# MULTI-OBJECTIVE DECISION-AID TOOL FOR PAVEMENT MANAGEMENT SYSTEMS

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## ABSTRACT

This paper presents the development and implementation of a Multi-Objective Decision-Aid Tool (MODAT) tested with data from Oliveira do Hospital's Pavement Management System (OHPMS). Nowadays, the OHPMS Decision-Aid Tool uses a deterministic section-linked optimization model with the objective of minimizing the total expected discounted costs over the planning time-span while keeping the road pavements within given quality standards. The MODAT uses a multi-objective deterministic section-linked optimization model with three different possible goals: minimization of agency costs (maintenance and rehabilitation costs); minimization of user costs; and maximization of the residual value of pavements. This new approach allows the Pavement Management Systems (PMS) to become an interactive decision-aid tool, capable of providing road administrations with answers to "what-if" questions in short periods of time. The MODAT also uses the deterministic pavement performance model used in the AASHTO flexible pavement design method that allows closing of the gap between project and network management. The information produced by the MODAT is shown in maps using a Geographic Information System. In this application, the Knee point, that represents the most interesting solution of the Pareto frontier, corresponds to an agency costs weight value of 5% and an user costs weight value of 95%, demonstrating that user costs, because are generally much greater than agency costs, dominates the decision process.

*Keywords: Road Assets, Pavement Management System, Pavement Performance Models, Optimization Model, Maintenance & Rehabilitation.*

# INTRODUCTION

An efficient Pavement Management System (PMS) for a road network is one that would maintain all pavement sections at a sufficiently high level of service and structural condition, allowing low user costs, but would require only a reasonably low budget and use of resources, and does not create any significant adverse impacts on the environment, safe traffic operations, and social and community activities (Fwa *et al*. 2000). Unfortunately, many of these are conflicting requirements and therefore, the decision process in programming maintenance and rehabilitation (M&R) interventions involves multi-objective considerations (Wu, 2008; Wu *et al*. 2009). For example, a road network administration may wish to find M&R interventions that minimize agency costs while at the same time minimize user costs. Nevertheless, any M&R strategy that minimizes user costs would require that pavements be maintained at a high level of service, which consequently will increase agency costs considerably.

Almost all the pavement maintenance programming tools currently in use are based on single-objective optimization. In these single-objective analyses, those requirements not selected as the objective function are imposed as constraints in the model formulation. This can be viewed as interference in the optimization process by artificially setting limits on selected problem parameters. As a result, the solutions obtained from these single-objective analyses are suboptimal in comparison to one derived from multi-objective considerations (Fwa *et al*. 2000). In addition, only few applications have made use of multiobjective optimization techniques. Fwa *et al*. (2000) developed an optimization model with the following characteristics: three objectives, the maximization of the work production, the minimization of the total maintenance cost, and the maximization of overall network pavement condition; applied to 4 highway classes, each one with 3 need-urgency levels (high, medium, low); considering 4 M&R interventions; and considering a planning time-span of 45 working days. Wang *et al*. (2003) developed a different optimization model with the following characteristics: two objectives, the maximization of the total M&R effectiveness, and the minimization of the total M&R disturbance cost; applied to a small network of 10 road sections; and considering a planning time-span of 5 years. Wu and Flintsch (2009) developed another optimization model with the following characteristics: two objectives, the maximization of the network level of service, and the minimization of the total M&R cost; applied to 4 pavement state quality types (excellent, good, fair and poor); considering 4 M&R interventions; and considering a planning time-span of 10 years. None of these multi-objective optimization models considers the minimization of user costs or the minimization of residual value of pavements and is applied to a real-world road network.

This paper presents the development and implementation of a Multi-objective Decision-Aid Tool (MODAT) which considers three different objectives, the minimization of agency costs (maintenance and rehabilitation costs), the minimization of user costs, and the maximization of the residual value of pavements at the end of the planning time-span. The MODAT is tested with data of the Oliveira do Hospital's Pavement Management System (OHPMS) which actually uses a deterministic section-linked optimization model with the objective of minimizing the total expected discounted costs over the planning time-span while keeping the road pavements within given quality standards (Ferreira *et al*. 2009a).

# BACKGROUND

One of the main components of a PMS is the methodology used to select the best M&R strategy taking into account the expected evolution of pavement quality. This methodology, realized in a Decision-Aid Tool (DAT), may be based on prioritization (ranking) models (Sebaaly *et al*. 1996; Hawker and Abell 2000; Wong *et al*. 2003; Kulkarni *et al*. 2004) or optimization models (Golabi *et al*. 1982; Mbwana and Turnquist 1996; Wang and Zaniewski 1996; Ferreira *et al*. 2002a; Ferreira *et al*. 2002b; Abaza *et al*. 2004; Nunoo and Mrawira 2004; Picado-Santos *et al*. 2004; Abaza 2006; Madanat *et al*. 2006; Durango-Cohen and Tadepalli 2006; Abaza 2007; Yoo and Garcia-Diaz 2008; Ferreira *et al*. 2009a; Ferreira *et al*. 2009b; Li and Sinha 2009; Li 2009)

Using prioritization models, pavement condition data are combined into an index to represent the present pavement quality. Then, prioritization is sorted by ranking and categorizing all the pavement sections by using a priority-ranking criterion. The commonly used ranking parameters include road class, traffic volume, quality index, etc. The M&R resources are allocated to road sections based on ranking and priorities assigned to them.

In optimization models, the goal of the analysis can be the minimization of any combination between agency costs, user costs and residual value of pavements over a selected planning time-span subject to minimum quality level constraints (Golabi *et al*. 1982; Ferreira *et al*. 2002a; Ferreira *et al*. 2002b; Picado-Santos *et al*. 2004; Abaza *et al*. 2004; Abaza 2006; Madanat *et al*. 2006; Abaza 2007; Madanat *et al*. 2006; Durango-Cohen and Tadepalli 2006; Ferreira *et al*. 2009a), the maximization of the whole network quality or performance subject to annual budget constraints (Abaza *et al*. 2001; Nunoo and Mrawira 2004; Abaza 2006; Abaza 2007; Yoo and Garcia-Diaz 2008; Ferreira *et al*. 2009b; Li and Sinha 2009; Li 2009), or considering both at the same time (Fwa *et al*. 2000; Wang *et al*. 2003; Wu and Flintsch 2009). In these models, pavement condition data are used as model inputs, pavement performance models are used to predict future quality of pavements and annual budgets and minimum quality levels are constraints that must be assured. The pavement management problem is then formulated as an optimization model with variables representing the various M&R actions or operations. Basically, the optimal solution defines the amount and type of M&R work to be applied to each road pavement.

The main weakness of prioritization models is that they do not assure the selection of the best possible M&R strategy when considering long planning time-spans (for example 20 years). This can only be achieved if the approach followed for selecting the M&R strategy is based on optimization techniques.

