

OPTIMAL PAVEMENT MAINTENANCE PROGRAMS BASED ON A HYBRID GREEDY RANDOMIZED ADAPTIVE SEARCH PROCEDURE ALGORITHM

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Abstract. Insufficient investment in the public sector together with inefficient maintenance infrastructure programs lead to high economic costs in the long term. Thus, infrastructure managers need practical tools to maximize the Long-Term Effectiveness (LTE) of maintenance programs. This paper describes an optimization tool based on a hybrid Greedy Randomized Adaptive Search Procedure (GRASP) considering Threshold Accepting (TA) with relaxed constraints. This tool facilitates the design of optimal maintenance programs subject to budgetary and technical restrictions, exploring the effect of different budgetary scenarios on the overall network condition. The optimization tool is applied to a case study demonstrating its efficiency to analyze real data. Optimized maintenance programs are shown to yield LTE 40% higher than the traditional programs based on a reactive strategy. To extend the results obtained in this case study, a set of simulated scenarios, based on the range of values found in the real example, are also optimized. This analysis concludes that this optimization algorithm enhances the allocation of maintenance funds over the one obtained under a traditional reactive strategy. The sensitivity analysis of a range of budgetary scenarios indicates that the funding level in the early years is a driving factor of the LTE of optimal maintenance programs.

Keywords: maintenance program, network management, heuristic optimization, asset management, infrastructure management, pavement.

Introduction

Transportation infrastructure is one of the major assets of any country, as it contributes to economic and social development (Sivilevičius 2011; Uddin *et al.* 2013). Therefore, developing suitable maintenance standards must be one of the priorities of public agencies; they include programmed strategies such as preservation, maintenance and rehabilitation treatments over time (Uddin *et al.* 2013). An adequate maintenance program allows infrastructure to fulfill the ultimate purpose for which it was built, in a context where a structure performs successfully during its service life and where users demand higher quality, comfort, and safety. However, infrastructure managers often deal with limited budgets, which are not sufficient to satisfy the network maintenance needs (Karim 2010; Uddin *et al.* 2013). This leads to a noticeable deterioration of infrastructure, increasing the gap between infrastructure needs and historical rates of investment (AEC 2012;

ASCE 2013). Recent figures are worrisome: in the United States, one-third of the highways are in poor or mediocre conditions and one in nine bridges is classified as structurally deficient (ASCE 2013). Similar trends are found in Europe: in Spain, for example, pavements are in poor condition and the investment needed in road maintenance is estimated at more than 5,500 million of Euros, while annual budget was reduced 20% in 2012 (AEC 2012). Delaying maintenance implies not only a risk of structural failure but also an increase in user and maintenance costs, as most infrastructures require increasingly larger investments over time. Indeed, late maintenance has been proved to triple the cost of rehabilitation activities and vehicle operating costs (Geoffroy 1996).

Under these circumstances, transportation agencies need to optimize the allocation of available funds in order to maximize the Long-Term Effectiveness (LTE) of investments (Torres-Machí *et al.* 2014a; Marzouk *et al.*

2012; Uddin *et al.* 2013). LTE should be assessed from a social perspective, accounting for the overall costs and benefits in the infrastructure life-cycle and considering costs derived both from the agency and the users. At the network management level (Sivilevičius 2011), where the primary aim is to develop a priority program and schedule of work within overall budget constraints, agencies must decide which infrastructure to treat, which preservation, maintenance, and rehabilitation treatment to apply and when this treatment must be carried out (Uddin *et al.* 2013). This is known as the budget allocation problem and presents S^{TxN} possible solutions in the case of a network with N sections and S possible treatments over a planning horizon of T years. In order to solve this combinatorial problem, pavement management systems have a module to address the optimization of maintenance alternatives at the network level.

This combinatorial optimization problem can be solved using either mathematical or heuristic methods. Mathematical methods (including linear, non-linear, integer and dynamic programming) have been applied in previous studies dealing with both bridge (Frangopol, Liu 2007) and pavement maintenance (de la Garza *et al.* 2011; Gao *et al.* 2012; Marzouk *et al.* 2012). These methods have the advantage of providing optimal solutions for the network as a whole. However, the objective function in mathematical methods must be differentiable or continuous, or the reasonable region must be convex. This reduces its efficiency to problems with a few design variables. Therefore, their application is commonly limited to small networks (Torres-Machí *et al.* 2014b).

Heuristic methods, whose development is linked to the evolution of artificial intelligence procedures, include a large number of search algorithms based on iterations in which the objective function is evaluated and the constraints are checked. Previous studies have reported that heuristic methods lead to simpler and more computationally efficient solutions than mathematical methods (Ferreira *et al.* 2002). Heuristic methods include both evolutionary algorithms and local search heuristics. Evolutionary algorithms and more specifically, genetic algorithms have been extensively used to solve the problem of bridge maintenance (Zhu, Frangopol 2013) and large pavement networks (Meneses, Ferreira 2013). However, too little attention has been given to local search heuristics, which so far have only been applied to solve the problem at the project level (Tsunokawa *et al.* 2006; Chou, Le 2011). Actually, studies in other research fields (i.e. structural design (Torres-Machí *et al.* 2013b) and transportation routes (Yepes, Medina 2006) have reported the efficiency of local search heuristics to solve combinatorial optimization problems. Indeed, they have proven suitable to provide more robust results than the commonly used genetic algorithms (Rao, Shyju 2010). Having detected this gap in the literature, the objective of this study is to develop an optimization module based on local search heuristics to optimize the allocation of maintenance funds at the network level.

