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AN INTEGRATED METHODOLOGY FOR PLANNING ROAD PAVEMENT MAINTENANCE AND REHABILITATION INTERVENTIONS WITHIN HIGH-TRAFFIC CONTEX

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ABSTRACT

In the context of project level pavement management, planning maintenance and rehabilitation interventions on roads tends to be a complex process, particularly whenever high traffic flows are present. This paper describes a methodology developed in order to support the decision-maker while planning this type of interventions. The methodology relies on two key stages. At first, a computer model generates the set of feasible options concerning working plant layouts and schedules, and combines them in order to include all the options for the intervention's planning and undertaking. It takes in consideration, besides other elements, the type of maintenance or rehabilitation intervention to be carried out, traffic characterization and site features. There are three different attribute types intended to characterize each alternative of the intervention: agency cost, works' duration and the delay faced by users. Each intervention can be evaluated in such a way that the decision-maker may obtain a set of feasible and established alternatives. Subsequently, a multiple-criteria decision model is used to compare all the alternatives included in the previously obtained set using to the mentioned criteria (cost, duration and delay) according to the weights that correspond to the decision-maker preferences. The capabilities of the described methodology are illustrated by two case studies corresponding to two freeway stretches located in the Lisbon Metropolitan Area where a standard intervention is considered. The computation of the feasible alternatives set for the intervention allowed the comparison between them, based on the mentioned attributes and, consequently, on the results of the multiple-criteria decision model.

Keywords: pavement management; maintenance planning; work zones; user costs.

INTRODUCTION

The execution of maintenance and rehabilitation (M&R) interventions on road pavements may significantly affect users, depending on each particular analysis context. The intervention type, facility characteristics and traffic levels found will always determine to what extent users will be affected. Given the increase found for traffic levels in most road facilities, planning M&R interventions for road pavements has become a wider challenge where the potential impacts on users have also to be considered. Concerns regarding the service quality, such as the minimization of traffic disruptions or safety assurance during M&R interventions, have also lead to regulatory actions aiming for these purposes.

Within the road pavement management, accounting for user costs has typically been done by associating an estimated monetary value to these costs then adding it to the agency cost. For high traffic roads, user costs can often be the determinant factor for choosing a specific project. For these cases, user costs calculation produces values far higher than agency costs, as a result of the magnitude of the delays experienced by users (Haas, 2001), altering the main purpose of the process. This should not imply the omission of user costs but the need to weight them in the final assessment, in such a way that the decision-maker considers adequate (Hall et al., 2003).

Broader scope approaches meant for user cost evaluation such as the ROADWORK model included on Highway Development and Management Model version 4 (Bennett and Greenwood, 2001), the Texas Department of Transport Road User Cost Model (Daniels et al., 2000) or the Federal Highway Administration (FHWA) User Cost Model included on the Life-Cycle Cost Analysis in Pavement Design Technical Bulletin (Walls and Smith, 1998), are available. In addition, extensive research work has been done addressing road pavement-related work zones, including issues such as capacity, speed and delay estimation, or safety and operation conditions. There is found a vast number of variables (Benekohal, 2004; Weng and Meng, 2011) which can decisively influence these parameters like work zone capacity and vehicle speed while traversing it, with obvious impacts on delays and, consequently, user costs. Hence, the assessment of speed and queue formation within work zones and the resulting travel time delay have also been used as direct inputs for user cost estimation (Chitturi et al., 2008). Work zone features (e.g. work zone length or work scheduling) have been optimized in numerous procedures reported by the literature (Tang and Chien, 2008; Jiang and Adeli, 2003; Chen and Schonfled, 2005). However, user cost is widely used within the total costs functions to be minimized, which can lead to similar problems to the ones mentioned before.

Work zone simulation tools such as CA4PRS (Lee and Ibbs, 2005) or QuickZone (TFHRC, 2010) have also been developed aiming to provide the decision-maker a prior assessment of the potential impacts of a specific intervention alternative. While QuickZone is mainly meant for user effect estimation, CA4PRS also considers the construction process (Collura et al., 2010). Traffic micro-simulation models have also been used in the context of work zone analysis (Chien et al., 2002; Edara and Chatterjee, 2010). In terms of the legal and regulatory matters of the maintenance planning in terms of the impact on users has also been addressed (Mahoney et al., 2007). Alternative contracting methods have been used in order to provide the minimum work zone traffic disruption possible, as well as work scheduling regulations considering night-time operations for specific interventions.

Given the mentioned findings, it was found necessary to develop maintenance planning as an integrated approach capable of properly assisting decision-makers, reflecting as close as possible the different issues involved while planning work zones, especially when in the presence of high traffic flows where multiple alternative intervention options appear and several constraints exist. This integration should clearly allow the adequate perception of all the involved concerns, leading to better decisions.

METHODOLOGY

The road pavement maintenance and rehabilitation planning methodology here described is meant to be used in way that the intervention to take place is already defined, centering the analysis on the way it is planned and developed. It is desired to rely on an integrated approach, taking into consideration both agency cost and user-related effects without an explicit user cost calculation. Two key stages are considered:

1. the development of a model that is able to generate and characterize the feasible set of alternative planning options for the given pavement M&R intervention, considering both site and project characteristics;

2. the definition of a decision-support method which helps decision-makers while selecting the most appropriate options for a given context.

Considering an analysis context characterized by high-traffic facilities such as urban or suburban freeways, the methodology was developed specifically to roads with dual carriageway, comprising two or more lanes for each direction. In what concerns pavement type, due to the substantially different construction techniques related to each type, only flexible pavements were considered.

