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The inclusive 15-minute city: Walkability analysis with sidewalk networks

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ABSTRACT

In recent years, the design (and re-design) of cities to encourage walkability has taken on new urgency as part of a wider campaign for sustainable urban development. Complementary to other approaches like infrastructure improvements, increases in residential density, or traffic calming measures, here, we show how planning for walkability can be augmented by the adaptation of tools and approaches from the study of urban networks, by privileging the pedestrian perspective of short-distance access over the car (and rapid transit) perspective of flow and efficiency. Using a recently developed sidewalk network model that moves towards a more realistic representation of the pedestrian environment, we propose a framework for assessing multi-factor walkability using percolation theory and insights into pedestrian behavior. We apply our framework to the city of Barcelona, and show how it can be used to optimize service location and access for vulnerable populations (the elderly and young).

1. Introduction

For decades, urban planners have been promoting walkability as a key aspect of sustainable urban development (Claris & Scopelliti, 2016; Gehl, 1987; Gössling, Choi, Dekker, & Metzler, 2019; Jacobs, 1961; Pushkarev, 1975; Speck, 2012; Whyte, 1979). Today, this push is increasingly being translated into policy, as some cities slowly implement programs to encourage walking and reduce vehicle-miles travelled through solutions such as increased residential density, traffic calming measures, and more. The shock generated by the Covid-19 pandemic over the last two years created an opportunity for even more radical and rapid action in places where political will already existed (Combs & Pardo, 2021), as exemplified by the implementation of "Open Streets" programs of varying sizes and ambitions in cities around the world. Under such programs, vehicle access is partially or totally blocked along a selection of streets, with the aim of encouraging and facilitating walking over driving. In the period 2020–22, these innovative policies, along with related methods of tactical urbanism (Silva, 2016), most directly sought to provide residents with a sense of space and safety, with secondary effects such as supporting local businesses with foot traffic.

Despite their successes, it is unclear if small-scale implementations of programs like Open Streets can lead to global and lasting improvements, particularly in terms of two fundamental aspects of walkability: access to services and connectivity (Batty, 2009; Xu, Olmos, Abbar, & González, 2020). Certainly, Open Streets do have an immediate positive effect in terms of increasing pedestrian space on a block-by-block level, but their surgical nature (Combs & Pardo, 2021) –precise and discretionary– is not necessarily adapted to increasing the overall integration of pedestrian infrastructure, nor to making services more accessible. As the most urgent phase of the pandemic is slowly left behind, there is a chance for these recently pioneered, radical methods of tactical urbanism to be combined with more systematic planning for increased walkability: a goal best achieved with the aid of pedestrian-focused sidewalk networks.

The use of pedestrian-specific networks to study pedestrian issues is not new in planning contexts, and in fact is acknowledged as a best practice (Chin, Van Niel, Giles-Corti, & Knuiman, 2008; Tal & Handy, 2012). However, data on pedestrian-centered networks are difficult to find, and often unavailable without a significant geoprocessing effort. Consequently, work on pedestrian networks has often been restricted to a neighborhood scale (Cambra, Gonçalves, & Moura, 2019; Chin et al., 2008; Tal & Handy, 2012), where manually constructed networks are feasible. When city-scale analysis of walking connectivity between origins and destinations has been performed, it has most commonly been based on more easily available road network data (Boeing, 2019a; Orozco, Deritei, Vancsó, & Vasarhelyi, 2019). Despite the convenience of this approach (road network geometries are easily available in city-wide, standardized form), taking the sidewalk network as nearly reducible to the adjacent –but not identical– road network abstracts

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away geometric differences between sidewalks and roads, as well as the costs associated with sidewalk crossings. Likewise, with some exceptions (Zhao, Sun, & Webster, 2021), widespread approaches to measuring walking access to services, such as the well-known *Walk Score®* metric (Walkscore, 2022), tend to fall back on the road network, abstracting away from the specificities of pedestrian infrastructure and the diversity of pedestrian experiences. This is further reflected in many studies of general accessibility, which (perhaps problematically) tend to treat car transportation and the road network as the "default" parameters of urban transportation (Abbar, Zanouda, & Borge-Holthoefer, 2018; Xu et al., 2020).

Here, in an effort to overcome these limitations, we perform a network-based pedestrian access analysis of the city of Barcelona, Spain, taking as the underlying infrastructure layer a recently developed sidewalk network model (Rhoads, Solé-Ribalta, González, & Borge-Holthoefer, 2021) that more realistically captures the pedestrian environment: a city-wide, undirected graph, whose edges are richly annotated with actual data from the underlying sidewalk geometry and its environment – width, length, slope, and accident hazard level– as well as crosswalk location. This physical network is further enriched with geolocated data on population, and the location of essential services and amenities. See Fig. 1A for an overview of the network annotation process. It is worth noting that a realistic model of pedestrian infrastructure is not equivalent to realistically capturing the entirety of the pedestrian experience, which includes behaviours well beyond utilitarian and normative movement along sidewalks (Cambra et al., 2019; Pushkarev, 1975; Whyte, 1979), e.g. jaywalking, cut-throughs, and so on.

Equipped with this network, we next explore how well the city's walking infrastructure is able to support the needs of pedestrians who face mobility constraints related to sidewalk and environmental attributes. In general terms, such constraints can be interpreted as 'access costs', whether these costs be difficulty traversing steep slopes, the need for more sidewalk space, or the avoidance of sidewalks with high risk of car-pedestrian accidents. The needs of some pedestrians may weaken, and potentially fragment, the effective network they are actually comfortable using. In order to model this diversity of experiences, we employ targeted edge percolation, a standard approach to assess infrastructure robustness from a network perspective.

Percolation theory has been widely used to gain insights on a wide range of structural and behavioral features of networked systems (Li et al., 2021), including in the urban context (Abbar et al., 2018; Arcaute et al., 2016; Barrington-Leigh & Millard-Ball, 2019; Li et al., 2015; Molinero, Murcio, & Arcaute, 2017; Serok, Levy, Havlin, & Blumenfeld-Lieberthal, 2019; Shen & Karimi, 2016), and is a common tool in the vulnerability analysis (VA) (Chen, Yang, Kongsomsaksakul, & Lee, 2007; Gu, Fu, Liu, Xu, & Chen, 2020; von Ferber, Berche, Holovatch, & Holovatch, 2012) of urban infrastructure. In this work, we interpret VA not in the traditional sense (that of infrastructure security engineering and risk of failure), but rather from the perspective of a portion of the population –the most vulnerable–, for whom urban infrastructure is disrupted even before its components are considered at risk from external stresses. Accordingly, our simulated attack on the edges of the network proceeds according to different "pedestrian mobility profiles" (PMP) (Bolten & Caspi, 2021), considering the needs of pedestrians facing reduced mobility and/or traffic safety constraints.

We begin by applying percolation at the level of the entire city, in order to assess the robustness of the pedestrian infrastructure along a continuum of different PMP constraints, see Fig. 1B. Although pedestrian behavior is known to be highly distance-constrained (Daniels & Mulley, 2013), especially for pedestrians with different mobility restrictions (Berrett, Leake, May, & Whelan, 1988), a system-level connectivity indicator is relevant (Barrington-Leigh & Millard-Ball, 2019) when it comes to assessing the integrated whole of the city's walkable infrastructure, and the sometimes hidden discontinuities it may have, which can further impact local scale dynamics. We find that the consideration of even moderate mobility constraints already leaves tens of thousands of residents cut off from the network's largest component.