One common aspect of local search heuristics (such as Threshold Accepting, Simulated Annealing, Variable Neighborhood, etc.) is that they start with an initial solution and explore its neighborhood looking for better solutions within the constraints. This initial solution is normally generated randomly and improved in the iteration process until local optima is found. However, one of the main difficulties in solving the budget allocation problem is finding an initial feasible solution. This difficulty may be overcome by transforming the problem into an unconstrained one, by relaxing the constraints of the problem and/or by constructing an initial feasible solution. The transformation of the problem into an unconstrained one is done by considering a penalty function in the objective function (Ponz-Tienda *et al.* 2013; Torres-Machí *et al.* 2013a). On the other hand, relaxation strategies (such as the branch and bound method and Lagrangian relaxation) replace the optimization problem with a sequence of relaxed sub-problems that are easier to solve (Pardalos, Romeijn 2002). Finally, constructing solutions ensures that initial solutions fulfill the restrictions of the problem.

The heuristic proposed in this study considers these three strategies to relax the problem. It consists of a hybrid algorithm based on a Greedy Randomized Adaptive Search Procedure (GRASP) with Threshold Accepting (TA), GRASP-TA henceforth. In this study, GRASP (Feo, Resende 1989) allows for construction of a population of feasible solutions considering penalty functions and constraint relaxations; the TA (Dueck, Scheuer 1990) is a postprocessor of these constructed solutions that intensifies the search. The Hybrid GRASP strategy has been successfully applied in the engineering field, mainly in location and scheduling problems and routing design (Duhamel *et al.* 2012; Goodman *et al.* 2012). However, to our knowledge, no applications have been developed in the field of infrastructure maintenance management.

This study aims to assist pavement managers in the implementation of effective methods for the optimal design of maintenance programs subject to budgetary and technical restrictions. The scope of the study includes the definition of the optimization problem, the development of the optimization module and its application to a case study involving the maintenance of an urban pavement network. Although this numerical application analyzes a pavement network, other infrastructure networks could be similarly studied.

To achieve these objectives, the study considered a four-step method. First, the optimization problem faced by pavement managers in the design of maintenance programs at the network level was defined. Second, an evaluation computer module was developed; this module computes the LTE of maintenance alternatives and checks both technical and budgetary restrictions. Third, a computer module of the proposed local search heuristic was programmed and applied to a real case study. In order to extend the results obtained in this case study, a set of simulated scenarios based on the range of values found in the real example, were also optimized. Finally, a

parametric study analyzing the effect of different budgetary scenarios on network conditions was undertaken.

1. Formulation of the optimization problem

The proposed problem involves a single-objective optimization of the LTE (F , defined by Eqn (1)) while satisfying the constraints (g_j , defined by Eqn (2)):

$$\text{Max } F(x_1, x_2, \dots, x_m); \tag{1}$$

$$g_j(x_1, x_2, \dots, x_m) \leq 0. \tag{2}$$

In the expressions above, the objective function F in Eqn (1) is the LTE of the maintenance program, measured in terms of the infrastructure’s performance over time. Constraints g_j in Eqn (2) are technical and budgetary restrictions that the maintenance program must satisfy. Solutions that satisfy both constraints are called feasible solutions. Finally, x_1, x_2, \dots, x_m are the design variables of the problem.

1.1. Objective function

The optimization module intends to identify the maintenance program maximizing the LTE of the network. This study aims to assess LTE based on a life-cycle analysis, considering the evolution over time of infrastructure performance and maintenance treatment costs. Infrastructure performance is assessed in terms of an indicator that evaluates the degree to which the infrastructure serves its users and fulfills the purpose for which it was built or acquired (Uddin et al. 2013). Previous studies have developed performance indicators for different types of infrastructure: pavements (Chamorro, Tighe 2009; Chamorro et al. 2010; Sivilevičius, Vansauskas 2013), bridges (Neves, Frangopol 2005), etc., as well as other aspects in the construction management field (Ballesteros-Pérez et al. 2014).

This study considers a performance indicator developed by Osorio et al. (2014) to assess urban pavement condition based on objective measures of surface distresses and evaluations by an expert panel. The definition of this indicator, called Urban Pavement Condition Index (UPCI), is part of a project that is being developed in Chile “Research and Development of Solutions for Urban Pavement Management in Chile”. UPCI is an overall condition index for urban pavements that represents the more relevant distresses for use in network analysis. UPCI has been developed and validated for both asphalt and concrete pavements and rates pavement condition on a scale ranging from 1 to 10, being 1 the worst condition and 10 the best. Moreover, any performance indicator can be used to optimize the budget allocation problem using the framework described in this study.

