Instituto de Engenharia de Sistemas e Computadores de Coimbra
Institute for Systems Engineering and Computers
INESC - Coimbra

Nuno Sousa
nunosousa@dec.uc.pt

Eduardo Natividade-Jesus
ednativi@dec.uc.pt

João Manuel Coutinho Rodrigues
coutinho@dec.uc.pt

Multicriteria methodology
for
pedestrian infrastructure evaluation and management
- // -
Metodologia multicritério
para
avaliação de desempenho e gestão de infraestruturas pedonais

Nº 4/2015 2015

ISSN: 1645 – 2631

Instituto de Engenharia de Sistemas e Computadores de Coimbra
INESC – Coimbra
Rua Antero de Quental, 199; 3000-033 Coimbra; Portugal
www.inescc.pt

ABSTRACT

Sidewalks are important infrastructures of the built environment since they are the main support for the walking mode of transport, and practically every motorized trip begins or ends with nonmotorized travel. Assessment of sidewalk performance, taken in the sense of its adequate suitability for walking and concomitant asset management, involves consideration of multiple aspects, whose precise treatment requires in turn the use of multicriteria methods to support decisions, under an urban engineering scope. This article proposes a multicriteria methodology for this purpose, with an aim at managing subsequent intervention strategies by municipal authorities. The methodology is based on a set of intervenable infrastructure attributes and uses the ELECTRE TRI method to assign sidewalks under study to performance classes. The approach is thoroughly discussed, and demonstrated for a case study comprising several sidewalks in the city of Coimbra, Portugal.

Keywords:
Urban asset management, infrastructure assessment, sidewalks, multicriteria analysis, decision-making tools, maintenance planning.

RESUMO

Os passeios são uma parte importante das infraestruturas em ambiente urbano, uma vez que são o principal suporte do modo pedonal, modo em que desembocam praticamente todas viagens motorizadas. A avaliação do desempenho dos passeios, tomada no sentido da verificação da adequabilidade destes para o exercício do modo pedonal e consequente gestão de ativos, envolve a consideração de múltiplos aspetos, cujo tratamento preciso exige por seu turno a aplicação de metodologias multicritério no apoio à decisão, sob uma égide de engenharia urbana. Neste Relatório propõe-se uma metodologia multicritério específica para o efeito, direcionada à gestão de subsequentes intervenções pelas autoridades municipais. A metodologia é baseada na definição de um conjunto de atributos em que se pode intervir diretamente e usa o método ELECTRE TRI para afetar os passeios em estudo a classes de desempenho. A abordagem é discutida em pormenor e exemplificada para um caso de estudo de vários passeios na cidade de Coimbra, Portugal.

Palavras-chave:
Gestão de ativos urbanos, avaliação de desempenho de infraestruturas, passeios, análise multicritério, ferramentas de apoio à decisão, planeamento de manutenção.

Table of Contents

1. Introduction

It is well known that sidewalk networks are fundamental urban infrastructures, providing the support for an active transport mode used by practically everybody everyday, connecting housing, workplaces, services, public facilities, commerce, etc. among them, and providing the basic link to all the other modes of transport. Infrastructure condition assessments provide key information for decision makers to monitor their respective quality, which is essential for subsequent planning and budgeting of maintenance actions. As a consequence, e.g. in what concerns roadway pavement and bridges, the literature is rich in condition assessment methods. However, as recognized by some authors (e.g., Gharaibeha & Lindholm, 2014), such methods are missing for other road related resources such as roadside assets. Sidewalks, despite their omnipresent existence as a primary infrastructure supporting an important transport mode, have not also captured the attention of so many researchers, usually worried with infrastructures that, at least at first sight, may impose more intense danger for life and property of the respective (motorized) users.

Recent years have witnessed an increasing interest in active travel modes, prompted by sustainability worries, traffic congestion and health issues (Woodcock, Banister, Edwards, Prentice, & Roberts, 2007). The walking mode is an active travel mode that is favoured for small trips, of up to 1 km (Millward, Spinney & Scott, 2013; Buehler & Pucher, 2012), a distance which is expected to increase if proper infrastructural facilities are provided (Rahul & Verma, 2014). Active transport offers the greatest potential to improve health and lower transport-energy use, increasing physical activity, being non-polluting and socially inclusive, and posing little danger to others. Because walking is the most basic travel mode it will always have a considerable share among all transport modes, and affects people of all ages and social status. It is therefore natural and desirable that municipal decision makers provide pedestrians with adequate infrastructures for exercising their choice for this mode, especially if they wish to foster that choice.

There has also been a surge of interest lately in the concept of walkability, a concept whose definition in the literature is manifold, but which can be broadly described as the extent to which the built environment is walking friendly (Abley, 2005) or, more strictly, as ‘a “match” between residents' desires and expectations for types of destinations, their willingness to walk a given distance and the quality of the required path’ (Manaugh & El-Geneidy, 2001). A lot of research has been done on how to define, assess and improve a neighbourhood's walkability indexes (Kelly, Tight, Hodgson, & Page, 2011; Gallin, 2001; TRL, 2003), including from a medical viewpoint (Saelens, Sallis, Black, & Chen, 2003; Cerin, Saelens, Sallis, & Frank, 2006; Ewing, Handy, Brownson, Clemente, & Winston, 2006), as this would potentiate the aforementioned environmental and health benefits (Frank et al., 2006), together with economical ones. Indeed walkable neighbourhoods register a higher share of walking as transport mode, at least for non-work trips (Cervero & Radisch, 1996). Walkability indicators often include sidewalk-related factors in their definition (see e.g. references above and Park, 2008), thus giving decision makers more motivation for evaluating performance of the later.