Following this, we move from the system-level to a local scale, allowing us to assess the unequal quality of the walking infrastructure that pedestrians at different points in the city have access to within a short, comfortable walk - in other words, their distance-constrained catchment areas. In this case, a targeted percolation process is again applied, except that now it operates on a set of overlapping, 15-min

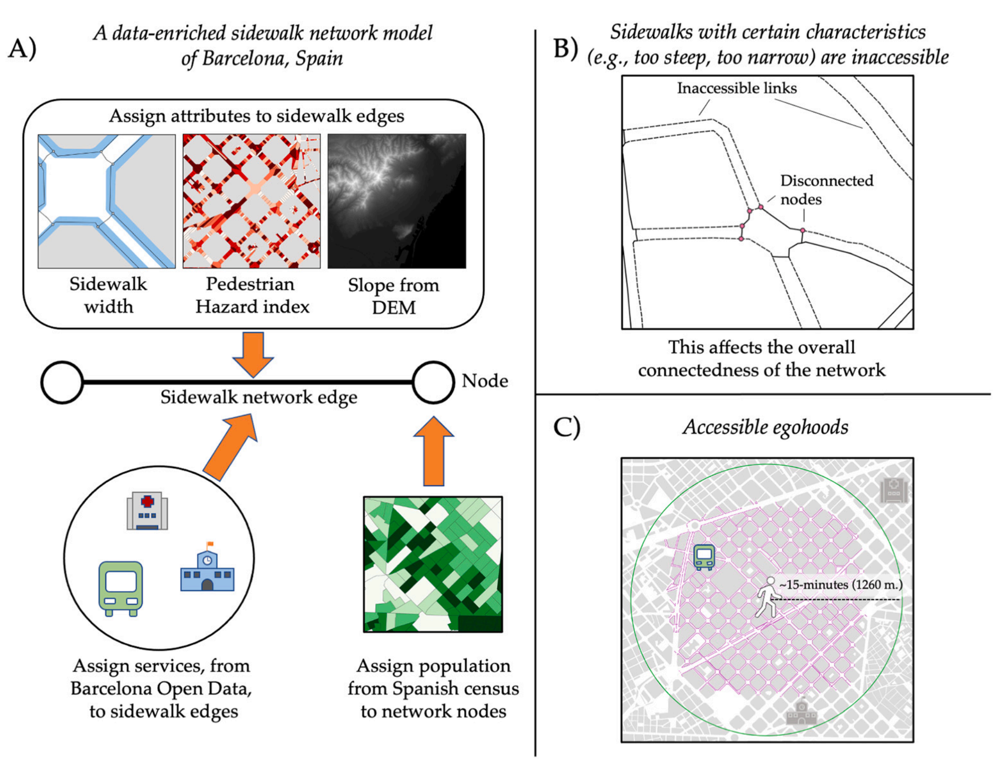

Fig. 1. A: A sidewalk network for the city of Barcelona was constructed using data from OpenStreetMap, as well as municipal and regional data sources. Edges of the network were annotated with various attributes relevant to walkability, namely: width, slope, and pedestrian-car accident hazard level. Further, a variety of geotagged services and amenities were assigned to network edges, and population was assigned to nodes. B: The attributed network allows us to remove edges that do not meet certain requirements for pedestrians with mobility constraints. C: By focusing our analysis on the level of the pedestrian catchment area (egohood), we can learn more about the real, day-to-day accessibility of the network.

walkable subgraphs extracted from the entire sidewalk network (see Fig. 1C). We call these sub-graphs "egohoods" (also sometimes referred to as "pedsheds", or "walksheds") (Bolten & Caspi, 2021; Chin et al., 2008; Glas, Engbersen, & Snel, 2019; Hipp & Boessen, 2013; Porta & Renne, 2005). Each egohood is further enriched by incorporating data on service and amenity location, allowing us to easily determine whether a pedestrian at node i can reach any service of type s within a 15-min walk.

Our results indicate that a significant fraction of Barcelona residents have limited or no access to certain services within a comfortable walking distance, given various mobility constraints. For this reason, our descriptive efforts are rounded off with several examples of actionable proposals informed by our analysis. In particular, we explore how percolation by accident hazard level can inform residents and cities about school locations that are safely reachable on foot; and, how percolation by sidewalk width and slope might be used to design efficient access solutions for neighborhood medical clinics.

Besides the specific achievements of these analyses, our work stresses yet again that, without the underlying structure of the sidewalk network, it is difficult to assess the consequences of manually selected interventions at the neighborhood or city-wide levels. The network-theoretical framework represents an emerging opportunity to embed more explicit and inclusive hypotheses of pedestrian experience into urban planning. Major cities, like Paris and Barcelona, which are committed to maintaining and expanding strategies to improve walkability implemented over the past years, have a chance to lead the way in the use of empirically-grounded, systems-level planning tools like urban network analysis.

2. Data and methods

2.1. Sidewalk network

A sidewalk network for Barcelona was generated with data from OpenStreetMap, the OpenDataBCN portal of the Barcelona city government, and the Institut Cartogràfic i Geològic de Catalunya (ICGC), using a method introduced in (Rhoads, Solé-Ribalta, González, & Borge-Holthoefer, 2021). Following 15 years of literature emphasizing the importance of using pedestrian-centered networks when addressing pedestrian issues (Cambra et al., 2019; Chin et al., 2008; Tal & Handy, 2012), we move away from the common reduction of the walking network to the geometry and topology of the road network, instead employing a network model that better captures the experience of the pedestrian on their walk. Rather than being built from street center lines, the network is based on the geometries of sidewalks. Like in the most common "primal" road network model (Porta, Crucitti, & Latora, 2006), nodes are placed at decision points: sidewalk network intersections or crosswalks, which allow the pedestrian to reach another sidewalk on the other side of the street. The resulting network is denser than the road network (approximately 4 to 1 in both nodes and edges). It also contains 3 distinguishable edge types: sidewalks, crosswalks, and pedestrian-only paths. The latter category includes pedestrianized streets, living streets, and paths through parks and plazas. Thus the network is composed of more than just sidewalks, and is in fact close to the full, normative walkable system of the city, but sidewalks and crosswalks do constitute the vast majority of the its structure.

2.2. Edge attributes

One of the advantages of a detailed, pedestrian-focused sidewalk network is the capacity to tag edges with metadata corresponding to real-world attributes of the sidewalk. The limits of relevant attributes up for consideration is set only by the availability of data, as can be seen in some comprehensive surveys of sidewalk quality (Saha et al., 2019). Here, we select 4 attributes –length, width, slope, and pedestrian hazard– all of which were both available (outright or through geoprocessing) and relevant to our goal of developing a flexible tool to measure walkability in a variety of contexts. Fig. 1A provides a visual summary of the data added to the network substrate, and the specific process for deriving each of these edge attributes is described below.

Length, ℓ, is the most straightforward attribute to measure the extension of the path the edge represents. This is necessary for routing and, especially, for determining the extent of node-by-node egohoods, described below.

Width is a crucial property of sidewalks, but its measurement is challenging, since it requires linking network elements to planimetric data regarding sidewalk geometries. The entire process is detailed in Section S1 of the Supplementary Materials, but the general idea is to consider the length, ℓ, and area, a, of the sidewalk corresponding to each network edge. Using these attributes, the average width of a given sidewalk, w, can be estimated as $w = a\ell$.

To determine the area a of a sidewalk corresponding to a single network edge, points are generated over graph edges at regular and small intervals. Then, a Voronoi tessellation is constructed from these points. Finally, the area of each of each Voronoi polygon is assigned to the network edge that its seed point was derived from. Note that, since crosswalk geometries were only available in *line* and not in *polygon* form, we assume their width is large enough to not limit mobility.

The slope of each edge is obtained from digital elevation maps (DEM) of the Barcelona area, sourced from the ICGC. The DEM has a resolution of 5×5m per pixel, and an estimated slope for each network edge was calculated by taking the angle in degrees between the minimum and maximum elevation along its length.