Recently, researchers (Fwa *et al*. 2000; Kaliszewski 2004; Flintsch and Chen 2004; Wu and Flintsch 2009) have concluded that maintenance planning and programming requires optimization analysis involving multi-objective considerations. However, traditionally single-objective optimization techniques have been employed by pavement researchers and practitioners because of the complexity involved in multi-objective analysis. Other researchers (Fwa *et al*. 2000; Mansouri 2005; Deb 2008; Iniestra and Gutiérrez 2009; Wu *et al*. 2010) concluded that it is possible to develop a Multi-objective Decision-Aid Tool, incorporating into the same optimization model several objectives, for example one for minimization of maintenance costs and another for minimization of user costs using the concepts of Pareto optimal solution set and rank-based fitness evaluation (Pareto 1906; Goldberg 1989).

# PROPOSED MULTI-OBJECTIVE DECISION-AID TOOL

## Optimization model

The Multi-Objective Decision-Aid Tool (MODAT) is constituted by the following components: the objectives of the analysis; the data and the models about the road pavements; the constraints that the system must guarantee; and the results. Several objectives can be considered in the analysis, including the minimization of agency costs (maintenance and rehabilitation costs), the minimization of user costs, the maximization of the residual value of pavements at the end of the planning time-span, etc. The results of the application of the MODAT to a road network are constituted by the M&R plan, the costs report, and the structural and functional quality report. The optimization model is formulated as follows:

Objective functions

$$\mathrm{Min}\,AC = \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{t=1}^{T} \frac{1}{\left(1+d\right)^{t}} \cdot AC_{rst} \cdot X_{rst} \tag{1}$$

$$\mathrm{Min}\,UC = \sum_{s=1}^{S} \sum_{t=1}^{T} \frac{1}{\left(1+d\right)^{t}} \cdot UC_{st} \tag{2}$$

$$\mathrm{Max}\ RV = \sum_{s=1}^{S} \frac{1}{\left(1+d\right)^{T+1}} \cdot RV_{s,T+1} \tag{3}$$

Constraints

$$\boldsymbol{PSI}_{st} = \Psi p(\boldsymbol{PSI}_{s0}, X_{1s1}, \ldots, X_{1st}, \ldots, X_{Rs1}, \ldots, X_{Rst}),\ s=1,\ldots,S;\ t=1,\ldots,T \tag{4}$$

$$\boldsymbol{PSI}_{st} \geq \overline{PSI}_{s},\ \ s=1,\ldots,S;\ t=1,\ldots,T \tag{5}$$

$$X_{rst} \in \Omega\left(\boldsymbol{PSI}_{st}\right),\ r=1,\ldots,R;\ s=1,\ldots,S;\ t=1,\ldots,T \tag{6}$$

$$\sum_{r=1}^{R} X_{rst} = 1,\ s=1,\ldots,S;\ t=1,\ldots,T \tag{7}$$

$$AC_{rst} = \Psi a\left(\boldsymbol{PSI}_{st}, X_{rst}\right),\ r=1,\ldots,R;\ s=1,\ldots,S;\ t=1,\ldots,T \tag{8}$$

$$UC_{st} = \Psi u\left(\boldsymbol{PSI}_{st}\right),\ s=1,\ldots,S;\ t=1,\ldots,T \tag{9}$$

$$RV_{s,T+1} = \Psi r\left(\boldsymbol{PSI}_{s,T+1}\right),\ s=1,\ldots,S \tag{10}$$

$$\sum_{r=1}^{R} \sum_{s=1}^{S} AC_{rst} \cdot X_{rst} \leq B_{t},\ t=1,\ldots,T \tag{11}$$

$$\sum_{r=2}^{R} \sum_{t=1}^{T} X_{rst} \leq N_{\max_{s}},\ \forall\, s=1,\ldots,S \tag{12}$$

Pavement condition functions

$$PSI_{0} = 5 \cdot e^{-0.000065 IRI_{0}} - 0.000535 \cdot R_{0}^{\ 2} - 0.21 \cdot (C_{0} + D_{0} + Pa_{0})^{0.5} \tag{13}$$

$$PSI_{t} = PSI_{0} - \left(4.2 - 1.5\right) \cdot 10^{\left[\left(\log_{10}\left(W_{18}\right) - Z_{R} \cdot S_{0} - 9.36 \log_{10}\left(SN+1\right) + 0.2 - 2.32 \log_{10}\left(M_{R}\right) + 8.07\right) \cdot \left(0.4 + \frac{1094}{\left(SN+1\right)^{5.19}}\right)\right]} \tag{14}$$

$$SN_t = \sum_{n=1}^{N} H_n \times C_n^e \times C_n^d \quad (15)$$

$$W_{80_t} = 365 \times TMDA_p \times \frac{(1+tc)^{Y_t} - 1}{tc} \times \alpha \quad (16)$$

User cost function

$$VOC_t = 1.20487 - 0.49116 \times PSI_t + 0.05458 \times PSI_t^2 \quad (17)$$

Residual value of pavements function

$$RV_{s,T+1} = C_{s,rehab} \cdot \frac{PSI_{s,T+1} - 1.5}{PSI_{s,rehab} - 1.5} \quad (18)$$

Where:
$AC_{rst}$ is the agency cost for applying operation *r* to road section *s* in year *t*; $B_t$ is the budget for year *t*; $C_0$ is the total cracked pavement area in year 0 (m$^2$/100m$^2$); $C_n^e$ is the structural coefficient of layer *n*; $C_n^d$ is the drainage coefficient of layer *n*; $C_{s,rehab}$ is the cost of the last rehabilitation action applied in pavement section *s*; *d* is the discount rate; $D_0$ is the total disintegrated area (with potholes and raveling) in year 0 (m$^2$/100m$^2$); $H_n$ is the thickness of layer *n* (mm); $IRI_0$ is the pavement longitudinal roughness in year 0 (mm/km); $M_R$ is the subgrade resilient modulus (pounds per square inch); $N\max_s$ is the maximum number of M&R operations that may occur in road section *s* over the planning time-span; $W_{80}$ is the number of 80 kN equivalent single axle load applications estimated for a selected design period and design lane; $Pa_0$ is the pavement patching in year 0 (m$^2$/100m$^2$); $PSI_t$ is the Present Serviceability Index in year *t*; $PSI_{s,rehab}$ is the *PSI* value after the application of a rehabilitation action in pavement section *s*; *R* is the number of alternative M&R operations; $R_0$ is the mean rut in year 0 (mm); $RV_{s,T+1}$ is the residual value for the pavement of section *s*; *S* is the number of road sections; $S_0$ is the combined standard error of the traffic prediction and performance prediction; $SN_t$ is the structural number of a road pavement in year *t* (AASHTO 1993); *T* is the number of years in the planning time-span; $tc$ is the annual average growth rate of heavy traffic; $TMDA_p$ is the annual average daily heavy traffic in the year of construction or the last rehabilitation, in one direction and per lane; $UC_{st}$ is the user cost for road section *s* in year *t*; $VOC_t$ are the vehicle operation costs in year *t* (€/km/vehicle); $X_{rst}$ is equal to one if operation *r* is applied to section *s* in year *t*, and is equal to zero otherwise; $Y_t$ is the time since the pavement's construction or its last rehabilitation (years); $Z_R$ is the standard normal deviate; $PSI_{st}$ are the pavement condition for section *s* in year *t*; $\overline{PSI}$ is the warning level for the pavement condition; $\alpha$ is the average heavy traffic damage factor or simply truck factor; $\Delta PSI_t$ is the difference between the initial value of the present serviceability index ($PSI_0$) and the value of the present serviceability index in year *t* ($PSI_t$); $\Psi a$ are the agency cost functions; $\Psi p$ are the pavement condition functions; $\Psi r$ are the residual value functions; $\Psi u$ are the user cost functions; $\Omega$ are the feasible operations sets.