The assessment of LTE of maintenance alternatives is set in terms of the area limited by the performance curve and a threshold value of the infrastructure’s condition (Area Bounded by the Performance Curve, here-

after *ABPC*). The rationale of this approach is simple: a well-maintained infrastructure (having therefore a larger *ABPC*) provides greater benefits than a poorly maintained infrastructure (Khurshid et al. 2009; Chamorro et al. 2012). Moreover, as benefits derived from a well-maintained infrastructure are numerous and difficult to quantify in monetary terms, the *ABPC* can be used as a surrogate for overall user benefits (Khurshid et al. 2009).

Therefore, the objective function is defined as the maximization of the LTE of the network maintenance program. This function (*LTE*, defined by Eqn (3)) is evaluated by adding the *ABPC* of all the sections comprised in the network:

$$\text{max } LTE = \text{max} \left(\sum_{n=1}^N ABPC_n \right), \tag{3}$$

where $ABPC_n$ is the area bounded by the treatment performance curve of section n (with $n \leq N$, being N the total number of sections in the network).

1.2. Constraints

Constraints in Eqn (2) include budgetary and technical restrictions. The budgetary restriction limits annual maintenance costs based on available budget (Eqn (4)). Technically, a minimal condition for all the sections in the network is required (Eqn (5)):

$$g_1 = \sum_{t=1}^T \sum_{n=1}^N \text{cost}(x_n) \cdot \frac{1}{(1+i)^t} \leq B_t ; \forall t; \tag{4}$$

$$g_2 = UPCI_{n,t} \geq UPCI_{min,n} ; \forall t \text{ and } \forall n, \tag{5}$$

where t is the analysis year (with $t \leq T$, being T the analysis period); n is the section being analyzed (with $n \leq N$, being N the total number of sections in the network); $\text{cost}(x_n)$ is the unit cost of maintenance alternative x in

infrastructure n ; $\frac{1}{(1+i)^t}$ is the present value factor

for discount rate i in year t ; B_t is the present value of available budget in year t ; $UPCI_{n,t}$ is the Urban Pavement Condition Index of section n in year t ; and $UPCI_{min,n}$ is the minimum UPCI allowed for section n .

1.3. Variables

The variables of the optimization problem define the network maintenance program. Specifically, they determine which section should be treated and which treatment should be applied each year over the analysis period. A total of $m = N \times T$ variables define a solution for the budget allocation problem of a network with N sections over an analysis period of T years. Each of these m variables can take S_n possible values, being S_n the number of treatment alternatives available for each section n . Given a set of values for the variables of the present problem, the verification of constraints (g_1 and g_2) and the evalua-

tion of the objective function (LTE , Eqn (3)) are straightforward.

1.4. Parameters

Parameters are the magnitudes that remain constant in the optimization process. These parameters are divided into inventory, technical, economic and strategic level data. Inventory data include information regarding section reference (name, code, location, width, length, etc.), climate (e.g. dry, Mediterranean and humid), structure (road surface type) and traffic data (traffic types and characteristics, traffic volume per road, etc.) for all the sections of the network.

Technical parameters required for network analysis include the network initial condition, its progression over time and information regarding the set of possible maintenance treatments. In this study, maintenance treatments are classified as preservation, maintenance and rehabilitation activities. Preservation activities restore the pavement's function and extend its service life, but do not increase its capacity or strength. Preservation treatments are implemented while pavements are still in good condition and before the onset of serious damage (Fig. 1). Maintenance treatments delay future deterioration and maintain or improve the functional condition of the infrastructure (without significantly increasing the structural capacity). Maintenance is typically applied to pavements in good or fair condition, having significant remaining service life (Fig. 1). Rehabilitation activities consist of structural enhancements that extend the service life of an existing pavement and/or improve its load carrying capacity. They may be applied to pavements showing bad or very bad condition (Fig. 1). The pavement condition threshold values considered in this study for preventive, maintenance and rehabilitation activities are shown in Figure 2. The application of each of these activities leads to an increase in pavement service life (ΔSL) and, therefore, an immediate improvement in pavement condition ($\Delta UPCI$) at the moment of application (Fig. 1).

Economic parameters are related to the costs of maintenance alternatives. Finally, strategic level data are related to the agency's objectives and goals. These data include minimal condition requirements ($UPCI_{min}$), available funding level (B_t), study period (T), and discount rate (i).

2. Development and application of the proposed hybrid heuristic

The heuristic method used in this study is a hybrid optimization strategic method based on Greedy Randomized Adaptive Search Procedure (GRASP) and Threshold Accepting (TA), GRASP-TA henceforth. First, a population of feasible solutions is constructed based on GRASP. The GRASP procedure implemented in this study considers both a relaxation of the economic constraint and the application of a penalty function if the technical constraint is not fulfilled. Once a population of constructed solutions is obtained, they are subjected to a local search based on TA. Each of these processes is explained in detail in the following sections.

2.1. Construction of feasible maintenance programs based on GRASP

The GRASP procedure is a multi-start or iterative process that facilitates the construction of a population of feasible maintenance programs (MP_{GRASP}). At each construction iteration, all the possible movements are analyzed and ranked with respect to a greedy function. The greedy function measures the benefit of selecting each possible movement and therefore its priority to be selected. From this ranked list, a movement is selected based on a probabilistic function. This random selection combines the quality and the variability of the configurations obtained in the construction phase.

