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KEYWORDS: MIVES - Multi-criteria - Urban Pavements - Pavement Condition Index - Pavement Serviceability Index - Pavement Distress

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1: INTRODUCTION

Over half of the global population live in urban areas (Petit et al., 2016) today and the exodus from rural areas is expected to continue at the rate of 1.3 million people per year (The World Bank, 2014 and UN, 2011). One of the priorities in cities is to ensure the effective management of the built environment in which people live and the services that they depend upon (Pujadas et al., 2017). Urban pavements are counted among these keystones of daily life. In cities such as Barcelona, pavements represent more than 18% of the total metropolitan area and almost 2/3 of public space. The city council and its agencies have a public duty to assure the quality standards of urban pavements. They do so through the use of a Pavement Management System (PMS) that also assists decision-makers with the consolidation of strategies for the maintenance of safe pavement conditions (Gendreau and Soriano, 1998). However, a PMS requires indicators that represent the current conditions of the urban pavement that forms a central input to the decision-making process.

Indicators such as the Pavement Condition Index (PCI), Present Serviceability Index (PSI), and VIZIR have been used to evaluate the state of pavements exposed to distresses and degradation. The work of Baladi et al. (1992) contains a list of further indexes that highway agencies apply, most of which were developed for road networks. Their application to urban networks is complex and hardly straightforward. The main reason is the wide variety of pavement types (concrete, asphalt and tiles) and functions (automobile traffic, pedestrian traffic or both) found in urban areas. Consequently, the existing indexes are not adapted to the particular typologies of distress in the urban environment.

A common problem found in the definition of the indexes is how to integrate different types of damage in a single result that precisely represents the overall condition of the pavement. Most methods reported in the literature rely on qualitative assessments and category and grade-related classifications decided by the person in charge of the evaluation and will therefore depend on individual perceptions. This type of evaluation may compromise the capacity of the user to distinguish between pavements that appear to be of the same class or grade, complicating their comparison and generating inconsistencies. In this context, it is necessary to develop a comprehensive condition index for urban pavements that covers the most relevant distress pathologies (Osorio et al., 2014), including a semi-quantitative analysis conducted in a simple and straightforward manner.

The aim of this study is to define an Urban Pavement Condition Index that is developed through a multi-criteria-based approach using the MIVES methodology applied to data from visual inspections of surface distress. The MIVES methodology combines Multi-criteria Decision Making (MCDM) and Multi-Attribute Utility Theory (MAUT), and it incorporates both the Value Function (VF) concept and Analytic Hierarchy Process (AHP) weight assignment. Following its presentation, the index is used in a sensitivity evaluation for the case study and assessment of pavement distress in the city of Barcelona. The simple, straightforward approach developed in the paper produces an accurate, consistent, and repeatable categorization of the urban network. The method provides an objective and rational basis for future cost-effective maintenance and pavement management strategies (PMS) and could easily be extended to road pavements.

2: BRIEF OVERVIEW OF EXISTING METHODOLOGIES

The Pavement Condition Index (PCI), developed in the late 1970s by the U.S. Army Corps of Engineers (USACE) is considered the basis for most modern functional evaluation procedures. According to Gendreau and Soriano (1997), rather than a comprehensive functional performance indicator, the PCI is a surface distress index. Even though the direct measurement of surface distress measures neither functional nor structural pavement performance, there is a relation between them. Therefore, the PCI provides a standard and an indirect method for rating both the structural integrity and functional condition of pavement sections (Shahin, 1980).

The PCI provides a numerical index of pavement condition, the values of which range from 0 (extremely poor condition) to 100 (excellent condition). It uses weighted deduct values that are functions of the type, the severity, and the extent of visible distress, combining data on individual distress types into a single condition value. These data are collected through visual surveys with some direct measurements to evaluate the severity of certain distress types, such as rut depth. It is, therefore, a semi-objective index. Each section in the survey process is subdivided into sample units of which only a random number are evaluated. The PCI value is then computed from the average for the sample units inspected in that section.

The Present Serviceability Index (PSI) is an alternative developed by AASHTO through which pavement ratings can be estimated from in-situ measurements (Carey and Irick, 1960). The PSI depends on slope variance, patching, cracking, and rut depth for the road sections under assessment. The VIZIR method was developed by the Laboratoire Central des Ponts et Chaussées (LCPC) for the quality rating of flexible pavements (Autret and Brousse, 1991). It is designed to classify zones at three damage levels and thereby provide a picture of road surface conditions at any given time. These damage levels are used to determine the nature and type of work required. In some cases, the identification of the damage determines the solution, while in others it is only one factor in a more complex diagnosis involving other criteria. Each area of damage is divided into two categories: type A or structural (deformation; rutting; fatigue cracking; and crazing; etc.) and type B or functional (longitudinal joint cracks, transverse shrinkage cracks; potholes, raveling; and all surfacing defects such as fretting, and bleeding, etc.).