Equation (1) is one of the objective functions of the optimization model and expresses the minimization of agency costs (maintenance and rehabilitation costs) over the planning time-span. Equation (2) is the second objective function and expresses the minimization of user costs over the planning time-span. Equation (3) is the third objective function and expresses the maximization of the residual value of pavements at the end of the planning time-span.

Other objective functions can be included in the optimization model; for example the maximization of the road network performance (Ferreira *et al*. 2009b).

The constraints represented by Equation (4) correspond to the pavement condition functions. They express pavement condition in terms of the *PSI* in each road section and year as a function of the initial *PSI* and the M&R actions previously applied to the road section. The functions shown in Equations (13)-(16) are used to evaluate the *PSI* over time. The quality of the road pavements in the present year is evaluated by the *PSI*, representing the condition of the pavement according to the following parameters: longitudinal roughness, rutting, cracking, surface disintegration and patching. This global quality index, calculated through Equation (13), ranges from 0.0 to 5.0, with 0.0 for a pavement in extremely poor condition and 5.0 for a pavement in very good condition. In practice, through this index, a new pavement rarely exceeds the value 4.5 and a value of 2.0 is generally defined as the minimum quality level (MQL) for municipal roads considering traffic safety and comfort. Equation (14) represents the pavement performance model used for flexible pavements. This pavement performance model is the one used in the AASHTO flexible pavement design method (AASHTO 1993; C-SHRP 2002). This design approach applies several factors such as the change in *PSI* over the design period, the number of 80 kN equivalent single axle load applications, material properties, drainage and environmental conditions, and performance reliability, to obtain a measure of the required structural strength through an index known as the structural number (*SN*). The *SN* is then converted to pavement layer thicknesses according to layer structural coefficients representing relative strength of the layer materials. The *SN* in each road section and year of the planning period can be calculated by Equation (15). The number of 80 kN equivalent single axle load applications are computed using Equation (16). The use of a pavement performance model for pavement design into a PMS allows the gap to be closed between project and network management, which is an important objective to be achieved and that has been mentioned by several researchers (Haas 2010).

This pavement performance model was chosen from a range of current models implemented in several PMS because it is widely used and tested. Nevertheless, other pavement performance models can be used instead, as for example the deterioration models developed for local authority roads by Stephenson *et al*. (2004) or the deterioration models developed for use in the Swedish PMS (Andersson 2007; Ihs and Sjögren 2003; Lang and Dahlgren 2001; Lang and Potucek 2001). The Present Serviceability Index in year $t$ ($PSI_t$) ranges between its initial value of about 4.5 (value for a new pavement) and the AASHTO lowest allowed *PSI* value of 1.5 (value for a pavement of a municipal road in the end of its service life). The constraints given by Equation (5) are the warning level constraints. They define the MQL considering the *PSI* index for each pavement of the road network. The warning level adopted in this study was a *PSI* value of 2.0. A corrective M&R operation appropriate for the rehabilitation of a pavement must be performed on a road section when the *PSI* value is lower than 2.0.

The constraints represented by Equation (6) represent the feasible operation sets, i.e., the M&R operations that can be performed on each road section and in each year. These operations depend on the pavement condition characterizing the section. In the present study the same five different M&R operations were considered, corresponding to nine M&R actions applied individually or in combination with others, as in previous studies (Ferreira *el al*. 2009a; Ferreira *et al*. 2009b).

The types of M&R actions and operations considered are presented in Tables 1 and 2. The M&R action costs considered in this study, calculated using information from M&R works executed on the Oliveira do Hospital road network, are also presented in Tables 1 and 2. The operations to apply to the road sections depend on the warning level. M&R operation 1 that corresponds to “do nothing” is applied to a road section if the *PSI* value is above the warning level, i.e., if the *PSI* value is greater than 2.0. M&R operation number 5 is the operation that must be applied to the road section when the warning level is reached, i.e., this operation applies to solve pavement serviceability problems. This operation has the longest efficiency period which is defined as the time between its application to the pavement and the time when the pavement reaches the warning level for the *PSI*. M&R operations 2, 3, 4 and 5 are alternative operations that can be applied instead of operation 1. In this case they constitute preventive M&R operations. The application of M&R operations may be corrective or preventive. An M&R operation is corrective if it is performed when the warning level is reached, and it is preventive if it is performed before the warning level is reached. When deciding which M&R operations should be applied in a given year to a given road section with *PSI* value above the warning level, it is possible to select either the simplest operation (M&R operation 1) or a preventive operation (M&R operation 2, 3, 4 or 5). The constraints given by Equation (7) state that only one M&R operation per road section should be performed in each year. The constraints represented by Equation (8) represent the agency cost functions. They express the costs for the road agency involved in the application of a given M&R operation to a road section in a given year as a function of the pavement condition in that section and year. These costs are obtained by multiplying the unit agency costs for the M&R actions involved in the M&R operation by the pavement areas to which the M&R actions are applied. The constraints defined by Equation (9) represent the user cost functions. They express the cost for road users as a function of the pavement condition in that section and year.

Table 1 - Types of M&R action

| M&R action | Description | Cost |
|---|---|---|
| 1 | Do nothing | €0.00/m$^2$ |
| 2 | Tack coat | €0.17/m$^2$ |
| 3 | Longitudinal roughness levelling (1 cm ) | €0.92/m$^2$ |
| 4 | Longitudinal roughness levelling (2 cm) | €1.84/m$^2$ |
| 5 | Membrane anti-reflection of cracks | €0.70/m$^2$ |
| 6 | Base layer (10 cm) | €6.50/m$^2$ |
| 7 | Binder layer (5 cm) | €3.30/m$^2$ |
| 8 | Non-structural wearing layer | €0.70/m$^2$ |
| 9 | wearing layer (5 cm) | €4.46/m$^2$ |

Table 2 - Types of M&R operation

| M&R operation | Description | M&R actions involved | Cost |
|---|---|---|---|
| 1 | Do nothing | 1 | €0.00/m$^2$ |
| 2 | Non-structural maintenance | 2+3+2+8 | €1.96/m$^2$ |
| 3 | Minor rehabilitation | 2+4+2+5+2+9 | €7.51/m$^2$ |
| 4 | Medium rehabilitation | 2+4+2+5+2+7+2+9 | €10.98/m$^2$ |
| 5 | Major rehabilitation | 2+4+2+5+2+6+2+9 | €14.18/m$^2$ |

For calculating the vehicle operation cost Equation (17) was used. The constraints represented by Equation (10) represent the pavement residual value functions. They express the value of the pavement of a road section at the end of the planning time-span as a function of pavement condition at that time. For calculating the residual value of pavements Equation (18) was used. The constraints given by Equation (11) are the annual budget constraints. They specify the maximum amount of money to be spent on M&R operations during each year. The constraints represented by Equation (12) were included in the model to avoid frequent M&R operations applied to the same road section.

