A Multi-criteria Decision-making Analysis Method for the Appraisal of Alternative Pavement Maintenance and Rehabilitation Investments

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ABSTRACT: A well known issue regarding pavement management is the need to account for road user costs, for instance, when life cycle cost analysis is performed. Every time a specific maintenance and rehabilitation policy is planned, the cost associated to effects such as delays due to road works, should be taken into account. Several methodologies have been developed to do this. However, such methodologies typically address the estimated monetary cost associated to the mentioned effects, adding it to the agency cost. This paper describes the framework of a multi-criteria decision analysis method meant to be applied to the appraisal of alternative pavement maintenance and rehabilitation investments. This method was developed specifically to allow a reliable way to include road user effects in the decision-making process, including them as attributes of the alternatives instead of computing monetary cost. These effects are measured by criteria such as works' duration or user delay in addition to, of course, agency cost.

KEY WORDS: User costs, work zones, pavement management.

1 INTRODUCTION

In the context of pavement management, important progress has been made with regard to user costs. Motivated, in part, by the greater dependency of people and goods' mobility on road infrastructure, several methodologies have been developed aiming to include these kinds of costs in the decision-making process in addition to agency costs.

User costs can be analysed from the moment when costs are incurred by users (i.e., during roadworks or in normal operating conditions). Existing methodologies include the estimate of user costs associated to a specific maintenance or rehabilitation intervention. Typically, these methodologies compute an estimate of user costs based on inputs relative to the intervention (e.g., work zone layout, capacity and permitted speed) and the traffic characteristics. For instance, the Federal Highway Administration (FHWA) methodology, based on the abovementioned factors, analyses traffic flow conditions at the work zone (free flow or forced flow) and then computes the delays (which are subsequently converted into a monetary cost) as well as the vehicle operating costs relative to the expected speed change cycles (Walls and Smith, 1998). Other studies have been developed to make an integrated analysis of work zones. Besides optimisation procedures, where an overall intervention cost (agency cost plus user cost) is minimised in order to achieve, for instance an optimal work zone length (Chien and Schonfeld, 2001), simulation models have also been developed to assess the impact of work zones (Lee and Ibbs, 2005).

This paper describes a method meant to be used in the appraisal of pavement preservation investments, calculating different attributes of a specific maintenance or rehabilitation intervention, permitting a subsequent multi-criteria decision analysis. This paper focuses mainly on determining attributes instead of the subsequent decision-making process.

2 PROPOSED METHOD

2.1 Objectives and scope

This method intends to provide an accurate estimation of the agency cost for a given pavement intervention, as well as other attributes of that intervention related to effect that roadwork has on road users. The main difference from the implemented methodologies is the fact that road user effects are included in the decision-making process as attributes of the alternatives instead of computing a monetary cost for them. This approach will allow the decision-maker to consider the analysis of an intervention as a multi-criteria decision process.

Two main advantages can be identified in this approach. In cases where very high levels of traffic exist, the calculation of user cost produces values far higher than the agency cost, as a result of the magnitude of the delays experienced by users (Haas, 2001), altering the main purpose of the process. This situation should not imply the omission of user costs but rather the need to weight them in the final assessment, in such a way that the decision-maker considers adequate (Hall et al., 2003). Hence, the adoption of a multi-criteria decision-making process can avoid situations such as those above, also permitting the decision-maker to define the weight each attribute should have in the final assessment.

Another factor supporting the abovementioned option for multi-criteria decision-making is the flexibility to address different priorities based on the characteristics of each intervention. Site and project features, traffic volume, road hierarchy and role in the network clearly should be taken into account.