Finally, using a recently produced fine-grained map of estimated pedestrian safety in Barcelona (Bustos et al., 2021), we can assign a hazard level, H_{ij}, to each edge e_{ij} of the sidewalk in the city. The value of H_{ij} attempts to quantify how dangerous each sidewalk segment is for a pedestrian, in terms of the risk of getting hit by a car. Since it is difficult to obtain H_{ij} by solely using statistical analysis upon real data, the work in (Bustos et al., 2021) exploits Deep Learning tools. In particular, they train a ResNet50 (Deep Learning) model (He, Zhang, Ren, & Sun, 2016) to classify Google Street View images as either dangerous or safe locations, based on accident data and the visual features of the scene. For each street-level input image, the classifier returns a level of "certainty" that the input image belongs to each class –"dangerous" or "safe"– reaching accuracies up to 75%. The hazard level for a given location is obtained as the level of certainty that the model had of classifying that location as "dangerous". In the case of Barcelona, the hazard index provides a hazard estimation approximately every 15–20 m along a street segment, with each estimation corresponding to a geotagged street view photo. We construct a Voronoi diagram from these photo locations, where each cell of the diagram covers the area closest to that photo location and no other photo location. Sidewalk hazard is taken as the average of the Voronoi cells that the sidewalk edge intersects. The hazard H is scaled such that $H \in [0,1]$, where 0 indicates the lowest hazard, and 1 the highest.

Fig. 2 below shows the spatial and statistical distribution of each of the 3 attributes considered in the percolation processes. As can be observed, the statistical distribution of each attribute is quite unique. Sidewalk width exhibits an interesting almost bimodal behavior, with peaks at 2.5 and 5 m. The shape of the distribution is an artifact of urban planning –in particular, the tight peak around 5 m represents l'Eixample ("the Expansion"), the famous grid-iron district of the city planned by Ildefons Cerdà in the mid-19th century (located in the geographic city center). In contrast, sidewalk slope is characterized by a smooth, exponential-type decay from the densely populated, mostly flat coastal plain where the majority of sidewalks lie, to the sparser, hilly periphery. Finally, sidewalk hazard is slanted towards danger ($H \approx 1$, indicating a generally high level of accident risk in Barcelona), with a median hazard of 0.63, and hazardous sidewalks are visibly concentrated in the city center.

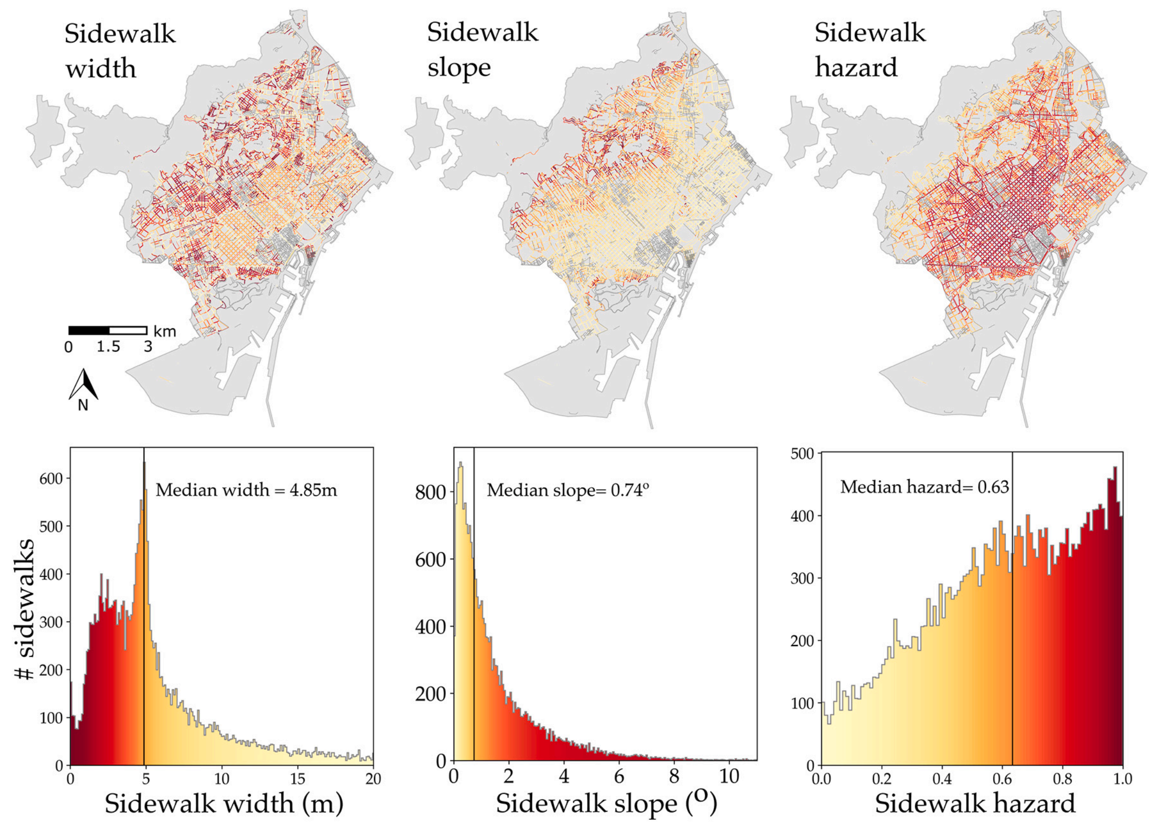

Fig. 2. The spatial and statistical distributions of each of the 3 sidewalk characteristics considered vary widely. Width is controlled by past and present urban planning decisions, while hazard is dependent on dynamic traffic demand and street design, and slope is heavily determined, of course, by nature relief patterns in the environment.

2.3. Urban amenities

Geotagged point data on amenities and services were downloaded from the Barcelona city government's open data portal (https://opendata-ajuntament.barcelona.cat/). The categories of services considered are listed in Supplementary Table S1. In general, we sought to include services that could be considered essential and of regular use, such as schools and health clinics. In many cases, these services are also publicly provided. Public services that do not rely on customer revenue, and thus do not need to compete for customers, are subject to different location incentives than private, competitive firms. In effect, their location can be determined based on designated social criteria (such as maximum accessibility), a fact which is reflected in empirical data (Um, Son, Lee, Jeong, & Kim, 2009). If a certain area or population lacks access to such publicly-funded facilities, then, this might indicate a failure in the spatial allocation of public resources. Pharmacies are private firms, but their location is also highly regulated in Spain based on ensuring maximum service to the population. One exception to this rule among the facilities selected is supermarkets which, while essential, are privately owned and unregulated in Spain.

2.4. Attribute-based bond percolation

Percolation analysis on networks is a rich field with a variety of methods and applications (Li et al., 2021). Most commonly, site (node) or bond (edge) percolation are used to measure the robustness of networks to random or targeted attacks (Albert, Jeong, & Barabási, 2000). In this work, we follow the latter path and perform targeted bond percolation on Barcelona's sidewalk network according to edge metadata. The process works as follows: edges (sidewalk segments) are ordered by a given property (i.e., width, slope, or hazard), and are then sequentially removed from the network, starting with the most vulnerable sidewalk (the narrowest, the steepest, the most dangerous). Each step in the percolation process thus corresponds to a set threshold for the given attribute, which we designate as $\tau(X)$ where X refers to the attribute in question –W for width, I slope, and H hazard. For example, then, $\tau(W) = 2.5$ meters means that all sidewalks of width $w_{ij} < 2.5$ have been removed in the percolation process.