In this study, solutions are iteratively constructed for each year of the study period (t , with $t \leq T$). At each construction iteration, the algorithm evaluates the effect of applying all the possible treatments (s_n , with $s_n \leq S_n$) to each section in the network (n , with $n \leq N$). This evaluation quantifies three values (Fig. 2): the area limited under the performance curve if the treatment under evaluation is applied ($ABPC_{n,s_n}$); the area bounded under the performance curve if no treatment is applied ($ABPC_{n,0}$); and the year of failure (time in which ICPU equals zero) if no treatment is applied ($t_{failure,0}$).

These values can be used to assess the greedy function (Eqn (6)) that quantifies the benefits of selecting the treatment under evaluation (s_n). This greedy function considers two components: the increase in LTE if the treatment s_n is applied ($ABPC_{n,s_n} - ABPC_{n,0}$) and

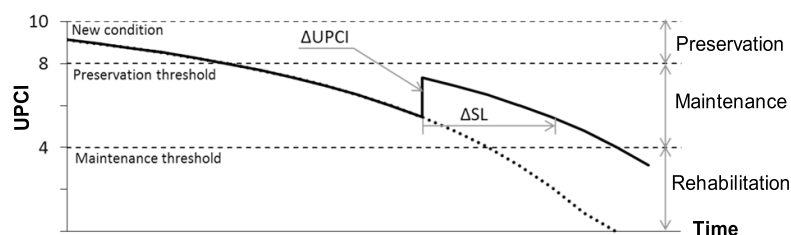


Fig. 1. Maintenance activities lead to an increase in pavement service life (ΔSL) and, therefore, an immediate improvement in pavement condition ($\Delta UPCI$) at the moment of application

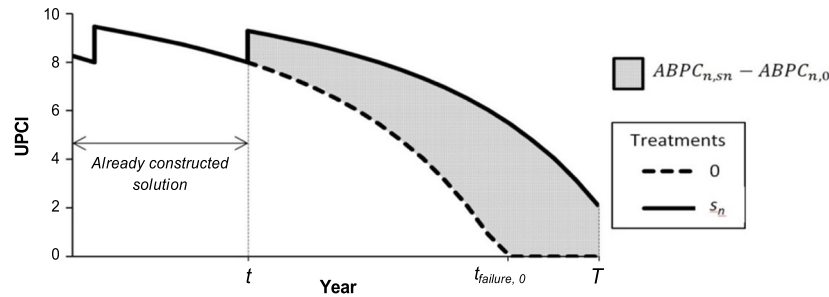


Fig. 2. Effect of the treatment s_n to construct the solution in year t with GRASP algorithm

a penalty value $(\alpha \cdot (T - t_{failure,0}))$. This penalty value is controlled by the parameter α (defined in Eqn (7)), which prioritizes those sections that will fail before the end of the study period if no treatment is applied:

$$GF_{n,sn} = ABPC_{n,sn} - ABPC_{n,0} + \alpha \cdot (T - t_{failure,0}); \quad (6)$$

$$\alpha = \begin{cases} 100 & \text{if } t_{failure,0} \leq T \\ 0 & \text{if } t_{failure,0} > T \end{cases} \quad (7)$$

Once all the possible treatments (s_n) on all the sections in the network (n) have been quantified, they are ranked in terms of the value of the greedy function ($GF_{n,sn}$). This ranking ensures that the most effective treatment is more likely to be included in the maintenance program than less effective alternatives. The elements to be included in the maintenance program in year t are then selected based on a probability function if their consideration fulfills economic restriction. As stated in the introduction, the economic restriction considered in the construction process is relaxed by means of a parameter β (Eqn (8)). To select elements for the ranked list, this study considers a parametric probability function proposed by Yepes and Medina (2006) and defined in Eqn (9). Based on a list of r candidates, the best i th has a probability of $p(i,r)$ of being chosen. This probabilistic function is controlled by the parameter η , which includes the extreme cases of deterministic selection (when $\eta = 0$) and equiprobable selection among all the candidates (when $\eta = 1$). Numerical experiments developed in this study resulted in better solutions considering this probabilistic method. In this study, a value of $\eta = 0.1$ was used:

$$\xi_{1,relaxed} = \sum_{t=1}^T \sum_{n=1}^N cost(x_n) \cdot \frac{1}{(1+i)^t} \leq \beta \cdot PWB_t; \quad \forall t; \quad (8)$$

$$p(i,r) = \eta^{i-1} \cdot \frac{1-\eta}{1-\eta^r}; \quad 0 \leq \eta < 1. \quad (9)$$

This construction process, repeated for all the years in the study period, results in a maintenance program at the network level (MP_{GRASP}) whose annual cost does not exceed the available budget.