The rising importance of the walking mode, a trend which is expected to continue, especially if its supporting infrastructure is improved (Gase, Barragan, Simon, Jackson, & Kuo, 2015; Pucher & Buehler, 2010; Buehler & Pucher, 2012), makes it a natural necessity to assess the performance and condition of the pedestrian network infrastructure, of which sidewalks are perhaps the most important element. It is in this context that the present research is presented, as a tool to help evaluating sidewalk performance and prioritizing eventual maintenance/improvement interventions in those facilities. Assessment of this performance is however a multidimensional task, as there are several technical aspects to be considered, as well as non-technical ones, all contributing to a smooth and pleasant walking experience. Sidewalk performance issues appear in some walkability and pedestrian level of service studies but they are approached in a very simple manner (see e.g. Gallin, 2001; TRL, 2003), mostly by merely summing up weighted scores on the various criteria, which may lead to mismatches in the decision due to the compensatory nature of such methods (i.e., a very bad performance in an attribute may be completely compensated by a very good one in another attribute). A more substantive treatment is that of Khisty (1994), but it does not focus exclusively on criteria that are easily intervenable by municipal authorities, nor does it use the multicriteria methods advocated herein.

This article is thus motivated by the need to develop methodologies that can evaluate sidewalk performance more in a systematic way, using multicriteria methods, and with an eye at designing subsequent intervention schemes that can improve performance indicators. It is recognized that multicriteria analysis has emerged as a decision support methodology to integrate various technical information and stakeholder preferences (Kabir, Sadiq, & Tesfamariam, 2014). The methodology proposed in this research evaluates sidewalk performance by classifying them into categories reflecting overall performance status using the ELECTRE TRI method (see e.g., Yu (1992); Mousseau, Figueira, & Naux (2001)). This method was selected because it mimics aspects of human judgement, has been used as an appropriate technique to assess the conservation status in other engineering problems (e.g., Natividade-Jesus, Coutinho-Rodrigues, & Tralhao, 2013), and because its outcome is very simple to interpret. To best of our knowledge, it is the first time that such methods are used for sidewalk performance evaluation. Criteria scoring was developed with the chief concern that data collecting should be simple and straightforward, so as to allow for quick, large scale cadastral surveys, possibly even full city scale. We stress that our aim is to evaluate *sidewalk performance* (in a context of asset management, aiming at maintenance/improvement actions), not neighbourhood walkability or pedestrian level of service (as defined by e.g., Muraleetharan, Takeo, Toru, Seiichi, & Ken'etsu, 2004; Tan, Wang, Lu, & Yang, 2007), which are broader concepts that encompass more than just sidewalk infrastructure-related attributes.

This article is organised as follows. In section 2 the methodology is introduced, in the context of a case study of 23 sidewalks in the city of Coimbra, Portugal. Section starts by the defining and motivating the criteria set, and proceeds applying ELECTRE TRI to field data and analysing the output. Section 3 summarises and concludes.

2. Methodology for evaluating sidewalk performance

The methodology proposed concerns the following problem:

Given a number of sidewalks and respective scores in the criteria under scrutiny, assign each of them to the (previously defined) performance class that best represents its actual performance, e.g. 'unsuitable', 'major repairs required', 'minor repairs required', 'suitable'.

This configures, by definition, a multicriteria problem of the 'sorting (or β) problematic' type (Figueira, Mousseau, & Roy, 2005). The outcome of this classification process can then be easily fed into statistical representations (frequency tables, histograms) to give municipal decision makers an overall picture of how sidewalks stand in their city when it comes to suitability for walking and ease thereof. Output can also be plugged into a Geographical Information System (GIS) for spatial visualisation. Class assignment output makes subsequent decision making straightforward, allowing the compatibility with budget constraints, safety requirements, etc. A typical decision would be e.g. *'we shall intervene sidewalks that are unsuitable or require major repairs'*. When combined with spatial output, it adds this dimension to decision making: if e.g. most unsuitable sidewalks lie clustered on a particular location in the city, municipal authorities may decide to broach that location first.

2.1. The criteria set

As mentioned, the proposed methodology for evaluation of sidewalk performance aims at subsequent intervention works, so the set of criteria to choose from focuses on those that can be intervened. This leaves aside hard geographic characteristics, such as e.g. slope or road intersections, and socio-economic variables, such as e.g. adjacent land use, which may contribute for a more/less pleasant walk but are not affected by intervening on the sidewalk alone.

The proposed criteria set is shown in table 1. Some criteria, if too abstract to assess directly, are broken down to more tangible sub-criteria (e.g., Nannan, 2011). These are the referred to "constructed criteria" below (Keeney, 1992) and were used in previous literature on infrastructure assessment for measuring of the achievement of an objective for which no natural attribute exists.

Criterion	Description	Type	Scale	Scale type

1. Width	Sidewalk average width	Benefit	metres	continuous
2. Pavement suitability	Suitability of pavement type for walking	Benefit	0-4 (unsuitable, poor, reasonable, good, very good)	discrete
3. Conservation status	Floor damage, path irregularities	Benefit	0-4 (unsuitable, poor, reasonable, good, very good)	discrete
4. Accessibilities	Connectivity between sidewalk segments, sidewalk access	Benefit	0-1 constructed criterion	continuous
5. Safety from traffic	Separation between pedestrians and traffic	Benefit	0-4 constructed criterion	discrete
6. Lightning	Existence of good lightning conditions	Benefit	0-4 (unsuitable, poor, reasonable, good, very good)	discrete
7. Obstacle density	Presence of vertical obstacles throughout the sidewalk	Cost	0-4 (none, low, tolerable, considerable, cumbersome walk)	discrete
8. Walking environment	Conditions for a pleasant walk; vegetation, urban furniture	Benefit	0-1 constructed criterion	continuous
9. Pedestrian density	Density of people using the sidewalk at peak hour	Benefit	HCM level of service (A to F scale, transformed to 0-5)	discrete

Table 1. Criteria for evaluating sidewalk performance.

