are the building entrances in the district, which constitute a geodatabase of 9,927 points (Comunidad de Madrid, 2020). The destinations are food stores, retail outlets and other services (bank branches and education facilities), in a geodatabase of 1, 461 points (OSM Contributors, 2018). The built environment characteristics and the street network were obtained from the databases of the Madrid Municipality (Ayuntamiento de Madrid, 2017b) and OpenStreetMaps (OSM Contributors, 2018).

Table 2
Main characteristics of the geodatabases

Database	Description	Source
Madrid Centro street network	Geodatabase of polylines representing street pavement and attributes relevant for scenario generation	Instituto de Estadística de la Comunidad de Madrid, 2018
Origins of walking trips	Geodatabase of 9927 points corresponding to building entrances in the district	Comunidad de Madrid, 2020
Destinations of walking trips	Geodatabase of 1461 points representing food shops, retail outlets, bank branches and education facilities	OSM Contributors, 2018

Stage 2. Definition of street walking quality

In this stage the street walking quality is computed for each street section in the 4 reference scenarios and 11 exploratory scenarios defined. This value will be used to weight the travel time for the streets. The street sections are classified from least to most walkable to define their street walking quality. After obtaining all the values for the factors in the reference and exploratory scenarios in Stage 1, they are then aggregated, and each street section is assigned a value for each of the four walking needs.

We performed a weighted sum method, which is the most widely used method for tackling spatial multiattribute decision making (Malczewski, 1999). This multi-attribute decision technique aggregates multiple attributes, assigning a score to each feature based on the attribute values and a weight based on its relative importance (e.g. Ren et al., 2017; Sojobi et al., 2021). The higher the score, the more suitable the feature. The following equation is used:

$$W_k = \sum_{i=1} \alpha_i f_i \tag{1}$$

Where:

W_k is the walkability value in each street section k. α_i is a weight value ($\alpha = 1$ to 5, and $i = 1$ to the number of factors in each walking need); and f_i is the value of the urban design factor in each street ($i = 1$ to the number of factors in each walking need) from 0 to 1, and calculated as follows.

Before applying the equation, the values of the factors were converted to the same scale so all the values have a score of between 0 and 1, according to Equation 2:

$$f_i = \frac{R_i - R_{min}}{R_{max} - R_{min}} \tag{2}$$

Where R represents the value of indicator f_i in its units.

In order to reduce the influence of non-representative extreme values, the range ($R_{max} - R_{min}$) for facilities, art, building height, trees, street width, vehicle parking, slope, pavement width and intersection distance were calculated excluding the outlier values, which were computed following the interquartile range method.

In the case of noise, traffic intensity, slope and obstacles, the value introduced in Equation 1 is equal to $1 - f_i$, as high values of these indicators imply reduced walkability.

The α values were obtained from a survey of 12 transport planning experts. The experts were asked to indicate a relative weighting value

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[3] This facilitates a balanced between the space reserved to motorised and non-motorised modes in small streets, which is relevant for the urban configuration of the case study.

from 0 to 5 for the different factors belonging to each of the 4 walking needs, with the aim to identifying which factors are considered most important when choosing a specific walking route. The final α value for each factor is the statistical average for the set of answers. The α values are listed in Table 1.

The values from Equation 1 were then converted to a scale of 0 to 1 according to Equation 2, but with the maximum value, 1, assigned to the lowest value and 0 to the highest. This value is used to weight the travel time for the streets.

This calculation process – the weighting factor of the street sections according to their street walking quality – is repeated for each of the 11 exploratory scenarios (*ES_i)* and for the reference scenarios (*RSA, RSC, RSS* and *RSEW*).

