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Evaluating walkability: a capability-wise planning and design support system

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We present a methodology and a planning and design support software tool for evaluating walkability and pedestrian accessibility of places which are relevant for people's capabilities, and thus an important component of quality of life in cities. A multicriteria evaluation model, at the core of the decision support system, is used to assign walkability scores to points in urban space. Walkability scores are obtained through algorithms which process spatial data and run the evaluation model in order to derive potential pedestrian routes along the street network, taking into account the quality of urban space on several attributes relevant for walkability. One of its notable characteristics is a certain reversal of perspective in evaluating walkability: the walkability score of a place does not reflect how that place is *per se* walkable, but instead how and where to can one walk from there, that is to say, what is the walkability the place is endowed with. This evaluation incorporates three intertwined elements: the number of destinations/opportunities reachable by foot, their walking distances, and the quality of the paths to these destinations. In this article, we furthermore demonstrate possible uses of the support system by reporting and discussing the results of a case-study assessment of a project for the Lisbon's *Segunda Circular* (Second Ring Road). The software tool is made freely available for download.

Keywords: walkability; pedestrian accessibility; capability approach; urban quality of life; decision support systems

1. Introduction

Our quality of life in cities greatly hinges on services, facilities, activities and places accessible to us. Places where we can recreate, go or send children to school, meet people, do and buy things mould our capabilities.

We use 'capability' here in specific sense of the so-called *capability approach* (Sen 1993): a person's capabilities are valuable states of being that a person has effective access to. Thus, a capability is the effective freedom of an individual to choose between different things to do or to be that he/she has reason to value. In this conception, a capability constitutively requires two preconditions: (1) the *ability*, a person's internal power, detained but not necessarily exercised, to do and to be; and (2) the *opportunity*, the presence of external conditions which make the exercise of that power possible. A person is thus capable, has the capability to do or to be something, only if both conditions – internal and external, ability and opportunity – allow him/her to. The physical urban

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*Corresponding author. Email: ivan@uniss.it space – the city's hardware – influences capabilities primarily through the channel of the opportunity component of capabilities.

Many conventional approaches to the opportunity-based assessment of quality of life usually measure the distribution, population density and distances of different opportunities in space. But distance is not all there is. If we want to reason in terms of capabilities, we should also take into account the *quality* of accessibility. Besides the mere distance, it matters a great deal if a place can be reached also by foot or by bicycle, if the pedestrian route is pleasant and spatially integrated with its surroundings by good urban design, if it is brimful of urban activities, if it is well maintained and (perceived as) secure, if it is not submissive and surrendering to the car traffic, whether by design or by predominant social practices of use of that space.

In this article, we present a methodology and a planning and design support tool, *Walkability Explorer* (WE), for evaluating the opportunity-based quality of life by employing the concept of walkability. It considers both the actual pedestrian routes along the street network as well as their quality relevant for their walkability. There is a Chinese proverb, 'the journey is the reward'. Proverbs should never be taken too literally. Alas, in this work, we commit this mistake and propose a method for its operational treatment. We do that in this article in the following steps: first in Section 2, we discuss some background on the current state of the art; then in Section 3, we present the proposed decision support system (DSS), including the general formulation of the evaluation model and implementation details. Section 4 is dedicated to the case study, where we show and discuss the results of the application on the area of Lisbon's *Segunda Circular* (Second Ring Road); some conclusions are in Section 5.

2. **Background and related work**

Urban scholars, planners and designers are showing an ever-growing interest in accessibility as the ability to access and benefit from urban opportunities. As a result, a change of paradigm has occurred in approaches to transport planning: a shift from mobility to accessibility, considered as two distinct concepts with largely different implications for planning (Handy 2002, 2005).

While mobility planning is centred around the means of transportation and on the performance of the system with actions oriented to improve its efficiency, the planning for accessibility focuses on the trip ends and on travellers. This shifts the core of transport planning from automobile to 'people's needs'.

Such evolution implies also a change of what the relevant features to observe, and parameters to measure, are (Levine and Garb 2002). In most cases, measures of accessibility include both an impedance factor, reflecting the time or cost of reaching a destination, and an attractiveness factor, reflecting the variety of available destinations and travel choices, the qualities of the route and trip experience. The latter component recalls Hansen's definition of accessibility (Hansen 1959) as 'the potential for interaction'. Hence, the concept of accessibility is multidimensional. It may be defined in multiple ways: in terms of affordability, acceptability, availability and spatial accessibility (Litman 2011).

When expressed as a cost, the accessibility is conceptualized in terms of *impedance* between a location and attractive facilities, combining, in some way, distance, travel time (perhaps distinguishing objective and perceived) and monetary costs. When expressed in terms of attractiveness, it is very often based on the number and kind of facilities contained within a given unit or within a given distance (in time or space) from a point of origin (Apparicio *et al.* 2008), with measures including factors relevant for how a particular trip may be experienced by the traveller/pedestrian.

According to Geurs and Ritsema van Eck (2001) and Geurs and van Wee (2004), there are three basic approaches to accessibility measurement:

(1) *Infrastructure-based*, measuring the mobility performances of a transport system by taking into account the network geometry, levels of congestion and travel speed;
(2) *Activity-based*, grounded on the distribution of activities in space and time, most commonly using geographical measures of accessibility at a location (or zone) to all other destinations, and space−time measures representing the potential of activities in which individuals can participate given a time constraint; and
(3) *Utility-based*, measuring the benefits people derive from access to the spatially distributed activities.

Guers and van Eck also identify four interdependent sets of factors which determine accessibility: a transport component (reflecting travel times, costs and effort to travel between an origin and a destination), a land-use component (reflecting the spatial distribution of activities at destinations (e.g. jobs, schools, shops) and the demand for those activities (e.g. workers, pupils, inhabitants), a temporal component (reflecting the time restrictions of individuals and availability of activities at different times of the day), and an individual component (reflecting the needs and abilities of individuals).

But non-motorized travel requires a different analytic approach compared to measures of motorized accessibility (Cervero and Duncan 2003, Iacono *et al.* 2010). In the last decades, many studies and researches have explored methods and models to measure whether and how places (with their features, forms, elements, phenomena and social practices of use) are ‘walkable’ and conducive to walk, and to entangle these measurements with the attractors and opportunities available in space.

The most promising approaches combine physical environmental features and qualities with individual travel behaviours and attitudes. However, such studies encounter many obstacles due to source limitations, data availability and reliability, lack of coherence and incompatibility between scales of analysis and measurement methods.

The majority of studies contemplate environmental characteristics as a mix of land uses, street connectivity and residential density, known as D variables introduced by Cervero and Kockelman (1997). The main differences consist basically in the level of detail of measurements (macro or micro scale), data sources (censuses, surveys and ad hoc audits, secondary data) and methods of data processing and evaluation (statistics, additive methods, predictive models, etc.). Among the most referenced contributions, our research draws inspiration from methodologies and tools developed in Cervero and Duncan (2003), Porta and Renne (2005), Frank *et al.* (2006), Clifton *et al.* (2007), Forsyth *et al.* (2008) and Páez *et al.* (2013).

In Frank *et al.* (2006), the authors designed a walkability index considering walkable neighbourhoods as characterized by mixed use, connected streets, high residential density and pedestrian-oriented retail. Using similar accessibility features, Cervero and Duncan (2003) estimate the probability that residents in a certain place decide to walk or ride a bicycle, using a discrete choice model in which urban design (street and city block characteristics), land-use diversity and density patterns of built environment exert an influence on people’s travel choice.