Model presentation

According to Figure 1, the model inputs consist of a fully described pavement intervention, traffic characterization and all the 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 characterization includes daily traffic volume and hourly distribution. By site and project constraints, can be understood as any relevant constraint that could restrict, from the beginning, the feasible set of alternatives.

The variables module is the main source of variation allowing the model to generate different alternatives based on the different work schedule policies and different work zone layouts. Each activity's duration is calculated by considering the necessary work quantity and the expected productivity for a chosen work zone layout. The estimated cost of each activity depends on the schedule policy selected, and it 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.

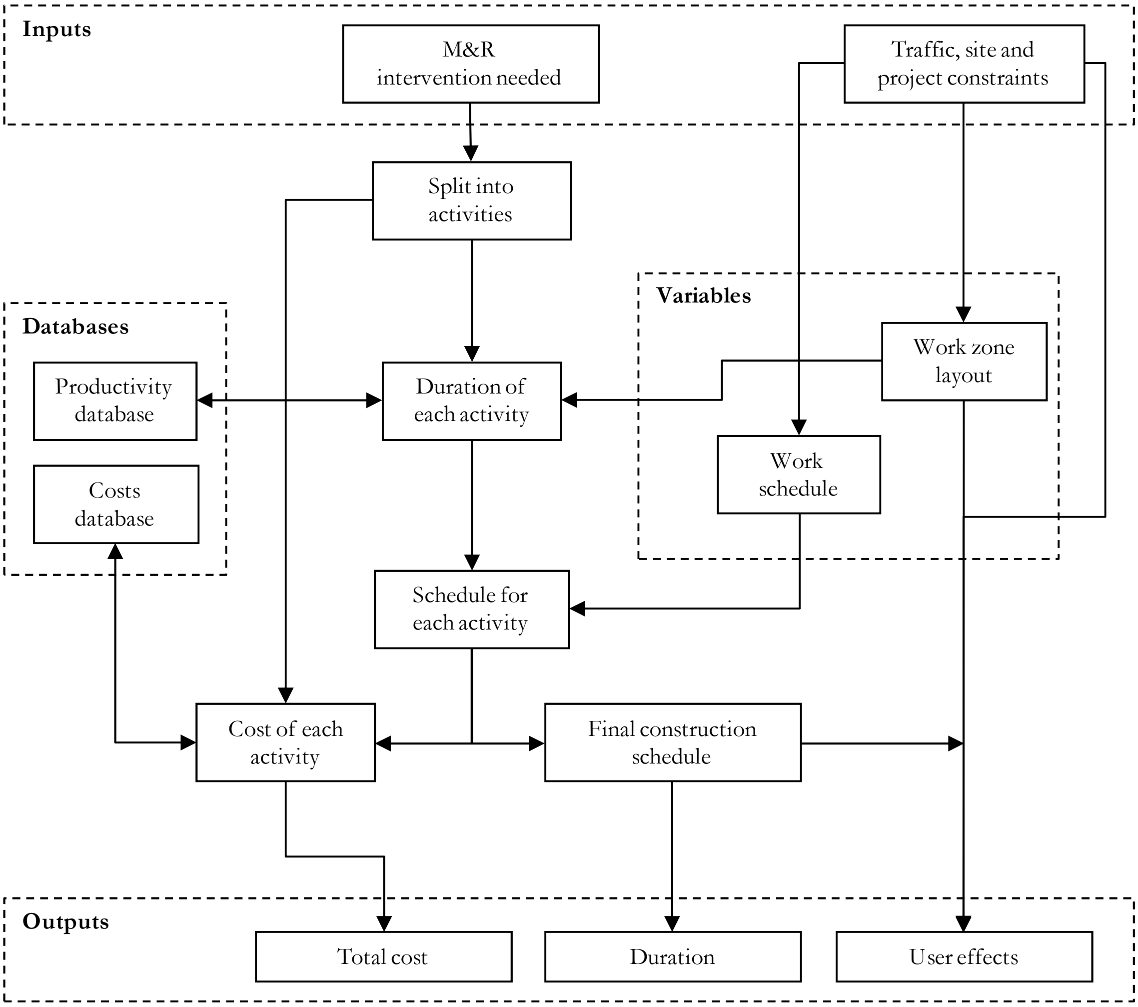


Figure 1 – Model general flowchart

The model outputs are three different attribute types intended to characterize each alternative by the total cost (supported by the agency), intervention duration and traffic-related effects that users will be experiencing.

Alternatives generation

The alternatives generation process relies on how different work zone layouts and work schedules (defined as variables in Figure 1) can be combined in order to achieve the feasible set of alternatives which can then be subject to further analysis. Regarding the work zone layout, among other options found and given the context for which the model was developed, the include work zone layout options are the following:

- to forbid or allow the use of traffic shifting;
- any lane closure option from n to n-1, to n to 1 (being n the original number of lanes), depending on the shoulder use or narrower lanes use;
- having work zone length defined by the available time frame or being a fixed value;
- work zone type to be considered.

The work zone type refers to the option to maintain the work zone in place exclusively during the moment when the works are being done (temporary work zones) or, by opposition, to maintain the work zone in place during all the intervention duration (permanent work zones). Besides the different management that has to be made regarding the handling of materials and equipment, the key distinction relies on the impact on traffic in each option. While for temporary work zones the traffic constraints are kept exclusively during an intervention period duration (e.g. 10 hours), for permanent work zones the constraints exist during the whole duration of the intervention (whether works are being carried out or not).