## Generation of Pareto optimal solutions

Given the mathematical formulation of the optimization model presented in the previous section, the next step consists of the adoption of the appropriate mechanism for generating a representative set of Pareto optimal solutions. At this point it is evident that, given the particular features of the optimization model (a combinatorial problem with multiple objectives), it is not possible to use an exact algorithm for solving the problem efficiently. In this section, the use of a genetic algorithm approach was considered that could overcome the difficulties inherent in the nature of the optimization model.

There are several optimization methods that can be used to generate the set of Pareto optimal solutions. Hwang and Masud (1979) and later Miettinen (1999) classified them into the following four types: no-preference methods; posterior methods; a priori methods; and interactive methods. The no-preference methods do not assume any information about the importance of different objectives and a heuristic is used to find a single optimal solution. Posterior methods use preference information of each objective and iteratively generate a set of Pareto optimal solutions. Alternatively, a priori methods use more information about the preference of objectives and usually find one preferred Pareto optimal solution. Interactive methods use the preference information progressively during the optimization process.

According to Marler and Arora (2004), no single approach is, in general, superior to the other methods. Rather, the selection of a specific method depends on the users' preferences, the type of information provided, the solution requirements, and the availability of software. This study uses a genetic algorithm approach with the incorporation of the weighting sum method. This method, as the name suggests, combines a set of objectives into a single objective by pre-multiplying each objective with a user-defined weight. This method is the simplest approach and is probably the most widely used (Deb 2008; Wu and Flintsch 2009). Setting relative weights for individual objectives becomes a central issue in applying this method. As the weight vector for the multiple objectives often depends highly on the magnitude of each objective function, it is desirable to normalize those objectives to achieve roughly the same scale of magnitude. Equation (19) represents the application of the weighting sum method (Deb 2008) to the three objective functions of the optimization model presented in the previous section.

$$\text{Minimize } \overline{Z} = w_{AC} \cdot \frac{AC_i - AC_{\min}}{AC_{\max} - AC_{\min}} + w_{UC} \cdot \frac{UC_i - UC_{\min}}{UC_{\max} - UC_{\min}} + w_{RV} \cdot \left( - \frac{RV_i - RV_{\min}}{RV_{\max} - RV_{\min}} \right) \tag{19}$$

where: $\overline{Z}$ is the normalized value of a solution; $w_{AC}$, $w_{UC}$, and $w_{RV}$ are the weight values for each objective function; $AC_i$, $UC_i$, and $RV_i$ are the individual objective function values that depend on the decision variables values; $AC_{\min}$, $UC_{\min}$, and $RV_{\min}$ are the minimum values obtained for each objective; $AC_{\max}$, $UC_{\max}$, and $RV_{\max}$ are the maximum values obtained for each objective.

The third objective corresponds to the maximization of the residual value of pavements at the end of the planning time-span. When an objective is required to be maximized, the duality principle (Deb 2008) can be used to transform the original objective of maximization into an objective of minimization by multiplying the objective function by (-1). The range of values for the various objective functions ($AC_{\min}, AC_{\max}$), ($UC_{\min}, UC_{\max}$), and ($RV_{\min}, RV_{\max}$) are obtained by applying the optimization model considering only one objective at each time, i.e., varying the weight values vector ($w_{AC}, w_{UC}, w_{RV}$) among the extreme situations of (1,0,0), (0,1,0) and (0,0,1) and considering that initially all minimum values are 0 and all maximum values are 1. Considering only two objectives (Figure 1), the minimum values obtained for each objective corresponds to the ideal solution ($Z^*$). In general, this solution is a non-existent solution that is used as a reference solution and it is also used as lower boundary to normalize the objective values in a common range. The nadir solution ($Z^{nad}$), which is used as upper boundary to normalize the objective values in a common range, corresponds to the upper boundary of each objective in the entire Pareto optimal set, and not in the entire search space ($Z^{**}$).
The Pareto optimal solution set is finally obtained by using the objective function defined by Equation (19) considering different combinations of the weight values.

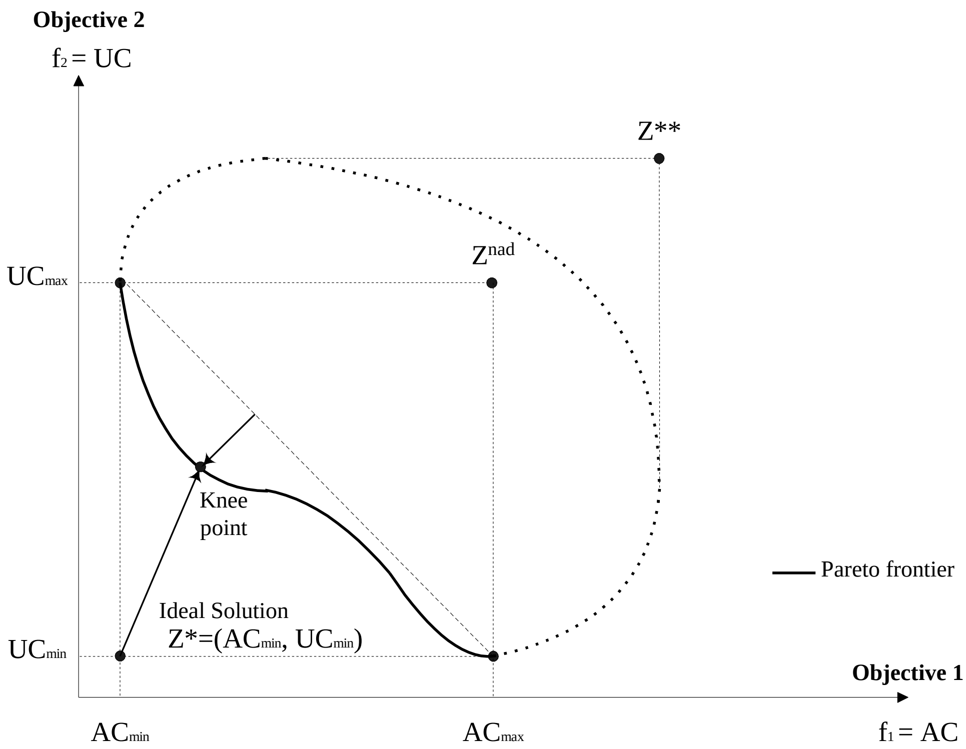


Figure 1 –The Pareto frontier and the ideal and nadir solutions

## Knee points and identification procedure

In general, when dealing with a multi-objective optimization problem, the decision maker has great difficulties in selecting a particular solution for implementation from the Pareto optimal solution set. Das (1999), to avoid this difficulty, developed the Normal-Boundary Intersection (NBI) method to identify the so called “Knee point” of the Pareto frontier. Considering only two objectives (Figure 1), the Knee is a point on the region of the Pareto frontier that results from the projection of a normal vector from the line connecting the end points of the Pareto frontier (the two individual optima). The “knee point” is the farthest away Pareto point from this line in the direction of the normal vector. Knee points represent the most interesting solutions of the Pareto frontier due to their implicit large marginal rates of substitution (Iniestra and Gutiérrez 2009). Wu and Flintsch (2009) considered another method to identify the best solution of the Pareto frontier. As the ideal solution may not be achieved due to the conflicting objectives, the best solution is the solution of the Pareto frontier that has the shortest normalized distance from the ideal solution, computed using Equation (20).

$$D_i = \left[ \left( \frac{AC_i - AC_{\min}}{AC_{\max} - AC_{\min}} - \overline{Z}_1^* \right)^2 + \left( \frac{UC_i - UC_{\min}}{UC_{\max} - UC_{\min}} - \overline{Z}_2^* \right)^2 + \left( \frac{RV_i - RV_{\min}}{RV_{\max} - RV_{\min}} - \overline{Z}_3^* \right)^2 \right]^{\frac{1}{2}} \quad (20)$$

Where: $D_i$ is the normalized distance between each Pareto solution point and the ideal solution point; $\overline{Z}_1^*$, $\overline{Z}_2^*$, and $\overline{Z}_3^*$ are the normalized values for each objective of the ideal solution (are equal to 0 or 1 depending on whether it is a minimization or maximization objective).