Karan et al. (1983) developed the pavement quality index (PQI) for statistically capturing information from an expert panel. Later on, FHWA (1990) described an index representing an overall aggregation of the different measures of pavement condition. In addition to those indexes, several comprehensive ranking index approaches based on fuzzy set theory have been developed. Juang and Amirkhanian (1992) advanced the Unified Pavement Distress Index (UPDI) and Zhang (1993) presented the Overall

Acceptability Index (OAI). Shoukry et al. (1997) adopted a fuzzy logic approach to the design of a universal pavement distress evaluator defined as the Fuzzy Distress Index (FDI). Thube et al. (2007) developed both a PSI and PCI-based composite pavement deterioration model for low volume roads in India. Other indices of functional performance were proposed in Kher and Cook (1985), Majidzadeh et al. (1992), Mosheni et al. (1992), and Shah et al. (2013). The numerous indices reflect the variety of perceptions that exist on this issue

3: THE BASIS OF THE URBAN PAVEMENT CONDITION INDEX (UPCI)

Nowadays, both user and stakeholder perceptions of public infrastructure play a fundamental role in their management. From the public perspective, urban pavements are valued for three essential qualities: functionality, appearance, and safety (López-Carreño, 2017). Distress is considered a problem that will negatively affect one of these three qualities. In this context, the proposed index should be able to distinguish between user perceptions and the factor that affects it: the distress. Therefore, the methodology developed in this paper (as with the PCI) is based on a surface distress index.

The process of obtaining the Urban Pavement Condition Index (UPCI) comprises four steps, as shown in Fig. 1. A detailed description of each step is presented in the following sections. Throughout the description, examples of urban pavements in Barcelona will be used to facilitate comprehension of each distress type.

Fig 1: Flowchart of the proposed methodology

3.1: Inspection and Network inventory

Urban pavements may be categorized by dividing the network into relatively small units called knots (KNi) and sections (Si), as shown in Fig. 2. The sections are stretches of streets, while the knots are the common area formed by the junction of two or more streets. Both elements may be further divided into polygons (Pi) that represent the minimum fraction of the urban network. The polygons should display homogenous characteristics throughout their extension in terms of function (sidewalk or carriageway), pavement materials, and construction history. In some cases, where traffic is channelized through special lanes (*i.e.* busways and taxiways), parallel polygons may be defined for different lanes of the same carriageway. An example is presented in Fig. 3.

Fig 2: Schematic urban network division into knots (KNi) and sections (Si)

Fig 3: Example of division into polygons (Pi)

A wide variety of pavement surface materials may be found in urban areas depending on the pavement use: bituminous bound materials (asphalt concrete, mastic asphalt); cement bound materials (concrete, concrete elements); small paving elements (tiles or block pavers, modular materials, stone, *terracotta*), and composite pavements (a combination of the above-mentioned materials). The choice of the surface material depends on several aspects (comfort, safety, noise, esthetic, durability, maintenance and rehabilitation frequency). Therefore, the pavement material is part of the information of the inventory, as each of them may present typical surface distresses. A summary of pavements generally used in Barcelona is shown in Table 1.

Table 1: List of pavements for general use in Barcelona

Attention is focused in this paper on paving tile distress observed on pavements in Barcelona and their categorization through an adaptation of the MIVES methodology. The tile paving program in Barcelona started in 1916, and the continuous development of the city and its surrounding areas has over the last 100 years led to the placement of over five-million square meters of tiles (known as *panots*). Besides the initial patterns, there are many others used throughout the urban environment for both esthetic and functional purposes (see Fig 4)

Fig 4: Common paving tile patterns used in Barcelona

3.2: Distress characterization

The method considers five parameters that characterize distress according to the perception of the user. These parameters are: Distress scale (DSc); Distress severity (DSe); Distress class (DCl); Distress extension (DEx), and Distress location (DLo).

<u>Distress scale (DSc)</u>

The distress scale is used to pinpoint the unit of observation under assessment from which data will be gathered. Individual signs of distress affect the smallest unit that forms the pavements. As shown in Fig. 5a, tile-paving defects on a sidewalk may be localized within the confines of a single tile. On the contrary, interface distresses are observed in the contact between the smallest units. In the example from Fig. 5b, these defects occur in the joints between tiles. Finally, global distress can affect a general area. In the example of Fig. 5c, these defects appear across a wider area in a group of several tiles.

Fig 5: Distress Scale (DSc): a) Individual; b) Interface; and, c) Global

Distress severity (DSe)

Pavement service should be understood in terms of esthetics, comfort, and safety for the user. These three basic parameters are therefore the categories used to classify the intrinsic seriousness of each form of distress. Esthetic distress compromises the visual appearance of the pavement, but has no repercussions on serviceability or safety. Comfort distress affects the subjective satisfaction of the citizen during the use of the pavement without compromising its. Safety distress refers to damage that increases the risk of accidents during transit on the pavement.