The proposed method is meant to be used in the context of pavement management in such a way that the intervention to take place is already defined (maintenance treatment type, extent, etc.), centring the analysis on the way in which it is planned and executed. The definition of the maintenance treatment to be carried out constitutes an input to the model, along with traffic and other site features. The model intends to generate a set of feasible options concerning, for example, working plant layouts and schedules, and combine them in order to include all the options in the intervention’s planning and undertaking. As model outputs, the attributes for each feasible alternative are calculated, in order to be used subsequently in the multi-criteria decision-making process. This method is to be used in the appraisal of interventions high traffic roads where divergent objectives (e.g., the minimisation of agency cost for the intervention and the minimisation of the intervention’s effect on the users) can arise.

2.2 Framework

Figure 1 describes the layout supporting the proposed model. As noted earlier, the inputs consist of a fully described pavement intervention, traffic characterisation and all relevant site and project constraints. The intervention description includes all the activities necessary (e.g., site preparation, existing pavement milling, placement of new layers, etc.) and work quantities involved. Traffic characterisation includes daily traffic volume; hourly, weekly and monthly variation; traffic composition (percentage of light and heavy vehicles) and average vehicle speed. By site and project constraints, we mean any relevant constraint that could restrict, from the beginning, the feasible set of alternatives.

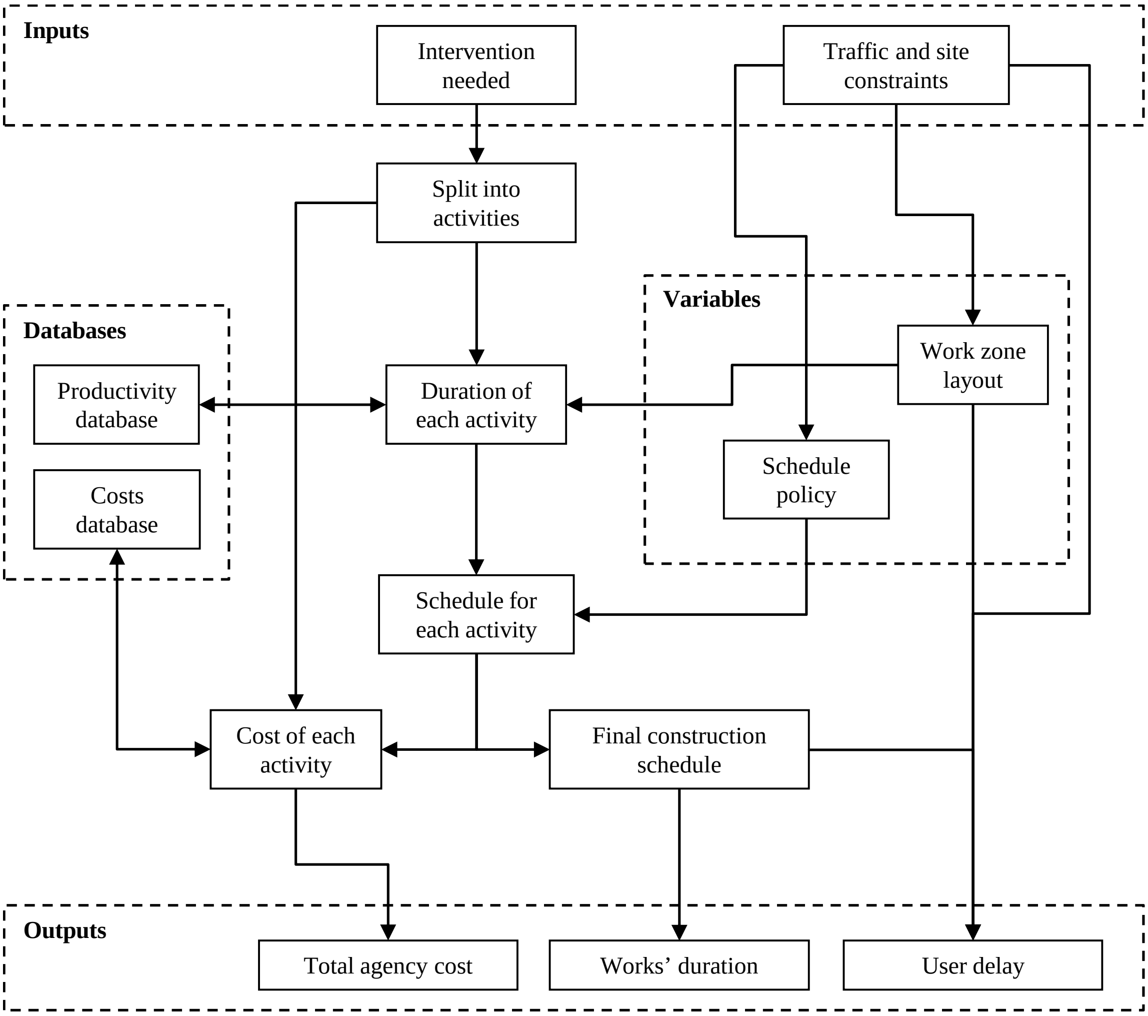

Figure 1: Simplified model layout

The variables module, described below, is the main source of variation allowing the model to generate different alternatives based on different work schedule policies and different work zone layouts. Each activity's duration is calculated by considering the necessary quantity of work and the expected productivity for a chosen work zone layout. The estimated cost of each activity depends on the schedule policy selected, and is computed using the activity's unit cost. The cost and the duration, estimated for each activity, relies on the unit costs database (containing the unit cost for each activity and for each work schedule) and on the productivity database (where, depending on the work zone layout, productivity values are available for each activity), respectively.

The model outputs are three different attributes intended to characterise each alternative by cost (supported by the agency), total works' duration and average delay that users face.

2.3 Variables