Stage 3. Walking accessibility calculations

For the accessibility calculations, extensive reviews of accessibility indicators can be found in Reggiani (1998) and Geurs & Ritsema van Eck (2001), among others. We selected a potential indicator used in many previous studies (Gutiérrez et al., 2011; Monzón et al., 2013; Ortega et al., 2020b). Potential indicators calculate the destinations that can be reached, discounted by a negative function of the effort required to reach them (Vulevic, 2016), and are formulated as follows (Equation 3). A higher value indicates a higher accessibility from a location.

$$Acc_i = \sum_{j-1} \frac{D_j}{C_{ij}} \tag{3}$$

The accessibility Acc_i is calculated for each of the 9927 origins *i* to destinations *j*. The destinations *j* considered are less than 15 minutes' walk (from the origin *i*) from the set of 1461 total destinations. Since there are no available data to rank the destinations, they are all considered to have the same attractiveness, hence D_j is equal to 1. C_{ij} is the cost from origin i to destination j, i.e. the walking travel time using the street network considering the street walking quality value described in Section 4.2. The accessibility calculations were made using the O-D cost matrix function, available in the ArcGIS 10.X network analyst tool. This tool gives the C_{ij} values as the minimum cost path from the street network arc cost, which includes the walking travel time needed to walk along it, weighted by the street walking quality value.

A unique value of accessibility A_{ESi} is calculated as the average value according to Equation 4, where Acc_i is accessibility for each of the 9927 origins *i* to destinations *j* calculated in Equation 3:

$$A_{ESi} = \frac{\sum_i Acc_i}{i} \tag{4}$$

The accessibility calculation Equations 3 and (4) is performed for each of the 11 exploratory scenarios and for the reference scenarios (A_{RSA}, A_{RSC}, A_{RSS} and A_{RSEW}), in which the urban design factors remain unchanged. The same set of origins and destinations (Figure 1) is considered in each scenario.

The assessment is performed by comparing scenarios: the four reference scenarios with the current street walking quality (*RSA, RSC, RSS* and *RSEW*) vs. the 11 exploratory scenarios (*ES_i)*, i.e. RSA vs. ES_1, ES_2, ES_3 and ES_4; RSC vs. ES_5; RSS vs. ES_6, ES_7, ES_8 and ES_9; RSEW vs. ES_{10} and ES_{11}. By comparing the indicator values, the effectiveness of a measure can be assessed in terms of the improvement in accessibility. These differences are computed in relative terms, expressed as follows (Equation 5):

$$AC_{ES_i} = \frac{A_{ref} - A_{ESi}}{A_{ref}} * 100 \tag{5}$$

For each exploratory scenario ES_i, the accessibility change is calculated in percentage AC_{ESi}. A_{ref} is the indicator value in the reference scenarios with the current street walking quality (*RSA, RSC, RSS* and *RSEW*), and A_{ESi} is the indicator in the exploratory scenarios ES_i. The change in urban design factors implies an improvement in street walking quality and hence an improvement in walking accessibility.

Results

Figures 3a, 3b, 3c and 3d show the distribution of the accessibility values in the current situation, considering the attractiveness, comfort, safety and ease-to-walk of the street sections. All of them have similar distribution patterns, with higher accessibility values around the building entrances in the centre and north of the district, which decrease as we move away from this area. The lowest values are located in the south, although it should be noted that quite apart from the street characteristics, this is partly due to the lower number of potential destinations.

For attractiveness-related accessibility, the maps resulting from the pedestrianisation of the streets show very similar accessibility distribution patterns to each other and to the reference scenario[1]. The highest accessibility values are concentrated around the building entrances in the centre and north of the district, and decrease with distance from this area. The lowest values are located in the south. Regarding the modification in the number of trees (comfort-related accessibility), the RSC and ES_5 maps are generally similar for attractiveness-related accessibility. Both scenarios have comparable distribution patterns, with the highest accessibility values around the building entrances in the central and northern districts, and the lowest values in the southeast and southwest. However, it is notable that the high accessibility area is considerably larger in the ES_5 scenario, while the low accessibility area is reduced to the southeast and southwest extremes of the 'Centro' district. In the exploratory scenario for safety-related accessibility, the maps generally resemble the accessibility maps for the other walking needs. The accessibility distribution patterns are also similar in the scenarios considered (ES_6, ES_7, ES_8 and ES_9). Finally, in regard to the ease-to-walk of the streets, as the width of the pavement increases, both exploratory scenarios can be seen to have similar accessibility distribution patterns, again akin to the reference scenario and hence to the rest of the walking needs. For reasons of space, the maps of the assessment scenarios are not included.