Fig 6: Examples of Distress Severity (DSe) a) Esthetic; b) Comfort; and, c) Safety

Fig. 6 shows examples of different distress severities. In Fig. 6a, discoloration is observed in the tile-paving on the sidewalk, due to localized repositioning of the pavement. Even though it may lead to negative user perceptions, it has no influence on comfort or safety. Hence, its designation as esthetic distress. Conversely, a small vertical displacement is observed between adjacent elements. Although not large enough to provoke serious accidents, the user might experience the uncomfortable feeling that characterizes comfort distress while walking over an uneven surface. Greater unevenness, as shown in Fig 6c, due to missing tiling, significantly increases the risk to users of stumbling and accidents. This sort of defect characterizes a safety distress.

Distress class (DCl)

On the basis of field observations, different types of distress were considered (cracking, patching, and potholes, surface deformation, miscellaneous distress types). Table 2 summarizes the distress classes for urban tile pavements grouped by DSc and DSe. Different distress classes should be considered for other pavement types, according to pavement evaluation protocols.

Table 2: List of distress classes for urban tile pavements

Distress extension (DEx)

Even though an initial scaling of the distress is achieved with the DSc, it may be necessary to establish the proportion of the polygon that is affected. By doing so, it would be possible to discriminate between polygons with similar damage over different extensions. The DEx parameter will provide information on the pavement segment that is affected by a certain distress. The larger the affected extension, the worse the pavement condition is likely to be. Depending on its scale, stresses may be measured using either the number of units/tiles (for individual distresses), the length (for interface distresses), and the area (for global distresses). Each area of distress that is measured should be relativized, using the percentage portion of the distress over the total value of the pavement section or knot. By doing so, distress on different scales and in different polygons can be summed up and compared.

Distress location (DLo).

The localization of pavement distresses has a direct influence on the user perception of the distress. The perception of distress at less transitable points (away from the main circulatory flow) will be less negative than the perception of the same type of distress at points where transit is frequent. Three different levels of transit are therefore expressed in terms of a circulation coefficient (α) that penalizes those areas with higher levels of transit. A maximum α of 1.0 should be assigned to areas with very high levels of transit, where the effects of distress are highly likely to affect pedestrians and traffic directly. Intermediate values (0.75, for example) should be assigned to distress located in areas where transit is less likely, while lower values (0.50, for example) should be assigned to distress that is visible, but where there is little or no circulation (see Fig. 7).

Figure 7 – Generic scheme of the UPCI methodology using a MIVES framework

3.3: MIVES multi-criteria analysis framework for the urban pavement condition index

The development of multidimensional classification models can be traced back to the linear and quadratic discriminant analysis of Fisher (1936) and Smith (1947). Since then, a number of multi-criteria methodologies have been developed with the aim of providing a systematic framework for breaking the problem into its constituent parts, in order to understand it better and, consequently to arrive to a proper evaluation (Cafiso et al., 2001). The multi-criteria approach applied in this paper to evaluate the urban pavement condition is based on the Integrated Value Model for Structural Assessment (MIVES). This Multi-Criteria methodology was originally developed for the assessment of sustainability (San Jose and Cuadrado, 2010; Aguado et al. 2012; Pons et al. 2012; Aguado et al. 2017) and the prioritization of homogenous (Viñoles et al., 2009) and heterogeneous (Pardo and Aguado, 2014; Pujadas et al., 2017) alternatives. Its main contribution is that it combines Multicriteria Decision Making (MCDM) and Multi-Attribute Utility Theory (MAUT), incorporating the VF function concept (Alarcón et al. 2011) and assigning weights using the Analytic Hierarchy Process (AHP) (Saaty, 1980). In this paper, the problem is structured within the MIVES multi-criteria analysis framework, adapted to evaluate urban pavement conditions according to pre-established criteria. The problem was disaggregated into three levels. The scale of the distress (DSc) represents the first level, the severity of the distress (DSe) defines the second level, while the third level depends simultaneously on the distress class (DCl), location (DLo), and extension (DEx). A scheme of the methodological framework is presented in Figure 8.

Figure 8 – Generic scheme of the UPCI methodology using a MIVES framework

Analytic Hierarchy Process (AHP)

The weights assigned using the Analytic Hierarchy Process (AHP) reflect the relative importance of each level on the condition index. The AHP, originally devised by Saaty (1980), is a linear additive model converting subjective assessments of relative importance into a set of overall scores or weights, which are based on pairwise comparisons. The decision maker is asked a series of questions on how important one particular criterion is relative to another. In this case, the pairwise comparison matrixes from table 3 and 4 were built to assess the weight for the scale and severity levels. The relative importance of each comparison was obtained by consulting a panel of experts with different management responsibilities for pavement maintenance in the city of Barcelona. Note that these matrices may be adapted to the contexts of other cities.

Table 3 – Scale levels pairwise comparison matrix (w_{DSc})

Table 4 – Severity levels pairwise comparison matrix (w_{DSe})

A number of methods may be used to estimate the weights from the pairwise comparison matrix. Saaty's method depends on relatively advanced matrix algebra used to identify the value of the weights that are calculated as the elements in the eigenvector associated with the maximum eigenvalue of the matrix. A more straightforward alternative that also has some theoretical basis is as follows: first, calculate the geometric mean of each row in the matrix; then, calculate the total sum of the geometric means; (3) finally, normalize each of the geometric means by dividing it by the total. The weights estimated by the two different approaches tend to be close although not identical. The latter approach was used in this paper to obtain the weight of each level.