As previously mentioned, the variables module is the main source of variation allowing the model to generate different alternatives for the intervention, corresponding in each case to a specific schedule policy and a possible work zone layout. For both issues, all the relevant options are considered and the model generates the set of all feasible options for the intervention. With regard to work zone layout, depending on the road type and other constraints, the number of lanes affected by the intervention, different work zone lengths and traffic management schemes can be tested. In respect to schedule policy, all potential work schedules are tested. This analysis includes, for instance, day work with no restrictions, day work in the off-peak period, night or weekend work only, etc. Specific site and project constraints could clearly determine if those different alternatives are not feasible, excluding them from the analysis.

2.4 Attributes

The selection of the attributes for each alternative generated by the model was based on the need for the results to be sufficiently representative of the issues involved. Agency cost is naturally the first choice and the most relevant attribute. Its importance is only equalled by other attributes in locations characterised by high traffic flows. The other two attributes – total works' duration and average user delay – both related to the effects that users will have to face, were chosen in order to measure distinct aspects. Total works' duration aims to evaluate how long users will have to face traffic disruptions caused by roadwork; the average user delay is an indicator of the magnitude of those disruptions in terms of increase in travel time due to the presence of the work zone. As can be seen in Figure 1, the average user delay will depend on the work zone layout, the estimated traffic flow and the chosen construction schedule.

3 CASE STUDY

3.1 Description

In this part of the paper a single intervention on a road segment of an urban motorway in the Lisbon Metropolitan Area (Portugal) with high traffic flows is described. Based on the actual traffic flows and cross-section geometry (Table 1), we examined a possible intervention concerning the placement of a new asphalt wearing course (for the entire width of the carriageway) and removal of the previous one. Several scenarios will be analysed according to the previously described model. The segment length is 2,700 meters and the cross-section has three lanes on either side plus a hard shoulder. The carriageways are separate, with a concrete barrier between them.

Table 1: Cross-section details

Lanes (in each direction)	3
Carriageway width (m)	13.50
Lane width (m)	3.50
Right shoulder width (m)	2.50
Left shoulder width (m)	0.50
Average speed (km/h)	95
Capacity (vphpl)	2200

The abovementioned average speed was obtained by the automatic traffic counters that are located on this road segment, and the capacity per lane was calculated following the Highway Capacity Manual 2000 methodology (TRB, 2000).