With regard to the perceived aspects of the environment which play a role in influencing individual travel choice, audit tools represent an interesting method of analysis because they consider people behaviours, travel choices and perception of urban space. Among others, the so-called Pedestrian Environment Data Scan audit instrument (Clifton *et al.* 2007) rates the overall sense of safety/security of street segments for both walking and cycling. Audit tools are very close to our research method, as they focus on micro-level factors going beyond the mere 'objective' analysis of census–block indicators and assess the individual perception of the space.

In particular, these methods allow to analyse individual behaviours and investigate urban features that make places 'walk-conducive', factors which are very difficult to capture from 'objective' data (as stressed by Ewing and Handy 2009). The study by Porta and Renne (2005) overcomes this problem by proposing a method to investigate urban design linked to social urban sustainability through objective indicators. Through a set of urban-fabric and street indicators, they investigate features representative of the urban environment's ability to encapsulate the pedestrian: the sense of enclosure, the sense of safety and welcoming, the interaction between people and activities. However, the authors' evaluation concerns discrete street shots expressing a static view, while in our work we consider the whole edge in order to depict the spatial and temporal continuity of pedestrian perception.

Advances in geospatial technology and the availability of online maps and data sets made possible the development of a number of evaluation methods and tools available online (such as 'Walk Score', 'Walkshed', 'Ped Shed', among others), which attempt to capture features of walkability. Walk Score (Walk Score Website), for instance, represents a quick, free and easy-to-use proxy of neighbourhood density and accessibility to nearby amenities. The method consists of a summary measure of walkability based on the distance to amenities within a 1 mile radius from an evaluated location. Walk Score uses publicly available data addressing time-sensitive limitations of ordinary measures of the physical environment and it represents a useful measurement of access to facilities on a large scale. However, it does not afford to explore and measure exhaustively the relationship between the individual and the features of urban space which affect the propensity to walk. In this sense, various authors who validated the index (Carr *et al.* 2010, Duncan *et al.* 2011, Manaugh and El-Geneidy 2011, Steiniger *et al.* 2013) in the US and Canadian cities recommended to integrate Walk Score with supplementary measures of built environment related to pedestrian friendliness, such as aesthetics, topography, security and weather conditions in order to take into account factors which are objectively and subjectively relevant for people's propensity to walk. In accordance with such recommendations, the method proposed in this article combines available open data of the street network and urban design features with direct in situ observations of further features (see Section 3.1) for the purpose of calculating a composite walkability score which, in our opinion, more carefully and comprehensively captures the concept of walkability. The Walkshed web tool (Walkshed Website) derives a 'walkability surface' that evaluates the quality and diversity of urban opportunities accessible without frictions (rivers, topological constraints, freeways, railway tracks, *cul-de-sac*, etc.) within a1 mile radius (During (1996)). The web tool asks users to provide and fine-tune the priority of a set of factors, which are then used by the tool to derive the heatmaps expressing the walkability of neighbourhoods. Other freely available calculators of walkability, such as 'Walkonomics' (Walkonomics Website), 'PERS' (PERS) and 'WalkYourPlace' (Steiniger *et al.* 2013), are similar in the conception as they stand out as rating tools which involve people in the assignment of single streets scores consistent with specific criteria or situations related to pedestrian friendliness (e.g. pedestrian level of service).

Building onto many aspects of the methods and tools discussed above, the model we developed aims at focusing on the quality of urban environment and conditions which influence individual behaviour. It is sensitive to spatial scale, goes beyond the analysis of travel times and focuses on urban design, physical features of the path, land-use patterns and social factors as more decisive measures of impedance related to the choice of walking. In particular, we made an effort to enrich the standard spatial information (street network and urban fabric) by introducing other qualities and features that do not emerge from classical measures of accessibility, but nevertheless play, we hold, a significant influence on people's preference and willingness to walk. Factors such as degree of (urban design) integration, degree of maintenance, car parking along the road, speed limits, and so on, which are all qualities of the urban environment important with respect to their conductivity to walk. These are all concerns related to the 'human scale', imageability (Ewing and Handy 2009), sense of safety and welcoming, interaction between people and activities and urban detractors (Porta and Renne 2005), which influence people's perceptions and behaviours. These aspects and principles, in many ways, echo Jane Jacobs' 'conditions for city diversity' Jacobs (1961) (mixed uses, small building blocks leading to a dense network for walking, concentration or density). In this sense, our evaluation method should be seen as an attempt to operationalize these principles and to link it to the capability approach perspective of urban quality.

Our research is an attempt to build an evaluation model and a planning and design support tool that takes into consideration many of these concerns, and focuses on the quality of pedestrian accessibility as an important factor for the extension of urban capabilities. The assumption of an accessibility-enhancing perspective requires very strict integration and collaboration between transportation planning, land-use planning and urban design. From the point of view of planning and design practice, WE was developed both for evaluating the actual walkability of an urban area, as well as for assessing and comparing possible future scenarios related to urban projects and transformations. That is why, after presenting and specifying the evaluation model, we also present an example application of assessment of one urban project for Lisbon's *Segunda Circular*.

3. **The planning and design support system**

In this section, we present a methodology for evaluating and comparing pedestrian routes along a street network in relation to their walkability. Moreover, we describe the main characteristics of the software tool which implements the proposed evaluation procedure.

In the DSS, we model how people at different points in space can walk to destinations of interest in an urban area, using a detailed graph representation of the street network. Destinations may be divided into separate categories, each representing a different type of 'urban opportunity' (e.g. green areas, commercial and retail, services, etc.) For each category of destinations, we define the pedestrian behaviour as a maximization problem, given the distance and the quality of pedestrian accessibility of destinations belonging to that category. This then allows to produce a raster map of *walkability scores* in urban space from the point of view of pedestrians. This approach makes it possible to compare different planning and urban design scenarios by comparing their impacts on the respective walkability scores distributed in space.

3.1. ***Evaluation model***

We assume that a resident living at one point in space will walk to available destinations a certain amount of times, and will, from that, derive some benefit B defined by the following constant elasticity of substitution (CES) utility function:

$$B = \left(\sum_{i=1}^{n} X_i^{\rho}\right)^{\frac{1}{\rho}} \tag{1}$$

where n is the number of available destinations, X_i is the number of times the resident visits the i-th destination and $1/(1-\rho)$ is the elasticity of substitution (EOS) among destinations.

This choice of modelling the benefit from walking to available destinations contains the kernel of the evaluation method. It relates to the properties and features we want to incorporate when conceptualizing walkability, so let us provide some rationale of its underlying behavioural and normative assumptions. Equation (1) exhibits several desirable properties which plausibly account for relevant aspects related to the walking behaviour we intend to model. First, the function represents convex preferences, that is, in our case, the benefit from visiting a destination multiple times is marginally diminishing. Second, and more importantly, it incorporates the assumption of differentiation of destinations belonging to the *same category*. Should we, in the context of this type of modelling, instead assume destinations of the same category to be undifferentiated (i.e. 'homogeneous' in the terminology of economics), the optimal behaviour for a resident with more than one destination available at different distances would be to always and only walk to the closest one. This is clearly in contrast to the observable behaviour, and points at the fact that two destinations of the same category are, from the point of view of an individual, not considered as perfect substitutes. Another way of framing this is to say that there is a preference for variety, even among destinations belonging to the same category (among categories of the kind we are classifying destinations in our model). Lastly, to add another turn of the screw, recall that our pivotal methodological orientation is to formulate walkability within the framework of the capability approach, which is grounded on a core assumption that we need to draw a distinction between functionings and capabilities of an individual. Functionings are the set of effective (observable) endowments and states of being (what people are, do and have), while capabilities are the set of all the potential and possible functionings one may have reasons to value (what people choose to pursue to be, do and have). Grounded on the idea that well-being and quality of life are intrinsically connected with the possibility of free and (self-)responsible human agency, this attitude thus places a relevant weight on the amplitude of available capabilities one is free to choose from. All this has a precise normative implication in our case, an implication embedded in our choice of modelling: what we want to imply with Equation (1) is not so much that all the people, as a matter of their functionings, actually walk to all the available destinations, but rather that that availability, as a matter of their opportunities, is in itself a relevant fact, as part of people's capability sets, and therefore of their urban quality of life.