According to the values of the pairwise comparison matrix of table 1, all the scale levels were considered equally important. This assumption leads to a Rank 1 matrix (all the rows are linearly dependent on the first), and they consequently have the same weight (w_{DSci}) for the three scales of distress. The same organization was also assumed for the DCl, in which the same weights (w_{DSli}) were obtained for all the distress classes. On the contrary, different weights were obtained with the pairwise comparison matrix of the severity levels (w_{DSei}, see table 2). Safety-related distresses have a greater impact on the final assessment of the urban pavement condition than the functional or esthetic distresses.

The severity weights assigned by the decision-makers represent a first step in the definition of the pavement management strategy. Although distress may progress quite differently depending on its class, generally if left unrepaired, the heightened severity will turn an esthetic problem into a safety problem. Therefore, a stricter criteria followed by the decision-makers, in which functional and comfort-related distress is assigned higher weights and will consequently have greater impact on the pavement condition, will result in a preventive strategy that keeps distress levels below a safety-related threshold.

Value function concept

The extension of distress affecting the pavement condition will depend on its severity and class. In some cases, a small extension will significantly affect the pavement condition, while in others, even larger extensions may not impair the state of the pavement. The methodology applies the VF concept in accordance with the format of Eq. 1, in order to consider such circumstance. This equation is a single mathematical function that converts the qualitative and quantitative variables of the indicators, with their different units and scales, into a single scale from 0 to 1 (Alarcón et al. 2011). Such extremes represent the minimum and the maximum degree of decision-maker satisfaction. The value function in MIVES depends on 5 parameters, the variations of which generate the four basic types of curves: concave, convex, lineal, and S-shaped. The parameters that define the function type are Ki, Ci, X max., X min. and Pi. The value of B that appears in equation 3 is calculated in accordance with Eq. 2.

$$IV_i = B_i * \left[1 - e^{-Ki*\left(\frac{|X - X_{min_i}|}{C_i}\right)^{P_i}}\right] \quad [1]$$

where: X_{min} is the minimum x-axis of the space within which the interventions take place for the indicator under evaluation.

X is the quantification of the indicator under evaluation (different or otherwise, for each intervention).

P_i is a form factor that defines whether the curve is concave, convex, linear, or "S" shaped: concave curves are obtained for values of $Pi < 1$, convex and

"S" shaped forms for Pi > 1, and quasi linear forms for Pi = 1. In addition, Pi gives an approximation of the slope of the curve at the inflection point.

C_i approximates the x-axis of the inflection point.

K_i approximates the ordinate of the inflection point.

B_i is the factor that maintains the function within the value range of 0 to 1, which is defined by Eq. 2.

$$B_i = \left[1 - e^{-Ki*\left(\frac{|X_{max_i} - X_{min_i}|}{C_i}\right)^{P_i}}\right]^{-1} \quad [2]$$

where: X_{max} is the x-axis of the indicator that generates a value equal to 1 (in the case of functions with increasing values).

The esthetic quality standards in Barcelona are highly demanding and the same is true of its pavements. In consequence, almost all the polygons under evaluation are close to the point of maximum satisfaction. Hence, a convex curve (in which there is hardly any increase in satisfaction for small changes around the point that generates minimum satisfaction, see Figure 9a) was used for esthetic distresses, so that the discrimination is better and the incentive for improvement higher. On the contrary, a concave type curve (in which satisfaction rapidly increases at first in relation to the indicator, see Figure 9c) was used for safety-related distress. This type of relationship is chosen when the most important point is to move away from the point of minimum satisfaction rather than reaching the point of maximum satisfaction. In this case, small changes in unsafe polygons are highly valued. Finally, a linear function with a proportional relationship throughout the range was used for functional distress, showing a steady increase in the satisfaction produced by the alternatives (see Figure 9c). Table 5 presents the values chosen for the definition of the value functions

Figure 9. Different types of value functions: a) convex, b) linear, and, c) concave

Table 5 – Values chosen for the definition of the value functions

3.4: Final Urban Pavement Condition index (UPCI)

Section 3.3 presented the integrated MIVES approach for the categorization of urban paving tiles. The steps of the methodology are briefly summarized as follows:

Step 1: Definition of the portion (in percentages) of the pavement affected by each surface distress class (DCl) under analysis. Depending on the distress scale, the DEx may be defined as a percentage of the number of units, length, or area for individual, interface, and global distress, respectively.