To measure the robustness of the network under this type of attack, common practice is to monitor the fraction of nodes, S, belonging to the largest connected component, C_1, of the network i.e. $S = C_1/N$, with N being the size of the network. This effectively treats all nodes as equally important. In practice, however, population density varies widely across the city, and two topologically similar network nodes might serve widely varying numbers of people, depending on their location. For this reason, instead of measuring S (where each network node is given the same importance), we consider the number of people "residing" in the largest connected component. To achieve this, we assign a population to each network node using a geodataset of Spanish census data made up of polygons (census sections), each containing a few thousand residents. Each network node falls within exactly one of these non-overlapping population polygons. The assignment of population to a node i, p_i, is simply an even distribution of the population of its polygon among the nodes of the sidewalk network that fall within it.

In order to make the percolation results more tangible, the population $P_{C_1} = \sum_{i \in C_1} p_i$ that resides within the largest connected component of the network is not normalized, so that the unit of measure remains "people" or "residents". The same goes for P_{C_2}, the population within the second largest connected component, C_2. Of course, not every resident will be subject to the same (if any) mobility constraints, but considering the entire population in the percolation process allows us to be neutral and make fewer assumptions about particular residents' current and future needs.

2.5. Pedestrian egohoods

The length of a trip is a crucial determining factor in modal choice (De Witte, Hollevoet, Dobruszkes, Hubert, & Macharis, 2013), and walking in particularly is known to be strongly distance-constrained (Berrett et al., 1988; Daniels & Mulley, 2013; Iacono, Krizek, & El-Geneidy, 2008; Yang & Diez-Roux, 2012). In other words, most walking trips are relatively short, and the likelihood of a traveller choosing to walk has been observed to fall exponentially with increasing distance (Iacono et al., 2008). Unsurprisingly then, the pedestrian catchment area, indicating the space accessible to a pedestrian at a given location within a given time-frame, is a commonly-used construct both in studies on walkability, and in planning practice itself. In reference to the hydrological notion of watersheds, pedestrian catchments have been referred to as "pedestrian sheds", "pedsheds" (Porta & Renne, 2005), or occasionally "walksheds" (Bolten & Caspi, 2021), here we use "pedestrian egohood", or just "egohood" (see Fig. 1C), a term borrowed from the spatial criminology literature (Glas et al., 2019; Hipp & Boessen, 2013). We prefer egohood because it effectively transplants the network theoretic concept of the "ego network" (Newman, 2003) –a subgraph centered on the connections of an individual node– to a spatial, urban, and pedestrian context.

Although results vary, standard practice considers 15 min as the preferred upper bound for regular walking trips for people with no specific mobility constraints, an assumption which is being codified in the increasingly popular concept of "the 15-min city" (Moreno, Allam, Chabaud, Gall, & Pratlong, 2021). In our experiments, we focus our analysis on the 1260m that can be travelled in 15 min at a walking speed of 1.4 m/s, in accordance with literature (Bosina & Weidmann, 2017), but it is important to emphasize that individual mobility restrictions can significantly reduce the distance a pedestrian can cover in 15 min (Berrett et al., 1988). That said, there is a large variance in velocities achieved depending on the kind of mobility restriction a pedestrian faces, which makes a single standardized speed more useful for general analysis. Different walking speeds can easily be integrated into the egohood analysis, depending on the particular context.

We formally define the egohood of a location as the total amount (length) of sidewalk a pedestrian at that location has access to within a limited time, 15-min in our case. By using this metric definition, we draw on the concept of the "interface catchment" (Pafka & Dovey, 2017), which measures the total length of the "public-private interface" accessible to a pedestrian. This is understood as a good, neutral proxy for the activity opportunities available to a pedestrian within the distance of a comfortable walk.

Determining this egohood from a graph algorithmic point of view means identifying all of the edges a pedestrian can traverse within a given threshold time. To find such a set of links, we extended the classic Dijkstra algorithm to (1) explore all nodes within the threshold time from a single source, and (2) to record all edges that can be traversed within the threshold, not only the ones that form part of a shortest path. A formal description can be found in Section S3 of the Supplementary Materials, while the implementation was done in Python, using the igraph library (Csardi & Nepusz, 2006).

3. Results

3.1. City-scale percolation

A functional transportation network should be connected, allowing theoretical travel between all pairs of destinations. However, pedestrians may have different mobility needs that limit their use of sidewalks with certain physical characteristics. In other words, while the sidewalk network may function well for some pedestrians, it might effectively be disconnected for others. To assess this, we begin with a vulnerability analysis of Barcelona's sidewalk network by means of network percolation, measuring its connectivity at various levels of constraint: sidewalk width W, sidewalk slope I, sidewalk pedestrian hazard level H, and combinations thereof. It is worth highlighting that the percolation process presented here is solely dependent on the aforementioned structural constraints, and does not take into account dynamical factors that may cause an edge to be removed, e.g. excessive pedestrian demand (crowding). More precisely, our analysis purposefully abstracts away from pedestrian flow information: by focusing on physical sidewalk width (or slope, or hazard), we are assessing whether or not it is feasible for a pedestrian with given constraints to use the sidewalk. For a given constraint, the percolation process without considering demand represents a "best-case" scenario: if a city, neighborhood, or point performs poorly, it can only perform worse when demand is taken into account. Thus, the analysis presented here represents a baseline.

3.1.1. Uni-dimensional percolation

As is shown in Fig. 3, the largest connected component G of the sidewalk network reaches its critical breakdown point, indicated by the maximum value of the second largest connected component P_{C_2} in red, at a percolation threshold of about 5 m of width, which is a relatively generous sidewalk width. However, before reaching the collapse point, the largest connected component is steadily pruned limiting mobility of tens of thousands residents for every 0.5 m increment of sidewalk width.

Hazard percolation presents a more concerning picture. The distribution of hazard locations around the city make that P_{C_1} immediately begins to fall precipitously, and P_{C_2} sees several peaks (indicating critical breakdowns in the second largest component) at $H = 0.8$ and $H = 0.7$, before reaching its maximum around $H = 0.65$.

Turning finally to sidewalk slope, we can observe a breakdown pattern that is similar to but more gradual than the case of width percolation. Specifically, connectivity falls more slowly when removing very high-slope sidewalks ($I > 4.5^{\circ}$), but falls quickly in the mid-slope range before reaching it's critical point near $I = 1.0^{\circ}$.

In sum, each particular attribute-based percolation process exhibits a distinct breakdown pattern. This can be explained by the differing spatial distributions of each attribute across the city, which are presented in Fig. 2. As can be observed, pedestrian hazard is strongly concentrated in the central areas of the city, explaining the network's swift breakdown. Meanwhile, high slopes are to be found in the city's North and Northwest extremes, where the coastal plain gives way the Collserola hills. This clustering of high slopes on the peripheral parts of the city makes the network as a whole less vulnerable to slope-based edge removals. Note that this also depends on the relative orientation of sidewalks and streets with respect to the topography of the city. As was reported in Boeing (Boeing, 2019b), Barcelona has a somewhat uniform distribution of the street orientation with respect to other cities, which may affect the percolation profile. Finally, in contrast to the other two attributes, sidewalk width is biased slightly towards the center, but is generally distributed quite homogeneously.

3.1.2. Multi-dimensional percolation

The mobility constraints faced by pedestrians usually cannot be reduced to a single feature of their built and natural environment. For instance, wheelchair users require adequate sidewalk space, but also have difficulties traversing steep or extended slopes due to the physical exertion required. To get a fuller picture of the real functionality of the network for certain residents, we perform a percolation process along multiple dimensions of sidewalk segment metadata.