Given the benefit function (1), we further impose the following constraint upon the pedestrian:

$$\sum_{i=1}^{n} c_i X_i \leq M \tag{2}$$

where c_i is the cost the pedestrian foregoes to reach the destination i, and M is the available budget with a conventional constant value.

A path from an origin to a destination is a set of n interconnected edges of the graph representing the street network. Besides sole distances, we describe edges on further attributes which shape the quality of the pedestrian accessibility, characteristics such as physical features, urban design and presence (or absence) of variety of urban activities. These attributes serve to model the cost of a path used in Equation (2). We define the cost of a path of p edges, each having n_a attributes, as

$$c = c_o + \sum_{k=1}^{p} l_k \left[\!\left[1 - \left(\sum_{j=1}^{n_a} w_j a_{k,j}^{r} \right)^{\frac{1}{r}} \right]\!\right] \tag{3}$$

where c0 is a fixed cost, l_k is the length of the k-th edge in the path, $a_{k,j} \in [0,1]$ is the value of that edge's j-th attribute, w_j is the weight of the attribute (with $\sum w_j = 1$) and r is a parameter with 1/ (1- r) being the EOS among attributes. This expression yields unit variable cost of 1 when all attributes are at their lowest value (i.e. 0), and approaches 0 when attributes approach the highest value of 1.

Among many alternative paths from an origin to a destination in a street network, we plug the cheapest one into Equation (2) (see Section 3.4).

Under the constraint in Equation (2), the benefit in Equation (1) is maximized when

$$X_i = \frac{c_i^{\frac{1}{\rho-1}} M}{\sum_{j=1}^{n} c_j^{\frac{\rho}{\rho-1}}} \tag{4}$$

The *walkability score W* we attribute to a point in space is this maximum benefit which, under the assumption of the behavioural model, may be yielded by a person residing at that specific point. In other words, for each node in the graph:

$$W = \max B \tag{5}$$

It follows from this modelling that we directly account for possible single-purpose walks. This must be acknowledged as a limitation we assumed for the sake of greater modelling and implementation simplicity. A potentially interesting development may be to explore how, within this modelling framework, to coherently account in an explicit manner also for multipurpose trips (visiting more destinations in one go) and zero-purpose trips (pure leisure/recreational walks). Although what we now evaluate may, to some degree, represent a proxy of the overall landscape of walking opportunities, we are aware that overcoming the aforementioned limitation requires worthwhile further investigation.

3.2. ***Edge attributes***

To evaluate the quality of pedestrian accessibility, we define the cost of a path in Equation (3) as a function of edge attributes. These attributes are factors relevant for the walkability of a pedestrian route. In the general formulation of the model, they are intended to describe the urban quality, traffic and road conditions, land-use patterns, building accessibility, degree of integration with the surroundings, safety and any other feature and practice of use of space important to pedestrians.

In Table 1, we report the attributes, their weights and scales of measure used in our preliminary application discussed in Section 4.

Table 1. The edge attributes included in the DSS and their values adopted for the example application discussed in Section 4.

		Weight w	Scale (values of a in Equation (3) are in parentheses)
Urban design	Building density	1/9	dense (0.8) – rarefied (0.5) – undeveloped (0.2)
	Degree of integration	1/9	integrated (0.8) – filtered (0.5) – separated (0.2)
	Street type	1/9	access (0.8) – residential (0.5) – crossing/bypass (0.2)
Physical features	Bicycle track	1/30	present (0.8) – absent (0.2)
	Number of car lanes	1/30	0–2 (0.8) – 3–4 (0.5) – more than 4 (0.2)
	Car speed limit (in km/h)	2/30	less than 40 (0.8) – 40–60 (0.5) – more than 60 (0.2)
	One-way street	1/30	yes (0.8) – no (0.5)
	Car parking along the road	1/30	not allowed/practiced (0.8) – allowed/practiced (0.2)
	Footway width (in meters)	2/30	more than 3 (0.8) – 1.5–3 (0.5) – less than 1.5 (0.2)
	Degree of maintenance	2/30	good (0.8) – sufficient (0.5) – bad (0.2)
Land-use pattern	Commercial activities	2/9	predominant (0.8) – present (0.5) – absent (0.2)
	Services and offices	1/9	predominant (0.8) – present (0.5) – absent (0.2)

The attributes are organized in three categories: *urban design*, *physical features* and *land-use patterns*. Their meaning should be straightforward, except perhaps for the attributes of urban design, where our attempt is to capture three noteworthy aspects:

(1) *Building density* surrounding the street, for which 'dense' stands for a continuous urban fabric; 'rarefied' for a non-continuous, scattered urban fabric; the 'undeveloped' modality stands for undeveloped land, *terrain vague*, abandoned or obsolete spaces and buildings;

(2) *Degree of integration* of the street with the surrounding buildings and space: 'integrated' stands for a complete spatial and functional continuity between the street and the surrounding building and space; 'filtered' means that it is possible to access the surroundings, but it is filtered by some architectural and urban design device or pattern, such as fences or other type of barriers with entrance gates or pathways; 'separated' stands for a complete separation between the street and the surrounding urban fabric, such as continuous walls or fences;

(3) *Street type*, which may function as an 'access' to publicly available activities along the street, as a primarily 'residential' road, or as a 'crossing', with a bypass or underground pedestrian passage. Furthermore, as can be observed from the attributes of a land-use pattern, we attach commercial and retail activities and services directly to the edges of the street-network graph. As explained in Section 3.3, this information is then used by the software to determine attractive nodes for these categories of destinations, while for parks, green and recreational nodes of destination, we use the polygons representing such urban areas which are included in the geodata.

The list of edge attributes in Table 1 is, of course, far from complete. Further attributes may show to be useful to assess walkability, and we are surely failing to account for important aspects such as practices of use of space, social climate, perception of personal security, and many more. Nonetheless, our primary objective in this work was to lay down an evaluation framework in general terms. Given the flexibility of our DSS software tool, scholars and practitioners are of course welcome to enrich, adapt and plug in other attributes according to particular normative assumptions, empirical findings and available data.

3.3. ***Origins, destinations and interpolation of walkability scores***

As described in the previous section, the model assigns a walkability score to all the graph nodes, which are potential origins of trips to destinations accessible by foot.

However, the available street network does not represent all the areas accessible to pedestrians. For example, the pedestrian paths internal to private areas or parks are often not included in the available data. As a result, the scattered walkability scores corresponding only to the nodes of the graph would be too coarse to provide a suitable evaluation tool. For this reason, we also spatially interpolate walkability score values in a raster of a (user-)given resolution representing the urban area under study.

The first step of the evaluation procedure consists of defining the origin and destination nodes of the graph representing the street network.

As for the origins, in order to optimize the quality of the interpolation, we need nodes as much as possible uniformly distributed in space. This is not always the case for a graph representing a street network (e.g. in case of streets with widely separated intersections). For these reason, we obtain the set S of origin nodes through a preliminary *intensification* process in which the number of nodes in the graph is incremented in order to avoid edges longer than a predefined distance δ.