Step 2: For each of the extensions (DEx_i) defined in Step 1, a circulation coefficient α_i, (see section 3.2) is assigned. Thus, obtaining a modified distress extension (DEx_i*)

Step 3: Weighted sum of the DEx_i* calculated in step 2 (DSc already penalized by the circulation coefficient) of all the distresses of the same scale and severity (*i.e* individual esthetic distresses). Note that the maximum (ΣDEx_i*) of each category on the distress scale and its severity will not exceed 100%.

$$\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*} w_{DCl,i} = \sum_{DCl=1}^{i} \left(DEx_{DCl,i}\ \alpha_i\right) w_{DCl,i} \qquad [3]$$

Step 4: For a given distress scale (DSc), apply the VF of each of the severity levels (DSe), for each modified extension ($\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*} w_{DCl,i}$) obtained in step 3.

$$VF_{DSe,m}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*} w_{DCl,i}\right) \qquad [4]$$

Step 5: For a given distress scale (DSc), apply the weighted sum of the results in step 4 to each of the three levels of distress severity.

$$\sum_{DSe=1}^{m} \left(VF_{DSe,m}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*} w_{DCl,i}\right)\right)_{m} w_{DSe,m} \qquad [5]$$

Step 6: Finally, a weighted sum of the three levels of the distress scale (respectively affected by its $w_{DSc,j}$) yields the integrated index of the pavement condition:

$$UPCI = \sum_{DSc=1}^{j} \left(\sum_{DSe=1}^{m} \left(VF_{DSe,m}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*} w_{DCl,i}\right)\right)_{m} w_{DSe,m}\right)_{j} w_{DSc,j} \qquad [6]$$

As previously mentioned, the evaluation process is based on a 3-level framework: scale (DSc); severity (DSe); class (DCl). Organization of the framework permits further analysis of the urban pavement condition, as partial indexes may be directly retrieved. Table 6 presents the partial indexes which may be obtained as a result of grouping the distress classes by scale or severity.

Table 6 – Partial indexes

4- SIDEWALK TILE-PAVING

The feasibility, robustness and coherence of the UPCI multicriteria approach is assessed in this section in a sensitivity evaluation of 3 streets in Barcelona: Carrer Bruc (between Còrsega and Roselló), Parc Estació del Nord (between Nàpols and Sandenya), and Carrer de Moscou.

4.1- Description of the studied examples

The general condition of Bruc street is good, however, occasional spots of esthetic distress concentrated in certain areas of the street such as cracked tiles (Fig 10a), loss of chromatic properties (Fig 10b) different tile styles (Fig 10c), wear and tear (Fig 10d), and surface aging (Fig 10e) can be identified. However, these defects have no effect on pedestrian comfort and safety.

Figure 10. Different images of distress in Carrer Bruc

Figure 11 shows the most significant and representative surface distress on the sidewalk pavement of the Parc de l'Estació del Nord. This pavement was constructed with 60mmx40mm precast paving tiles. Apart from broken and/or cracked tiles (Fig 11a and 11b), other aspects of esthetic distress can be identified such as discoloration (Fig. 11c). Moreover, risky situations with raised paving tiles alongside green areas were found during the inspection, at some distance from areas with frequent pedestrian circulation.

Figure 11. Different images of distress in Parc Estació del Nord

Figure 12 presents some of the most representative distress in Carrer de Moscou (Fig 12a). This polygon (in the Sant Martí neighborhood) corresponds to the sidewalk paving, built with high quality 30mmx20mm precast tiles. The condition of the pavement is highly affected in comparison with the general state of sidewalk pavements in Barcelona. Most of the distress shown in the photos is caused by underground roots close to the tree pits (Fig 12b). Additionally, throughout the section (Fig 12c), tile movement (Fig 12d), wear and tear of curbstones (Fig 12e) and interface distress (Fig 12e) can be identified together with some missing elements (Fig 12f).

Figure 12. Different images of distress in Carrer de Moscou

4.2- Results

Table 7 presents the results of the UPCI Index together with the scale and the severity indexes. Note that the overall UPCI index is obtained from the weighted sum of the three levels of the scale or the three levels of severity.

Table 7 – Results of the UPCI and partial indexes

The case study on Barcelona paving tiles have yielded very satisfactory results, showing that accurate, consistent, and repeatable pavement evaluation can be performed with the MIVES methodology. The partial indexes together with the UPCI index are a step towards the prioritization of future maintenance and management strategies in the face of limited resources.

Finally, one can conclude from the global assessment, following the analysis and the assessment of the selected streets together with the overall observations of the sidewalks, that the general state of urban paving in Barcelona is of high quality.

5- CONCLUSIONS

Most of the existing indexes for the assessment of pavement conditions were developed for interurban pavements and their application to urban networks is consequently not representative. Hence the meaningful contribution of this paper to the assessment of the various indexes on the condition of urban pavements in the city of Barcelona. The following conclusions have been drawn from the present study:

- The network of urban pavements has been efficiently categorized with the MIVES multi-criteria methodology in a simple and straightforward manner. It has also been used to assess the service condition of the pavement (through the distress survey) assessed with the MIVES quality index.
- The quality index represents a global assessment of the urban pavement that considers the scale, severity, class, extension, and location of each distress point. The global index assigned to the urban pavement therefore incorporates, partial indexes on both severity and scale that can be directly retrieved.
- The various examples of paving tiles in Barcelona have yielded very satisfactory results, showing that accurate, consistent, and repeatable categorizations of pavement condition can be performed with the MIVES pavement quality index.
- Moreover, the index provides a further step towards research on an effective urban pavement design that maximizes the performance of pavement sections and makes efficient use of scarce resources.