Table 3 shows the mean accessibility values in each scenario for each walking need, and the difference from the reference scenario in percentages. Hence for attractiveness, the pedestrianisation of approximately 15,700, 29,700, 31,800 and 52,900 m in length of street sections, representing 14.1%, 26.6%, 28.5% and 47.4% respectively of the total street length in the study area, produces an improvement in accessibility values from 14.81 to 29.12%. The lowest increase after the change occurs when the scenario goes from low to average pedestrianisation. It is worth noting that the pedestrianisation of 15,700 m – 141 streets – represents a greater improvement in accessibility levels than the pedestrianisation of 29,700 or 31,800 m – 276 and 301 street sections respectively – in the length of the streets. This is because the ES_1 scenario considers pedestrianising street sections with a high level of commercial activity, which influences the final average accessibility levels. The lowest increase after the change occurs in the mid (ES_2) to high (ES_3) pedestrianisation scenarios. There is a 48.8% change in comfort-related accessibility with the increase in the number of trees on the streets. This is very substantial, partly because the application of the measure implies acting on 758 street sections, which represent 94% of the total length in the study area. The results show that a reduction in traffic produces a very low average change in the safety-related accessibility level. It should be noted that this indicator does not assess other benefits resulting from traffic reduction (environmental and health-related), and these low change values are largely due to the low current traffic flow in the 'Centro' district. Finally, for accessibility relating to ease-to-walk, the increase in pavement width in 45,000 and 56,100 m of the streets – 40.3% and 50.3% of the total respectively – represents a change in accessibility values of 2.62% and 3.40% respectively. The improvement percentage is low even though it affects a considerable