The above criteria are, in one way or another, all related to factors identified in the literature as influencing walkability of neighbourhoods or pedestrian routes. See e.g. Gallin (2001), TRL (2003), and Kelly et al. (2011).

Criteria that cannot be directly evaluated (and some components of constructed criteria) are assessed by visual inspection using a five-values discrete Likert scale, with start set at zero (not one) for all cases, to reflect zeroing of the quantity at hand. Visual inspection is common in engineering when measurements based on rigorous definitions is difficult, time consuming or outright impossible. For recent examples of visual inspection see Dirksen et al. (2013) (sewer inspection), Sadeghi and Askarinejad (2011) (railway tracks), and Pellegrino, Pipinato, and Modena (2011) (bridges). In the context of sidewalks, Likert scales have been used in e.g., Gallin (2001), TRL (2003), and Jaskiewicz (2000). The approach of using visual inspection in tandem with Likert scales is justified because the methodology herein proposed aims at large scale surveys, so quick collecting of individual data is required, hence simple, easy to evaluate forms of registering that data are necessary. Since field measurements are to be done by experts (engineers or seasoned technicians), the accuracy of these surveyors' judgement should, for practical purposes, suffice. Simplicity does not necessarily mean less accuracy; in fact, recent research has shown that excessively detailed survey sheets for visual inspection may lead to *less* quality of the outcome (vd Steen, Dirksen, & Clemens, 2014). Finally, highly heterogeneous sidewalks should be divided into more homogeneous segments for analysis purposes and the length of all sidewalks/segments needs also be measured, as it is necessary to calculate some of the constructed criteria.

Details on the above sidewalk criteria is now given, together with some motivation and details on how to calculate them.

1. *Width*

This is a natural criterion to choose, as sidewalks need to be wide enough to accommodate for pedestrians and, the wider they are, the less prone to jams. Also, wide sidewalks make for a more pleasant walk, from an architectonical point of view. It is the *service*, or *effective*, width that is considered here, i.e. width useable by pedestrians on a straight line. Width taken e.g. by trees planted along a strip of the sidewalk is not to be accounted for. However, if the linear density of these trees is small enough, the full width can be taken into account. It is up to the surveyor to judge the situation.

2. *Pavement suitability*

Smooth pavement makes walking a pleasant experience, whereas bumpy surfaces can be cumbersome to walk through. While some of the negative effect may be mitigated by footwear, sidewalks that perform well in this criterion should provide for a pleasant experience regardless. Pavement should also provide an adequate amount of friction. Suitability is evaluated by the surveyor on a 0-4 Likert scale with: 0-unsuitable, 1-poor, 2-reasonable, 3-good, 4-very good.

3. *Conservation status*

Bad conservation status leads to irregularities that in turn in cause discomfort to pedestrians, may force them to change direction, and can, in extreme cases, lead to accidents. This criterion is evaluated in a 0-4 Likert scale by the surveyor as follows: 0-unsuitable, 1-poor, 2-reasonable, 3-good, 4-very good. When evaluating this criterion, the surveyor should be on the lookout for phenomena such as uneven ground/stub toes [13+ mm tile vertical displacement, PBT (2013)]; floor holes; pavement damage/cracks [crack: 13+ mm wide, PBT (2013)]; tilts along the width direction; and root bumps.

4. *Accessibilities*

Sidewalks are accessed via curbs and crossings. Sidewalk curbs should not be too tall and access ramps are needed to cater for disabled people. Four components are considered here: (1) curb height/conservation; (2) crossing visibility (stoplights, vertical signs, visibility of pedestrians and zebras); (3) density of crossings; (4) density of access ramps. Curb condition and visibility are evaluated in a 0-4 scale (0-unsuitable, 1-poor, 2-reasonable, 3-good, 4-very good) whereas densities are evaluated comparing the quotient Q = *nr. of crossings/sidewalk length* (likewise for ramps) to the reference value of 1 crossing (ramp) per 100 m (Q_{ref}) (NZTA, 2009). A score of Q/Q_{ref} is given if Q

< Q_{ref}, and 1 otherwise. If a sidewalk has no crossings, scores of visibility and ramps are set to zero. Likewise, if the street is short and quiet enough to be classified as 'not needing crossings' (TENC, 1998), a score of 1 is given to these components. Finally, because components (1) (2) are scored 0-4 and components (3) (4) scored 0-1, the former two should be normalised to 1 prior to doing the final weighted sum.

The final accessibilities score is given by:

$$Access = \sum_i WA_i \, n_i \, x_i$$

Where:

WA_i = weight of accessibility component i (i = 1,...,4).

n_i = normalisation factor for component i (respectively 1/4, 1/4, 1, 1).

x_i = score of accessibility component i.