## Model solving

The deterministic optimization model presented in the previous section is extremely complex, being impossible to solve with exact optimization methods (except, for small, highly idealized instances, through complete enumeration) available through commercial packages like XPRESS-MP (FICO 2009) or GAMS-CPLEX (IBM 2009). Indeed, it can only be solved through heuristic methods. Nowadays, a large number of classic and modern heuristic methods are available (Deb 2008, Gendreau and Potvin 2005, Michalewicz and Fogel 2004) to solve these kind of complex optimization models. The optimization model and its heuristic solver were implemented in a computer program called MODAT. The heuristic method used to solve this optimization model is a genetic-algorithm (GA) that was implemented in Microsoft Visual Studio programming language (David *et al*. 2006, Randolph and Gardner 2008) adapting and introducing new functionalities to an existing GA program called GENETIPAV-D (Ferreira 2001, Ferreira *et al*. 2002b) previously developed to solve single-objective deterministic optimization models. Since they were proposed by Holland (1975), genetic algorithms have been successfully used on many occasions to deal with complex engineering optimization problems. The MODAT applied to the Oliveira do Hospital road network was run on a 2.0 GHz personal computer (PC) with 1.0 GB of RAM and 120 GB of capacity. Each best solution given by the MODAT was obtained in approximately 30 minutes of computing time.

# CASE STUDY

The MODAT was tested with data from the Oliveira do Hospital Pavement Management System (Ferreira *et al*. 2009a; Ferreira *et al*. 2009b) to plan the maintenance and rehabilitation of the road network considering two objectives, the minimization of agency costs and the minimization of user costs. The main road network has a total length of 65.8 km, and the corresponding network model has 36 road sections. The secondary roads of the network were not included in this study. Figure 2 shows the quality of pavements for Oliveira do Hospital's road network using a PSI representation with 9 levels (0.0 ≤ PSI ≤ 0.5; 0.5 < PSI ≤ 1.0; 1.0 < PSI ≤ 1.5; …; PSI > 4.0). There are several road sections with PSI value below 2.0, which is the quality level that indicates the need for rehabilitation of the pavement.

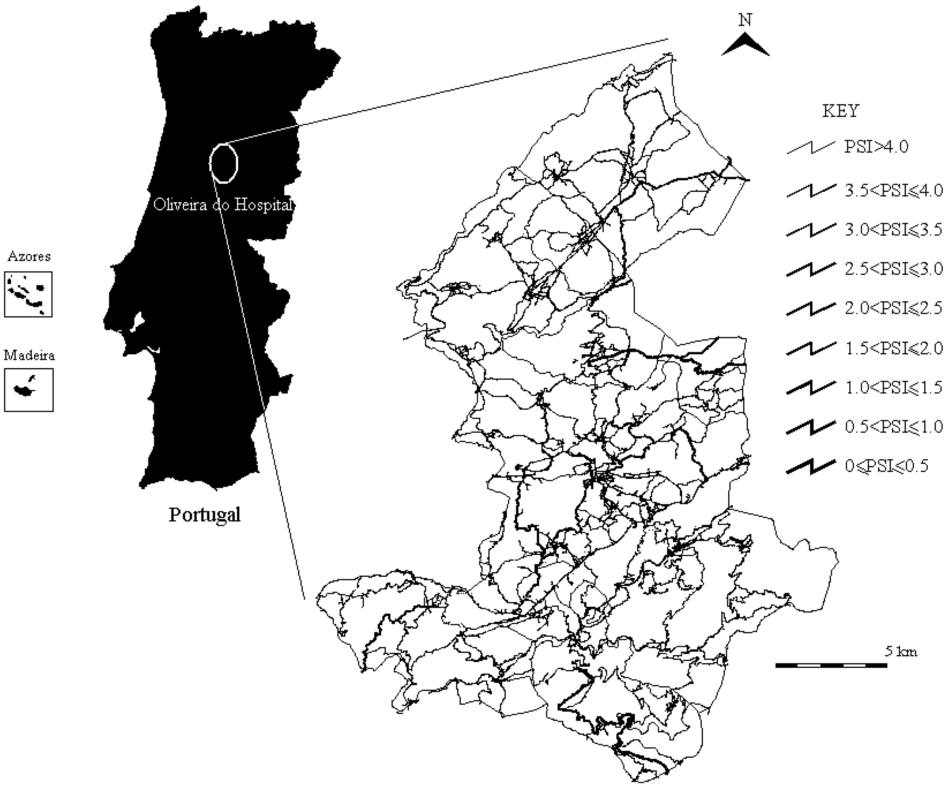


Figure 2 - Current state of pavements of Oliveira do Hospital's road network

Figure 3 represents the Pareto optimal set of solutions in the objective space by varying the weight values while Figure 4 represents the optimal set of normalized solutions. The point with black color represents the "Knee point" and was obtained considering the following weight values: ($w_{AC}, w_{UC}, w_{RV}$) = (0.05,0.95,0.00); and it corresponds to the following objective values ($AC, UC, RV$) = (€2476361.6, €2386407.3, €2793815.6). The range of values for the two objective functions are ($AC_{\min}, AC_{\max}$) = (€2061528.8, €13426199.3), and ($UC_{\min}, UC_{\max}$) = (€2374058.4, €2840482.9). From Figures 3 and 4 it can be concluded that, when varying the two weights through a grid of values from 0 to 1 with a fixed increment step, as for example 0.05, the two objective values were not transformed maintaining the same fixed range. Therefore, each weight value not only indicates the importance of an objective, but also compensates, to some extent, for differences in objective function magnitudes.