The main concern in work schedules is to define a set of typical policies including all the relevant and commonly adopted choices within the context of this type of interventions. It is also relevant to group together the schedule-related options considering the work zone type (temporary or permanent) for which they are meant. For instance, night-time work is obviously meant for temporary work zones where the constraints are expected to be concentrated exclusively during this work period.

Table I describes the work schedule base options meant for both temporary and permanent work zones. Considering temporary work zones, the first two options (Schedules 1 and 2) refer both to night-time work, but the first option only includes the nights from Monday to Thursday, while the second one refers to every night. Schedule 3 corresponds to the weekend work from Friday night until early Monday morning. Schedule 4 refers to day time work during business days where the most demanded peak hour is excluded accordingly to the traffic distribution found in both directions, e.g. working from 10:00 to 20:00 in one direction and from 7:00 to 17:00 in the opposite. However, this schedule is only applicable when asymmetric directional hourly traffic distributions exist and for work zone layouts that do not involve traffic shifting.

Regarding permanent work zones, options 5 and 6 consider work only during the business days and options 7, 8 and 9 consider work every day. Options 6 and 8 are related to higher duration daily work schedules, e.g. from 8:00 to 20:00 instead of 8:00 to 17:00. At last, work schedule option 9 refers to 24-hour occurring in a continuous way, using necessarily 2 or 3 teams. Knowing the available options for the work zone layouts and work schedules it is now possible to combine them, generating a set of alternatives. Before the alternatives generation process, regarding both the work zone layout and work schedule, it is possible to select the desired options to be considered or excluded among the subsequently generated alternatives.

Table I – Available Work Schedules for Temporary and Permanent Work Zones

Temporary work zones						
Option	Business days				Weekend	
	Morning	Off-peak	Evening	Night-time	Daytime	Night-time
1				•		
2				•		•
3				• [a]	•	•
4	• [b]	•	• [b]			
Permanent work zones						
Option	Business days				Weekend	
	Daytime			Night-time	Daytime	Night-time
5	•					
6	• [c]					
7	•				•	
8	• [c]				• [c]	
9	•			•	•	•

[a] *Including Friday night and Monday early morning*
[b] *Depending on the hourly traffic distribution for each direction*
[c] *Extended schedule*

Each generated alternative (n) will be then characterized by a number of work cycles (m), allowing to consider interventions with a different complexity. Given the mentioned activities to be included within the model, a single cycle intervention refers to the replacement of the wearing course, while a two cycle intervention can involve milling and replacement of the existing pavement by a reinforcement layer in the first cycle and, in the second, the placement of a new wearing course. A cycle can be characterized as a complete work sequence for the analyzed stretch (as illustrated in Figure 2).

Each cycle is then characterized by a work zone layout (i) where a set of activities (r) is carried out. In what concerns the wearing course placement, some bituminous mixtures (such as porous asphalt) often require that the layer placement occurs continuously on whole carriageway width. Moreover, regarding the construction quality issues, it also could be desired that the wearing course could be placed continuously, minimizing the number of construction joints. Thus, the use of traffic shifting is mandatory for these cases and the corresponding work cycle layout can be distinct from the previous one (for reinforcement layers, for instance). The chosen work schedule (j) is meant to be common to all cycles given its relation to the expected traffic constraints.

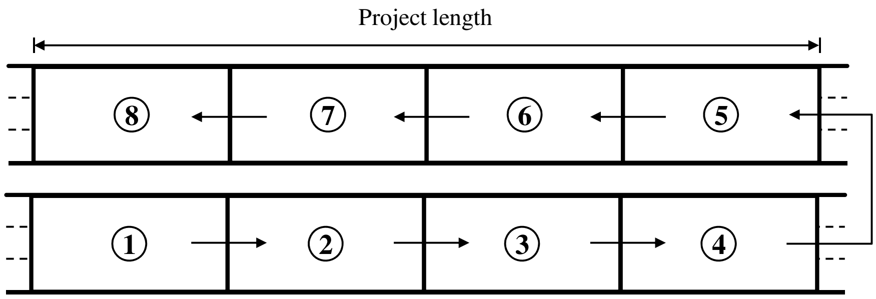


Figure 2 – Works progression sequence along a freeway stretch

Attributes calculation

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 and also bearing in mind its subsequent use within the decision-support methods. Agency cost is naturally the first choice and the most relevant attribute. Its importance is only comparable with other attributes in locations characterized by significantly high traffic flows where the chances of traffic disruptions are also higher, which is the current analysis context. Besides the agency cost and now relying on the users' perspective, several attributes can be considered. Hence, two other attribute types were chosen in order to measure distinct aspects: intervention duration and user effects. Intervention duration aims to evaluate how long users will have to face the traffic disruptions caused by roadwork (or in a broader sense, exposed to a construction site). The user effects (which can include attributes as the travel time delay or queue length) are meant to be an indicator of the magnitude of those disruptions due to the presence of a work zone. Due to paper size constraints, the attributes calculation will be briefly described. Detailed information can be found in the work of Morgado (2012).

Agency cost

The computation of the intervention cost is simple when the work quantities and unit costs are known. However, these unit costs are available for typical situations such as daytime time operations. Due the relevancy of studying different work schedules, the unit cost has necessarily to include the increase of labor cost for certain situations. Moreover, since the mobilization and demobilization activities are also included within the model in such a way that they represent an increase on cost, it is also required to include their contribution for the total cost. It was then decided to do it by adding a fixed percentage (5%) to each work period cost.