Table 2: Activities, costs and productivities

Activity	Average cost				Average productivity	
	Day (week)		Night/ Weekend			
1 – Traffic mgmt. implementation	22.71	€/100m^2	31.71	€/100m^2	2:00	h/work period
2 – Milling (4 cm)	2.50	€/m^2	3.50	€/m^2	600	m^2/h
3 – Wearing course placement (4 cm)	4.80	€/m^2	6.70	€/m^2	800	m^2/h
4 – Temporary road marking	0.27	€/m^2	0.37	€/m^2	1:00	h/work period
5 – Traffic mgmt. removal	15.14	€/100m^2	21.14	€/100m^2	1:30	h/work period

The intervention (asphalt wearing course replacement in 4 cm depth and previous layer milling) under study was split into five activities (Table 2) in order to analyse cost and productivity. Clearly, other activities are necessary for this type of intervention (e.g., tack coat placing, construction joint sealing, final road marking, etc.) but they were excluded from the analysis.

The activities' costs were derived from inquiries made to several contractors and road infrastructure concessionaires with exception to activities 1 and 5 (traffic management scheme implementation and removal). For both, it was assumed that they could lead to an increase in the amounts for the other activities (i.e., milling, paving and temporary road marking): 3% for activity 1 and 2% for activity 5. In terms of productivity, several inquiries were also made to contractors and road infrastructure concessionaires.

In what it concerns traffic flow, hourly distributions were computed for weekdays and weekends based on one complete month (March 2009) for the road segment under analysis, using the data provided from the automatic traffic counters. Table 3 shows these distributions for the inbound direction. A homogenisation factor of 2 was used to convert trucks to passenger cars.

Table 3: Hourly average traffic flows (weekday and weekend)

Hour	Weekday	Weekend	Hour	Weekday	Weekend
0h - 1h	782	1418	**12h - 13h**	3947	3551
1h - 2h	276	715	**13h - 14h**	3895	3254
2h - 3h	242	588	**14h - 15h**	4386	3561
3h - 4h	221	426	**15h - 16h**	4186	3939
4h - 5h	344	396	**16h - 17h**	4198	3796
5h - 6h	763	534	**17h - 18h**	5183	4097
6h - 7h	3059	1040	**18h - 19h**	5185	4157
7h - 8h	4642	1869	**19h - 20h**	4333	3634
8h - 9h	3933	2423	**20h - 21h**	3194	2629
9h - 10h	4258	3014	**21h - 22h**	2268	2043
10h - 11h	4305	3081	**22h - 23h**	1821	1976
11h - 12h	4036	3182	**23h - 24h**	1494	1645
			Total	**70951**	**56968**

3.2 Scenarios

In order to generate the intervention scenarios, three assumptions first were made. The complete closure of the road segment was not considered as an option since a network analysis model was needed to assess it. In terms of the number of simultaneous work zones, it was assumed that, due to contractors' resources constraints, only one work zone could be in place at any given. Since the intervention being studied refers only to the inbound direction carriageway and a concrete road barrier exists between both carriageways, shifting the entire traffic flow to the opposite side is not an option.

Therefore, two possible work zone layouts were considered, using only the inbound direction carriageway. Layout A comprises two stages: at first the work occurs on the left side of the carriageway (half of the width) keeping two lanes open to the right (using the hard shoulder width); then the opposite situation is set up. The first stage of layout B reduced the number of open lanes down to one on the right side and the work takes place in within a greater width on the left side. At stage 2, since the remaining paving width is smaller, three lanes are open on the left side (though narrower, as illustrated in Table 4).