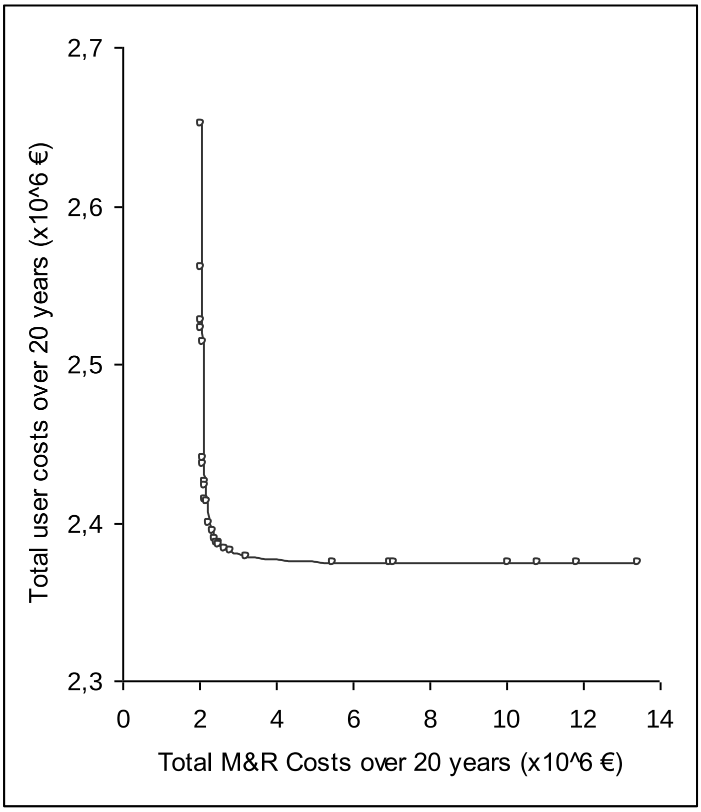


Figure 3 - Pareto optimal set of solutions

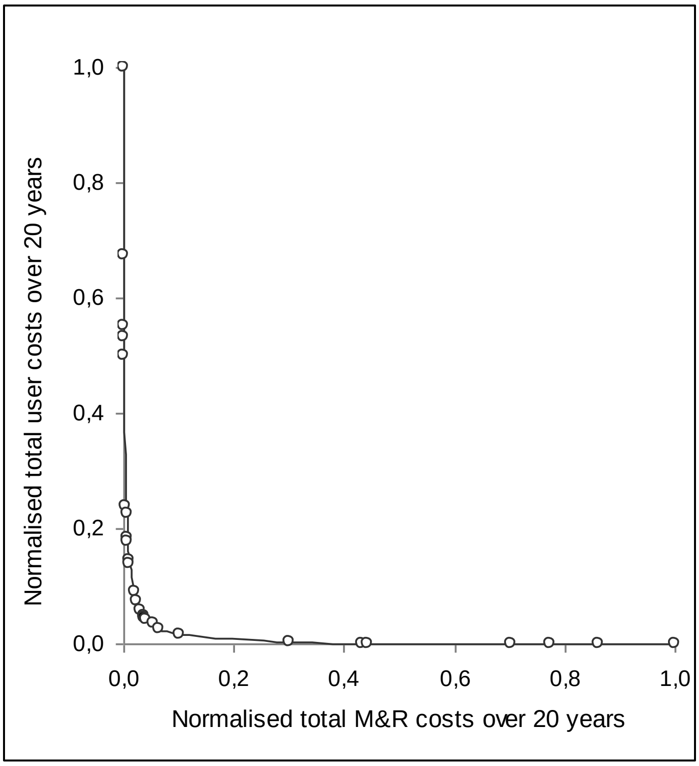


Figure 4 - Pareto optimal set of normalized solutions

In multi-objective problems there is no perfect method to select one “optimal” solution from the Pareto optimal set of solutions. The final best-compromise solution is always up to the decision maker. For that purpose, four different M&R solutions of the Pareto frontier were considered for comparison.

a) Solution I: Multi-objective optimization approach (corrective-preventive) considering the “Knee point” ( $w_{AC}$ =0.05, $w_{UC}$ =0.95, $w_{RV}$ =0.00);
b) Solution II: Multi-objective optimization approach (corrective-preventive) considering the following weights ( $w_{AC}$ =1.00, $w_{UC}$ =0.00, $w_{RV}$ =0.00);
c) Solution III: Multi-objective optimization approach (corrective-preventive) considering the following weights ( $w_{AC}$ =0.00, $w_{UC}$ =1.00, $w_{RV}$ =0.00);
d) Solution IV: Multi-objective optimization approach (corrective-preventive) considering the following weights ( $w_{AC}$ =0.50, $w_{UC}$ =0.50, $w_{RV}$ =0.00).

The costs and normalized costs during the entire planning time-span for these four Pareto optimal solutions are summarized in Figures 5 and 6, respectively. Figure 6 shows that, as expected, solution I (“Knee point”) is the Pareto optimal solution with less normalized value of M&R costs plus user costs. Considering the non-normalized value of M&R costs plus user costs (Figure 5), one can verify that this optimal solution does not have the least value. Figure 6 also shows that solution I (“Knee point”) is not the Pareto optimal solution with less total normalized costs, computed by adding M&R normalized costs and user normalized costs and deducting the residual normalized value (in this case the solution with less total normalized costs is solution IV). This happens because this solution I (“Knee point”) was defined considering only two objectives (minimization of agency costs and minimization of user costs).

Figure 7 represents the predicted PSI average value over the years of the planning time span for all the road network pavements and for each solution. By analyzing this Figure it can be seen that solution III, i.e., the solution of the multi-objective optimization approach (corrective-preventive) considering the weights ( $w_{AC}$ =0.00, $w_{UC}$ =1.00, $w_{RV}$ =0.00), corresponds to the largest average PSI values as expected because this solution corresponds to the minimization of user costs.