Regarding the variation in the labor cost due to the work schedule, it was analyzed each one of the considered schedules (4 for temporary work zones and 5 for permanent work zones) according to the current Portuguese labor legislation (see Table II). The estimation of the adopted labor cost variation coefficient relied on typical start and end times for the selected schedules and, within a real case context, should be properly validated. Every time that the need for more than one team is found (schedule 3 for temporary work zone or schedule 9 for permanent work zones), then the labor cost variation also reflects this need. In order to obtain a cost variation factor due to the work schedule it was assumed a 20% contribution of labor cost within the total cost, based on the experience of several contractors which were contacted regarding also the need to obtain default cost and productivity value.

Table II – Cost variation factor for each schedule

Schedule	Labor cost variation due to work schedule	Cost variation factor due to work schedule
Schedule 1 (for TWZ)	1.80	1.16
Schedule 2 (for TWZ)	2.00	1.20
Schedule 3 (for TWZ)	4.00	1.60
Schedule 4 (for TWZ)	1.00	1.00
Schedule 5 (for PWZ)	1.00	1.00
Schedule 6 (for PWZ)	1.30	1.06
Schedule 7 (for PWZ)	1.30	1.06
Schedule 8 (for PWZ)	1.60	1.12
Schedule 9 (for PWZ)	4.00	1.60

TWZ – Temporary work zones; PWZ – Permanent work zones.

The total intervention cost is defined as the sum of each activity's cost (obtained considering the unit cost and the corresponding work quantity) and the mobilization and demobilization cost.). This sum is then multiplied by the corresponding cost variation factor due to the work schedule. Given its greater simplicity, the mobilization and demobilization cost component is set to zero for permanent work zones.

Intervention duration

The intervention duration is mainly based on the productivity rates found for each activity that is being carried out, considering, obviously, the corresponding work quantity. In addition, due to other activities not included directly within the model, such as the implementation and removal of the traffic management scheme, bituminous mixtures cooling process or temporary road marking, there were considered fixed periods defined as mobilization and demobilization, which are described on Table III.

Table III – Operations period duration

Operation	Duration [hours:minutes]
Mobilization (TWZ)	02:00
Demobilization (TWZ)	02:30
Mobilization (PWZ)	00:30
Demobilization (PWZ)	00:30

Each time a work period (e.g. day-time work or night-time work) takes place, after subtracting the operations period duration it is estimated how much road length is possible to pave, relying on the productivity rate for the corresponding activity. If more than one activity exists for the same cycle (e.g. milling plus a bituminous layer placement), a determinant productivity which equals the lower one found among the different activities is defined. The process is repeated in an iterative way until the end of the stretch is reached. Then, it is assumed that the works will proceed on the following day (if it is a working day for the used schedule or on the next working day) in the opposite direction, respecting also the works progression sequence defined earlier (see Figure 2). If another work cycle exists, then the same sequence is repeated.

User effects

In what concerns user effects, several attributes can be considered as well as several methodologies can also be used to compute them. Traffic modeling is a wide research field where the analysis of work zones has been also subject of significant attention. The FHWA LCCA User Cost Model (Walls and Smith, 1998) was selected as the most viable one considering, the capability to represent the desired work zone attributes in a suitable way, as well as the easy integration in the developed model. Within FHWA Model, before the calculation of the total user costs related to work zones every time a pavement M&R intervention occurs, the travel time delay and queue lengths are computed (as well as the vehicle operating cost which is also related to the work zones). It relies fundamentally on the work zone capacity to establish the corresponding operating conditions on a deterministic way (free-flow or forced-flow) and consequently compute the results on an hourly basis.

Table IV summarizes the different types of expected delays given the conditions found (considering if a work zone is in place and also the relationship between traffic demand and roadway/work zone capacity). All the mentioned delays are computed in an hourly basis.

Table IV – Operating conditions and expected delays

Work zone presence	Traffic demand/capacity	Operating condition	Expected delays			
			WZ reduced speed delay	WZ speed change delay	Queue reduced speed delay	Queue stopping delay
No	demand > capacity	Queue	-	-	•	•
	demand < capacity	Free flow / no queue	-	-	-	-
Yes	demand > capacity	Queue	•	-	•	•
	demand < capacity	Free flow/no queue	•	•	-	-

However, the user effects computed by the FHWA Model will depend on the work zone layout, the estimated traffic flow and the chosen construction schedule, which may vary during the intervention duration. Regarding the work zone layouts, several situations can occur depending on the layout stage and the direction where works are being carried out. Based on these results, for each alternative the developed model is able to compute other attributes related to the effect that users will be experiencing, such as the traffic percentage which will be facing delays (i.e. traversing a work zone), the traffic percentage which will be queuing an, in addition, the model is also able to calculate the traffic delay distribution. In a given context, evaluating an alternative based on its maximum traffic delay can be inadequate if this value is significantly higher when compared to the rest of the distribution and only a small number of users will experience that level of delay. Thus, it was decided that the evaluation of each alternative can also be made in a reliable basis considering the 85^{th} percentile of the traffic delay distribution (which consists of the delays along the entire life time of the intervention computed for each vehicle that traverses the work zone).