As for the destinations, we select a set D of nodes from the graph as follows:

(1) First, a set of polygons representing attractive areas is identified on the map; each polygon should be sized so as to represent a zone of attraction fairly independent of its neighbouring areas;
(2) Then, the set D of destination nodes on the graph is constructed by finding the nodes of the graph closest to the centroids of those polygons.
(3) In Figure 1, we show an example of a street network with origin nodes, an attractive area and the corresponding destination node.

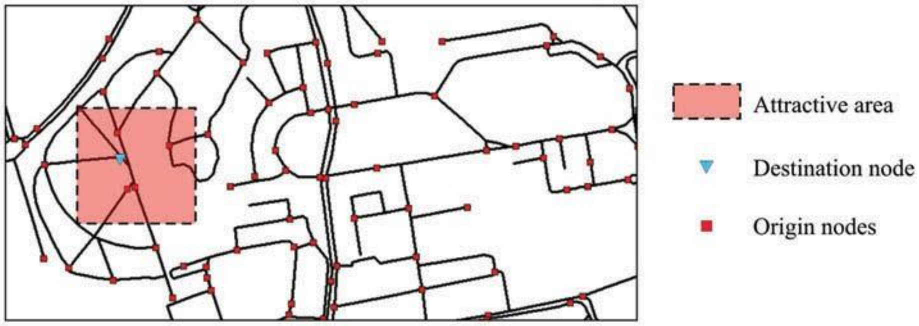

Figure 1. Origin nodes, attractive area and the corresponding destination node.

3.4. Evaluation procedure

To compute a suitable map of walkability scores associated to a street network and a set D of attractive nodes, we first determine the walkability score associated to each origin node in the set S: We then interpolate the score values to obtain a raster representation.

The walkability scores are computed according to Algorithm 1, which takes as inputs the graph of the street network, the set S of origin nodes (i.e. the nodes for which the walkability score is to be calculated) and the set D of destination nodes (i.e. those representing attractive zones of the urban area under consideration).

The first step of Algorithm 1 (lines 1−2) consists of applying a suitable graph search procedure for determining all the cheapest paths between the nodes in S and the nodes in D: For that purpose, in the current implementation of the DSS, we use an efficient version of the well-known Dijkstra's algorithm (Dijkstra 1959), which solves the single-source shortest path problem for a graph with non-negative edge costs. In our case, the edge cost is defined by Equation (3). The main characteristic of the Dijkstra's algorithm is to determine the cheapest paths between a given node and a set of destination nodes belonging to the graph. For this reason, and since usually $|D| \ll |S|$, it is much more convenient to execute the graph search starting from each node in D (i.e. from the destinations to the origins, as defined in Section 3.3).

Subsequently, in lines 3−11, for each origin node $n_S \in S;$ the costs of the cheapest paths to each destination node $n_D \in D$ are used for the computation of the node walkability score according to Equations (1) and (4).

Algorithm 1: Computation of the walkability score for each node in the set S:

```
(1)  foreach destination node $n_D \in D$ do
(2)      Compute the cheapest paths $P_{(n_D,n_S)}$ $\forall\, n_D \in S$;
(3)  foreach origin node $n_S \in S$ do
(4)      $x_d \leftarrow 0$;
(5)      $u \leftarrow 0$;
(6)      foreach destination node $n_D \in D$ do
(7)          $c_{DS} \leftarrow$ cost of $P(n_D; n_S)$ based on Equation (3);
(8)          $x_d \leftarrow x_d + c_{DS}^{\rho/(\rho-1)}$
(9)      foreach destination node $n_D \in D$ do
(10)         $u \leftarrow u + M\, c_{DS}^{\rho/(\rho-1)}$
(11) Assign to $n_S$ the walkability score $(u/x_d)^{1/\rho}$;
```

As explained in Section 3.3, we interpolate the scattered walkability score values computed by Algorithm 1 on a raster of a given resolution representing the urban area. In particular, we use the simple inverse distance weighting (IDW) (Shepard 1968) method, which proved suitable for the purpose. More in detail, for each point *x* of the raster, the interpolation phase considers the nodes holding a walkability score which fall within a fixed radius σ. The value of the latter should reflect the distance that a pedestrian would walk to reach the main street network. If the number of nodes $n_i \in S$ falling within *r* is $n_X;$ the walkability score of x is calculated as

$$W\,(\mathrm{x}) = \sum_{i=0}^{n_X} h_i W_i \tag{6}$$

where W_i is the known walkability score of $\mathbf{n}_i$ computed through Algorithm 1. We compute the weight h_i of each node holding walkability score, as proposed in (Franke and Nielson 1980):

$$h_i = \frac{\left(\frac{r - d_i}{rd_j}\right)^a}{\sum_{i=0}^{n_X} \left(\frac{r - d_i}{rd_j}\right)^a} \tag{7}$$

where $d_i = dist\ (\mathbf{x}, \mathbf{n}_i)$ is the distance between the point $\mathbf{x}$ and $\mathbf{n}_i$, and α is the so-called *power parameter*. The latter should take into account the decay of walkability score, which is due to walking between the point x and the nodes $\mathbf{n}_i$. In general, a higher α corresponds to a stronger decay in the walkability score (i.e. to a lower walkability of the areas not included in the street network). Typically, the value of α is chosen between 1 and 3.

3.5. **Implementation**

We have implemented the above-presented approach in a DSS application, WE, developed for MS Windows systems and freely available for download.[1]

The user interface of WE allows an easy assessment of the effects on walkability of projects and alternative scenarios of street network, planning and urban design.

To perform an evaluation, a WE user is asked to provide the current and the modified (alternative project or scenario) road networks, in the format defined by the *Open Street Map* (OSM) project (The OpenStreetMap Foundation 2014). The latter is a collaborative project for the creation of street maps that currently makes available a huge database covering most parts of the world. In addition to the availability of street network data, the advantage of using OSM for this application lies in the ease of introducing new attributes and topological changes to the graph. For this purpose, there are several effective editing applications freely available.

As shown in the WE workflow scheme in Figure 2, given the OSM data enriched with the attributes relevant for walkability (such as those listed in Table 1), the DSS identifies the areas of attractions using a regular grid of cells, according to a resolution set by the user, and constructs the sets of destination nodes. It is worth noting that the size of such cells can be set independently for different types of attractions. More in detail, WE identifies the areas with prevalence of retail/commercial and service activities using the

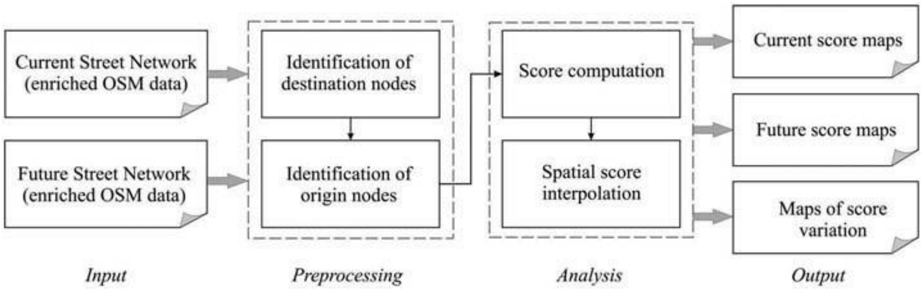

Figure 2. Typical WE workflow. The only required input data are the current and future street network data in OSM format enriched with the attributes in Table 1. After the preprocessing and analysis phases, the main output is represented by the maps of walkability scores at the desired resolution.

specific attributes attached to the edges in the OSM data. For the green areas and recreational attractions, the current implementation of WE exploits the polygons representing such urban areas, which are typically included in the OSM data. As explained in Section 3.3, the software tool builds the set of destination nodes by finding for each attractive cell the node of the street network closest to its centroid.