2.2. Local search using threshold accepting algorithm

To intensify the optimization, a postprocessor based on TA is proposed. TA explores the neighborhood of the population of solutions constructed using GRASP (MP_{GRASP}) in order to obtain the locally optimal solution. TA starts with an initial solution (MP) and an initial high threshold value (T_0) for accepting solutions. This solution (MP) is gradually altered by applying moves to the values of the variables. The new generated solution (MP') is evaluated and it is adopted as the new current solution if it improves the objective function and it fulfills the constraints. In this postprocessor optimization, the constraints of the problem are not relaxed, using the expressions g_1 and g_2 defined in Eqns (4) and (5). Less effective solutions are also accepted when the reduction in LTE is smaller than the current threshold. The acceptable threshold decreases with the number of iterations following the schedule defined in Eqn (10). According to this schedule, the acceptable threshold is decreased linearly during a determined number of iterations (n_{iterTh}). After this process, a local search only accepting better solutions ($T = 0$) is undertaken. The algorithm stops after a specific number of iterations ($n_{itermax}$);

$$T = \begin{cases} T_0 - \frac{T_0}{n_{iterTh}} \cdot n_{iter} & \text{if } n_{iter} \leq n_{iterTh} \\ 0 & \text{if } n_{iterTh} < n_{iter} < n_{itermax} \end{cases} \quad (10)$$

Compared to other local search heuristics, TA allows for the local optima to be left by letting the degradation of a solution within an acceptance threshold. The authors have previously applied local search heuristics to solve the budget allocation problem using Simulated Annealing (Torres-Machí et al. 2013a). However, in this study, the authors propose the use of TA, as low thresholds allows to control better that the search remains near the neighborhood of the constructed solution. Moreover, hybrid algorithms using TA as a postprocessor local search lead to successful results in other optimization problems (Yepes, Medina 2006; Torres-Machí et al. 2013b).

3. Case study

The proposed algorithm was applied to a case study considering an urban pavement network composed of 20 sections including both flexible and rigid pavements. Differ-

ent maintenance strategies are evaluated for each type of pavement in order to identify the optimal maintenance program in terms of LTE.

3.1. Data

This study considers a pavement network located in Santiago (Chile), characterized by a Mediterranean climate (Table 1). This network includes asphalt and concrete pavements belonging to urban network.

Table 1. Inventory data parameters and network initial conditions considered in the analysis

ID	Structure	Width [m]	Length [m]	UPCI _{ini}
1	Asphalt	3.5	1,800	6.0
2	Asphalt	3.5	1,300	7.3
3	Asphalt	3.5	1,800	8.5
4	Asphalt	3.5	2,500	9.1
5	Asphalt	3.5	2,300	8.3
6	Asphalt	3.5	1,400	9.1
7	Asphalt	3.5	2,100	4.8
8	Asphalt	3.5	1,000	5.4
9	Asphalt	3.5	2,000	8.3
10	Asphalt	3.5	1,500	8.5
11	Concrete	3.5	1,800	5.3
12	Concrete	3.5	1,300	6.5
13	Concrete	3.5	2,700	6.0
14	Concrete	3.5	2,200	6.5
15	Concrete	3.5	2,700	6.0
16	Concrete	3.5	1,200	4.5
17	Concrete	3.5	1,700	3.5
18	Concrete	3.5	1,700	8.0
19	Concrete	3.5	1,600	6.0
20	Concrete	3.5	1,000	7.2

This study considers the network initial condition (UPCI_{ini} in Table 1) based on manual field evaluations carried out in February 2013 as part of the project being developed in Chile. As the development and validation of urban performance models are currently under evaluation, this study has considered the model developed by Smith (1986) (Eq. (11)). Even though these performance models may not reflect the true deterioration of urban pavements, they would not affect the optimization process, which is the main aim of the present study. Indeed, other performance models may be similarly considered and other urban performance models will be incorporated in the future. Based on these considerations, performance models for both asphalt and concrete pavements were adjusted using data from field evaluations (Table 2).

$$UPCI = \left(100 - \frac{\rho}{(\ln(\alpha) - \ln(\text{age}))^{1/\beta}} \right) \frac{1}{10}. \quad (12)$$

Table 2. Parameters of performance models considered in the analysis

Structure	ρ	α	β
Asphalt	38.82	37.54	0.54
Concrete	14.39	29.70	0.90

The increases in service life considered herein for each treatment (Tables 3 and 4) were taken from American and Canadian studies (Hicks *et al.* 2000; TAC 2013). The present study also considers a 10% reduction in treatment service life each time it is applied. This consideration means a loss in efficiency of treatments applied repeatedly (Wei, Tighe 2004).

Unit costs of maintenance alternatives considered in this study (Tables 3 and 4) were mainly obtained from Chilean maintenance contracts in the Municipality of Santiago and from meetings with professionals from the

Table 3. Treatment alternatives considered for asphalt pavements

Treatment	Classification	Service life increase (ΔSL) [years]	Cost [US\$/m ²]
Do nothing	–	0	0
Crack sealing	Preservation	2	0.99
Fog seal	Preservation	3	1.02
Slurry seal	Maintenance	4	2.82
Surface treatment 1	Maintenance	5	3.07
Surface treatment 2	Maintenance	6	9.42
Surface treatment 3	Maintenance	7	9.89
Milling and functional resurfacing	Maintenance	10	23.24
Milling and structural resurfacing	Rehabilitation	12	25.44
Hot in place recycling	Rehabilitation	10	35.39
Cold in place recycling	Rehabilitation	13	36.50
Full depth reclamation	Rehabilitation	13	41.93
Reconstruction	Rehabilitation	25	66.74