Appendix A: Checking the consistency of the pairwise comparison matrix.

The weighting of each alternative will usually result in some inconsistencies (causing errors and uncertainty) in terms of fully logical results. The AHP incorporates an effective technique for checking the consistency of the evaluations to which the decision-maker contributes when building each of the pairwise comparison matrices that form part of the process. Hence, Saaty introduced the Consistency Ratio (CR) for pairwise consistency matrices. If the CR exceeds 10%, it is recommended that the decision-maker review the preferences. The CR may be calculated using the Consistency Index (CI) and the Random Index (RI), according to eq. A1.

$$CR = \frac{Consistency\ Index}{Random\ Index} = \frac{CI}{RI} \quad [AA.1]$$

Saaty proposed that the Consistency Index (CI) be computed from the largest eigen value (λ_{max}) and the size (m) of the pairwise comparison matrix, as shown in eq. AA.2.

$$CR = \frac{\lambda_{max} - n}{n - 1} \quad [AA.2]$$

The Random Index can also be interpreted as a consistency index when the entries of A are completely random. The values of RI for small problems (n ≤ 10) are shown in Table AA.1.

Table AA.1 Random Consistency Index (RI)

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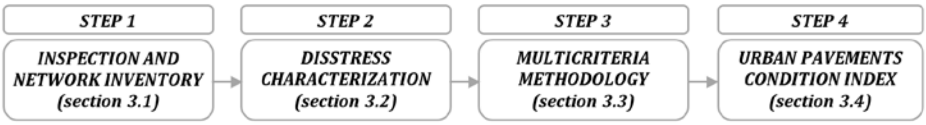

Fig 1. Flowchart of the methodology proposed

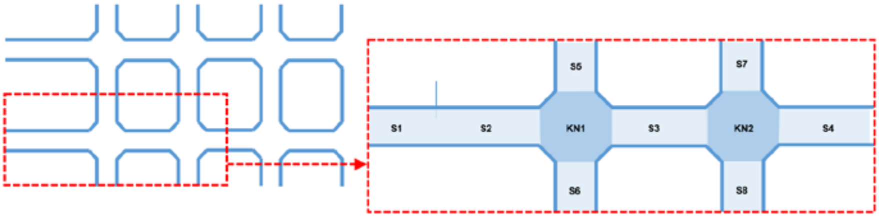

Fig 2. Schematic urban network division into knots (Ki) and sections (Si)

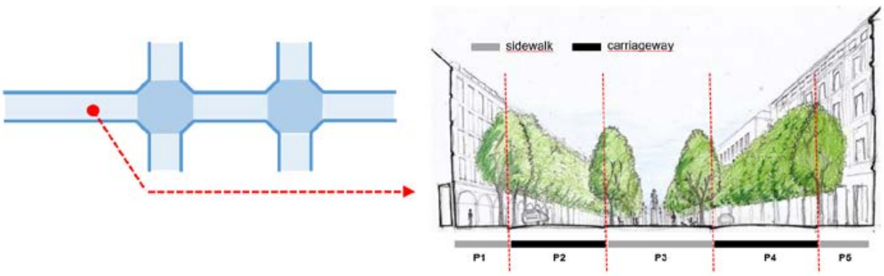

Fig 3. Example of division intro polygons (Pi)

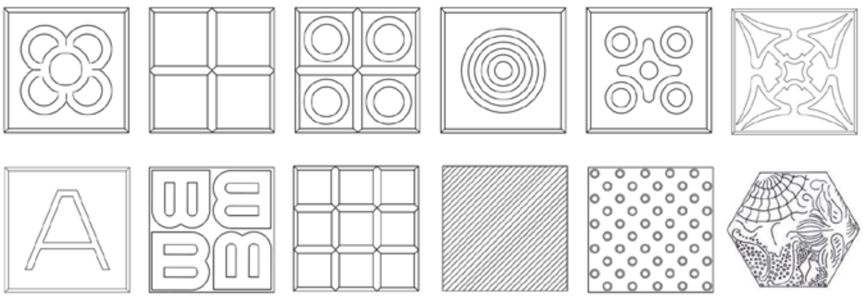

Fig 4. Designs of the common paving tiles used in Barcelona

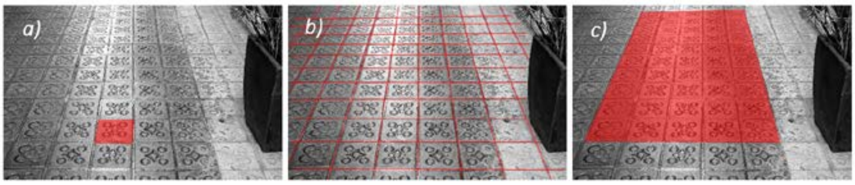

Fig 5. Distress Scale (DSc): a) Individual; b) Interface and c) Global

Fig 6. Examples of Distress Severity (DSe) a) Aesthetic; b) Comfort and c) Safety