Surveyors should however be critical when assigning final accessibility scores, as situations may arise that call for specialized treatment. Indeed, if a sidewalk without crossings is just shy of, or barely over, 100 m, its score may oscillate between 0 and 1; a sharp score difference for a low *de facto* difference. In this case surveyors should exercise judgement to decide what would be the more appropriate score (e.g., by looking at the distance to the nearest crossing). The same applies to contiguous sidewalks/segments of less than 100 m: individually none would require a crossing, but seen as a chain some crossings may be necessary. Surveyors should be on the lookout for situations like the above and judge them appropriately.

5. *Safety from traffic*

Existence of separation between pedestrians and street traffic contributes to the sense of safety. Traffic flux also needs to be taken into account, as quiet/busy streets require less/more separation to give pedestrians the same sense of safety. Some of the factors contributing to this criterion have been identified on previous work by e.g. Landis, Vattikuti, Ottenburg, McLeod, & Guttenplan (2001). Here a simpler approach is proposed, which requires collecting only buffer zone width and type, and traffic volume. The formula for safety score is:

$$Safety = 4 - (TVol - Buffer) \times \theta(TVol - Buffer)$$

Where:

$TVol$ = traffic volume, on a 0-4 scale.

$Buffer = \mathrm{round}[\ln(1 + WBuff \times (\sum_i f_i \, x_i))]$.

$\theta(x)$ = unit step function; 1 if $x \geq 0$, 0 if $x < 0$.

WBuff = width of buffer zone.

f_i = multiplier factor for buffer type *i*. (i = 1,...,4)

x_i = binary variable for existence of buffer type *i* in buffer zone (cumulative).

Traffic volume is evaluated qualitatively by the surveyor as 0-none, 1-quiet, 2-normal, 3-busy, 4-very busy. The score should reflect not only traffic flux but also vehicle type and speed. Buffer types considered are 1-void/bike lanes, 2-trees, 3-parking pins, 4-parking lanes (more types can be considered if desired); its f_i multipliers usually ranging from 0.5 to 3, in the appropriate units. For instance for trees a value of 3 m^{-1} is suggested, as it leads to a *Buffer* outcome in line with the example of (FDOT, 2009, p.64), where tree barriers have an 1.5-fold impact on separation.

Presence of the ln() function follows Landis et al. (2001), which found best field data fit for log-like regression on this criterion. Indeed, it seems logical that be first few meters away from traffic cause a higher impression of safety than the same meters added to a much wider sidewalk. Multipliers f_i for buffer zone type also appear in Landis et al. (2001), reflecting the fact that some buffer zones (e.g., trees) provide a higher sense of safety than others. The round() function transforms *Buffer* values into integers falling into the 0-4 range. This is done to mirror the 0-4 Likert scale in which traffic is evaluated. If the decision maker opts for plugging into this slot more precise, quantitative field traffic volume measurements, then the round() function should be removed from *Buffer*, so as to have all real numbers on the subtraction *TVol - Buffer*. Consequently, *TVol* measurements should be rescaled into a 0-4 continuous scale, to insure comparability with *Buffer*.

Because the model of Landis et al. (2001) requires collecting precise and extensive amounts data, doing so on a large scale is difficult and very time consuming. This is why the simple model of above is proposed instead, since it only requires data that is very easy and quick to collect, even on a large scale. Municipal authorities have in fact detected the same problem and devised ways to simplify Landis' model (see e.g., FDOT, 2009). Consolidating several factors into one single 'buffer separation function' (as is done here) is recommended by that reference. The scheme proposed here is slightly more complex than that of the former reference because it tries to capture Landis' logarithmic dependence on separation.

6. *Lightning*

This criterion becomes critical for pedestrians at night time. Nearly all urban sidewalks are lit, but insufficiently lit strips cause a sense of insecurity. Pedestrians may refrain from walking the street in those cases. Lightning is evaluated in a 0-4 scale with: 0-unsuitable, 1-poor, 2-reasonable, 3-good, 4-very good.

7. *Obstacle density*

Sidewalks become unpleasant if cluttered with (vertical) obstacles such as outdoors, incorrectly positioned large bins or urban furniture, water outlets, trees, etc. This criterion is scored 0-4 as follows: 0-none, 1-low, 2-tolerable, 3-considerable, 4-cumbersome walk.

8. *Walking environment*

This refers to the level to which a sidewalk is endowed with useful urban furniture, such as rubbish bins and rest places, and vegetation that can provide a soothing atmosphere and/or shade. It does *not* refer to the architectonical and social aspects of the surroundings, as intervening at the sidewalk level does not change these. The score is obtained similarly to accessibilities, with vegetation expressed in a 0-4 scale, and bin/rest place densities defined relative to a reference value, which can be e.g. the best score in the dataset. Thus $Q = nr.\ of\ bins/sidewalk\ length$ (likewise for rest places) and score equal to Q/Q_{best}. (Normalisation of scales necessary.)

$$WalkEnv = \sum_i WE_i\, n_i\, x_i$$

Where:

WE_i = weight of walking environment component *i.*

n_i = normalization factor for component *i*. (1/4 for vegetation, 1 for rest place/bins)

x_i = score of component *i*. (1 for best performing sidewalk.)

9. *Pedestrian density*

This is defined as the HCM level of service (TRB, 2000) (A-F scores), transformed into a 0-5 benefit scale. While not directly intervenable, it can be changed via sidewalk width. It is important to consider it because a sidewalk may be wide, but not wide enough to accommodate for large pedestrian peak fluxes, in which case it will be underperforming. The HCM level of service definition is precise but rather difficult to measure accurately. Hence, its evaluation is done qualitatively by the surveying expert, based on the HCM text description of service levels. While not completely accurate, it should not be too far off more precise, but time-consuming, measurements.