Table 4: Work zone layouts description

	Layout A		**Layout B**	
	Stage 1	**Stage 2**	**Stage 1**	**Stage 2**
Work side	Left	Right	Left	Right
Lanes open (in each direction)	2	2	1	3
Carriageway width (m)	6.70	6.70	3.90	9.60
Lane width (m)	2.90	2.90	3.00	2.90
Right shoulder width (m)	0.15	0.15	0.15	0.15
Left shoulder width (m)	0.15	0.15	0.15	0.15
Paving width (m)	6.80	6.80	9.60	3.90
Barrier width (m)	0.60	0.60	0.60	0.60
Speed (km/h)	60	60	60	60
Capacity (vph)	2940	2940	1050	4950

Using the methodology developed by Benekohal et al. (2004) and given the geometry of the open lanes and lateral clearance, the speed adopted by drivers when traversing the work zone was calculated. The capacities (vehicle per hour) for layout A (stages 1 and 2) and for stage 1 of work zone layout B were obtained using Figure 2 which reproduces the Highway Capacity Manual (1994 edition, updated in 1997). Choosing a probability factor of 80% and considering the type of lane reduction, Figure 2 provides the expected capacity (vehicles per hour per lane). For stage 2 of layout B, since the number of open lanes is the same as the original situation, HCM methodology cannot be used. The capacity of 4,950 vehicles per hour (1,650 vehicles per hour per lane) was given by methodology of Benekohal et al. (2004) which includes the effect of narrower lanes.

Figure 3 includes the hourly average traffic flows (weekday and weekend) earlier presented in Table 3 as well as the work zone capacities for each layout. During weekdays the morning and evening peaks are visible as well as a significantly high traffic flow during the day between peak periods.

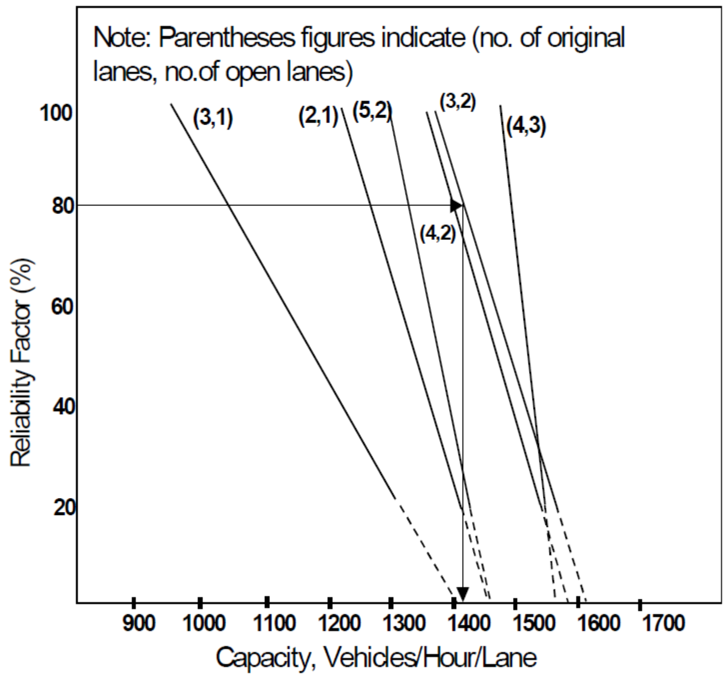

Figure 2: Cumulative distribution of observed work zone capacities (HCM, 1997)