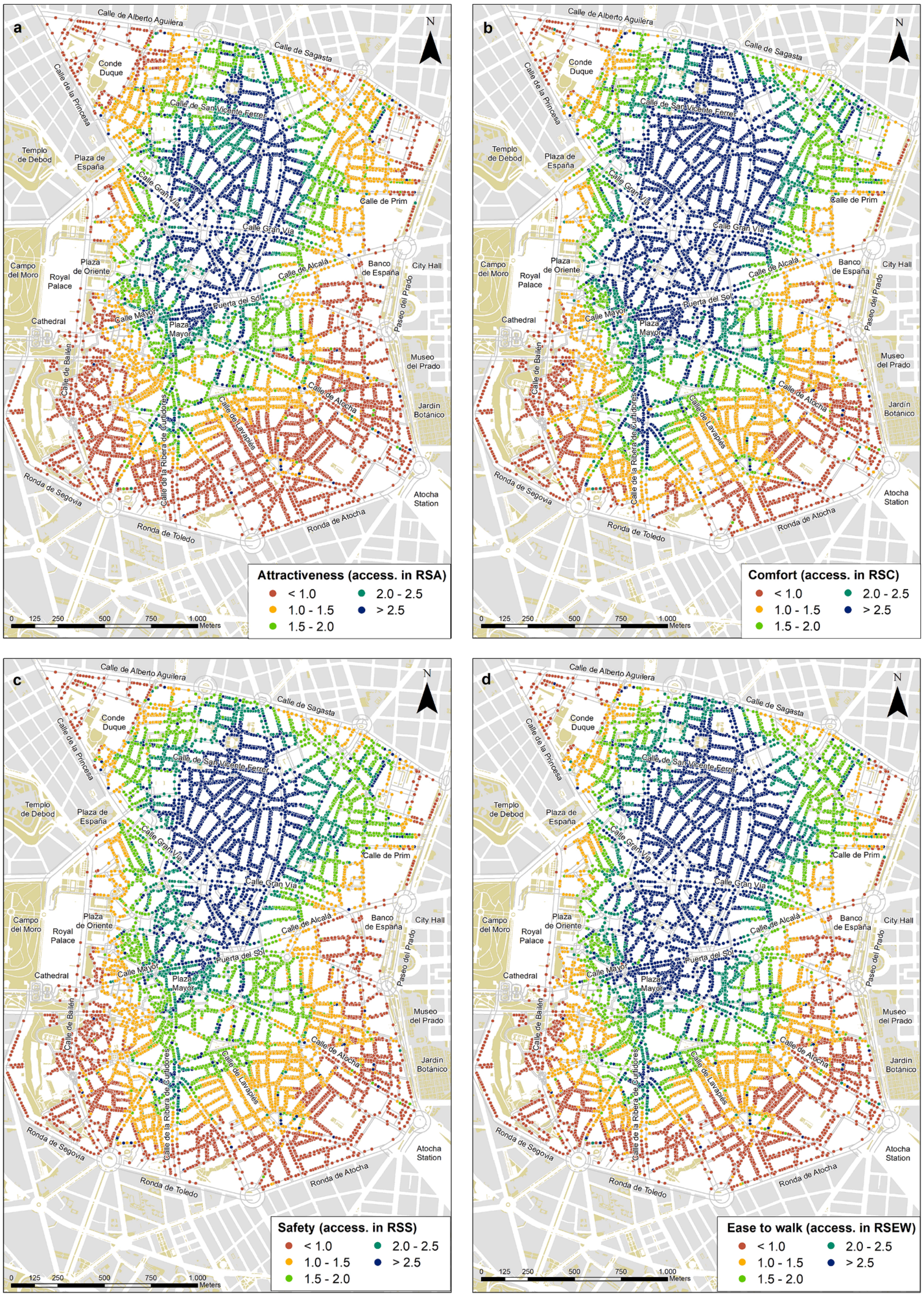

Figure 3. Distribution of the accessibility values in the current situation, considering: a) street attractiveness, (b) comfort, (c) safety, and (d) ease-to-walk.

Table 3
Mean accessibility values in each scenario for each walking need, and difference from the reference scenario (%)

Attractiveness	Comfort	Safety	Ease-to-walk								
Scenario	Value	Change (%) RSA vs ES_i	Scenario	Value	Change (%) RSC vs ES_i	Scenario	Value	Change (%) RSS vs ES_i	Scenario	Value	Change (%) RSEW vs ES_i
RSA	1.894		*RSC*	2.364		*RSS*	1.975		*RSEW*	2.163	
ES_1	2.262	19.43	ES_5	3.518	48.82	ES_6	1.979	0.21	ES_{10}	2.220	2.62
ES_2	2.175	14.81				ES_7	1.990	0.78	ES_{11}	2.237	3.40
ES_3	2.206	16.46				ES_8	1.992	0.90			
ES_4	2.446	29.12				ES_9	1.996	1.11			

number of streets, probably because many of the streets in the 'Centro' district are so narrow that they do not allow much increase in pavement width.

Figure 4 shows the changes between the reference scenario RSA and

Figure 4. Changes in attractiveness-related accessibility between the exploratory scenarios ES_1, ES_2, ES_3 and ES_4 and the reference scenario (RSA).

the exploratory scenarios ES_1, ES_2, ES_3 and ES_4, which include the pedestrianisation of the streets. In the low pedestrianisation scenario (ES_1), it can be seen that major changes occur in the northern half of the area and scattered throughout the 'Centro' district. These areas include the interior streets that are pedestrianised under the measure proposed, causing important changes in residents' attractiveness-related accessibility. It is significant that this does not occur to the same extent in the southern area. Nevertheless, in average pedestrianisation scenarios (ES_2 and ES_3) involving the pedestrianisation of almost 30,000 m of street sections, the notable improvements extend to the south-eastern area. It should be mentioned that although ES_1 implies pedestrianising fewer streets than ES_2 and ES_3, the greatest changes in accessibility occur in more areas in the district, and with higher values in specific locations. This is because the ES_1 scenario assumes the pedestrianisation of street sections with a high rate of commercial activity, which influences the distribution of accessibility values and the mean accessibility value in the scenarios. In the high pedestrianisation scenario (ES_4), the changes in accessibility are very substantial throughout the whole district, since 47.4% of the street length is pedestrianised. In all cases there are streets with minor changes compared to the adjacent streets, usually because these streets are already pedestrianised.