2.2. Classifying sidewalk performance - ELECTRE TRI

The present methodology proposes a classifying approach to sidewalk performance assessment; the aim being to assign sidewalks to performance categories, or classes. The multicriteria method used for carrying this out is ELECTRE TRI (Yu, 1992), a widely used classifying method that mimics characteristics of human judgement. ELECTRE TRI was conceived to place actions, objects or items into sorted predefined classes (C_1, C_2,…C_k), considering multiple criteria, with each class delimited by a lower and an upper profile (Figueira et al., 2005). It has been used in several other classification problems related to infrastructure and building performance, (see e.g. Natividade-Jesus et al, 2013; Rogers, Bruen, & Maystre (2010); Kabir et al., 2014 and references therein). To best of our knowledge, this research is the first time where it is applied to sidewalks in particular. Conceptual and technical details on the ELECTRE methods family can be consulted in Roy (1991).

Under ELECTRE TRI results are expressed using the absolute notions: “assign” or “not assign” to a class; “similar” or “not similar” to a reference profile. This methodological feature is particularly relevant in the context of our problem, since the assignment of sidewalks to pre-defined classes (related to their performance) is common in problems faced by municipal authorities. In defining the limits of these classes, the user can either select real sidewalks as reference or define hypothetical sidewalks with adequate values for the criteria.

ELECTRE TRI, given its characteristics, is particularly adequate for the study of the sidewalk performance, allowing to define (real or virtual) reference properties (according to current performance levels), and to group/classify the sidewalks into classes.

2.3. Case study

A total of 23 sidewalks in the city of Coimbra, Portugal, were selected from a varied range of locations for a case study. Data was collected on the field, apart from sidewalk length, which was derived on desktop, from Google Earth GIS tools. Two experts carried out the survey independently, and final criteria scores were averaged out when a consensus was not reached. Having two surveyors on the field is a procedure recommended by TRL (2003). Constructed criteria weights chosen were $WA_i = 0.25\ \forall i$; $WE_i = (0.4, 0.3, 0.3)$, and other parameters were $f_1 = 0.5$ (void space/bike lane); $f_2 = 3$ (trees); $f_3 = f_4 = 1.5$ (park pins, park lane) and Q_{best} was taken as reference for bin and rest place density. The data yielded the following performance matrix:

Sidewalk #	***Width***	***Suitability***	***Cons. stat.***	***Access.***	***Safety***	***Lightning***	***Obstacle***	***Walk envir.***	***Ped. dens.***
1	1.9	1.5	3	0.813	1	1	3	1	4
2	2	2	3.5	0.875	1	2	1	0	5
3	1.8	2	3.5	0.188	1	2	1.5	0	5
4	2.3	2	3.5	0.969	1	2	2	0.177	5
5	3	3	3.5	0.859	0	2	2	0.128	2.5
6	1	3	4	0.938	0	2.5	0.5	0.116	5
7	1.5	3	4	0.746	1	2	1	0.491	5
8	4.1	3	2.5	0.813	1	2	1	0.319	4.5
9	2.5	3	4	0.471	3	2	1.5	0.116	5
10	1.05	2.5	2.5	0.405	2	1.5	0	0	4
11	2.5	3	3.5	0.625	3	2	1	0	4
12	2.9	3	3.5	0.156	3	2	0	0	5
13	4.2	2.5	1.5	0.125	3	1.5	0	0.324	5
14	2.3	3	2	0.458	4	1	0	0.582	5
15	2.1	3	3.5	0.656	4	2	1	0.4	5
16	1	2.5	3	0.656	2.5	2	1.5	0.464	4.5
17	3.2	1	0	0	3.5	2	0.5	0.374	5
18	4.25	3	3	0.583	2.5	3	1	0.302	5
19	1.9	3.5	3	0.688	0	1.5	0	0.35	4.5
20	1.35	3	3	0.93	0.5	2	1.5	0.096	5
21	4.5	3	2	0.489	3	1.5	1	0.212	5
22	2.6	2	0.5	0.816	4	2	3.5	0.31	5
23	2.3	3	2.5	0.844	3.5	1.5	2	0.3	5

Table 2. Performance matrix.

As mentioned, prior to running ELECTRE TRI reference alternatives corresponding to lower and upper profiles of each predefined class must be established, as well as other parameters such as indifference, preference and veto thresholds, and criteria weights. For the case study three reference alternatives (A1, A2, A3) were defined (this leads to *four* classes) with criterion values (Figure 1)

A1 = (1.2, 1, 1, 0.3, 1, 1, 3, 0.3, 1)

A2 = (1.5, 2, 2, 0.5, 2, 2, 2, 0.5, 2)

A3 = (2.0, 3, 3, 0.7, 3, 3, 1, 0.7, 4)

Actual sidewalks are to be compared against these reference sidewalks, sorted from worst to best profiles as A1, A2, A3, leading to the delimitation of a corresponding sorted set of four classes, as represented graphically in Figure 1. Width references were set according to the guidelines of the Portuguese Decree-Law 163/2006 (DL, 2006), which defines 1,5 m as 'acceptable' and 2,0 m as ‘desirable’ sidewalk widths, and 1,2 m as ‘desirable’ for narrower streets where it is impossible to achieve 1,5 m widths. Reference values for other criteria were defined with a slight squeeze towards central values, so as to have better resolution in that zone, which is where criteria values most often sit in practice.