Fig. 4A shows the loss in population of the largest component G under a 2-dimensional percolation process by sidewalk width and slope together. Each color step represents a loss of $\sim 40k$ residents from the largest connected component of the network. Note that if we follow only the X or Y axis individually, we are essentially performing 1-dimensional percolation, and the results of panels C and A respectively of Fig. 3 are reproduced. Outside of these narrow bounds, the combined percolation

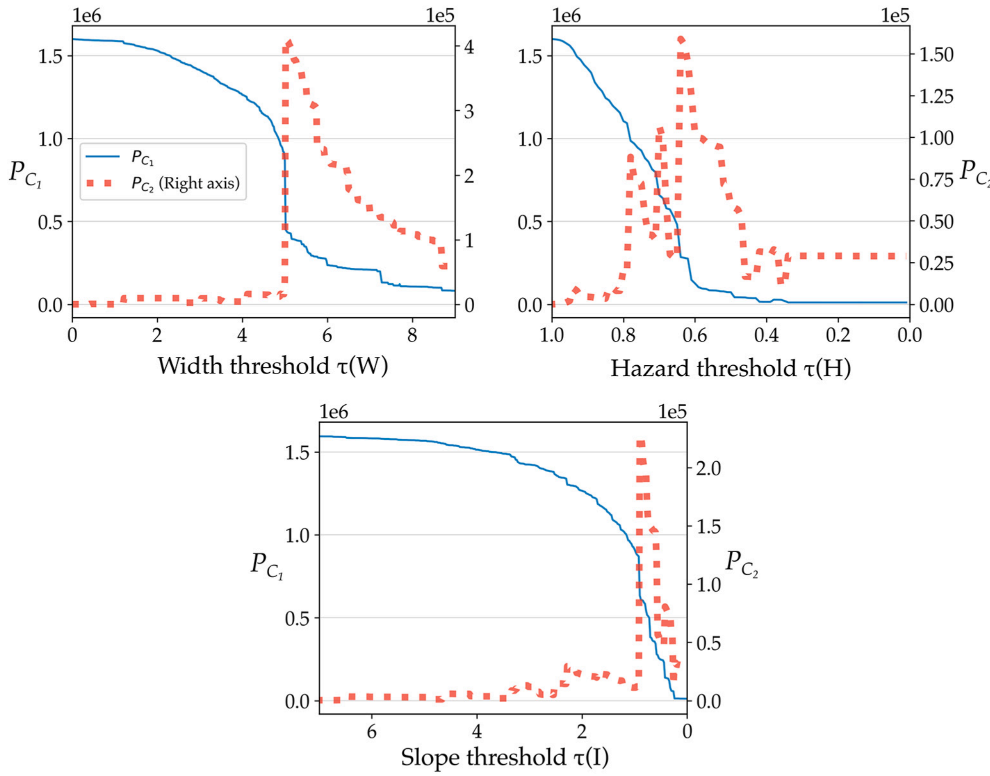

Fig. 3. Population size of the largest (blue) and second largest (red) connected component of Barcelona's sidewalk networks, as sidewalks are removed iteratively according to 3 sidewalk attributes: width W in meters, car-pedestrian accident hazard H, and slope I in degrees. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

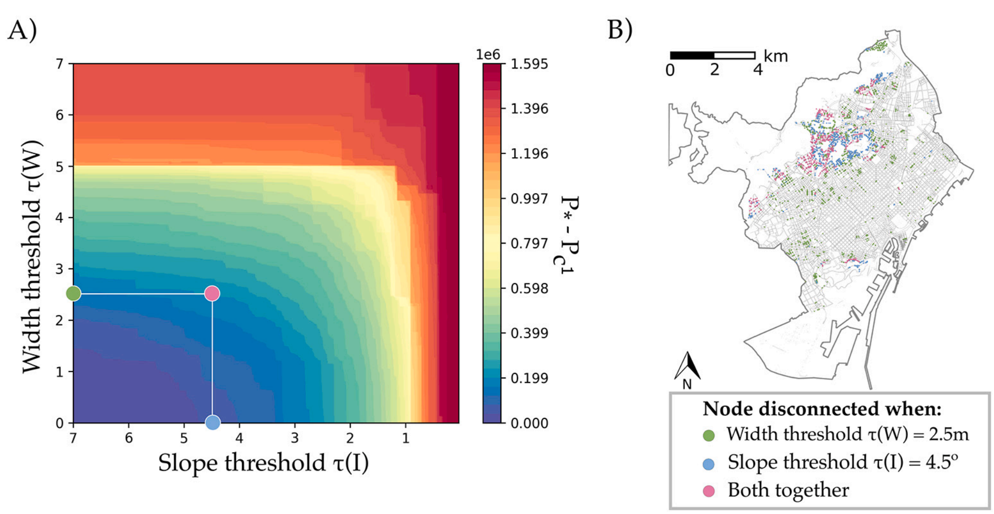

Fig. 4. Panel A: When considering both constraint properties, width and slope, at once, 10s of thousands more residents are disconnected from the largest component G of the sidewalk network. P^* is the baseline population of G prior to percolation, and $P^* - P_{C_1}$ gives the population loss. Panel B: This map shows the nodes disconnected from the network when $\tau(W) = 2.5$ meters (green), $\tau(I) = 4.5^{\circ}$ (blue), and when both constraints are applied simultaneously (pink). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

process reveals the effective connectivity of the network to be significantly lower. For example, at a combined threshold of $\tau(W) = 2.5$m and $\tau(I) = 4.5^{\circ}$., ~260k residents are disconnected from the largest component, versus 140k and 100k residents disconnected respectively when the two sidewalk attributes are considered considered separately.

The map in Fig. 4B provides insights into the geographic interplay of width and slope restrictions, again focusing on the case $\tau(W) = 2.5$m and $\tau(I) = 4.5^{\circ}$. While nodes and components disconnected by width are distributed relatively evenly throughout the ring of older street patterns that surround the famous Cerdà grid of l'Eixample and its generous sidewalks, the topography of the northern section of the city makes it more vulnerable to slope-based percolation. However, it is only when the two attributes are attacked together, as represented by the pink nodes in the map, that the central-northern area around El Carmel and the Vall d'Hebron hospital become entirely disconnected from the rest of the city. Information on additional 2-dimensional pairings of sidewalk attributes can be found in the Supplementary Materials (see Fig. S2).

3.2. *Egohood percolation*

While the full-network percolation process described above can provide information regarding the macro-scale functionality of the network, it does not allow for the assessment of local-level accessibility, and may overlook significant inequalities that exist across the urban landscape. To address this, we can shift our analysis to the pedestrian scale, and investigate the effect of percolation on the size of residents' pedestrian egohoods –the area of the city they can reach within a 15-min walk.

To generate the 15-min egohood centered on node *i*, we find the subgraph $G_i = V_i, E_i$ that contains all nodes and edges reachable within a 15-min journey originating from *i* (see Data and Methods, as well as Section S3). As can be seen in Fig. 1, the extent of a 15-min egohood will always be smaller than a circular buffer polygon with a radius of 15 min. Applying constraints to the egohood by sidewalk width, slope, or hazard through percolation will only reduce its size. As discussed in Data and Methods, our measure of performance follows the concept of "interface catchment" (Pafka & Dovey, 2017), meaning we will assess the total length (in meters) of sidewalk accessible to the pedestrian within their egohood.

Fig. 5A shows the decrease in total egohood length (extent) for each location of the network as sidewalks are iteratively removed by width. On average (blue line), pedestrians have lost 20% of their egohood extent when all sidewalks of a narrow $W < 2m$ have been percolated ($\tau(W) = 2$). However, even more notable is the wide range of results when examined on a node-by-node basis (box plots). By the same point, $\tau(W) = 2$, there are city locations whose egohoods have fallen to 50% of their initial extent. Likewise, once all sidewalks of $\tau(W) = 2.75$ have been removed, the global average egohood has fallen by about 70%, but many have fallen to 0. Supplementary Figs. S3A and B describe the same process for accident hazard and slope percolation with notable differences which, ultimately, depend on the distribution of the feature of interest.