Table 4. Treatment alternatives considered for concrete pavements

Treatment	Classification	Service life increase (ΔSL) [years]	Cost [US\$/m ²]
Do nothing	–	0	0
Crack sealing	Preservation	5	1.75
Diamond grinding	Preservation	10	15.39
Partial depth slab repair	Maintenance	7	12.57
Milling and functional resurfacing	Maintenance	11	33.77
Milling and structural resurfacing	Rehabilitation	12	37.36
Reconstruction	Rehabilitation	25	134.60

Ministry of Public Works of Chile. Treatments not currently applied in Chile were extracted from international literature and included in the analysis to broaden the scope and future applications to other countries (Hicks et al. 2000; Chan, Tighe 2010).

With respect to strategic level data, the annual budget considered in this study corresponds to the minimal cost to maintain the network above the minimal pavement condition under a reactive strategy. With this reactive maintenance strategy, sections are treated using the cheapest treatment when their condition reaches a trigger value ($UPCI_{min}$). Over a planning horizon of 25 years, this strategy implies a total present cost of US\$ 5,065,782. In this study, a uniform distribution of this available budget over time is considered. The values of strategic level data considered in this study are given in Table 5.

Table 5. Strategic level data considered in this study

Parameter	Value
Minimal pavement condition ($UPCI_{min}$)	2
Study period (T)	25 years
Discount rate (i)	4%
Present value of available budget in US\$ in year t (PWB_t)	$311,800 \cdot \frac{1}{(1+i)^t}$

3.2. Results

The proposed hybrid routine (GRASP-TA) was developed in Matlab 12 on a PC AMD Phenom II X6 1055T Processor 2.80 GHz. A population of 100 maintenance program solutions was constructed using GRASP procedure considering values of the relaxation parameter ranging from 0.90 to 1.25. The calibration of the TA routine recommended 30,000 iterations with a reduction in the threshold ($n_{iter Th}$) and a total of 31,000 iterations

($n_{iter max}$) as the stop criterion. The initial threshold (T_0) was adjusted following the method proposed by Medina (2001). Regarding the movements in TA, the calibration recommended a random variation of 25 or up to 25 variables of the 500 in the problem as the most efficient move.

Table 6 presents the record solutions obtained considering different values of the relaxation parameter (β). It is apparent that a slight relaxation of the economic constraint during the construction of solutions ($\beta = 0.99$) leads to better solutions than the non-relaxed algorithm ($\beta = 1.00$). However, this relaxation must be limited and controlled because excessive relaxation (for example, $\beta = 1.25$) may lead to constructed solutions that cannot be repaired in the TA process and therefore, they do not satisfy the non-relaxed economic constraint (g_1). The solution obtained with a relaxation parameter of β equal to 0.99 presents the highest LTE.

Compared to the traditional design of maintenance programs based on a reactive strategy, the proposed optimization tool leads to values of LTE which are 40% higher. Under similar budgetary restrictions, the proposed optimization tool allows the network maintenance at a significantly higher level of service than that obtained under a reactive strategy (Fig. 3).

With respect to the treatments selected in the optimal maintenance program, preservation treatments are

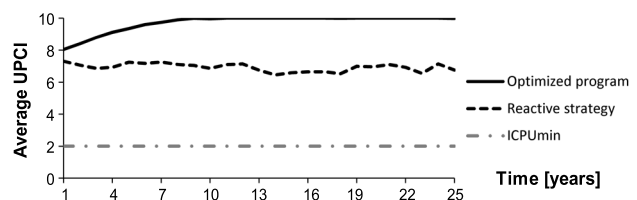


Fig. 3. Under similar budgetary restrictions, optimized maintenance programs yield higher levels of service than the traditional reactive strategy

Table 6. Record solution obtained considering different values of the economic relaxation parameter

β	1.25	1.20	1.15	1.10	1.05	1.01	1.00	0.99	0.95	0.90
LTE	4,262(*)	4,319	4,143	4,438	4,427	4,521	4,561	4,590	4,446	4,298

Note: where (*) is a record solution which does not satisfy the non-relaxed economic constraint (g_1 in Eqn (4)).

the most frequently selected activities (80% of the times, whereas maintenance and rehabilitation treatments are selected in a ratio of 19% and 1%, respectively). It can therefore be concluded that preservation treatments are more effective in the long-term than maintenance and rehabilitation treatments.

In addition, it should be noted that none of the alternatives involving recycling techniques are included in the optimal solution. This may be due to the fact that preservation is preferred to maintenance and rehabilitation. Recycled alternatives imply higher costs than other treatments, but present similar effects in terms of service life. Certainly, the optimal maintenance program obtained in this case study included only 1% of rehabilitation treatment, namely milling and structural resurfacing. Other rehabilitation treatments having a similar service life and being more respectful with the environment (such as hot in place and cold in place recycling) are, in contrast, not selected in optimal maintenance programs. This result highlights the need to incorporate environmental benefits when using recycled alternatives.