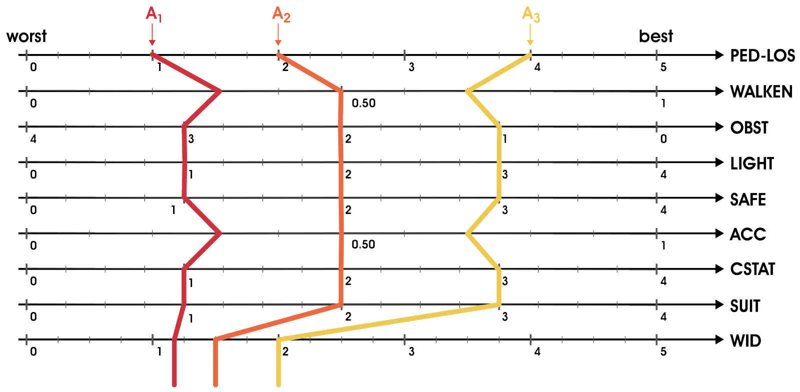

Fig. 1. Sidewalk classes delimited by reference profiles A1, A2, A3.

For the purpose of our case study two sets of criterion weights were adopted, the first focusing on ease and comfort of walking (W1), the second on pedestrian safety (W2):

W1 =	(2.5,	15,	40,	2.5,	5,	5,	10,	10,	10)%
W2 =	(5,	5,	10,	2.5,	50,	10,	10,	2.5,	5)%

Finally, indifference, preference and veto thresholds, standard parameters required by ELECTRE TRI (see e.g., Mousseau et al., 2001) were set to

Indifference =	(0.2,	0.1,	0.2,	0.1,	0.1,	0.1,	0.1,	0.1,	1.1)
Preference =	(0.5,	0.5,	0.4,	0.3,	0.5,	0.5,	0.5,	0.3,	1.5)
Veto =	(1.5,	1.5,	0.5,	0.5,	0.9,	1.1,	1.1,	0.5,	2.5)

Thresholds for Likert scale criteria were chosen to be consistent with the scale itself, in the sense that one cannot distinguish criteria within the same level, can objectively distinguish between two adjacent levels (hence prefer one to the other), and put a veto on levels that are two or more away. For pedestrian density-LOS (which has a 6-level scale), indifference between adjacent levels was considered, with preference and veto starting from two and three levels away respectively. A stricter veto threshold was put for conservation status and safety from traffic, as these are the more critical performance attributes.

The results with pessimistic assignment are, for both sets of weights, depicted in Figure 2.

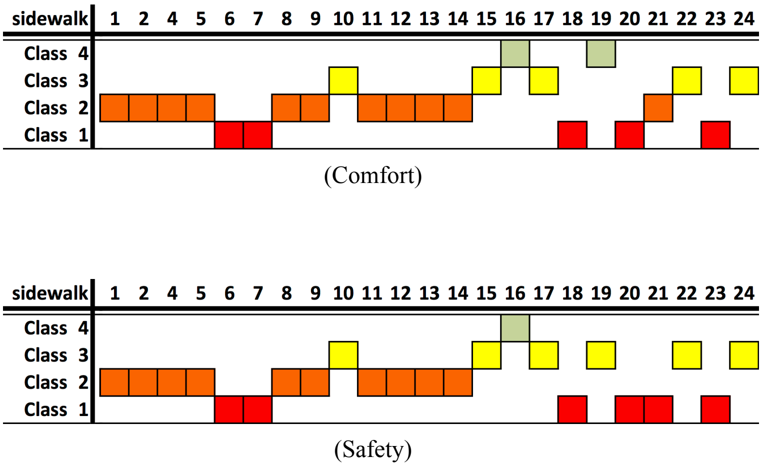

Fig. 2. Results of sidewalk multicriteria classification by ELECTRE TRI.

The outcome is very similar for both sets of weights, with difference in only two sidewalks changing class (#19, #21). Further tests performed showed robustness of the results against large weights changes, which is in fact a plus-value, as high fluctuations require more ponderation by the decision maker.

Clearly, sidewalks in the lower class need to be intervened. Closer inspection reveals that this is mainly due to low scores in the safety and conservation status attributes, which veto progression to the next class. With the more urgent cases dealt with, in a second stage the decision maker can devise a mid-term plan for intervening sidewalks that fall into class 2.

As an example of the ELECTRE TRI outcome classification, eight real situations classified for both sets of weights described above are depicted in Figure 3.

Class	Safety	Confort
1 (worst)		
2		
3		
4 (best)		

Fig. 3. Eight real situations classified for ease and comfort of walking (W1) and pedestrian safety (W2).

3. Conclusions and future work

In this article a methodology for evaluating sidewalk performance based on multicriteria classifying methods was presented. The methodology was developed to be widely applicable by municipal decision makers, regardless of city location and size, and aiming at subsequent design of intervention schemes for repairs or improvements. The use of scientific multicriteria methods covers a gap in the literature, which has so far approached the subject with straightforward models. These models also often mixed other walkability elements into the analysis, which not directly or easily intervenable by municipal authorities. Simplicity and ease of data collecting was however kept in the present methodology, to insure its wide applicability. The methodology proposed also allows treating discrete and continuous criterion values on the same foot.

A problem that naturally arises subsequently to the application of this methodology is that of designing optimised intervention plans for the sidewalks. Such plans would have two natural objectives: one would be to maximize the benefits derived from the interventions, while another would be to minimize the budget necessary to implement those. Solving this multi-objective problem would require developing a model for repairs and doing calculations in it.