The maps in Fig. 5B show the similarly uneven geographic spread of egohood vulnerability to width percolation, in this case for $\tau(W) = 2.5$. Unsurprisingly, the wide sidewalks in the central l'Eixample district keep, as well as the ample pedestrianized streets in the medieval Ciutat Vella neighborhoods, ensure that even width-sensitive pedestrians have access to robust egohoods. In contrast, the greatest losses in egohood extent are concentrated in the west and northwest of the city. Compounding the effects of this spatial inequality, city census data indicates that the neighborhoods whose egohoods are most robust to width constraints (i.e., those in the southeast, nearest the coastline) also tend to have relatively younger populations.

3.3. Service-centered percolation

So far, we have moved from a city-wide scale, focusing on population and connectivity, to a pedestrian-view level, considering egohood extent and local walkability. Now we attempt to synthesize both approaches, while at the same time bringing a new dimension to the problem: that of the urban services and amenities that pedestrians may walk *to*. This analysis opens up the door to potential interventions in the spatial allocation of services that could be informed by our approach, as will be explored later.

3.3.1. Access to a basket of services

For a resident, the most relevant questions regarding the walkability of their urban environment will likely be of the kind: "can I reach a grocery store on foot within a comfortable timeframe?". Measures of accessibility, when framed in this simple, use-centered way, are transparent, easy to implement, and easily explained to both residents and policy-makers' (Handy, 2020). Recent initiatives advocating the design of "15-min cities" move in this direction (Moreno et al., 2021). The basis for such initiatives is, quite simply, a belief that residents should be able to reach all their daily necessities within 15 min.

Here, following these principles, we evaluate Barcelona's performance as a "15-min city", particularly emphasizing walkability, by incorporating data on service and amenity locations into the preceding egohood percolation analysis. Fig. 6 shows the number of residents without access to some of a basket of 8 crucial services (note that 13 services overall are analyzed throughout the paper, but 8 have been selected here for clarity –see Supplementary Table S1) as sidewalks are percolated from narrowest to widest. By the time all sidewalks of less than 2.5m have been made inactive, 100 thousand people are without access to bus stops and pharmacies, the services with the largest geographic coverage. In the worst case, 400 thousand cannot reach a library or a social services center on foot. More generally, when $\tau(W) = 2.5$, an average node only has access to 10 of the 13 total services considered.

It is also interesting to see the evolution and the relative order in which the access to services is lost. Several regulated services such as bus stops and pharmacies are the least affected by the percolation process, since they are, by design, evenly spread across the city. Likewise, walking access to supermarkets is also quite robust, in line with previous research showing that some private enterprises such as marketplaces tend to locate similarly to socially-optimized public services (Um et al., 2009). However, remarkably, access to other public services such as libraries, neighborhood clinics, and day centers, degenerate much faster as width restrictions are imposed. The case of neighborhood clinics is of special interest, since without imposing width restrictions their accessibility is relatively good, but access deteriorates quickly as width restrictions rise, to the point where neighborhood clinics end up being the 3rd least accessible services by the time $\tau(W) = 3.5$.

From another perspective, we can evaluate the deterioration of access by considering the number of residents able to reach a *particular* facility location –i.e., the facility's serviceable population– before and

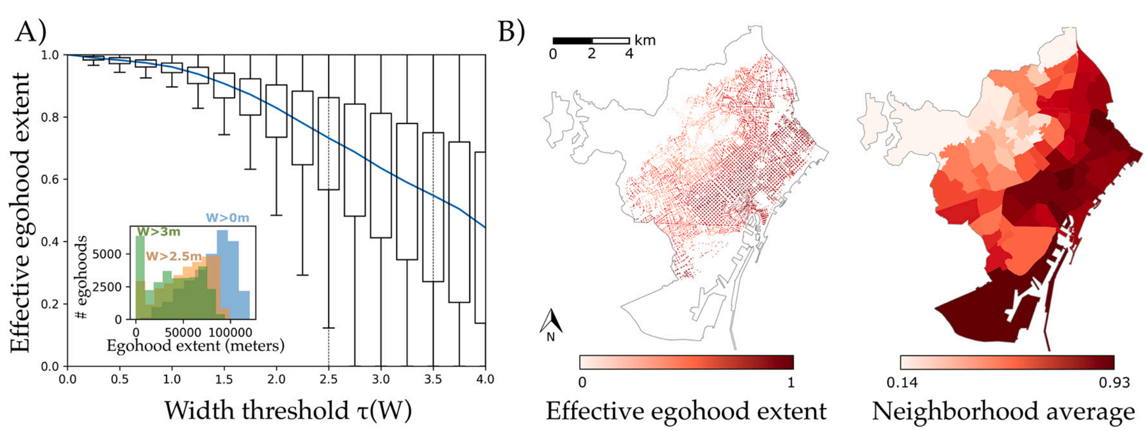

Fig. 5. Panel A: as sidewalks are removed from narrowest to widest, the median normalized egohood length falls quickly to less than 50%, with high variance. The insets show the distributions of egohood extent for selected $\tau(W)$ in more detail. Panel B: These maps show the geographic spread of the breakdown in egohood extent at $\tau(W) = 2.5$ meters. It is evident that peripheral egohoods suffer more than central ones.

