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DEVELOPMENT OF A DECISION MAKING TOOL FOR PAVEMENT MAINTENANCE MANAGEMENT UNDER SUSTAINABILITY CRITERIA

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This paper focuses on solving the problem of budget allocation for the pavement maintenance management of an urban road network. To do this, a decision-making tool is developed. The tool is based on a quantitative valuation of six sustainable criteria to obtain a priority ranking. The relative weights are calibrated with the aim of obtaining a higher benefit-cost ratio to a horizon of 4 years. The tool is applied to a sample of Valencia's urban road network. The work concludes that decision-making based on sustainable criteria increases the ratio benefit-cost in 53%, compared with the plan based only on the condition of the pavement, which is typical in management agencies lacking an assessment tool. The application of the tool to an urban road network that differs in conditions with the sample analyzed must be preceded by a calibration similar to the one raised, in order to define the optimal scenario in relative weights.

Keywords: Infrastructure management, Urban pavements, Budget allocation, Valencia.

1 INTRODUCTION

A nation's road network is one of its greatest patrimonial assets. The road infrastructure provides a fundamental basis for economic performance and development. Likewise, it contributes significantly to environmental damage during its construction, maintenance, and use (Santero and Horvath 2009). Schliessler and Bull (2003) said that a country that allows the deterioration of its road infrastructure may have a surcharge of vehicular operation in a range of between 1 and 3% of its national GDP. On the other hand, Hajj *et al.* (2010) said that the typical cost of maintaining a road network is equal to 15-20% of the cost of its rehabilitation or reconstruction. To get an efficiently pavement manage, it is necessary to use standardized tools and processes such as the implementation of a pavement management system, known as PMS (Pavement Management System). A PMS is a set of tools used and designed to give, assess, and maintain pavements in acceptable service conditions for a period of time (AASHTO 1985). Steger (1978) pointed out that a PMS is due to two fundamental characteristics: the monitoring of pavements and the use of a decision-making tool for maintenance work. Instead, Hudson *et al*. (1979) established that a PMS should be developed in such a way that it can be used by the managers of all or most levels in charge of pavement management. This paper focuses on solving the existing problem with respect to the maintenance management of pavements. This problem has been previously dealt by other authors. Torres-Machi *et al.* (2017), raised an optimization of budget allocation, in which there were ST x N possible solutions, being "N" the number of pavements and "S" the number of possible solutions to be applied in a horizon of analysis of “T” years. The authors focused on the development of an optimization tool to maximize the long term effectiveness of maintenance and minimize the emissions of GHG (global greenhouse gas) with the constraints of a limited budget and a minimum threshold of condition. Meneses and Ferreira (2015), instead, dealt with the problem as an optimization whose objective function was to minimize maintenance costs and maximize the residual value of the pavement network considering a minimum threshold of condition and an annual budget as restrictions. Based on the aforementioned, this work focuses on the development of a decision-making tool for the annual management of pavement maintenance whose main objective is to achieve a greater long-term benefit-cost ratio, guaranteeing the sustainability of the infrastructures. Another of the objectives pursued is the easy adaptability of the tool by the managers and decision makers of a road network.

2 METHODOLOGY

The proposed methodology solves a multi-criteria decision-making problem based on SAW (simple additive weighting) method. Six quantitatively valuation criteria are proposed to establish an annual prioritization of the pavement maintenance that allows accommodating the available budget of a network efficiently. Value functions are used to normalize each criterion to values between zero and one and rate the level of satisfaction of an alternative with respect to certain criteria. The relative weights of each criterion, conditions the prioritization and the long term results. Thus, this study calibrates the weights to obtain the best benefit-cost ratio and define the best scenario. Results are compared to the conventional situation, in which only user’s comfort is considered. For the weight’s calibration, a long-term economic evaluation (four years) is done.

2.1 Criteria for Decision Making

The proposed valuation criteria are as follows:

Criterion one: User’s comfort. This is used to rate the comfort of the road network’s users. With the aim of evading a subjective valuation, the valuation of the comfort was made based on the condition of the pavement. For this purpose, a step function is used (Table 1), which score the values between zero and one depending on the PCI (Pavement Condition Index).