Subsequently, WE determines the origin nodes for both the current and the alternative street networks, as explained in Subsection 3.3. It is worth noting that, to increase the comparability of walkability score maps, during the intensification process, the program tries to assure that the origin nodes of the current and the alternative street networks coincide. This is obviously not possible when the alternative scenario includes geometrical and topological changes of the network.

The analysis run allows to determine the walkability score according to the procedure described in Section 3.4. The computation is carried out for the current and the alternative street networks and for the required categories of attraction. In order to shorten the run time, WE exploits the available multicore CPU computers implementing a parallel multithread computation for executing Algorithm 1.

The final outputs of the program are geo-referenced walkability scores for both the current and the alternative street networks and for the required categories of attractions. Moreover, WE generates the maps of variation in walkability scores between the current and the alternative scenarios. All the above maps can be exported in a suitable GIS format, and the raw output data can be saved as CSV files for further elaboration and analysis.

The processing described above requires extensive elaboration of geo-referenced data, as well as the possibility to efficiently perform spatial queries. For this reason, the DSS has been implemented using the C++ MAGI library (Blečić *et al.* 2009a,b), which makes available efficient spatial indexing functions.

4. **An example application**

To present the functioning and outputs of the DSS, we developed an example application on the area of the Lisbon's *Segunda Circular* (Second Ring Road). We want to primarily demonstrate WE's vocation as a planning and design DSS, so we briefly present here an assessment of a project of redesign and reorganization of the road network, public spaces and land-use destinations around the area of the *Segunda Circular*.

The categories of attractions we used were: commercial/retail activities, recreation (parks, green areas, etc.) and services. The parameters adopted for the assessment are reported in Table 2, while the weights of the edge attributes were those reported in

Table 2. The parameters used in the assessment of the *Segunda Circular* project. (EOS – elasticity of substitution)

Parameter	Value
EOS among destinations $1/(1-\rho)$	2.5
Virtual budget M	1000.0
Fixed cost c_0	0.0
EOS among attributes $1/(1-r)$	0.3
Intensification distance δ [m]	100.0
Interpolation radius σ [m]	500.0
Power parameter α	2.0

Table 1. On the account of this specific example parameterization, we again must emphasize that our primary goal here is to present the general formulation of the evaluation model and the kind of analysis that may be obtained from running it. For the purpose of the example application, the parameters were set to values that are plausible and coherent with the logic of the capability approach. The two most relevant parameters, the two EOS, deserve a brief comment. When deriving the walkability component of edge costs, the EOS among attributes was set relatively low (0.3) in order to model a low degree of substitutability among attributes (EOS = 0 yields Leontief — that is perfect complements — utility function). Intuitively, if an edge has a low rating on a small number of attributes, if should tend to have a low overall walkability. In other words, for an edge to be reasonably well walkable, it should be rated well on many, possibly all, attributes, since this specific parameterization does not permit strong compensations among attributes.

As for the EOS among destinations, the value (2.5) models an intermediate degree of substitutability among destination (Equation (1) becomes the Cobb−Douglas utility function when EOS = 1, and tends to the perfect substitutes function when EOS tends to infinity). This is in accordance with the motivation for the choice of modelling provided above (the assumption of differentiation – i.e. non-homogeneity – of destinations, see above Section 3.1), which asks for some, but not perfect substitutability among destinations belonging to the same category.

All in all, we are aware that the validity of the results ultimately relies on the possibility of modes of empirical validation of parameters. We are undertaking a study of choice modelling based on experimental design of stated preferences (Hanley *et al.* (2001)) specifically devised for the purpose of parameterization of the hereby presented evaluation model. We again should add that WE DSS is fairly flexible, and offers user-friendly interfaces which allow users to set and adjust the parameters of the model and to modify the attributes, according to particular normative assumptions or empirical findings. The baseline OSM street network was enriched by us with the attributes in Table 1 through direct observation assisted by Google StreetView. The locations of attractive destinations were further derived from ancillary sources such as Google Maps, Yellow Pages and census data.

Figure 3 shows a side-by-side comparison of the street network graph, with the computed unit cost attached to edges, before and after the project. As can be seen, the downgrading of the *Segunda Circular* from highway to urban avenue, which is the main feature of the project, is reflected by the lower costs along the central traffic artery.

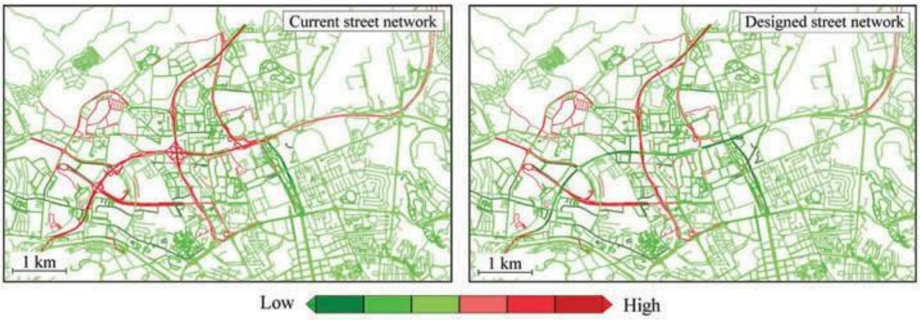

Figure 3. Street network and computed unit cost of edges.

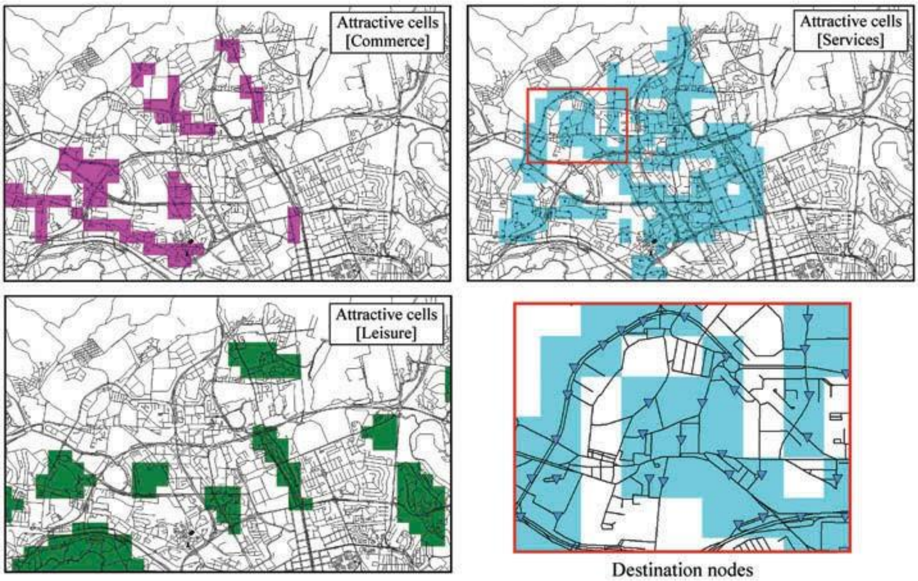

Figure 4. The destination cells for the three different type of attractions. To each cell, a destination node belonging to the street network was associated.

The destination nodes were identified considering attractive areas represented by 200 m cells. In Figure 4, we highlight the cells holding destination nodes for the three categories of attraction.

In Figure 6, in the left-hand column (maps a, c and e), we represent the current distribution of walkability scores for each category of attractions, using a raster with 20 m interpolation resolution.

By definition, the theoretical minimum of the scale of walkability is 0, while the maximum is unbounded, although it is, in practice, limited by the possible configurations and number of possible destinations in urban space. To build some intuition of what walkability scores reflect on the ground, in Figure 5, we present examples of walkability scores for a few origin nodes, their respective retail/commercial destination nodes and the unit cost of edges to get there.