3.3. Analysis of inventory scenarios

The application developed in the previous section shows the benefits, in terms of LTE, of the proposed optimization algorithm. This case study corresponds to a real urban network with its specific characteristics in terms of inventory. In order to extend the conclusions derived from this case study, a set of scenarios having different inventory information was analyzed. Due to the difficulty to obtain real data for this problem, the inventory data parameters for these new scenarios were simulated based on the range of values that were found in the real example.

The new scenarios consider variations in pavement structure and initial pavement condition of the sections in the network. Three levels of each of these factors were analyzed. With respect to structure, the levels correspond to networks in which 25, 50 or 75% of the sections have an asphalt structure (having the remaining percentage of sections a concrete structure). With respect to network condition, the analyzed levels were: good, fair or poor. These levels correspond to the type of treatment that can be applied to improve pavement condition. Considering the threshold values defined in Figure 1, this study considers that a network in good condition can be treated with preservation activities and, therefore, the average network condition is between 10 and 8. A similar reasoning was considered to define the categories of fair condition (average network condition between 8 and 4) and poor condition (average network condition below 4). The combination of these factors leads to nine possible scenarios that were optimized. It is important to note that the case study analyzed in the previous section corresponds to a scenario with an initial network in fair condition (average $UPCI_{ini}$ is 6.8) with a 50% of sections with asphalt structure.

The analysis of inventory scenarios found that, compared to the reactive strategy, the proposed optimization algorithm increases the average LTE in 21%. Figure 4

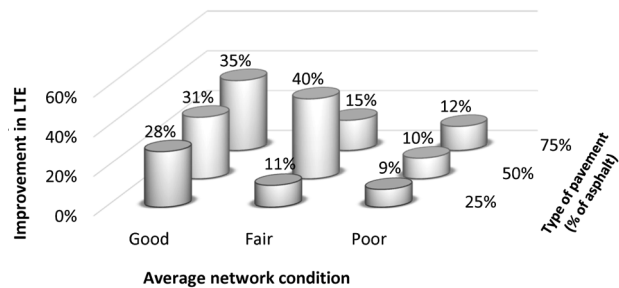


Fig. 4. Improvement in LTE obtained with the proposed optimization algorithm considering different inventory scenarios

presents the results, in terms of improvement in LTE, obtained from the analysis of each scenario. In all cases, optimized maintenance programs show a higher LTE than programs designed with a traditional reactive strategy. What is apparent in Figure 4 is that the results match those observed in the real case study. In conclusion, the analysis of inventory scenarios has allowed extending the benefits of using the proposed optimization algorithm to a wider range of situations. Therefore, it can be concluded that, in the nine scenarios analyzed, the proposed optimization algorithm allows a better allocation of maintenance funds than the one obtained under a traditional reactive strategy.

3.4. Analysis of budgetary scenarios

One of the major advantages of the proposed optimization tool is that it enables infrastructure managers to evaluate the impact of strategic level data on network performance. In order to analyze this capability, this section describes different budget scenarios. Eleven budgetary scenarios were studied to evaluate their impact on network performance. For comparative purposes, the budget scenario presented in Section 4.1 is taken as a base case (Scenario 0). The first set of scenarios (Scenarios 1 to 8) consists of percentage increases and reductions of the base case. Meanwhile, the second set of scenarios (Scenarios 9 to 11) consists of budgets having a similar total present value of funds during the study period but differing in their distribution over time (Fig. 5). These eleven budgetary scenarios were optimized using GRASP-TA routine with a relaxation parameter β equal to 0.99.

Scenarios 1 to 8 can be used to analyze the impact of percentage variations in funds on network performance. Figure 6 shows the variation of LTE of optimal maintenance programs with variations in the total present value of available budget. It is apparent from this analysis that reductions in available budget have a greater impact in LTE than increments. Indeed, variations of 20% in available budget lead to a decrease of nearly 11% in LTE when the budget is reduced; whereas it induces an increment of only 1.4% when the budget is increased. From the data in Figure 6, two different trends can be observed. On the one hand, slight variations in available budget lead to small fluctuations in LTE. On the other hand, higher

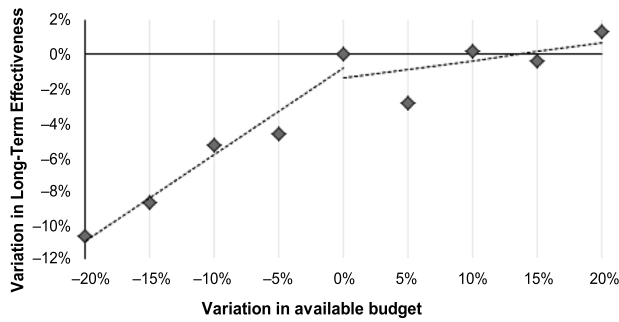


Fig. 5. Variation of LTE with total present value of available budget

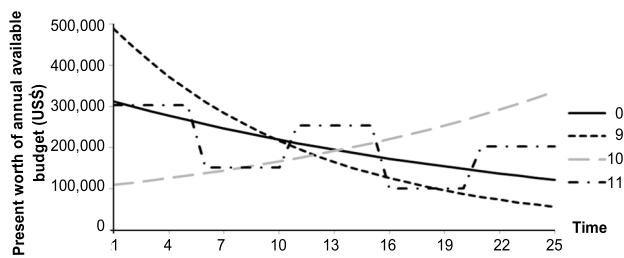


Fig. 6. Scenarios 9 to 11 have a similar total amount of funds but differ in their distribution over time

reductions in available budget lead to significant reductions in LTE.