Possible restrictions

Several restrictions are included within the model allowing the exclusion of alternatives which, for a given reason are related to the specific site and project constraints, they should not be considered on the subsequent decision process. The key restrictions included in the model are the following:

1. lane constriction (whenever it is desired to establish a minimum lane width);
2. minimum number of open lanes;
3. maximum traffic delay found (used to avoid that the maximum expected traffic delay will be higher than a certain value);
4. maximum intervention duration (used to avoid that the total intervention duration will be longer than a certain period).

The developed model aimed to provide in a simple way the list of all the relevant alternatives for the execution of a given pavement M&R intervention. Regarding the technical side, both model stages (alternatives generation and attributes calculation) are incorporated in a Microsoft Excel spreadsheet using Visual Basic for Applications. This spreadsheet allows to obtain in a few seconds the entire set of alternatives and also its attributes computation.

Besides the model validation considering two case studies, the next section presents also the required decision-support method which allows the evaluation of all the available alternatives, helping decision-makers while selecting the most adequate ones. As mentioned before, the decision-support method is the second key stage for the methodology presented in this paper.

IMPLEMENTATION RESULTS – CASE STUDIES ANALYSIS

General description

Two case studies were considered in order to show the application of the proposed approach. The selection was made bearing in the mind the context where the approach here described was developed for: urban or suburban freeways comprising considerably high traffic levels, where pavement M&R interventions planning could depend significantly on traffic. The two case studies correspond to two freeway stretches located within the Lisbon Metropolitan Area where significant traffic flows exist: A5 and A2.

The A5 is a freeway that connects Lisbon and Cascais, an important suburban area of Lisbon. It is a tolled freeway operated by Brisa – Auto-estradas de Portugal, S.A., a private freeway operator. The selected stretch for analysis is located between the Estádio node (km 8+100) and Oeiras node (km 11+600) comprising a total length of 3,500 m and 3 lanes each way, with separate carriageways. Lane width is 3.50 m, left shoulder is 1.00 m and the right shoulder has 3.00 m. The A2 is a freeway that connects Lisbon and the South of the Portugal. It is a tolled freeway and, as well as the A5. It is also operated by Brisa – Auto-estradas de Portugal, S.A.. The selected stretch is located between the Coina node (km 24+200) and Palmela node (km 35+400) comprising a total length of 11,200 m and 3 lanes each way, with separate carriageways. Lane width is 3.75 m, left shoulder is 1.00 m and the right shoulder has 4.05 m.

Traffic characterization

In terms of the traffic flow, the A5 freeway carries a very considerable amount of traffic, reaching over 5,000 vehicles per hour each way during the peak periods and nearly 65,000 vehicles each day. Comparing to A5, A2 carries significantly less traffic flow, ranging from 1,000 to 1,500 vehicles per hour each way during most of the day, totaling about 18,000 vehicles each day. Figure 3 shows the average traffic distribution during business days and weekends. Since both stretches are located within the Lisbon Metropolitan Area, the morning and evening peaks are present due to commuter traffic.

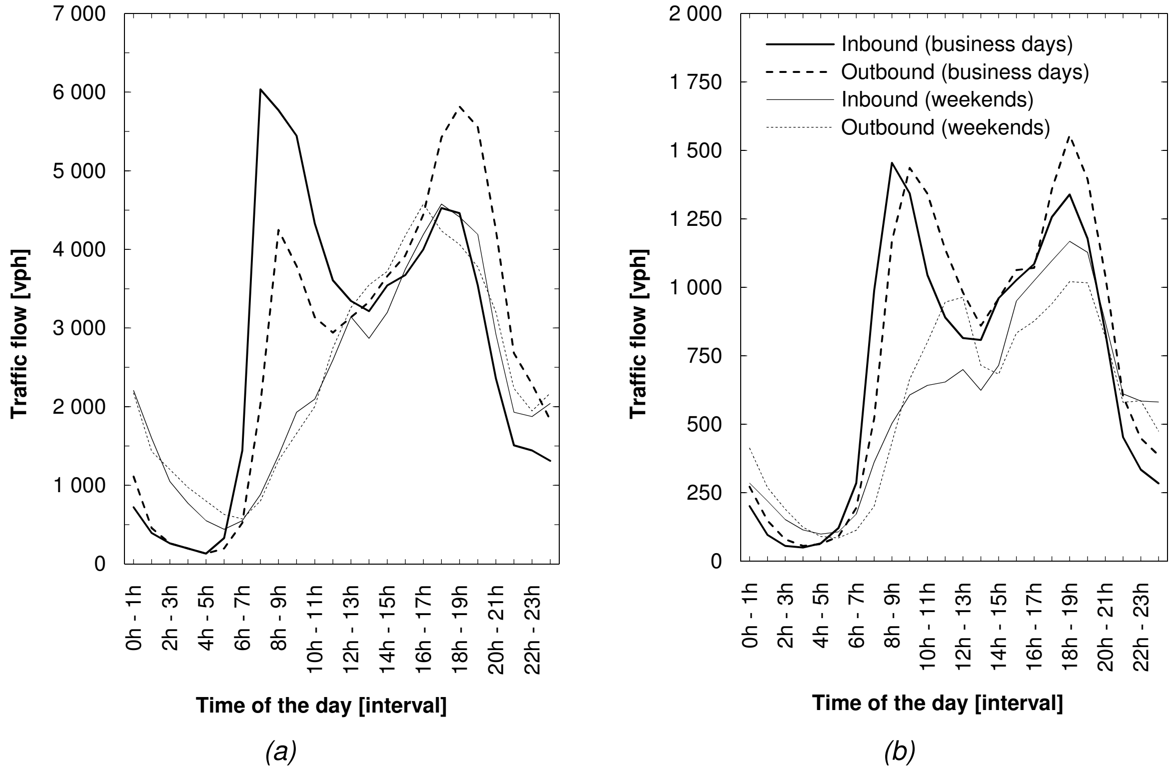


Figure 3 – Hourly traffic distribution for business days and weekends for A5 (a) and for A2 (b)