Table 1. Rule for the construction of the value function of the criterion 1.

PCI	F (PCI)
0 – 10	1.00
10 – 40	0.75
40 – 70	0.50
70 - 85	0.25
85 - 100	0.00

Criterion two: Accident cost. In order to ensure sustainability and reduce the damage to society and users, it was decided to include this criterion in the decision-making. This aims to prioritize maintenance work on the roads that have a higher accident cost per year. For its evaluation, Eq. (1) proposed by Forkenbrock *et al.* (1997) should be used. With this equation it is possible to obtain the accident cost per mile vehicle travel. PSR assesses the pavement condition, taking values between zero (poor) and five (excellent), PASRES takes value of one or zero in presence or lack of pass restriction, ADTLANE refers to the traffic expressed in miles vehicles per lane, RIGHTSH is the curb width expressed in feet, LANES takes values of one if the road has more than four lanes or zero if not. TOPCURV and TOPGRAD refer to the curvature in horizontal and vertical tracing of the road (Forkenbrock *et al.* 1997).

$$\frac{\text{Cost of Accidents}}{\text{Millions VMT}} = 1.587.580\left(0{,}994^{\text{PSR}}\right)\left(1{,}111^{\text{TOPCURV}}\right)\left(1{,}442^{\text{PASRES}}\right)\left(1{,}741^{\text{ADTLANE}}\right)\left(0{,}952^{\text{RIGHTSH}}\right)\left(0{,}936^{\text{LANES}}\right)\left(1{,}085^{\text{TOPGRAD}}\right) \tag{1}$$

Criterion three: Economic efficiency. In order to achieve obtain the highest benefit-cost ratio, economic efficiency is raised as a criterion. Carnahan *et al.* (1987), quantifies the efficiency of maintenance by increasing the PCI (Δ PCI). For the calculation of the economic efficiency, the Eq. (2) is proposed, in which the product of Δ PCI and the average daily traffic intensity (IMD) are divided, by the total cost of the maintenance's works.

$$\text{Ef Ec}=\frac{\Delta\text{PCI* IMD}}{\text{Cost Actuation}} \tag{2}$$

Criterion four: Proximity to social and tourist infrastructure. This criterion seeks to prioritize those roads close to relevant social and tourist infrastructures. For its valuation, it is proposed to classify the infrastructures in 3 levels of importance (N2, N1 and N0), according to the nature of the infrastructures that are in a circumference of 500 meters in diameter, drawn from the middle point of the road. A value function (Table 2) prioritizes with a convex function the N2, from the N1 with linear function and N0 with concave function.

Table 2. Functions used for the valuation of the criterion 4.

Proximity to infrastructure level	**Value function**
N2	$V = \frac{1}{1-e^{-3,5}}\left[1-e^{\frac{-3,5(100-PCI)}{100}}\right]$
N1	$V = \frac{1}{1-e^{-(10)^{-9}}}\left[1-e^{\frac{-(10)^{-9}(100-PCI)}{100}}\right]$
N0	$V = \frac{1}{1-e^{3,5}}\left[1-e^{\frac{3,5(100-PCI)}{100}}\right]$

Criterion five: Environmental efficiency. This criterion seeks to prioritize efficient maintenances from the environmental point of view. For its assessment, Eq. (3) is used. This equation is similar to (2) but replaces the monetary cost for the environmental cost, quantified as the kilograms of CO_2 generated with the maintenance.

$$\text{Ef Amb}=\frac{\Delta\text{PCI* IMD}}{\text{Kg of CO2}} \tag{3}$$

Criterion six: Inconvenience caused. This criterion seeks to prioritize those alternatives that generate minor discomfort to the society, that is to say, that they take the least amount of time for execution.