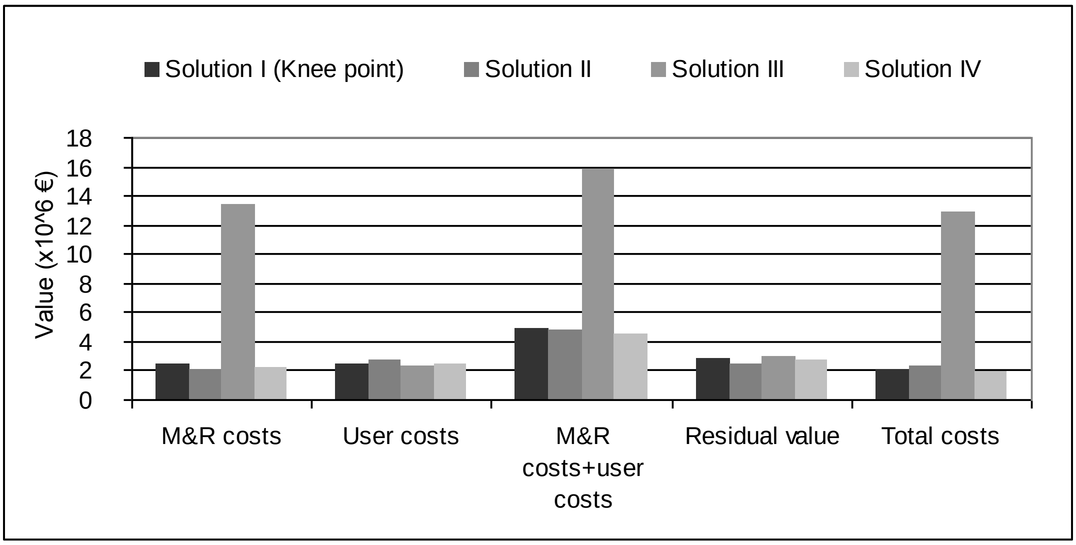


Figure 5 - Costs throughout the planning time-span of 20 years

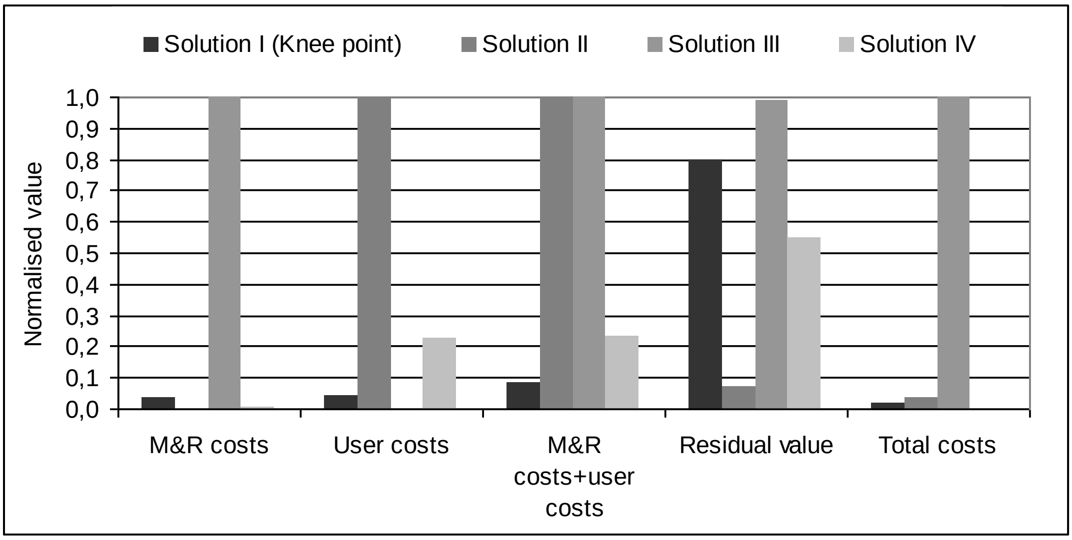


Figure 6 – Normalized costs throughout the planning time-span of 20 years

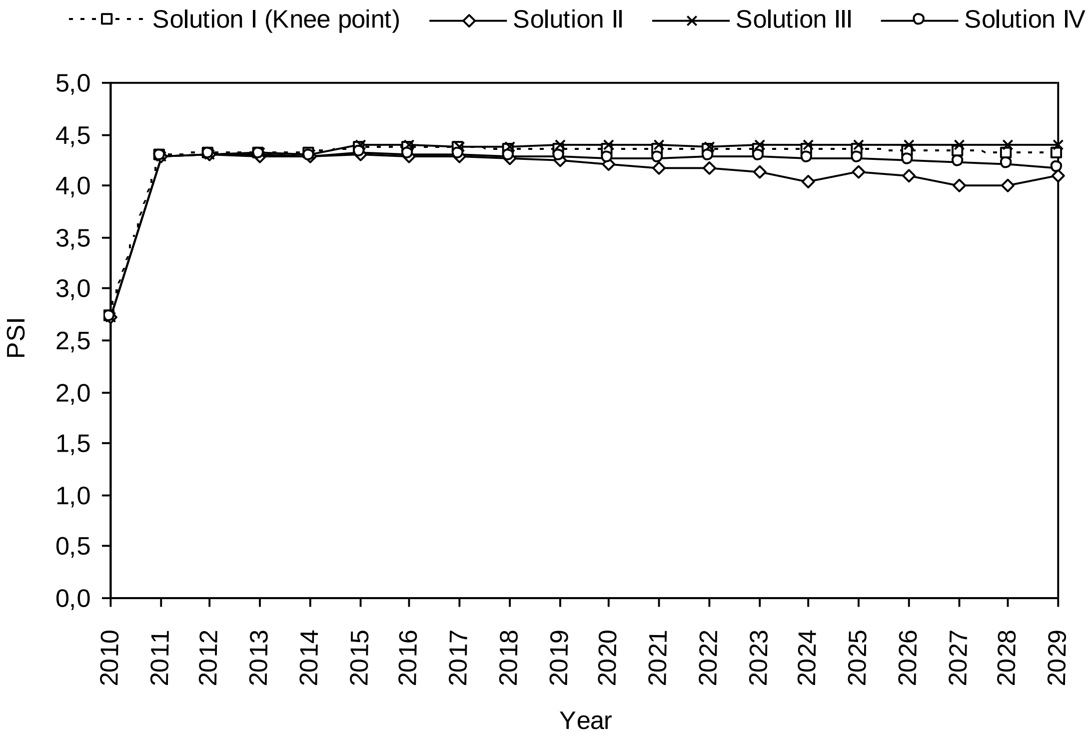


Figure 7 - PSI average value for all the road network pavements

The differences between the PSI curves are small because the present quality of almost all the pavements is low and because its degradation is slow due to the reduced values of the traffic volume in this road network. Solution I ("Knee point") is the second best solution in terms of average PSI values also as expected because corresponds to a high weight value for user costs and a small weight value for agency costs ( $w_{AC}$ =0.05, $w_{UC}$ =0.95, $w_{RV}$ =0.00).

In addition to these summarized results, the MODAT provides extensive information about the M&R strategy to be implemented for each road section.

To analyze these road section-linked results, four road sections were chosen with different attributes in the present year. Table 3 illustrates the attributes of these four road sections including their present PSI value. In Table 4 are presented the M&R operations to be applied in the four road sections considering the four M&R solutions of the Pareto frontier.

Figure 8 represents the predicted evolution of the PSI value over the years for pavement section 34 of municipal road EM 514 as a consequence of the execution of the M&R plan. For this pavement section, which has a PSI value of 3.67, if solution I of MODAT is adopted, the same M&R operation 2 (non-structural maintenance) would be applied in years 2012 and 2019. If solution II of MODAT is adopted the two M&R operations would be the same that were allocated considering solution I (M&R operation 2) but would be applied in different years (2013 and 2027). If solution IV of MODAT is adopted the two M&R operations would be the same that were allocated considering solutions I and II (M&R operation 2) but would be applied in different years (2012 and 2024). In terms of M&R operations it is a solution located between the other two solutions, as expected, taking into account the weights that were considered. If solution III of MODAT is adopted the recommended M&R operations are very different. The MODAT recommends the application of three M&R operations 5 (major rehabilitation) in years 2012, 2016, and 2020, and one M&R operation 4 (medium rehabilitation) in year 2024. In this solution the M&R operations are more and heavier because this solution corresponds to the minimization of user costs which means that the pavement quality must be always high.

An identical analysis could be made for each one of the other pavement sections.