Figure 7 – Generic scheme of the UPCI methodology using a MIVES framework

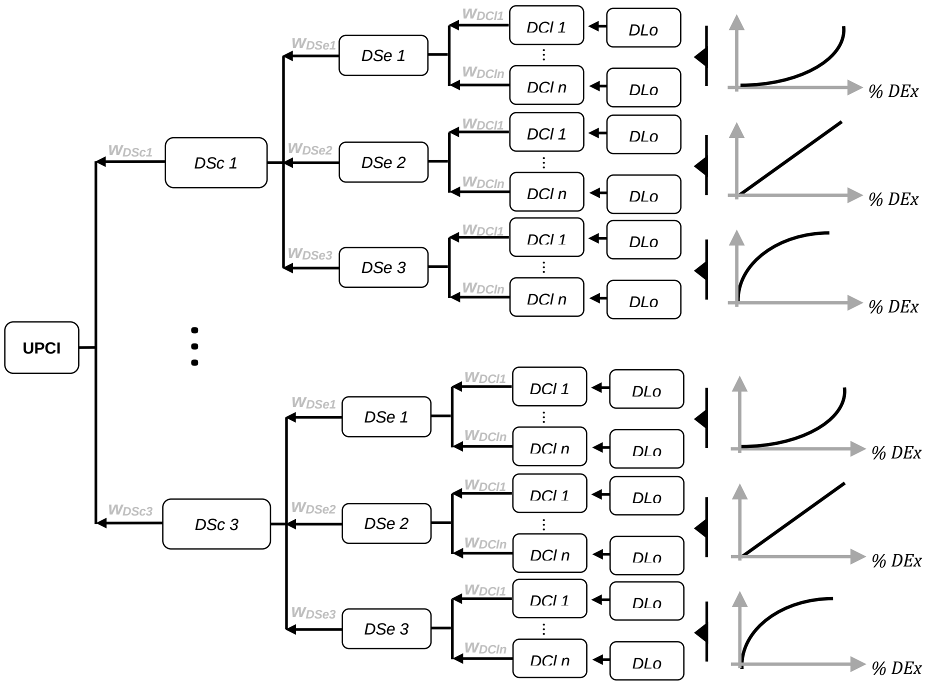

Figure 8 – Generic scheme of the UPCI methodology using a MIVES framework

Figure 9. Different types of value functions a) convex; b) linear and c) concave

Figure 10. Different images of distresses in Carrer Bruc

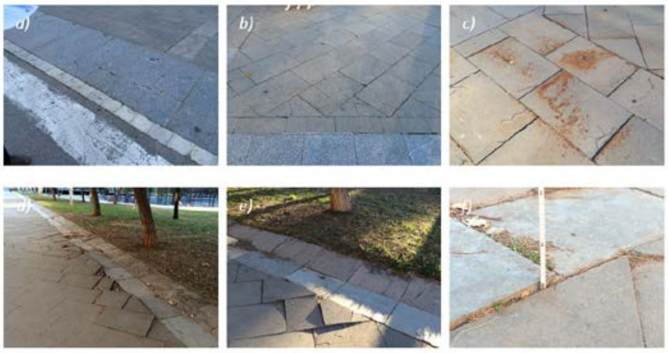

Figure 11. Different images of distresses in Parc Estació del Nord

Figure 12. Different images of distresses in Carrer Moscou

Table 1: List of pavements of general use in Barcelona

List of paving materials for pavements and sidewalks in Barcelona			
DISCONTINUOUS (BY PIECES)	PRECAST MORTAR/CONCRETE	1	20x20 mortar tile
		2	Precast concrete tile High quality concrete tile Regular quality concrete tile
		3	Precast concrete paver/cobblestone High quality concrete paver/cobblestone Regular quality concrete paver/cobblestone
	CERAMIC	4	Klinker ceramic paver/cobblestone
	ARTIFICIAL STONE	5	Artificial stone or terrazo tiles
	NATURAL STONE	6	Natural granite stone
		7	Natural sandstone stone
		8	Other natural stone
		9	Natural stone paver/cobblestone
CONTINUOS PAVEMENT	BITUMINOUS	10	Continuous hot bituminous pavement Continuous hot bituminous pavement for basic network street Continuous hot bituminous pavement for local network street
		11	Dual component resins for grout bituminous surface treatment
		12	Coulored bitumen slurry
	CONCRETE	13	Large concrete slabs
	GRANULAR	14	Saulo sand
		15	Stabilized Saulo sand
	SYNTHETIC	16	Recycled rubber