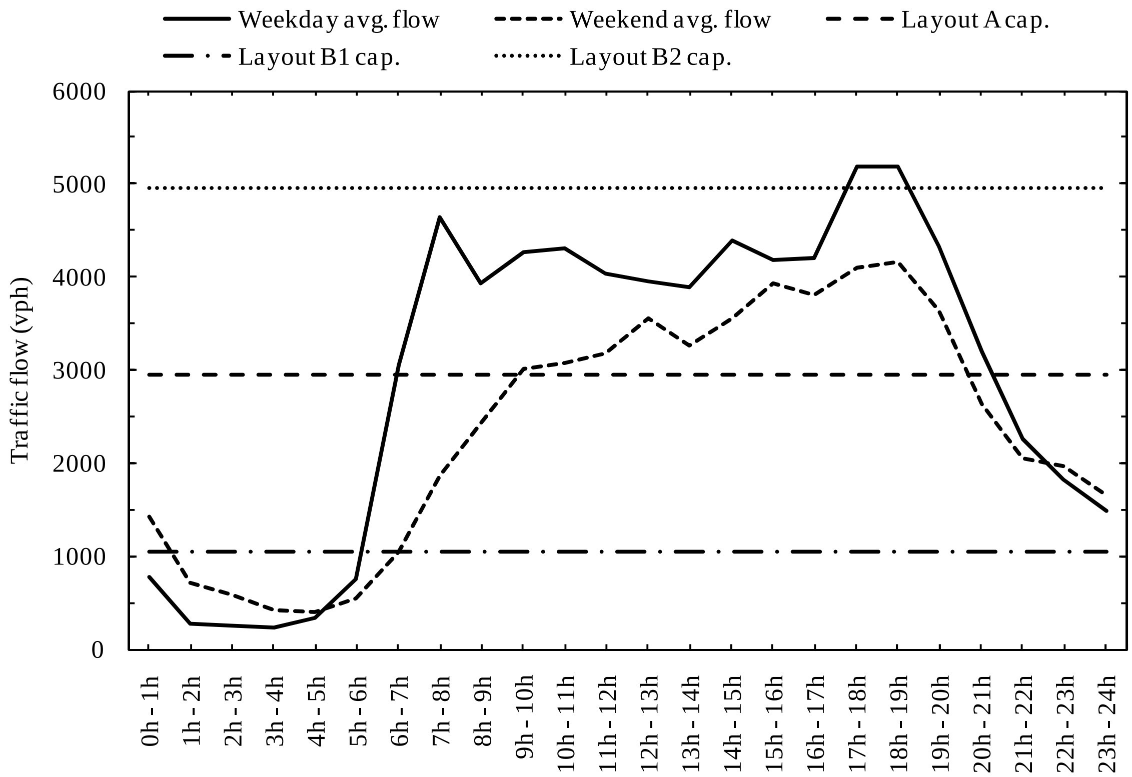

Figure 3: Hourly average traffic flows (weekday and weekend) and work zone capacities

A detailed analysis of Figure 3 defines all permitted work schedules. Preferred night-time schedules for layout A and layout B (stage 1) only allowed day work during the off-peak period for stage 2 of layout B (where three lanes are open). These schedules were set up to avoid periods where the demand is higher than work zone capacity in order to prevent queuing as a result of the work zone. It was assumed that the effective capacity reduction only takes place one hour after the beginning of the work schedule (due to site preparation, police intervention, etc.).

Table 5: Permitted work schedules

Layout	Weekday			Weekend		
	Start	End	Duration	Start	End	Duration
A	21h00	6h00	9h00	21h00	9h00	12h00
B1	23h00	6h00	7h00	0h00	7h00	7h00
B2	10h00	17h00	7h00	7h00	14h00	7h00

Combining the abovementioned work zone layouts and the schedules available, four alternatives were considered as presented in Table 6.

Table 6: Resulting alternatives

Alternative	Work zone layout	Work on weekends
1	A	Yes
2	A	No
3	B	Yes
4	B	No

3.3 Estimate attributes

For the four alternatives considered, several attributes were calculated regarding cost, works' duration and user delay. At first, given the available time frames for each scenario and the productivity of each activity, the maximum length that each work zone can achieve was estimated (Table 7). Milling was considered critical since its productivity is lower than paving. For layout A (both stages), we used the rate of 600 m^2/hour (average); a rate of 850 m^2/hour for stage 1 of layout B, due to the wider space available; and a rate of 350 m^2/hour for stage 2 of layout B, as a result of the narrower space available.