Criteria two, three, five and six need to be normalized to values between zero and one. Therefore, a value of one corresponds to the highest value (Eq. (4)), in the case of criteria two, three and five and the lowest value (Eq. (5)), in the case of criterion six.

$$rij = \frac{X-Xmin}{Xmax-Xmin} \tag{4}$$

$$rij = 1-\frac{X-Xmin}{Xmax-Xmin} \tag{5}$$

2.2 Long Term Comparison

The long-term outcome of the decision-making tool depends on the relative weights assigned to each criterion. For the comparison of maintenance strategies, a LCCA (Life Cycle Cost Assessment) is used over a 4-year horizon. The objective of the evaluation is to obtain a greater benefit-cost ratio. For the costs, only those incurred by the management agency in the maintenance works during the 4 years of analysis are considered. On the other hand, the quantification of benefits is carried out by calculating the increase in the residual value of the road network from the beginning of the year zero with respect to the end of 4 year period. Fullana and Puig (2012) defined residual value as the value of life remaining at the end of the analysis. Babashamsi *et al.* (2016) defined as a useful life of a pavement treatment, the time remaining for the pavement to deteriorate to a threshold established. The residual value was calculated under the previous premises using the deterioration curves of the pavements. It was defined a minimum threshold of PCI of 40, because a total reconstruction would be needed for values lower than 40. The residual value was monetized by multiplying the total reconstruction cost (CTR) by the percentage of the area under the corresponding deterioration curve at the time of analysis, obeying Eq. (6) and Figure 1.

$$\mathrm{VR} = \mathrm{CTR} * \frac{\mathrm{A2}}{(\mathrm{A1+A2})} \tag{6}$$

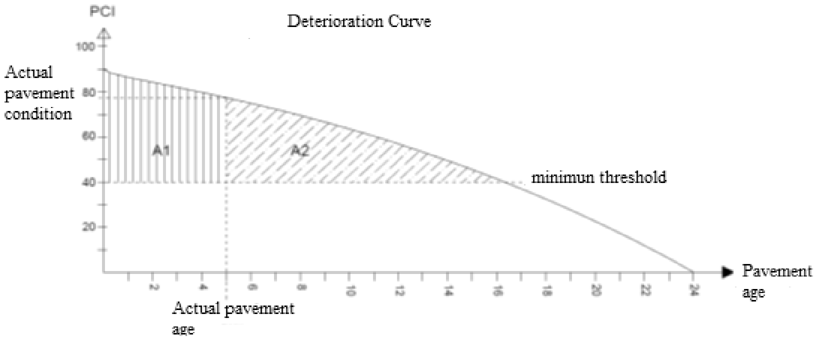

Figure 1. Residual value calculation through deterioration curves.

3 CASE STUDY

The case study focused on a sample of Valencia's urban road network, consisting of 13 asphalt roads. The characterization of the sample was made during the year 2016, including a geometric data extraction, pass restrictions and condition evaluation (PCI) made by images taken with the Google Earth Pro. The volume of traffic was extracted from the database of the Valencia Council. The typical actions carried out in the network were extracted from the research carried out by Guaita (2016). The unitary emissions of CO_2 of maintenance actions were taken from Torres-Machi *et al.* (2015). The annual budget for the maintenance of the network (€865282.32) was obtained proportionally to the area of the sample. Another restriction considered was to make at least a minimum investment of €10000.00, as well as allowing an investment of €100000.00 additional loading, or paying the deficit or super habit to the next year's budget. Due to the lack of performance data for the Valencia pavements, Eq. (7) proposed by (George *et al.* 1989) was used for evaluating the reduction of PCI over time.

$$PCI(t) = 90 - a\left[e^{age^{b}} - 1\right] log\left[\frac{ESAL}{SNC^{c}}\right] \tag{7}$$