Finally, it might also be interesting to make a comparative study of two types of results that can be obtained from the methodology. One type would be results obtained from applying the methodology ‘as is’. The other would be results obtained by replacing Likert scale qualitative assessments by more precise measurements. This would require defining and calibrating continuous scales for pavement suitability, conservation status, safety, lightning, obstacle density, and pedestrian density. A thorough statistical study of the differences between the two approaches could be interesting to consolidate the simple (but scalable) approach, or eventually fine-tuning it. We hope to address some of these issues in the future.

Acknowledgements

This work was partially supported by the Portuguese Foundation for Science and Technology under project grant UID/MULTI/00308/2013; and the initiative Energy for Sustainability of the University of Coimbra, supported by project Energy and Mobility for Sustainable Regions (EMSURE), under grant - CENTRO-07-0224-FEDER-002004.

4. References

Abley, S. (2005). *Walkability Scoping Paper*, sa001 3523 report, prepared for Land Transport New Zealand.

Buehler, R. & Pucher, J. (2012). Walking and Cycling in Western Europe and the United States: Trends, Policies, and Lessons. *Transportation Research News, 280*, 34-42. Retrieved from http://onlinepubs.trb.org/onlinepubs/trnews/trnews280WesternEurope.pdf

Cerin, E., Saelens, B.E., Sallis, J.F. & Frank, L.D. (2006). Neighborhood environment walkability scale: validity and development of a short form. *Medicine and Science in Sports and Exercise, 38*, 1682-1691. DOI: 10.1249/01.mss.0000227639.83607.4d

Cervero, R. & Radisch, C. (1996). Travel choices in pedestrian versus automobile oriented neighborhoods. *Transport Policy, 3*(3), 127-141. DOI: 10.1016/0967-070X(96)00016-9

DL - Decreto-Lei 163/2006. Regime da Acessibilidade aos Edifícios e Estabelecimentos que Recebem Público, Via Pública e Edifícios Habitacionais. *Diário da República, I Série, 152*(8 de Agosto), 5670-5689. Imprensa Nacional Casa da Moeda, Lisbon, Portugal. (Portuguese Decree-Law.)

Dirksen, J., Clemens, F.H.L.R, Korving, H., Cherqui F., Le Gauffre, P., Ertl, T., Plihal, H., Müller, K. & Snaterse, C.T.M. (2013). The consistency of visual sewer inspection data. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 9*(3), 214-228. DOI: 10.1080/15732479.2010.541265

Ewing, R., Handy, S., Brownson, R.C., Clemente, O. & Winston, E. (2006). Identifying and measuring urban design qualities related to walkability. *Journal of Physical Activity and Health, 3*(Suppl 1), S223-S240.

FDOT - Florida Department of Transportation (2009). *Quality/Level of Service Handbook.* Tallahassee: Department of Transportation, State of Florida.

Figueira, J., Mousseau, V. & Roy, B. (2005). ELECTRE Methods. In S. Greco, J. Figueira, M. Ehrgott (Eds.), *Multiple Criteria Decision Analysis: State of the Art Surveys* (pp. 133-162). Boston: Springer. ISBN 978-0-387-23081-8

Frank, L.D., Sallis, J.F., Conway, T.L., Chapman, J.E., Saelens, B.E. & Bachman, W. (2006) Many pathways from land use to health. Associations between neighborhood walkability and active transportation, body mass index, and air quality. *Journal of American Planning Association, 72*, 75–87. DOI: 10.1080/01944360608976725

Gallin, N. (2001). Quantifying Pedestrian Friendliness - Guidelines for Assessing Pedestrian Level of Service. *Journal of Road & Transport Research, 10*(1), 47-54.

Gase, L.N., Barragan, N.C., Simon, P.A., Jackson, R.J. & Kuo, T. (2015). Public awareness of and support for infrastructure changes designed to increase walking and biking in Los Angeles County. *Preventive Medicine, 72*, 70-75. DOI: 10.1016/j.ypmed.2014.12.033

Gharaibeha, N. & Lindholm, D. (2014). A condition assessment method for roadside assets. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, *10*(3), 409-418. DOI: 10.1080/15732479.2012.757330

Jaskiewicz, F. (2000). Pedestrian Level of Service based on trip quality. In Transportation Research Board (Ed.), *Transportation Research Circular E-C019*, Proceedings of the TRB Urban Street Symposium, Dallas, TX. Retrieved from http://onlinepubs.trb.org/onlinepubs/circulars/ec019/ec019.pdf

Kabir, G., Sadiq, R. & Tesfamariam, S. (2014). A review of multi-criteria decision-making methods for infrastructure management. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 10*(9), 1176-1210. DOI: 10.1080/15732479.2013.795978

Kelly, C.E., Tight, M.R., Hodgson, F.C. & Page, M.W. (2011). A comparison of three methods for assessing the walkability of the pedestrian environment. *Journal of Transport Geography, 19*(6), 1500-1508. DOI: 10.1016/j.jtrangeo.2010.08.001

Khisty, C.J. (1994). Evaluation of pedestrian facilities: beyond the level-of-service concept. *Transportation Research Record, 1438*, 45-50. ISBN: 0309055199

Keeney, R.L. (1992). *Value-Focused Thinking: A Path To Creative Decisionmaking.* Cambridge, Massachusetts: Harvard University Press. ISBN 9780674931985.