Figure 5 shows the changes between the reference scenario RSC and ES_5, including the increase in the number of trees along 94% of the total length of the study area, i.e. 758 street sections. It can be seen that the changes are very high (over 25%) in practically the whole district, and that the greatest changes occur to a limited extent in the central area. In large areas of the north, east and southeast of the district, the benefits are lower as the characteristics of the street section do not allow any

Figure 5. Changes in comfort-related accessibility between the exploratory scenario ES_5 and the reference scenario (RSC).

substantial increase in the number of trees; however the improvement is between 25% and 50%, since they benefit from the increment in trees in wide streets nearby.

Figure 6 shows the changes between the reference scenario RSS and scenarios ES_6, ES_7, ES_8 and ES_9, which include a traffic reduction. Safety-related accessibility values are highly influenced by traffic intensity. In the current situation, the lowest safety-related accessibility values are found for major axes and the highest values in the interior network, since the current traffic level is already low. Changes in safety-related accessibility are very low in most of the 'Centro' district – less than 1% in large areas –, and the greatest changes occur in the north-eastern and centre-south areas. With a 5% traffic reduction (ES_6), changes occur only in the northeast. As the traffic reduction increases, the changes extend to the aforementioned areas, which have intermediate traffic levels in relation to the whole of the 'Centro' district, so can benefit from these reductions. These improvements in percentage are barely appreciable in the main axes and the interior network in areas with narrow streets with very low traffic flows.

Figure 7 shows the changes between the reference scenario RSEW and the exploratory scenarios ES_{10} and ES_{11}, which include an increase in pavement width in 45,000 and 56,100 m of the streets, 40.3% and 50.3% of the total respectively. The figure shows that the greatest changes occur in the peripheral areas in the northeast and southeast, which include interior streets where the pavement width increases with the proposed measure, leading to significant changes in the residents' ease-to-walk-related accessibility. It should be noted that this is not the case in the south-eastern area. Despite the significant changes in this area with the ES_{11} scenario, as with the comfort-related accessibility, the