Works description and work zone data

As already described, the model was developed in a way that different work cycles could be included, allowing to represent simple or more complex interventions. In order to support the model application, a standard intervention consisting of resurfacing (where the wearing course requires full width paving) and reinforcement was considered which according to the model formulation, corresponds to two work cycles. Although costs and productivity values can be analyzed in further detail, representative values collected among several contractors were used. Hence, the cost assumed to this intervention was 12.30 €/m^2 (all activities), while for productivity it was considered an average value of 850 m^2/h for resurfacing (with traffic shifting) and 700 m^2/h or 550 m^2/h for the reinforcement layer (depending on whether traffic shifting is considered or not, respectively). Regarding the work zone capacity, various studies have been made providing several methodologies and tools. However, given the model validation purpose, average values were used assuming that the original free-flow capacity of 2,100 vehicles per hour per lane (vphl) is expected to drop to 1,500 vphl if a 3 to 2 lane reduction exists or to 1,300 vphl when a 3 to 1 lane reduction is in place. The speed limit for normal operating conditions is 120 km/h and 60 km/h within work zones.

Generated alternatives

Within the case studies, two different restrictions were adopted. Regarding the work zone layout, the potential alternatives whose lane width during road works is less than two thirds of its original width were excluded. This restriction is meant to fulfill the related legislation currently implemented in Portugal regarding road works on freeways. In addition, for each alternative resulting attributes, a maximum vehicle delay of 90 minutes with the purpose of avoiding high levels of traffic disruption was adopted. Cost and duration attributes were not used as restrictions since they will always depend on each project's length. Considering the mentioned restrictions, the model generated 192 different feasible alternatives for both cases. However, only 4 alternatives respect all active restrictions for A5 due to the fact of the delays found for the majority of the alternatives, which is evident due the much higher traffic flow that is observed when compared to A2 (where all the 192 generated alternatives fulfill the adopted restrictions).

Table V – Summary results for both cases

Results	Case 1 (A5)	Case 2 (A2)
Lowest cost [€/km]	415,484 (1,506,130)	344,400 (4,490,976)
Highest cost [€/km]	433,944 (1,573,047)	557,928 (7,275,381)
Lowest duration [days/km]	12.4 (45)	3.4 (44)
Highest duration [days/km]	19.6 (71)	19.4 (253)
Lowest delay [min]	0.6	0.5
Highest delay [min]	0.7	8.3
Alternatives respecting all active restrictions	4	192
Allowed schedules	2	8

Values in brackets refer to the entire stretch.

As described on Table V, regarding the total intervention cost per kilometer, by comparing both case studies, for A5 there are found values from €415,130 up to €433,944, while for A2 the range is much more wider (from €344,400 up to €557,928). The same type of behavior is found for intervention duration. For A2, the lowest duration alternative is almost six times shorter than the highest one, while for A5 the different is narrower.

Considering the A5 case study, it is obvious that the choice will rely on the night-time work schedules 1 or 2 since these are the ones that result on acceptable traffic delay levels. However, the A2 case study shows that in the presence of several and significantly different alternatives, further analysis are needed. Thus, the magnitude found on cost and duration intervals, justifies the need to adopt a subsequent decision-making procedure. Given these results, it is required to provide tools for the decision-makers so that alternatives' assessment and consequent choices can be made in an objective and structured way.

Alternatives assessment

Based on three attributes computed by the alternatives' generation model, it was considered a multiple-criteria decision-analysis procedure where these attributes were used as criteria. Total intervention cost, project duration (working days) and traffic delay (85th percentile of the traffic delay distribution for all the vehicles traversing work zones) are then used on a compensatory model, where value functions and weights are defined according to decision-makers' preferences for each specific analysis context, leading to an overall score for each alternative.

For the assessment of the obtained set of allowed alternatives (i.e., feasible in terms of construction process and fulfilling the adopted restrictions) it is followed the previously described procedure. Considering the value functions used for each criteria, intervention cost and project duration are evaluated in such a way that, among all the obtained results for each scenario, the lowest values achieve a score of 100 and the highest a score of 0, with the intermediate values being evaluated on a linear basis. Concerning delay, it was decided to evaluate how decision-makers assess it within this context.

M-MACBETH software (Costa et al., 2005) allows to quantify the relative attractiveness of options, requiring only qualitative judgments about differences. M-MACBETH software was used in two levels: at first, it was used to assess how decision-makers evaluate then different delay values, making possible to define a value function; then, it was also used to define the weights that should be assigned to each criterion, according to the preferences revealed by each decision-maker. Using the software while questioning senior professionals who usually deal with the issues of the interventions' planning, there were obtained a single delay value function and representative weights for the chosen criteria. For the resulting traffic delay value function, 5 minutes of added travel time is the upper reference and 45 minutes is the lower one, meaning that a 5 minutes delay will be given a score of 100, while 45 minutes will have a score of 0.