Table 7: Work zones' length calculation

Work zone layout	A (Stages 1 and 2)		B (Stage 1)	B (Stage 2)
Type of closure	**Week (9h closure)**	**Weekend (12h closure)**	**Week/weekend (7h closure)**	
Available time frame (h)	9h00	12h00	7h00	7h00
Milling + paving duration (h)	4h30	7h30	2h30	2h30
Milling productivity (m^2/h)	600	600	850	350
Max. length per hour (m)	90	90	90	90
Work zone length (m)	405	675	225	225

For construction cost estimates, the labour cost was assumed to represent 20% of the total construction cost and every time two consecutive work shifts take place, a 100% increase in labour costs is included, representing the need for another work crew.

Table 8 includes the calculation of the relevant attributes for the appraisal of the abovementioned alternatives. In terms of duration, given the length of the work zone, an estimate was generated for the number of working days (considering the permitted schedules) necessary to complete the intervention. The total agency cost was calculated as well as its distribution over daytime, night-time and weekends. Finally, the amount of traffic that would be forced to traverse a work zone and the average increase in travel time due to the work zones was calculated. This calculation was made based on the FHWA methodology for speed change delays (travelling at 95 km/h, decelerating to 60 km/h, traversing the work zone at 60 km/h and then accelerating back to 95 km/h).

Table 8: Final results (works' duration, cost and user delay)

Alternative	**1**	**2**	**3**	**4**
Work start	Sun. night (day 1)	Sun. night (day 1)	Sun. night (day 1)	Sun. night (day 1)
Work end	Thu. night (day 12)	Wed. night (day 18)	Friday (day 12)	Tuesday (day 16)
Duration (calendar days)	12	18	12	16
Duration (working days)	12	14	12	12
Total agency cost	€ 427,972	€ 407,592	€ 370,089	€ 364,986
Work during daytime (%)	0%	0%	23%	27%
Work during night-time (%)	75%	100%	60%	73%
Work during weekends (%)	25%	0%	17%	0%
Traffic traversing a work zone (%)	14%	9%	46%	37%
Average travel time increase (s)	29	27	23	23
Average travel time increase (%)	28%	32%	23%	23%

It is not within the scope of this paper to fully analyse the results obtained since it is mainly focused on the model framework discussion. However, some of the results obtained merit discussion here. In what concerns the intervention cost, alternatives 3 and 4 have lower costs due the higher amount of work performed during the daytime (much lower labour costs). Comparing alternative 1 with 2 and alternative 3 with 4, the same situation occurs since, in 1 and 3, work is done during weekends. Clearly, if a smaller duration is sought, then weekend work is a necessary option. As regards user perception, alternatives 1 and 2 (without work performed during the daytime) are more appealing, since less traffic will be traversing a work zone.

4 CONCLUSIONS

This paper has focused on a new assessment methodology of pavement preservation investments by comparing systematically different attributes, describing them in terms of layout, inputs, variables and outputs. The successful model validation through the comparison of estimated attributes with other methodologies' results and, its calibration using different kinds of maintenance interventions, are a crucial step. Then, each pavement preservation intervention can be evaluated in such a way that the decision-maker may obtain a set of feasible and established alternatives. Subsequently, the use of multiple criteria decision-making analysis emerges as a more suitable tool to address the decision-maker's different preferences as well as different site and project needs.

Moreover, important analyses could be made with this method, such as the comparison of weekday versus night-time or weekend working; or the evaluation of the trade-off between shorter interventions with higher user delays and longer interventions with smaller user delays. In terms of the differences identified in the computed attributes of the several alternatives that can be chosen for a single intervention, the importance of this kind of analysis was demonstrated, working as a valid aid to engineering judgement normally involved in this type of decision-making.

A main drawback of the proposed method, at this stage, could be that the network effect is not considered. The influence of drivers that choose another road to avoid queues at roadworks or even the drivers that choose to travel on the same road at different times in order to avoid delays remains ignored by the model. It also does not evaluate important issues related to night-time work (e.g., noise and the greater need for construction joints, affecting pavement roughness). Given the variation in many of the model inputs, the move to probabilistic analysis is also expected.

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