In interpreting these figures, it is important to recall that the walkability score incorporates three elements: the number of destinations (the more the better), the walking distances (the closer the better) *and* the walking quality of edges (the better the better). Therefore, one has to observe these three elements *in combination* to grasp why the walkability scores are what they are. When, for example, comparing the situations with scores 40 vs. 30, one notes that the node 40 is on average closer to reachable destinations, and its being more central makes it include two more destinations to the East. The case of the two nodes with the score 20 is interesting, because it illustrates the interplay of the trade-offs: the node 20(a) is somewhat closer to the bulk of destinations, and has more available destinations considering only distances, *but* it is also poorly connected to the rest of the street network via that first tract which has a high walkability cost. Conversely, 20(b) has less available destinations but is, in terms of walkability, better integrated into the street network to reach them. Finally, the node with walkability score of 10 shows an exemplary case of pedestrian isolation due to a barrier of a high-intensity road. The

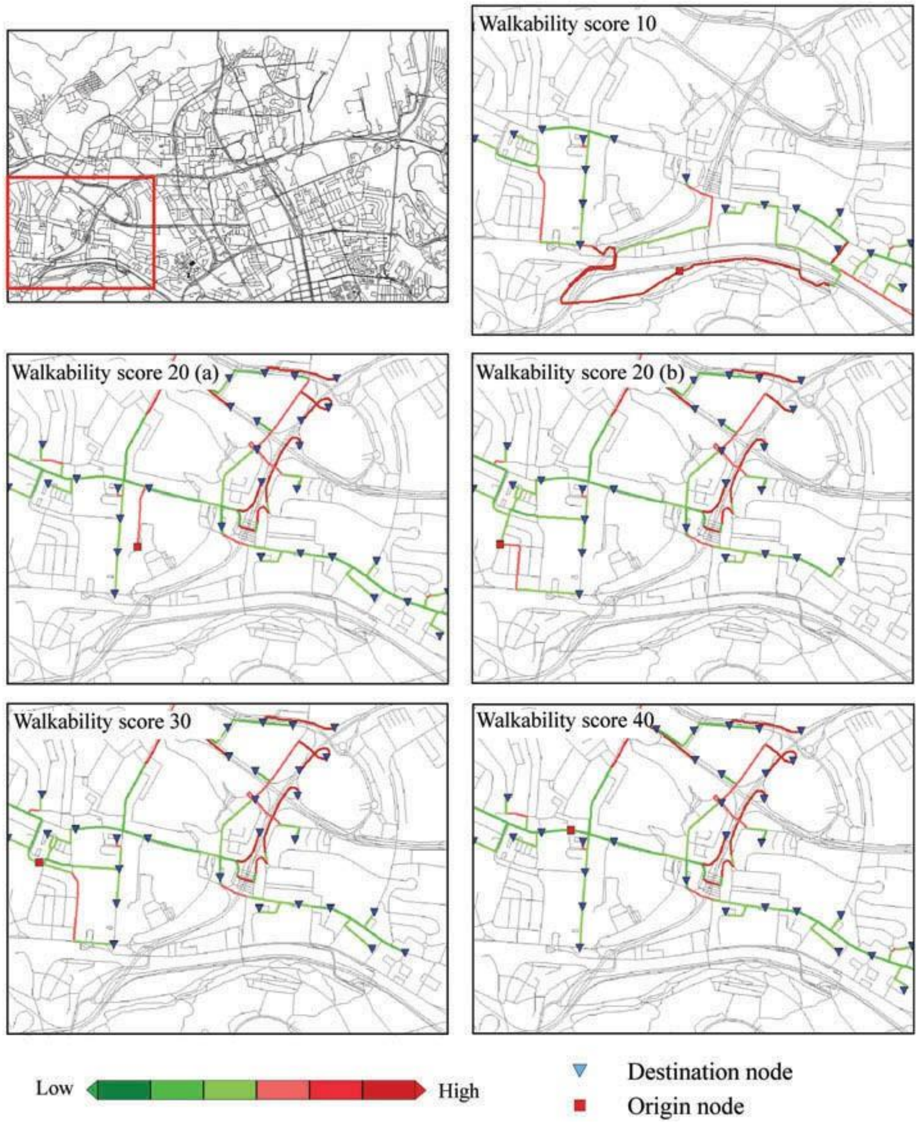

Figure 5. Examples of walkability scores. Each figure shows an origin node (square symbol) for which the score is computed, the retail/commercial destinations (point-down triangle symbol) reachable by foot and the unit cost of the edges used for paths.

impermeability of the roadway to the North forces someone finding oneself at that point to walk a long and poorly walkable way to get to the other side where the destinations of interests are.

To get onto properly planning and design support facets of WE, we have to present its analytic capabilities of *comparison* among alternative planning and design scenarios. The absolute variations in walkability scores after the project, for each category of attractions, are shown in the right-hand column (maps b, d and f) of Figure 6.

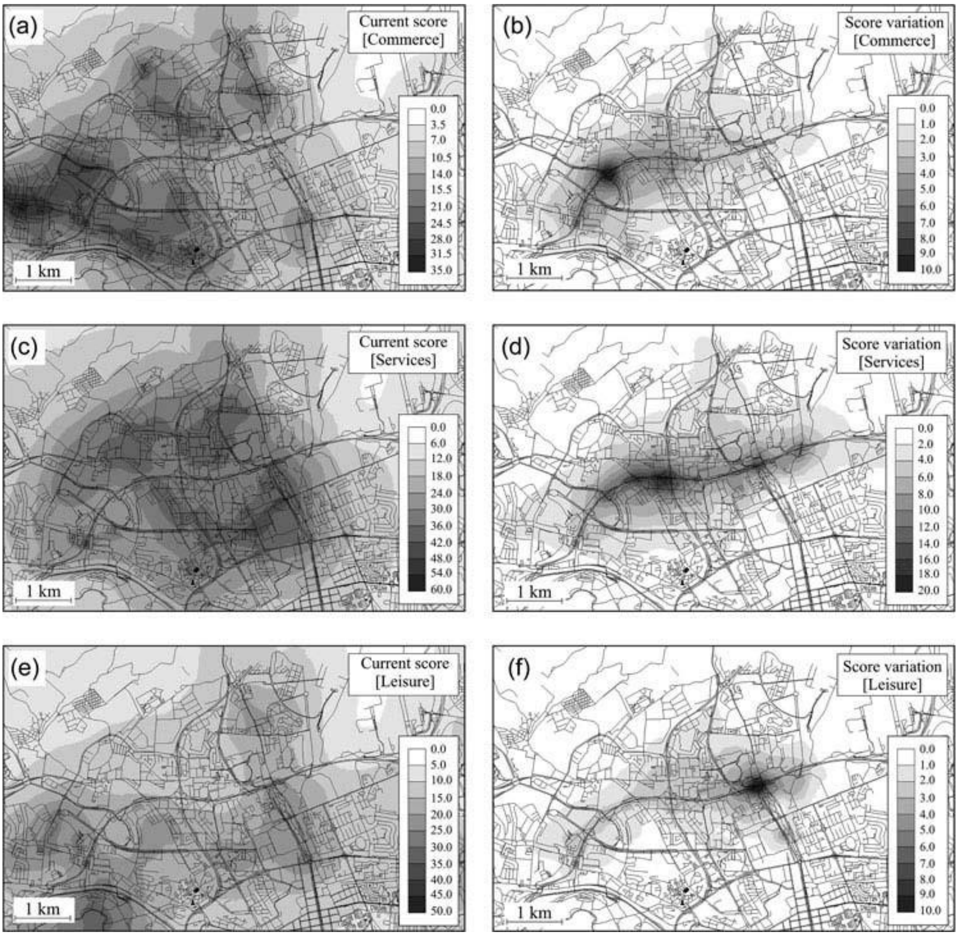

Figure 6. Current walkability scores for each category of attractions (left-side column: maps a, c and e) and changes in walkability scores due to the project (right-side column: maps b, d and f).