3.1 Decision Making

For decision making and comparison purposes, a first scenario was raised (E1) in which it was assigned a weight of 100% to criterion 1, and a second scenario (E2) was raised in which weights are calibrated to obtain the best benefit-cost ratio. E2 calibration obtained weights of 30%, 10%, 30%, 10%, 10% and 10% for the six criteria, respectively. Table 3 shows the decision-making scheme for E2 in 2016. This strategy suggests maintaining Viyarroya and Ayora streets during 2016. After performing the maintenance, the PCI of these roads increased to 100 and deteriorated during the following years using the deterioration curves. The process was repeated until the end of 2019 and the increment in the network's residual value (benefit) was calculated. This amount was divided by the total cost of maintenance executed in the 4 years given the benefit -cost ratio, which was 2.9. From the results, it worth noting that criterion 1 and 3 should take the same weight to avoid being given priority only in total rehabilitation maintenance works with low PCI values (as criterion 1) or preventive maintenance with low-cost maintenance actions (as criterion 3). Criteria 1 and 3 should take greater values than criteria 2, 4, 5, and 6. However, these last criteria cannot be forgotten as environment and social aspects should be taken into account for sustainable purposes. Table 4 compares E1 and E2. As mentioned above, a weight of 100% is allocated to the criterion of comfort in order to simulate the conventional decision making when there is a lack of a decision tool. As Table 4 shows, decision-making under sustainable criteria (E2) generates 1257024.77€ additional value increments, investing 762091.43 € less than E1 condition-based decision making. While the benefit-cost ratio of E1 is 1.9, the benefit-cost ratio of E2 is 2.9.

Table 3. Decision making of E2 at the beginning of 2016.

Weights:	30	10	30	10	10	10			Maintenance 2016
Street	***Crit1***	***Crit2***	***Crit3***	***Crit4***	***Crit5***	***Crit6***	***Val***	***Cost***	
VIYARROYA	0.50	0.02	1.000	0.104	0.111	1.00	0.5737	€46.060.00	Yes
AYORA	0.50	0.11	0.365	0.550	1.000	0.94	0.5202	€2.246.40	Yes
GIORGETA	0.50	1.00	0.095	0.400	0.376	0.37	0.3927	€878,421.28	No
BELTRAN	0.75	0.02	0.066	0.399	0.316	0.61	0.3791	€99,865.60	No
URUGUAY	0.50	0.10	0.200	0.182	0.538	0.84	0.3765	€878,421.28	No
PEREZ GALDOS	0.50	0.35	0.094	0.480	0.374	0.37	0.3354	€206,093.26	No
JESUS	0.50	0.07	0.076	0.802	0.301	0.34	0.3244	€4,399.56	No
CARTEROS	0.50	0.08	0.131	0.100	0.347	0.80	0.3217	€403,873.08	No
BRASIL	0.00	0.02	0.436	0.013	0.674	0.97	0.2989	€109,622.80	No
ARCHIDUQUE	0.50	0.04	0.061	0.430	0.241	0.47	0.2865	€649,100.80	No
CUENCA	0.50	0.01	0.020	0.340	0.036	0.64	0.2585	€187,107.00	No
TRES FORQUES	0.50	0.00	0.000	0.300	0.000	0.00	0.1800	€ 9,539.64	No
TOBEÑAS	0.00	0.01	0.088	0.080	0.105	0.94	0.1398	€955,555.38	No
							Total	€ 48,306.40	
							Sup.	€ 816 975.92	

Table 4. E1-E2 Comparison.

Esc	Crit1	Crit2	Crit3	Crit4	Crit5	Crit6	Δ Res Val	Inversion (Cost (€))	B/C
E1	100	0	0	0	0	0	6 573 975.66 €	3 460 811.50 €	1.90
E2	30	10	30	10	10	10	7 831 000.43 €	2 698 720.07 €	2.90

4 CONCLUSIONS

Of the developed work it was concluded that 30%, 10%, 30%, 10%, 10%, 10% are the relative weights of each criterion to obtain the highest cost-benefit ratio. It was concluded that the decision making should not be prioritized according to the condition as a unique criterion. Decision-making based on sustainable criteria allows obtaining a higher long-term benefit-cost ratio. Another important conclusion is that criterion 1 and 3 should have the same weight to compensate for rehabilitation maintenance works and preventive maintenance. Therefore, this strategy suggests that it is beneficial to carry out preventive maintenance but also maintain the infrastructures under worse conditions. As a recommendation, it is emphasized that the application of the tool to an urban road network that differs in conditions with the sample analyzed must be preceded by a calibration similar to the one raised, in order to define the optimal scenario in relative weights. The level of importance of urban infrastructures should be defined when evaluating the criterion 4. It is also recommended to adjust the tool with performance curves based on historical data with the purpose of estimating the maintenance actions more precisely.

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