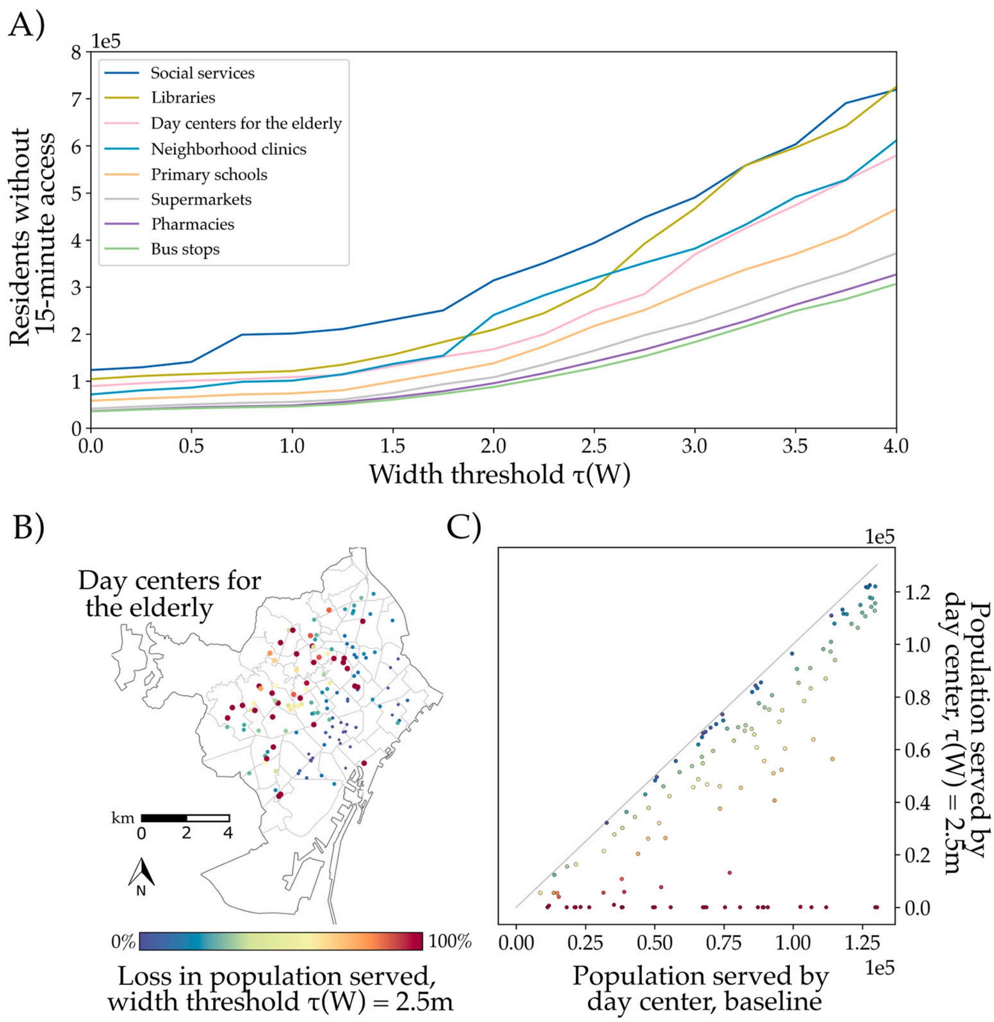

Fig. 6. Panel A: The number of residents (in thousands) without access to a given service in their 15-min egohood rises as sidewalk links are removed from narrowest to widest. Panel B: As sidewalks are made inactive, individual facilities are accessible to smaller and smaller numbers of residents. This loss in service level is mapped here for the case of day centers for the elderly. Panel C: The same information as Panel B, in scatter plot form. While some day centers are disconnected from the network, others remain connected but lose large portions of their serviceable population.

after percolation. Panels B and C of Fig. 6 illustrate this for the case of day centers for the elderly. Panel B maps the loss in serviceable population on a facility-by-facility basis. As in previous sections, we see a concentration of loss of access in the northern areas of the city (note the red points). However, the consideration of individual facilities allows us to note that, even in more central areas with generally wider sidewalks, some day centers lose access to large portions of their serviceable population (green and yellow points). The scatter plot in panel C accentuates this finding. While some day centers become completely disconnected from the network and fall to 0, others others (those points located between the diagonal and $Y = 0$) remain connected but lose a notable portion of their potential serviceable population.

Up to this point, we have approached our percolation analysis descriptively. In the following sections, we attempt to lay out how the developed framework might be used not just to evaluate, but actually to propose improvements to the city's walkable environment, by looking at two concrete use cases: access to schools and neighborhood clinics.

3.3.2. School access

Providing safe walking paths to schools for children and teenagers is a high priority for many cities. It has been shown that parental concern over traffic safety is a principal determining factor in the utilitarian walking habits of children and teenagers, particularly in the context of the daily commute to and from school (Giles-Corti et al., 2011; Mitra, 2013). Given this context, we evaluate the robustness of Barcelona's sidewalk network according to the accident hazard level H_{ij} of sidewalk edges. Specifically, we analyse the number of residents who have 15-min walking access to schools within their egohood, without having to traverse sidewalks of hazard $H_{ij} > H_{\tau}$. As can be seen in Fig. 7A, the number of residents without access to 3 different types of schools (kindergarten, elementary, and high school) rises rapidly to nearly half the population once all sidewalks of $H_{ij} > 0.8$ ($\tau(H) = 0.8$) are removed. Note also that all of the curves begin to saturate at $\tau(H) = 0.5$, the classification threshold to determine if a location is dangerous or not. This indicates that practically all residents need to cross at least one dangerous location in their path to school.

This information can be easily adapted to aid in the process of deciding which schools a student should attend. At present, the Barcelona city government provides a portal for parents where users can input their address and receive a list of schools with a maximum “location” score based on their address. The general selection criteria is distance from the address provided, but further criteria could be incorporated regarding the concept of safe and resilient 15-min egohood since, as we show here, the pedestrian network performs very different when mobility restrictions are imposed.

Fig. 7B presents an example in the form of a map, illustrating a set of nodes whose closest high school (Escola Secundària in the local Catalan) is different depending on whether the baseline egohood or the safe, effective ($\tau(H) = 0.8$) egohood is considered. In total, 4443 nodes (or 11.5% of the network) had different closest high schools within their egohood once the most hazardous sidewalks were removed. Of course, safe walks to school are not the only factor to account for when allocating school spots, but providing such information can enrich the decision-making process, both for parents and administrators.

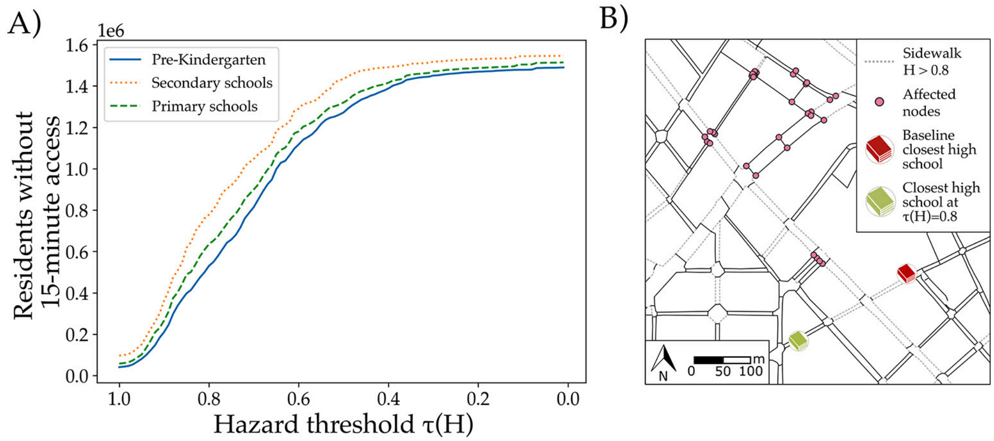

Fig. 7. Panel A: The number of residents (in thousands) without 15 min walking access to kindergarten, elementary and high schools rises as sidewalks are removed from most to least hazardous. Panel B: the closest school within each node's egohood may change under sidewalk hazard percolation. Here, orange nodes were originally closer to the red school and are now closer to the green one. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3.3. Access to neighborhood clinics

Apart from assessing access to existing services and amenities, we can also use egohood percolation to identify optimal locations for new services at very low computational cost. To explore the feasibility of such an effort, we consider the example of access to neighborhood health clinics in Barcelona.

As addressed earlier, mobility needs are often multi-dimensional. Following Bolten et al. (Bolten & Caspi, 2021), we can establish a "pedestrian mobility profile" (PMP) at a set threshold of width and slope where both values are reasonable for pedestrians with reduced mobility, here assumed as $width = 2.5m$ and $slope = 4.5^{\circ}$.Once the PMP-constrained 15-min egohoods (PMP-egohoods for short) have been calculated, we can identify the set of nodes that do not have 15-min access to a given service *s* given the constraints. From there, we can then identify the optimal location for a new service of type *s* by selecting the edge that appears in the most PMP-egohoods without access to *s*. The consideration of multiple services or facilities at once would require more complicated algorithms, but the base idea would be similar.

Constructing a new facility such as a neighborhood clinic is a capital-intensive project and a major long-term investment, and the most optimal location based on overlapping egohoods is not necessarily the most convenient, or economically feasible. For example, Fig. 8 shows the second-most optimal location for a clinic after percolation. 9500 residents who otherwise have no accessible clinic within their effective egohood are able to reach this point within a 15 min walk. As can be seen in the figure, the point is very close to an existing clinic which has been disconnected due to the steepness of surrounding sidewalks. This presents an opportunity: instead of building a new clinic a mere 350 m from an existing one as the crow flies, the location could be chosen as the optimal site of a pickup point for a shuttle to bring patients up the hill, to and from the clinic.