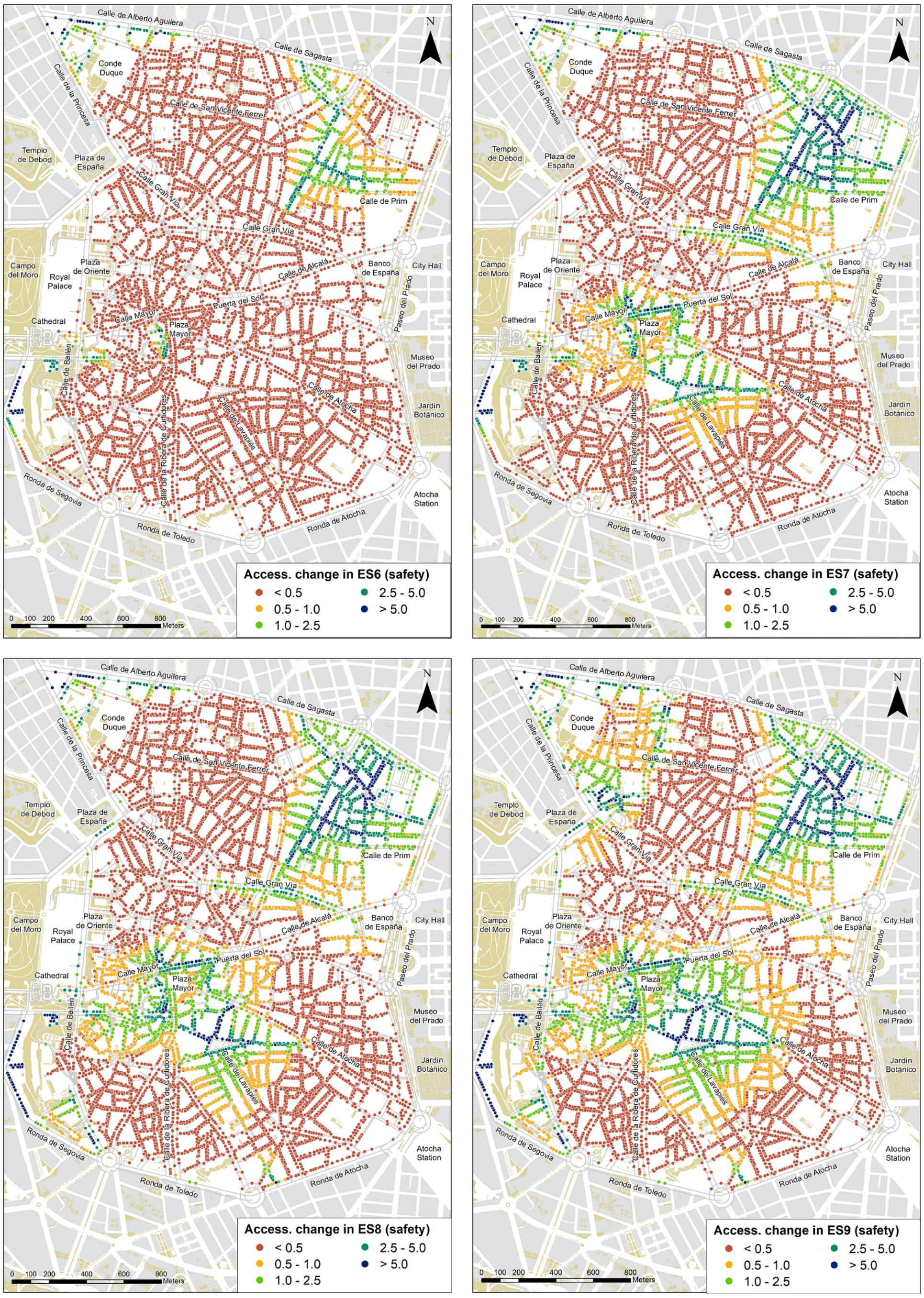

Figure 6. Changes in safety-related accessibility between the exploratory scenarios ES_6, ES_7, ES_8 and ES_9 and the reference scenario (RSS).

residents of these streets benefit less since these narrow streets do not allow any substantial increase in pavement width.

Discussion and conclusions

The aim of this paper was to assess the variations in walking accessibility levels after the application of urban design measures considering the four walking needs: attractiveness, comfort, safety and ease-to-walk. A set of exploratory accessibility scenarios were designed in the context of central Madrid, modifying urban design factors in the built environment. Specifically, the exploratory scenarios comprise new street pedestrianisations, increased number of trees, pavement widening and traffic-calming measures.

The research compared the current walking accessibility scenario with exploratory accessibility scenarios featuring improvements of different intensity applied to urban design factors. The current scenario (Figure 3) shows a common pattern of accessibility values corresponding to the four walking needs studied. The walking accessibility indicator always has higher values in all categories – attractiveness, comfort, safety and ease-to-walk – in the streets in the centre and north of the district, which are in the historical and commercial heart of the city. They contain the major tourist attractions and have a vibrant economic activity, largely related to retail and tourism. These activities are also present in the south of the district, although less intensively. This intense activity concentrated in the centre and north has consequences on the results, as the destinations chosen for the accessibility calculations are points where activities such as food shops, retail outlets and other services are located (see Figure 1, origins and destinations). Given the