As can be observed in the figures, the project has a notable impact on the walkability related to retail/commercial activities primarily in the West, on the walkability related to recreational areas in the East, and on that related to services in a wide stripe along the *Segunda Circular*. This effects are primarily due to the pre-existing distribution of destinations, which the project ‘simply’ made better accessible by foot.

The comparison between the current situation and the project deserves a further exploration, especially in terms of distributional concerns for inhabitants, concerns which, consistently with the capability approach, should be an important factor when assessing the effects of an urban projects and policies.

For that purpose, our DSS allows to import and combine the census data with the raster layer of walkability scores in order to assign residents to each cells. It thus becomes possible to assign a walkability score not only to cells in space, but also to inhabitants residing in those cells. The box plots in Figure 7 offer an overview of the distribution of walkability scores of inhabitants, before and after the project, for each of the three

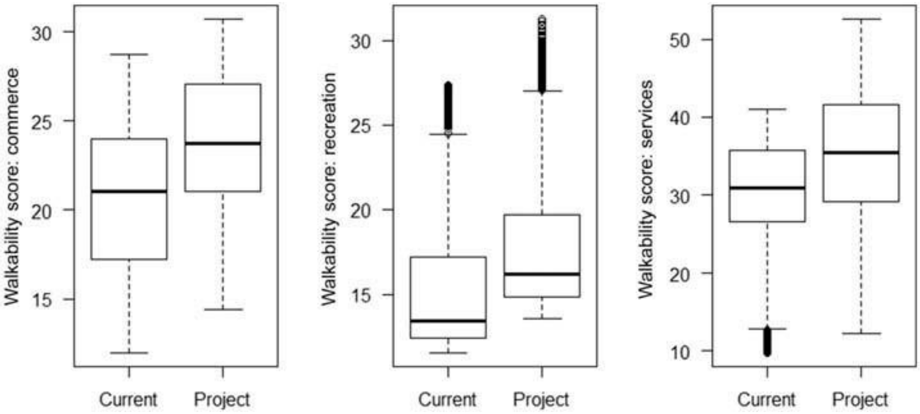

Figure 7. Box plots of the distributions of walkability scores of inhabitants, before and after the project, for each of the three destination categories.

categories of destinations. It may be observed that, indeed, the project has an overall beneficial effect on people's walkability.

Given the observable benefits on aggregate, a supplementary analysis is due here to answer another relevant question, of *who* exactly gets what. That is to say, it is important to register whose walkability score has improved, starting from what pre-project condition. The entire urban area in previous figures is inhabited by approximately 240,000 residents. This number is somewhat a contingency, deriving from the in-part arbitrary geographical boundaries of the area included in the figures (had we, for example, further zoomed out, the number would have been even greater). The detectable impact of the project on walkability scores is, of course, distributed only along a wide area around the Segunda Circular, so the actual number of people whose walkability has *significantly* (instead of only marginally) changed is lower than 240,000. This fact has to be taken into account in interpreting the following figures and tables, where we present the data for the whole population of the area. In Figure 8, we present scatterplots of walkability scores before and after the project, for all three categories of destinations. Each dot represents a person residing in the area, with his/her score before and after the project: the greater the positive y-distance from the diagonal division line, the greater his/her improvement of walkability score due to the project. One may observe in these scatterplots that the walkability score has improved for the great majority of residents. However, it is also possible to note some dots below the diagonal line. On closer scrutiny, we were able to identify those points in space and establish that, due to some changes in land-use destinations and the reconfiguration of the street network by the project, indeed they were made either cut-off or less accessible to some destinations. This again shows how the outputs of the DSS may be useful to evaluate urban projects and possibly hint at the ways to improve them in the light of the findings of walkability assessments with WE.

The data of these rich scatterplots are summarized in Tables 3, 4 and 5. Here, after dividing the walkability scores in 3-score-unit brackets, we count how many people have moved from which bracket into which bracket. Both scatterplots and tables allow to appreciate what is going on, and for whom (that is, from what starting condition), with the walkability scores after the project.

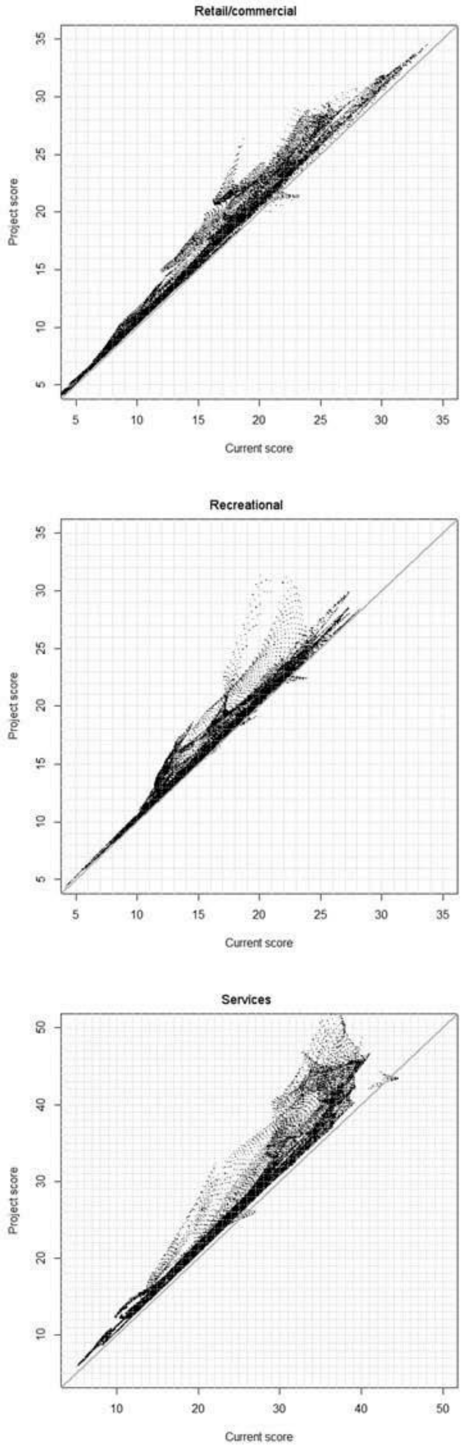

Figure 8. Scatterplots of walkability scores of the population living in the area, before and after the project, for all three categories of destinations.

Table 3. Retail/commercial activities: count of the population in 3-score-unit brackets, before and after the project.

	(0,3]	(3,6]	(6,9]	(9,12]	(12,15]	(15,18]	(18,21]	(21,24]	(24,27]	(27,30]	(30,33]	(33,36]
(0,3]	536	2476	0	0	0	0	0	0	0	0	0	0
(3,6]	0	58,447	3656	0	0	0	0	0	0	0	0	0
(6,9]	0	0	30,635	5102	0	0	0	0	0	0	0	0
(9,12]	0	0	0	18,966	4092	0	0	0	0	0	0	0
(12,15]	0	0	0	0	10,999	4638	158	0	0	0	0	0
(15,18]	0	0	0	0	0	11,380	13,118	3030	6	0	0	0
(18,21]	0	0	0	0	0	0	13,640	9723	213	0	0	0
(21,24]	0	0	0	0	0	0	55	12,666	10,359	1628	0	0
(24,27]	0	0	0	0	0	0	0	0	7092	8201	22	0
(27,30]	0	0	0	0	0	0	0	0	0	2963	2200	0
(30,33]	0	0	0	0	0	0	0	0	0	0	2572	395
(33,36]	0	0	0	0	0	0	0	0	0	0	0	117

Table 4. Recreation areas: count of the population in 3-score-unit brackets, before and after the project.