Table 3 - Attributes of road sections

| Attributes | Sections | | | |
|---|---|---|---|---|
| Municipal road | EM 508 | EM 506 | EM 509 | EM 514 |
| Section_ID1 | 14 | 4 | 22 | 34 |
| Section_ID2 | 3015050019 | 3015030012 | 3025080001 | 3025140017 |
| Road_class | Local dist. | Local dist. | Local dist. | Local dist. |
| Length (m) | 1200.00 | 2067.00 | 700.00 | 600.00 |
| Width (m) | 5.00 | 5.00 | 5.00 | 5.00 |
| Subgrade_CBR (%) | 10 | 10 | 10 | 10 |
| Thickness_of_pavement_layers (m) | 0.26 | 0.28 | 0.26 | 0.26 |
| Structural_number | 1.91 | 1.91 | 1.91 | 1.91 |
| Age_of_pavements (years) | 28 | 25 | 3 | 3 |
| Annual_average_daily_traffic | 38 | 260 | 64 | 25 |
| Annual_average_daily_heavy_traffic | 25 | 60 | 15 | 12 |
| Annual_growth_average_tax | 0.03 | 0.03 | 0.03 | 0.03 |
| Truck_factor | 2.00 | 2.00 | 2.00 | 2.00 |
| Cracked_area (%) | 23.00 | 8.00 | 0.00 | 2.20 |
| Alligator_cracked_area (%) | 8.00 | 0.00 | 0.00 | 0.00 |
| Potholes_area (%) | 19.00 | 0.00 | 0.00 | 0.00 |
| Ravelling_area (%) | 0.00 | 61.00 | 0.00 | 0.00 |
| Patching_area (%) | 50.00 | 29.00 | 0.00 | 0.00 |
| Average_rut_depth (mm) | 0.00 | 0.00 | 0.00 | 0.00 |
| IRI (mm/km) | 3500 | 3500 | 5500 | 3500 |
| $PSI_0$ | 1.88 | 1.90 | 3.50 | 3.67 |

Table 4 - M&R operations to be applied in road sections

| Section | $PSI_0$ | Year | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |
| Solution I - Knee point ( $w_{AC}$ =0.05, $w_{UC}$ =0.95, $w_{RV}$ =0.00) | | | | | | | | | | | | | | | | | | | | | |
| 14 | 1,88 | 5 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| 4 | 1,90 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 22 | 3,50 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 34 | 3,67 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Solution II ( $w_{AC}$ =1.00, $w_{UC}$ =0.00, $w_{RV}$ =0.00) | | | | | | | | | | | | | | | | | | | | | |
| 14 | 1,88 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 1,90 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 22 | 3,50 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 34 | 3,67 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 |
| Solution III ( $w_{AC}$ =0.00, $w_{UC}$ =1.00, $w_{RV}$ =0.00) | | | | | | | | | | | | | | | | | | | | | |
| 14 | 1,88 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 1,90 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 22 | 3,50 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | 1 |
| 34 | 3,67 | 1 | 1 | 3 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 |
| Solution IV ( $w_{AC}$ =0.50, $w_{UC}$ =0.50, $w_{RV}$ =0.00) | | | | | | | | | | | | | | | | | | | | | |
| 14 | 1,88 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 1,90 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 22 | 3,50 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 34 | 3,67 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 |

**KEY (M&R actions):**
**1** – Do nothing; **2** - Non structural maintenance; **3** - Minor rehabilitation; **4** - Medium rehabilitation; **5** – Major rehabilitation

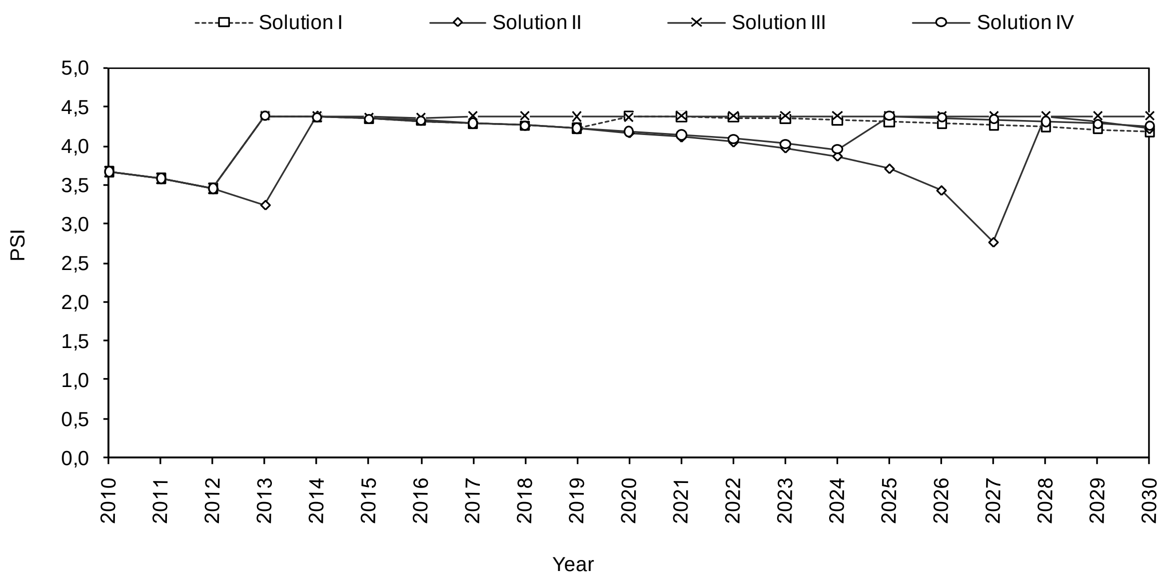


Figure 8 - Evolution of PSI for pavement section 34 of municipal road EM 514

# CONCLUSIONS

The Multi-Objective Decision-Aid Tool (MODAT) presented in this paper, incorporating several objectives into the same optimisation model, can solve the pavement management problem for the case involving major rehabilitation interventions. The MODAT, as well as the decision-aid tool currently in use in the Oliveira do Hospital's PMS, which has the objective of minimising costs over a selected planning time-span, allows closing of the gap between project and network management. This is made possible by replacing the traditional microscopic approach, which uses models that include independent variables explaining the pavement deterioration process (i.e. layer thickness, resilient modulus, asphalt characteristics, traffic, climate, etc.), with a macroscopic approach that uses models for predicting the future condition of the pavement based on measured condition data (i.e. cracking, ravelling, potholes, patching, rutting, longitudinal roughness, skid resistance, traffic, climate, etc.). The macroscopic approach requires that each road section is homogeneous in terms of quality, pavement structure, traffic and climate. It is assumed that each road section possesses one performance curve with any estimated future performance value representing the overall average pavement condition. The MODAT considers the pavement performance model used in the AASHTO flexible pavement design method but any other preferred model can be used as well. In the implementation of an optimum solution recommended by the MODAT, a field review must be conducted to identify continuous road sections with the same or identical M&R interventions with the goal of aggregating them into the same road project. It is recommended that whenever actual pavement performance data becomes available, it should replace the predicted PSI values from the AASHTO pavement performance model. Any other appropriate pavement condition indicator can easily be used as an alternative in this methodology. It is further recommended that the MODAT is applied as often as necessary (annually or bi-annually) to obtain revised optimum M&R plans that would incorporate the impact of any recent changes that might have taken place in the pavement network.

The MODAT constitutes a new useful tool to help the road engineers in their task of maintenance and rehabilitation of pavements. This new approach allows PMS to become interactive decision-aid tools, capable of providing road administrations with answers to “what-if” questions in short periods of time. In the future, because the MODAT is an open system, some modifications could be made to better serve the needs of road engineers. In the near future, our research in the pavement management field will follow two main directions. First, the MODAT will be applied to a national road network, with heavier traffic, to see if the results are identical. Second, pavement performance models will be developed using pavement performance data available in some road network databases and will be incorporated into MODAT for future applications to road networks.

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