Meanwhile, scenarios 9 to 11 simulates the effect of fund distribution over time, being the total present value of budget similar for all the scenarios (Fig. 5). Compared to the base case, Scenario 9 corresponds to an annual 5% reduction in the available budget. In contrast, Scenario 10 corresponds to an annual 9% increase of the available budget. Finally, Scenario 11 corresponds to a budget which does not follow a clear trend over time.

It is apparent from this analysis that funds distribution over time is significant in infrastructure LTE (Fig. 7). Surprisingly, Scenarios 9 and 11 result in maintenance programs with LTE similar to the base case scenario. Definitely, Scenario 9 leads to a maintenance program with

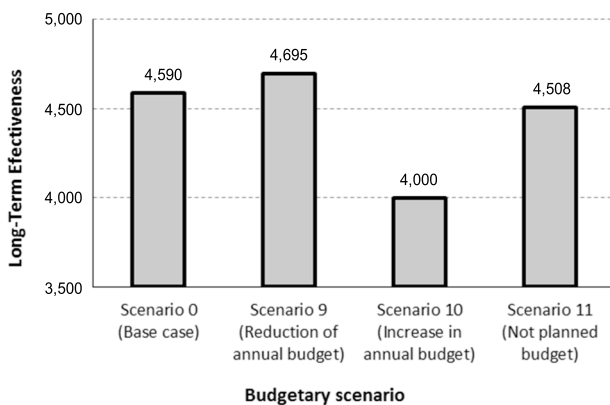


Fig. 7. Variation of LTE with different distribution of funds over time

a slightly higher LTE than Scenario 0. In contrast, Scenario 10 results in a maintenance program with a significant lower LTE (15% lower than the base case scenario). Compared to Scenario 10, Scenarios 0, 9 and 11 have a higher level of available funds in the early years of the study period (Fig. 6). Taken together, these results suggest that there is an association between funding levels in the early years of the maintenance program and the LTE of optimal maintenance programs. It can therefore be concluded that the funding level in the early years of the study period is a driving factor for the LTE of optimal maintenance programs.

Conclusions

This paper has described the suitability of a hybrid Greedy Randomized Adaptive Search Procedure and Threshold Accepting (GRASP-TA) heuristic considering a relaxation of economic constraints for the design of optimal maintenance program at the network level subject to technical and budgetary restrictions. For illustrative purposes, a case study consisting of an urban pavement network in Santiago (Chile) was analyzed. The proposed tool allows analyzing the effect of different budgetary scenarios on the network performance. In light of the results obtained in this study, the following conclusions may be drawn:

- The proposed GRASP-TA algorithm is an efficient tool to design optimal maintenance programs in terms of LTE under budgetary and technical restrictions. Optimized maintenance programs presented a LTE which was 40% higher than the traditional programs based on a reactive strategy.
- The construction of feasible solutions using GRASP with relaxed economic constraints has been used to find maintenance programs with a LTE 0.6% higher than the non-relaxed problem.
- The results of this study indicate that optimal maintenance programs consider preventive activities in 80% of the times, whereas maintenance and rehabilitation treatments are selected in a ratio of 19% and 1%, respectively. These results indicate that preventive activities are significantly more effective in the long-term than maintenance and rehabilitation activities.
- Regarding treatments considered in optimal maintenance programs, it can be detected that recycled alternatives were not considered. When compared to traditional treatments, recycled alternatives imply higher costs that are not compensated by higher increments in pavement service life. Therefore, recycled treatments do not result in competitive alternatives when only economic and technical aspects are considered. Sustainable network management will thus need additional performance indicators considering the benefits induced by environmentally friendly treatments.
- The proposed optimization tool enables infrastructure managers to evaluate the impact of strategic lev-

el data on network performance. This will help infrastructure managers to analyze the effect of budgetary restrictions on infrastructure performance.

- The analysis of different budget scenarios revealed that reductions in available budget have a greater impact on LTE than increments. In this study, variations of 20% in available budget lead to a decrease in nearly 11% in LTE when the budget is reduced; however, it induces an increment of only 1.4% when the budget is increased.
- With respect to funding distribution over time, it can be concluded that increasing budget scenarios lead to the least performing maintenance program. Compared to a base case with a constant annual budget, the increasing budget scenario analyzed in the case study yielded a 15% reduction in LTE.
- Results obtained in this study suggest that the funding level in the early years of the study period is a driving factor for LTE of optimal maintenance programs.

Further work is planned to incorporate sustainable aspects in the design of optimal maintenance programs. The incorporation of sustainable aspects, such as environmental and social impacts, would allow for managers to assess the overall costs and benefits induced by maintenance alternatives.

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