It should be noted that this same approach could be applied to the baseline network before percolation. However, the results (and optimal location identified) will not necessarily be the same. We see this in the case of neighborhood clinics in Barcelona. Considering the baseline network, the top two most optimal locations are identified in the extreme north-west of the city, where low intersection density lengthens walking paths to the existing local clinics. In contrast, after percolation applying the PMP described above, the top two optimal locations move to the city's hilly north, where steep sidewalks are the root cause of low levels of access.

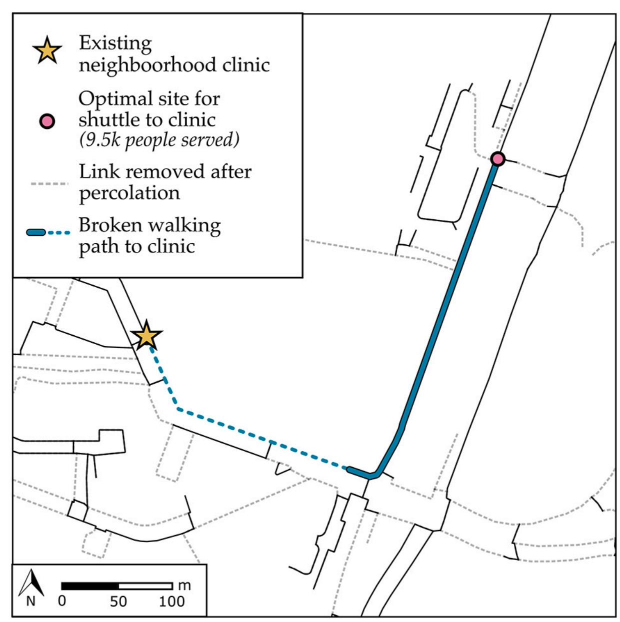

Fig. 8. Low widths and, especially, high slopes in a hilly area of Barcelona leave an existing neighborhood clinic (yellow star) inaccessible to some residents. The pink point represents an optimal location reachable by a significant number of residents without 15-min clinic access after percolation (about 9500). The pink point is only 561 m from the existing clinic along the shortest path, but the path is broken by inaccessible sidewalks (blue line). Given its proximity, this location could serve as a designated pickup point for a shuttle to the existing clinic. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

While work in the field of vulnerability analysis (VA) has led to the development of many methods to determine the risk of an asset's failure under perturbation (Chen et al., 2007; Gu et al., 2020; von Ferber et al., 2012), VA generally does not consider that, for a fraction of the population –e.g., the most vulnerable–, some infrastructure systems are disrupted even before their components are considered at risk from external stresses. Sidewalk networks provide a good example of this situation. In cities dominated by individual motorized transport, the topology of walking infrastructure is often effectively fragmented when physical constraints (even mild ones) are taken into account. In this work, we followed the idea of Personalized Pedestrian Networks and applied a widely used approach –percolation– to the problem of walkability, taking into account individual needs and vulnerabilities, both at the system-wide and egohood level.

Breaking with the common practice that monitors the size of connected components during a percolation experiment in terms of number of mutually-accessible nodes, we instead focused on the size of the mutually-connected population in our analysis. This allowed us to observe that, even when only moderate physical constraints were taken into account (e.g., no slope of more than 4.5 degrees, no sidewalks of less than 2 m), tens to hundreds of thousands of residents were cut off from the main component of the network, i.e., the city.

This finding indicated a dissonance between the macro- and micro-scales of the network. Accordingly, we moved from the bird's eye view to that of the individual pedestrian and their egohood, revealing spatial inequalities that an exclusive focus on the network as a whole would overlook. In fact, the results presented hint at an understanding of pedestrian networks that bridges the gap between these two scales. We might say that what makes a city truly walkable is the quality of its *system of walkable subgraphs*. Thus, when we see the size of accessible egohoods dropping at varying rates across different areas of the city, we are observing a structural failure of the city's walkable fabric to provide essential services within 15 min walking to as many residents as possible. This points to future work that might further contextualize pedsheds and egohoods as a system.

As both a planning and research tool, the approach we have presented here is a flexible and generalizable one, with a broad potential for application to many questions regarding pedestrian activity. First, as was demonstrated in this work, the width, slope, and hazard limits chosen can be adapted and applied to the needs of specific population segments. Beyond this, different sidewalk characteristics of interest to particular groups can be used for the analysis, well beyond the ones proposed in this work. For example, one could incorporate information about the presence of tactile paving or directional strips (i.e. textured ground surface indicators to assist pedestrians who are vision impaired) as sidewalk edge metadata, alongside other physical features, or even more subjective ones such as sidewalk “desirability” (Miranda, Fan, Duarte, & Ratti, 2021; Quercia, Schifanella, & Aiello, 2014) or perceived safety. Dynamical constraints such as sidewalk crowding could be added as well, be it from a city-wide perspective with empirical data, or from local-scale agent-based simulation (Sargoni & Manley, 2020). Finally, the analysis of egohoods can be extended to different sizes, uses, and centers, for example the relationship between walkability and public transport (e.g. metro stops) catchment areas.

It is important to emphasize that there is no one-size-fits-all solution to walkability. In fact, in some cases, an intervention to improve one aspect of walkability might impact another negatively. For example, a sidewalk widening might impact the sense of scale in a neighborhood, and decrease its pleasantness. These balances must be carefully considered, and the decisions of human planners and community stakeholders with local contextual knowledge should always be the final word. Measures of “pleasantness” and “desirability”, specifically, are difficult to define, and might easily come into conflict with other dimensions of accessibility, but they are fundamental to walking as a mode choice, and their future study in the context of walkable networks is very promising.

Notably, the most urgent limitation to the study of pedestrian issues on networks is not technical or methodological. Instead, it stems from a widespread lack of available and reliable pedestrian infrastructure data. While road networks in standardized formats are a click away for the vast majority of cities in the world, the collection and curation of sidewalk infrastructure data often needs to be painstakingly harvested from disparate and inconsistent sources. There is ample room for advocacy work in highlighting the need for enriched, precise and updated sidewalk networks made available on open-data portals, alongside expanding the availability of data on other contextualizing factors such as fine-grained land use/functional mix, job density, and pedestrian volume/flow data, to name a few.

In summary, we foresee a long way ahead to for the study of pedestrian-centered networks and their implications for planning and the wider goal of the development of low-carbon mobility. The promotion of walkability is conducive to healthy, sustainable and cohesive cities, well beyond its virtues as a transportation mode. Indeed, walking as an activity encapsulates much more than just transportation between an origin and a destination: it involves a social aspect as well, shaping the physical form, the commercial vigour and, ultimately, the cohesion of our communities (Jacobs, 1961; Loukaitou-Sideris & Ehrenfeucht, 2009). Furthermore, although practically every journey begins or ends on foot (Walker, 2012), walking is only one aspect of sustainable, multimodal transportation systems, and future work will need to address multimodality in its full scope. We cannot overlook the fact that pedestrian infrastructure forms an integral part of the greater fabric of urban transportation networks, which can be suitably represented within this paradigm as well, as a multilayer or multiplex network (Alessandretti, Natera Orozco, Battiston, Saberi, & Szell, 2022).

As the negative social and environmental impacts of car-dependent urban development are more broadly acknowledged, network models can provide the tools necessary to assess and plan for walkability while taking into account the complex, interdependent relationships between different aspects of the urban system, allowing us to effectively address challenges such as the redistribution of space, the greening of urban environments, and the undoing of car-dependent transportation regimes.

Author statement.

All authors conceived and designed the research. DR collected data, implemented the methods and performed analyses. All authors discussed the results, wrote, reviewed and edited the manuscript.

Data availability

The sidewalk network of Barcelona is available at OSF with the identifier https://doi.org/10.17605/OSF.IO/94TDC. All other data have been taken from OpenDataBCN portal of the Barcelona city.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compenvurbsys.2022.101936.

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