Landis, B., Vattikuti, V.R., Ottenburg, R.M., McLeod, D.S. & Guttenplan, M. (2001). Modeling the roadside walking environment: pedestrian level of service. *Transportation Research Record, 1773*, 82-88. DOI: 10.3141/1773-10

Manaugh, K. & El-Geneidy, A. (2011). Validating walkability indices: How do different households respond to the walkability of their neighborhood? *Transportation Research Part D, 16,* 309-315. DOI: 10.1016/j.trd.2011.01.009

Millward, H., Spinney, J. & Scott, D. (2013). Active-transport walking behavior: destinations, durations, distances. *Journal of Transport Geography, 28,* 101-110. DOI: 10.1016/j.jtrangeo.2012.11.012

Mousseau, V., Figueira, J. & Naux, J.-Ph. (2001). Using assignment examples to infer weights for ELECTRE TRI method: Some experimental results. *European Journal of Operational Research, 130*(2), 263-275. DOI: 10.1016/S0377-2217(00)00041-2

Muraleetharan, T., Takeo, A., Toru, H., Seiichi, K. & Ken'etsu, U. (2004, January). *Evaluation of pedestrian level of service on sidewalks and crosswalks using conjoint analysis.* Poster session presented at the Transport Research Board 83rd Annual Meeting, Washington D.C.

Nannan, W. (2011). Multi-criteria decision-making model for whole life costing design. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 7*(6), 441-452. DOI: 10.1080/15732470802670875

Natividade-Jesus, E., Coutinho-Rodrigues, J. & Tralhao, L. (2013). Housing evaluation with web-SDSS in urban regeneration actions, *Municipal Engineer, 166*(3) 194-207. DOI: 10.1680/muen.12.00022

NZTA - New Zeland Transport Agency (2009). Pedestrian planning and design guide. Victoria: New Zeland Transport Agency. ISBN 978-0-478-35228-3. Retrieved from http://www.nzta.govt.nz/resources/pedestrian-planning-guide/docs/pedestrian-planning-guide.pdf

Park, S. (2008) *Defining, Measuring, and Evaluating Path Walkability, and Testing Its Impacts on Transit Users' Mode Choice and Walking Distance to the Station.* University of California Transportation Center Dissertation No. 150. University of California, Berkeley.

PBT - Portland Bureau of Transportation (2013). *Sidewalk Repair Manual, seventh edition* (p.5). Portland, OR: City of Portland Bureau of Transportation. Retrieved from http://www.portlandoregon.gov/transportation/article/443054

Pellegrino, C., Pipinato, A. & Modena, C. (2011). A simplified management procedure for bridge network maintenance. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 7*(5), 341-351, DOI: 10.1080/15732470802659084

Pucher, J. & Buehler, R. (2010). Walking and Cycling for Healthy Cities. *Built Environment, 36*(4), 391-414. DOI: 10.2148/benv.36.4.391

Rahul, T.M. & Verma, A. (2014). A study of acceptable trip distances using walking and cycling in Bangalore. *Journal of Transport Geography, 38*, 106-113. DOI: 10.1016/j.jtrangeo.2014.05.011

Rogers, M.G., Bruen, M. & Maystre, L.-Y. (2010). *ELECTRE and Decision Support: Methods and Applications in Engineering and Infrastructure Investment.* Boston: Kluwer Academic Publishers. ISBN 978-1-4419-5108-3

Roy, B. (1991). The outranking approach and the foundations of ELECTRE methods. *Theory and Decision, 31*, 49-73. DOI: 10.1007/BF00134132

Sadeghi, J.M. & Askarinejad, H. (2011). Development of track condition assessment model based on visual inspection. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 7*(12), 895-905, DOI: 10.1080/15732470903194676

Saelens, B.E., Sallis, J.F., Black, J.B. & Chen, D. (2003). Neighborhood-based differences in physical activity: an environmental scale evaluation. *American Journal of Public Health, 93*(9), 1552-1558.

vd Steen, A.J., Dirksen, J. & Clemens, F.H.L.R. (2014). Visual sewer inspection: detail of coding system versus data quality? S*tructure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 10*(11), 1385-1393, DOI: 10.1080/15732479.2013.816974

TENC - Traffic Engineering Council Committee (1998). *Design and Safety of Pedestrian Facilities.* Washington DC: Institute of Transportation Engineers. ISBN 0-935403-17-5. Retrieved from http://library.ite.org/pub/e1d0e494-2354-d714-5188-fbe21cb21457

Tan, D., Wang, W., Lu, J. & Yang, B. (2007). Research on methods of assessing pedestrian level of service for sidewalk. *Journal of Transportation Systems Engineering and Information Technology, 7*(5), 74-79. DOI: 10.1016/S1570-6672(07)60041-5

TRB - Transportation Research Board (2000). *Highway Capacity Manual.* Washington D.C.: National Academy of Sciences. ISBN 0-309-06681-6.

TRL - Transport Research Laboratory (2003). Pedestrian Environment Review System. Crowthorne. Retrieved from http://www.walk21.com/papers/reid.pdf

Vanderpooten, D. (1989). The Interactive Approach in MCDA: A Technical Framework and Some Basic Conceptions. *Mathematical and Computer Modelling, 12*(10-11), 1213-1220. DOI: 10.1016/0895-7177(89)90363-4

Woodcock, J., Banister, D., Edwards P., Prentice, A.M. & Roberts, I. (2007). Energy and transport. *The Lancet, 370*(9592), 1078–88. DOI: 10.1016/S0140-6736(07)61254-9

Yu, W. (1992). *ELECTRE TRI: Aspects méthodologiques et manuel d'utilisation.* (Document du LAMSADE 74.) Université Paris-Dauphine, Paris. Retrieved from http://www.lamsade.dauphine.fr/mcda/biblio/Author/YU-W.html