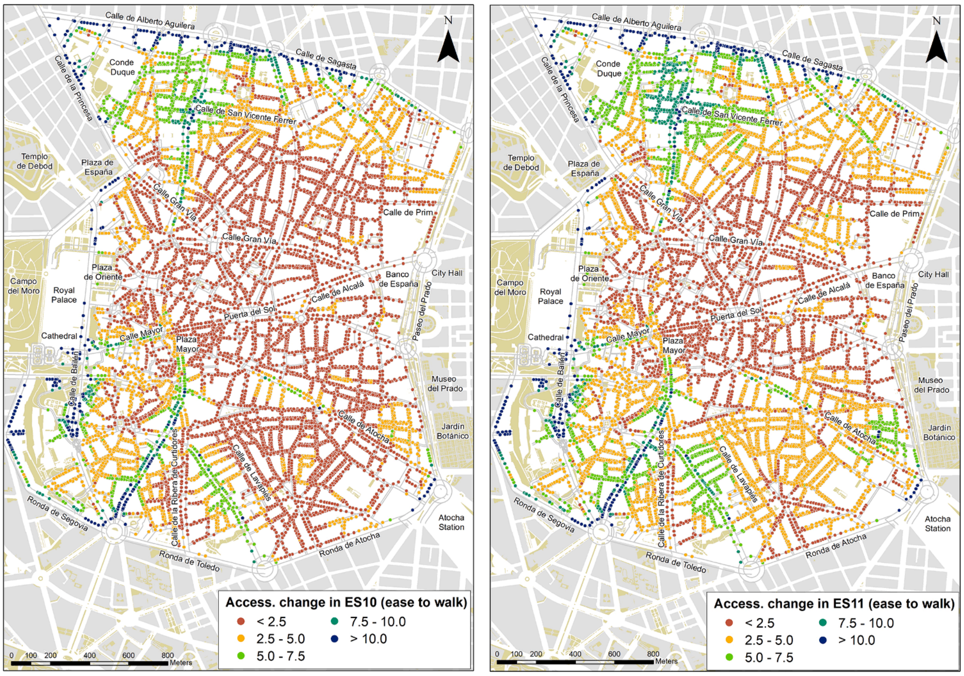

Figure 7. Changes in the ease-to-walk-related accessibility between the exploratory scenarios ES_{10}, and ES_{11} and the reference scenario RSEW.

nature of the indicators chosen, which penalize the distance to the destinations, it is logical that higher accessibility values occur where there is a greater concentration of destinations, namely in the centre and north of the case study.

In the remainder of this section, a series of specific issues will be discussed individually in order to distil the lessons learnt for further research and the practicalities for implementation:

The exploratory approach: while previous research has focused on determining the possible relevance of different walking needs (e.g. comfort) to accessibility and why (Blitz & Lanzerdorf, 2020; Deng et al., 2020), little attention has been given to how these findings can be translated into guidelines for practitioners. This paper bridges this gap between theory and practice using an exploratory scenario-building approach (Soria-Lara & Banister, 2018). The exploratory accessibility scenarios for each walking need involve analysing the variations in walking accessibility after undertaking actions in a single walking design factor, while all the other design factors remain unaltered. For example, it is particularly worth noting the case of the attractiveness walking need, in which accessibility improvements of nearly 20% are achieved in ES_1 (pedestrianisation of 15,700 m, with a width of over 10 m and a vibrant commercial activity). Although ES_4 implies a 29% improvement in accessibility, the intervention requires the pedestrianisation of a much higher number of street segments. The improvement in comfort-related accessibility obtained in ES_5 – close to 50% – is also worth highlighting. In this case the tree presence has been improved in 758 sections, representing 94% of the total length of the study area, where this does not impede transit. The improvements obtained in the safety- and ease-to-walk-related scenarios are much more moderate; in these scenarios the interventions concern traffic reductions and increases in pavement width. It is also important to note that the rate of increase in the intervention in the scenarios did not always lead to the same rate of increase in walking accessibility, as in the case of the pedestrianisation of streets in terms of attractiveness. According to our results, ES_1, which has the lowest intensity in terms of length and number of street segments, produces the second highest improvement in attractiveness. This supports our thesis as to the usefulness of this type of model in urban planning, since it allows the measures to be efficiently dimensioned. The ultimate goal of this approach is not to provide practitioners with real scenarios for implementation, but to offer a set of hypothetical scenarios where the influence of walking needs on accessibility values can be discussed and argued in depth, and to serve as the basis for an evidence-based and openly deliberative decision-making process (Hull et al., 2012). The 11 exploratory scenarios studied in this paper trigger an interesting discussion and serve as a starting point for understanding the possible effects of planning interventions on walking accessibility. Further research could focus on defining alternative scenarios or validating the scenarios defined in this work using techniques such as focus groups. It could be valuable to add more elaborate narratives to the exploratory scenarios, as this could produce scenarios with a more powerful approach as a collaborative instrument for planning actors' interactions. A sense-check of these narratives is also necessary to avoid inconsistencies.