Table 2 – List of distress categories for urban pavements

DSc	DSe	Distress Categories for tiled Urban pavements
INDIVIDUAL	ESTHETIC	Erosion and/or surface wear due to ageing
		Depressions other surface wear without risk
		Cracks without material loss or vertical slopes / gaps
		Loss of chromatic properties
	COMFORT	Peeling edges with mass loss or movement of part of the tile-piece
		Pointed corners with mass loss or movement of part of the tile-piece
		Movement between paving tiles due to loss of cohesion
	SAFETY	Loose tile or paving tile missing
INTERFACE	ESTHETIC	Vegetation growth
		Horizontal gap between paving tiles< 0.5 cm
		Vertical gap between paving tiles< 0.5 cm
		Sinking of the surrounding elements of the tree well (Vertical gap< 0.5 cm)
		Sinking of the sidewalk curb (Vertical gap< 0.5 cm)
	COMFORT	Loss of cohesion between paving tiles
		Horizontal gap between paving tiles < 1 cm
		Vertical gap between tiles < 1 cm
		Sinking of elements surrounding tree pits (Vertical gap< 1 cm)
		Sinking of sidewalk curb (Vertical gap< 1 cm)
	SAFETY	Horizontal gap between tiles > 1 cm
		Vertical gap between tiles > 1 cm
		Sinking of the surrounding elements of the tree pit (Vertical gap > 1 cm)
		Sinking of the sidewalk curb (Vertical gap> 1 cm)
GLOBAL	INDIVIDUAL	Patches with esthetic impact
	COMFORT	Small surface irregularities < 1 cm
		Pavements bumps < 1 cm
	SAFETY	Surface irregularities > 1 cm
		Pavements bumps > 1 cm

Table 3 – Scale levels pairwise comparison matrix (w_{DSc})

	Distresses			
	Individual	Interface	Global	w_{DSc}
Individual	1	1	1	0.33
Interface	1	1	1	0.33
Global	1	1	1	0.33

(Consistency: CR= 0,00)

Table 4 – Severity level pairwise comparison matrix (w_{DSe})

	Distresses			
	Safety	Comfort	Esthetic	w_{DSe}
Safety	1	3	9	0.69
Comfort	1/3	1	3	0.23
Esthetic	1/9	1/3	1	0.08

(Consistency: CR=-3.8284E-16)

Table 5 – Values chosen for the definition of the value functions

DSc	DSe	$X_{\text{mín}}$	$X_{\text{màx}}$	C_i	K_i	P_i	B_i
Individual distresses	Esthetic distress	0	100	1000	01	1.6	398.6074
	Comfort distress	0	100	10	0.00001	1	10000.5
	Safety distress	0	100	75	4	1	1.004851
Interface distresses	Aesthetic distress	0	100	80	01	2	6.13016
	Comfort distress	0	100	10	0.00001	1	10000.5
	Safety distress	0	100	100	4	1	1.018657
Global distresses	Aesthetic distress	0	100	40	0.2	1.5	1.830116
	Comfort distress	0	100	10	0.00001	1	10000.5
	Safety distress	0	100	60	6	1	1.000045

Table 6 – Partial indexes

Severity indexes		
Esthetic distress index	$\sum_{DSc=1}^{j}\left(\left(VF_{DSe,aesthethic}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*}w_{DCl,i}\right)\right)_{aesthetics}\right)_{j} w_{DSc,j}$	[7]
Comfort distress index	$\sum_{DSc=1}^{j}\left(\left(VF_{DSe,comfort}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*}w_{DCl,i}\right)\right)_{comfort}\right)_{j} w_{DSc,j}$	[8]
Safety distress index	$\sum_{DSc=1}^{j}\left(\left(VF_{DSe,safety}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*}w_{DCl,i}\right)\right)_{safety}\right)_{j} w_{DSc,j}$	[9]
Scale indexes		
Individual distress index	$\left(\sum_{DSe=1}^{m}\left(VF_{DSe,m}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*}w_{DCl,i}\right)\right) w_{DSe,m}\right)_{individual}$	[10]
Interface distress index	$\left(\sum_{DSe=1}^{m}\left(VF_{DSe,m}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*}w_{DCl,i}\right)\right) w_{DSe,m}\right)_{interface}$	[11]
Global distress index	$\left(\sum_{DSe=1}^{m}\left(VF_{DSe,m}\left(\sum_{DCl=1}^{i} DEx_{DCl,i}{}^{*}w_{DCl,i}\right)\right) w_{DSe,m}\right)_{global}$	[12]

Table 7 – Results of the UPCI and partial indexes

Street Segment	UPCI	SCALE INDEXES			Severity indexes		
		Distresses			Distresses		
		Individual	Interface	Global	Aesthetic	Comfort	Safety
Bruc	0.166	0.034	0.340	0.125	0.092	0.050	0.211
Parc Estació del Nord	0.230	0.353	0.024	0.311	0.052	0.112	0.286
Moscou	0.381	0.609	0.072	0.460	0.014	0.132	0.500

Table AA.1 Random Consistency Index (RI)

Matrix size n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51