Regarding the weights assigned to each criterion, the results were 55% for cost, 35% for delay and 10% for duration, which were then used for the alternatives assessment. As already mentioned, it is then possible to compute an overall score for each alternative and to rank them. However, bearing in mind cases where a higher number of alternatives are available, an alternate procedure for selecting the alternatives was also developed, besides computing their overall score. Hence, is was computed an indicator defined as user effects combined score, resulting from the obtained evaluation for the duration and delay according to the used value functions, weighted in the same proportion found, as shown on Figure 4. It results from the obtained weights for delay and duration set to sum 100%, being now 78% and 22%, respectively. This indicator permits to address the problem on a two-dimensional basis, having now the cost and user effects combined score, which can be plotted on an x-y graph (see Figure 5).

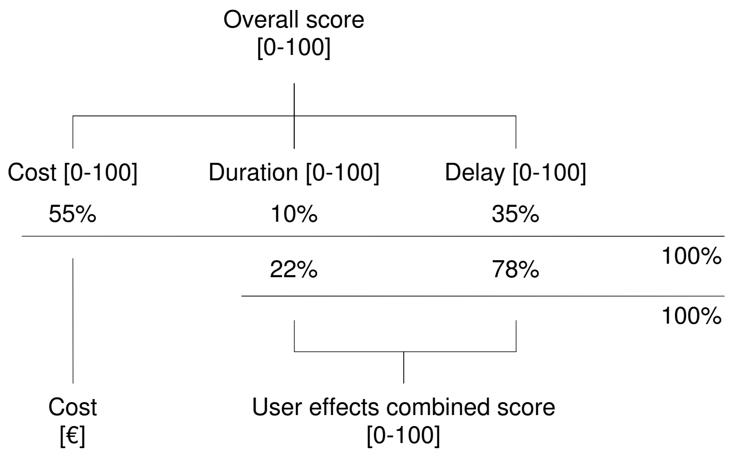
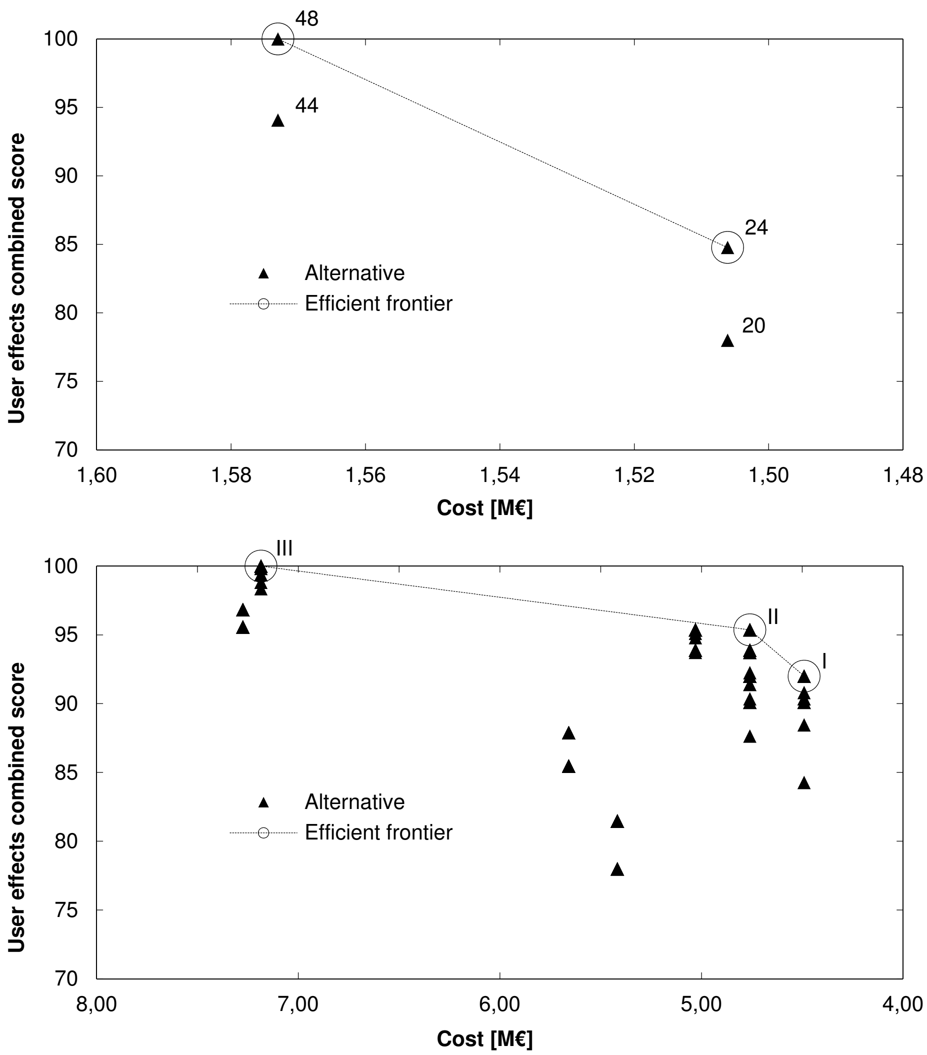


Figure 4 – Two-dimensional analysis (cost and user effects combined score)



(a)

(b)

Figure 5 – User effects combined score against cost for A5 (a) and for A2 (b)

It was chosen to plot the cost values on the x-axis in the reverse order so that a longer distance from the origin in both axes would mean a more interesting alternative. This type of approach, besides being simpler in terms of visualization, allows an easy identification of the dominated and non-dominated alternatives (Goodwin and Wright, 2004), as a complement to the obtained score. Thus, it can also be plotted the efficient frontier which connects the non-dominated alternatives resulting always on a convex shape, which is clearly noticeable if more than two non-dominated alternatives exist. Table VI includes the description of all the non-dominated alternatives for both case studies.