The geographic approach: this research adds value by implementing a geographic micro scale analysis, although the macro trend and non-spatial analysis have been predominant when considering walking needs in the past (Talavera-García & Soria-Lara, 2015). The geographic macro scale is key for decision making, as practitioners can locate specific actions and test their spatial effectiveness. The analysis of the results sheds light on the geographic distribution of the design improvements in the case study. In the case of ES_1, the improvements are concentrated where the initial accessibility was high, i.e. in the centre and north, while the improvements produced by ES_2, ES_3 and ES_4 are distributed throughout the district. The comfort-related measure (increase in the number of trees) has a very positive effect throughout the whole study area, especially in the wider streets. The traffic-reduction scenarios lead to relatively low improvements, while the increase in pavement width is generally low and excludes the narrower interior streets from the improvements.

The use of GIS as the core tool for implementing the methodology has been key to the geographical approach. In the past, the potential of tools for network analysis has been used to generate walking routes in walkability studies (e.g., Delso et al., 2018; Delso et al., 2019). In this study, the analytical capabilities of the GIS network have made it possible to generate more than 14,500,000 pedestrian routes between real origins and destinations in each exploratory scenario in the case study, and to simulate modifications in the street network by altering the urban factors in these scenarios.

A richer origin database with more detailed information would enable new lines of research to be addressed that have not been pursued in this study due to lack of data. These lines include the consideration in the scenarios of the personal characteristics of the population in the district, which have been reported as being relevant to the analysis of pedestrian mobility, including age, gender, educational level and income level (Paez et al., 2013). It is essential to take these variables into account in future work to ensure the efficient design of improvement measures and their distribution under criteria of equity. Likewise, by including age it would be possible to refine the speed considered in the calculations, which was assumed to be the same in all the scenarios in the study.

An open analytical approach: unlike blackbox tools, which provide global walkability scores (Ortega et al., 2020a), this research takes an analytical approach in which researchers, decision makers and planners can decide the weights of urban design factors and the intensity of the measures taken in regard to these factors. This can more easily stimulate dialogues between the participants in the planning procedures and lead to more collaborative decision-making schemes. We have applied a weighted sum rather than other aggregation methods frequently used in the literature, such as outranking multiple-criteria decision analysis methods. Although the weighting factors are based on expert knowledge, the obtained results may be biased according to tacit and explicit knowledge from participants. Future methodology improvements could consider other methods to get appropriate weighting factor. In this line, the weights of the urban design factors for each walking need are not homogeneous, making it difficult to compare the results for each one. In order to avoid the redundancies of the factors, the results of the evaluation of the four categories are not integrated, although this could be done by exploring the correlation between the factors and studying the possible compensatory effects between the results of the four walking needs.

Another aspect that could be improved in the methodology is the weight given to origins and destinations in the accessibility calculations. The methodology assigns the same importance to all origins (building entrances) regardless of the population living there, and assumes that all destinations are equally relevant whatever their degree of attraction. A more accurate analysis of walking accessibility in the proposed scenarios could be obtained by including the weight of origins and destinations based on detailed data obtained from mobility surveys or census data.

The results of the paper serve as a starting point for analysing how interventions on specific urban factors can modify levels of walking accessibility. We believe that the framework proposed in this paper represents a valuable design instrument for urban planners from an exploratory viewpoint ("what-if" assumptions). This instrument provides evidence-based information for prioritising strategic actions to improve active mobility in Madrid city centre.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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