	(0,3]	(3,6]	(6,9]	(9,12]	(12,15]	(15,18]	(18,21]	(21,24]	(24,27]	(27,30]	(30,33]	(33,36]
(0,3]	0	0	0	0	0	0	0	0	0	0	0	0
(3,6]	0	365	458	0	0	0	0	0	0	0	0	0
(6,9]	0	0	20,063	1147	0	0	0	0	0	0	0	0
(9,12]	0	0	0	50,952	8233	0	0	0	0	0	0	0
(12,15]	0	0	0	0	43,360	8114	20	0	0	0	0	0
(15,18]	0	0	0	0	5	35,412	8737	416	12	0	0	0
(18,21]	0	0	0	0	0	0	23,307	6372	153	120	36	0
(21,24]	0	0	0	0	0	0	7	18,735	4627	49	8	0
(24,27]	0	0	0	0	0	0	0	0	6064	2046	0	0
(27,30]	0	0	0	0	0	0	0	0	0	267	0	0
(30,33]	0	0	0	0	0	0	0	0	0	0	0	0
(33,36]	0	0	0	0	0	0	0	0	0	0	0	0

Table 5. Services: count of the population in 3-score-unit brackets, before and after the project.

	(0,3]	(3,6]	(6,9]	(9,12]	(12,15]	(15,18]	(18,21]	(21,24]	(24,27]	(27,30]	(30,33]	(33,36]	(36,39]	(39,42]	(42,45]	(45,48]	(48,51]
(0,3]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(3,6]	0	0	1340	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(6,9]	0	0	22,167	13,844	0	0	0	0	0	0	0	0	0	0	0	0	0
(9,12]	0	0	0	19,581	3611	0	0	0	0	0	0	0	0	0	0	0	0
(12,15]	0	0	0	0	13,133	8590	11	0	0	0	0	0	0	0	0	0	0
(15,18]	0	0	0	0	0	16,371	8796	81	0	0	0	0	0	0	0	0	0
(18,21]	0	0	0	0	0	0	9183	8870	96	41	0	0	0	0	0	0	0
(21,24]	0	0	0	0	0	0	0	7494	10,650	261	42	1	0	0	0	0	0
(24,27]	0	0	0	0	0	0	0	0	9732	13,562	412	45	0	0	0	0	0
(27,30]	0	0	0	0	0	0	0	0	3	8258	9256	3324	460	186	0	0	0
(30,33]	0	0	0	0	0	0	0	0	0	0	3793	6891	2014	1344	420	18	0
(33,36]	0	0	0	0	0	0	0	0	0	0	0	2797	6894	1706	4632	960	278
(36,39]	0	0	0	0	0	0	0	0	0	0	0	0	1649	6215	4025	1903	906
(39,42]	0	0	0	0	0	0	0	0	0	0	0	0	0	25	1009	1909	16
(42,45]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	153	0	0
(45,48]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(48,51]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(51,54]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

As an additional point, it must be observed here that the distribution and the characteristics of these variations are consistent with the nature and content of the project under consideration. In fact, its main focus is a set of interventions on the transportation and street network, without strong planning prescriptions on the distribution and (re-) localization of activities, services and attractions (e.g. new services, new green areas, etc.). As a consequence, in Tables 3, 4 and 5, we mainly observe bulk of people moving from their starting walkability score bracket to the immediately superior one, without great leaps forward for many people. That indeed would require not only improving the walkability of streets, but also adding places one actually would want to walk to.

Nonetheless, in the very fact one is induced to come to such observations stands the decision support character of the system. Again, walkability is an articulated concept, an interplay of the quality of pedestrian accessibility, of the richness of interesting destinations and opportunities distributed in space and, to add another turn of the screw, of how the urban environment (built environment, social practices, etc.) is conducive to walking. Capturing this interplay of factors may, we hold, prove to be a useful feature of our DSS for capability-wise planning. Well, that is its point.

5. Conclusions and future work

We claim that capability approach coupled with the analysis of accessibility provides a compelling theoretical framework for assessing aspects of the quality of life in cities. The space and urban environment are an important constituent of certain human capabilities. Among other dimensions of individual well-being (health, education, political participation, and so on), the way our cities and physical environment ‘function’– the way they are shaped, organized, and used by social practices – matters. For urban planning, there is a need to explore to which extent we can at least partially isolate this specific relation among capabilities, space, urban environment and social practices of its use, from other determinants and dimensions of human capabilities.

Architects, urban planners and policymakers should use urban capabilities to read and interpret the multiple relations between the individual and the city, to unveil the circumstances in which the city is an obstacle to the needs and aspirations of its inhabitants, to better define and govern urban design processes headed at removing these obstacles.

The aim of the research presented here was not merely to describe few relations between human capabilities and the city, but rather to develop an evaluation model and an operational DSS useful as a tool for improving effectiveness, relevance and inclusiveness of urban design and transportation planning.

We hope we succeeded to convey the idea on how this evaluation model could be used not only as a tool of analysis but also as a design and planning support system.

There are many areas in which this work may be extended and enriched. Foremost, attention must be put on options, alternatives and procedures for a faster and more automated construction of spatial data sets used by the DSS. This requires that we better explore the possibilities of integrating different sources and of a (semi)automatic data harvesting, perhaps in combination with techniques of pattern recognition and computer vision for some attributes relevant for the evaluation procedure.

Also, to become a more complete decision support, our model should be able to take into account not only pedestrian, but also car and public transportation accessibility. There is one relevant point easy to miss here: a DSS focused on walkability, when used for evaluating projects, needs also to take into account the trade-offs between walkability and pedestrian accessibility on one side, and motor traffic affordance on the other. Being the deadlock between the needs of drivers and of pedestrians (and of cyclists, skaters, etc.) at a certain elementary level unsolvable, the nature of this trade-off is not only a technical ʻproblem of optimizationʼ, but an immanently political one.

Furthermore, pedestrians with different attitudinal variables and different populations may exhibit differentiated walking propensity and behaviour (Páez 2013; Páez *et al.* 2013). This points at a possible extension of the DSS, incorporating differential evaluation of walkability for different populations and profiles of pedestrians based on age, gender, disabilities and other social variables. In practice, within the DSS, this would mean to produce assessments of walkability with different parameterizations of the evaluation model specific to each age, gender, disability and social group. Such differential parameterization may, in principle, go beyond the tuning of the parameters (weights of edge attributes, parameters of the benefit function, etc.) in the model we specified in our example application, and can as well comprise more significant alterations, such as the addition of further edge attributes and accommodating other benefit functions that may prove more appropriate. A worthwhile perspective to pursue, much in accordance with the capability approach.

There is finally one substantial promising prospect opened up by the DSS: the potential of developing not only evaluative, but also generative procedures. We envision the possibility to have the DSS itself generate hypotheses of projects, perhaps under some user-given objective function and constrains. Given the in-principle limitless combinatorial alternatives and a vast search space, this of course calls for devising specific search heuristics, which is a stimulating, though intricate, challenge.

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Note

1. The software can be downloaded at the Web address http://www.lampnet.org/downloads/WESetup.exe. The package includes the ʻQuick Start User Guideʼ and the example data of the case study discussed in this paper.

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