Table VI – Non-dominated Alternatives Summary for Both Case Studies

Case study	Alternative	Work zone type [(a)]	Cycle 1 layout [(b)]	Cycle 2 layout [(b)]	Schedule	Cost [€]	Duration[days]	Delay, 85th percentile [min]	Delay, maximum [min]	Cost value	Duration value	Delay value	Overall score	Overall rank	User effects combined score
A5	24	T	6	6	1	1,506,130	63	0.6	0.6	100.0	30.8	100.0	93.1	1	84.8
A5	48	T	6	6	2	1,573,047	45	0.6	2.8	0.0	100.0	100.0	45.0	3	100.0
A2	120 (I)	P	12	12	5	4,490,976	120	0.9	0.9	100.0	63.6	100.0	96.4	1	92.0
A2	144 (II)	P	12	12	6	4,760,435	88	0.9	0.9	90.3	78.9	100.0	92.6	25	95.4
A2	190 (III)	P	12	12	9	7,185,562	44	0.9	0.9	3.2	100.0	100.0	46.8	145	100.0

[(a)] *T – Temporary work zones. P – Permanent work zones.*
[(b)] *Layouts 6 and 12 correspond to work zones where the traffic is shifted to the opposite direction (with 3 to 2 lane reductions).*

For the A5 case study it can be seen that alternative 24 dominates alternative 20 and alternative 48 dominates alternative 44. In practical terms, alternatives 24 and 48 correspond to work zone layouts where the traffic is shifted to the opposite direction and, consequently, the productivity achieved is higher leading to shorter durations when comparing to alternatives 20 and 44, respectively. Alternatives 44 and 48 achieve a higher score for user effects given the work schedule (every night), which contributes to a shorter duration for both, though at a higher cost. The four alternatives assume temporary work zones. Bearing in mind the obtained results, temporary work zones are definitely mandatory for any type of intervention to be performed in A5. The traffic levels found require always night-time operations and work zone layouts where 2 lanes are open for each direction. Sensitivity analysis for traffic variation showed that the work schedule 3 (weekend work from Friday night to Monday early morning) becomes possible if the traffic flow is expected to drop at least 10%.

Concerning the second case study (A2) and given the significant number of allowed alternatives (192), the described procedure tends to be more relevant. However, in this case several alternatives achieve the same overall score and the same pair of cost and user effects combined score. This fact is due to the delay found for these alternatives, still being different, is less than 5 minutes which corresponds to a value of 100 according to the adopted value function, while cost and duration are identical. It means that different work zone layouts take into an equally accepted delay level. Given the existence of several alternatives which achieve an equal score, the corresponding point was now defined as a group of alternatives (sharing the same values on each attribute's evaluation).

Considering group I (represented by alternative 120 in Table VI), which achieves the highest overall score (96.4), all alternatives are associated with schedule 5 which is the one associated with a lower cost (business days without extended schedule). In what concerns alternatives group II, they are associated to schedule 6 corresponding to business days on a 12-hour work basis (from 8:00 to 20:00). The cost is higher when compared to the alternatives of group I but it achieved a reduction of 32 days for the total duration. At last, concerning group III (represented by alternative 190), all alternatives are based on schedule 9 (24-hour work) which allows to achieve the shortest duration among all options. However, the associated cost is significantly higher when compared to groups I and II. The lower traffic levels allow permanent work zones to be used all the time, as well as work schedules associated to lower costs. In this case, the use of work schedules that allow a significantly shorter duration will necessarily have a larger impact on cost.

CONCLUSIONS AND RECOMMENDATIONS

The chosen case studies to describe the application of the proposed methodology were meant to be different in terms of traffic levels and considering a standard pavement M&R intervention. For A5, even though the cost values are similar among the allowed alternatives for this specific case, the eventual magnitude found on cost or duration intervals for a certain intervention, justifies the need to adopt a subsequent decision-making procedure. The particularly high traffic levels found, act in a very restrictive way in what concerns the allowed alternatives given the maximum delay restriction. Considering the A2 case study, where a far higher number of available alternatives exist, tends to be essential to provide tools for the decision-makers so that alternatives' assessment and consequent choices can be made in an objective and structured way.

In a broader scale, important analyses could be made with this methodology. For instance, the comparison of daytime work 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, can constitute practical research topics to be addressed.

Besides computing an overall score for a given alternative, the identification of the non-dominated ones allows to define a short-list of alternatives that can be discussed at another level by decision-makers. The developed methodology, even integrating the most relevant attributes within this decision context, does not account for issues such as safety impacts of the different alternatives, for both road users and construction workers, or the environmental impacts due to the construction-related noise. In addition, the inevitable problem simplification so that it can be addressed within this methodology, leads obviously to the need for additional steps towards its implementations in real situations. Besides an extensive calibration for each model parameter, further research is desirable, aiming to address the same problem relying on a probabilistic approach.

Nevertheless, the importance of this kind of analysis was demonstrated, working as a valid aid to engineering judgment normally involved in this type of decision-making. It provides a simple tool that, in an early intervention planning stage, can point out the set of alternatives which deserve additional analysis.

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